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Assessing the cost of transfer inconvenience in public transport systems: A case study of the London Underground

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ABSTRACT

Few studies have adequately assessed the cost of transfers[2] in public transport systems, or provided useful guidance on transfer improvements, such as where to invest (which facility), how to invest (which aspect), and how much to invest (quantitative justification of the investment). This paper proposes a new method based on path choice,[3] taking into account both the operator's service supply and the customers' subjective perceptions to assess transfer cost and to identify ways to reduce it. This method evaluates different transfer components (e.g., transfer walking, waiting, and penalty) with distinct policy solutions and differentiates between transfer stations and movements.

The method is applied to one of the largest and most complex public transport systems in the world, the London Underground (LUL), with a focus on 17 major transfer stations and 303 transfer movements. This study confirms that transfers pose a significant cost to LUL, and that cost is distributed unevenly across stations and across platforms at a station. Transfer stations are perceived very differently by passengers in terms of their overall cost and composition. The case study suggests that a better understanding of transfer behavior and improvements to the transfer experience could significantly benefit public transport systems.

1. Introduction

Transfers are endemic in public transport systems, especially in large multimodal networks (Vuchic, 2006). Passengers in these systems often have to transfer between different modes and services to reach their destinations. For example, in London, about 70% of Underground trips and 30% of bus trips involve at least one transfer (Transport for London, 2001). In New York City, about 30% of subway and bus trips and 80% of commuter rail trips involve at least one transfer (NYMTC, 1998). In Munich and Paris, 70% and 40% of all public transport trips, respectively, include one or more transfers (GUIDE, 2000).

Despite their popularity, transfers often are seen as a necessary evil in public transport. On the one hand, they support enlarged service areas and hierarchical, multimodal networks; on the other hand, they disrupt the travel experience and reduce public transport's competitiveness with automobiles that provide door-to-door service. Inconvenient transfers could

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[1] Tel.: +1 617 253 5046; fax: +1 617 258 8073.
[2] Another term, interchange, is often used in Europe. This paper treats them as interchangeable.
[3] Path choice is different from "way-finding" and "route choice." "Way-finding" refers to the process by which a traveler finds a path to his (her) destination. The question in that case is how to acquire information to find a route in unknown terrain. "Route-choice" sometimes refers to a choice among different services in a public transport network, even if they follow the same physical path. In this case, the decision is whether to board an arriving vehicle or to wait for a later vehicle that will have lower in-vehicle time. Neither situation will be addressed in this research; therefore, a different term, path choice, is adopted.

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deter potential customers (CTPS, 1997; Gleave, 1998; Wardman, 2001), reduce the satisfaction of existing customers (Hine and Scott, 2000), and affect customers' use of public transport systems in terms of their paths and destinations (Lam and Xie, 2002).

The transfer is a fundamental issue, but it is largely overlooked in public transport planning (MIMIC, 1999; Iseki and Taylor, 2009). In a survey conducted by the US Federal Transit Administration (1996), only three out of 31 operators surveyed specified objectives for the transfer system in relation to passenger or operating convenience, revenue generation, or other factors. Many operators pay little attention to passengers' transfer behavior and do not consider transfers part of their overall service delivery philosophy (U.S. FTA, 1996), even though many of them are aware of the importance of convenient transfers (Smart et al., 2009). A similar survey conducted in 20 European cities by the European Commission found that many operators did not even know the volume of transfers taking place in their systems (GUIDE, 1999)[4] Only one city, Copenhagen, has integrated timetables, where coordinated timetables are produced and all-mode timetables are issued (GUIDE, 1999). In general, there is no tradition of treating transfers as a distinct topic in service planning (GUIDE, 1999).

There are several possible explanations for this relative lack of attention from operators. The first explanation is the organizational barrier. Transfers often involve multiple modes that belong to separate agencies, and many transfer-related issues cross organizational boundaries. As stated in a report by Transport for London (2001), "Making even the smallest interchange improvement can often be a complex organizational task involving many different agencies each with their own objectives, priorities, sources of funding, and methods for allocating resources". Even within the same agency, operation is normally managed by separate modes or lines. Transfers are often absorbed into other tasks instead of being a core, consolidated function.

Second, operators may view their role in transfer planning as very limited. Transfers cannot be eliminated entirely. Many attributes of transfers are not easily changed after the system is built (GUIDE, 1999). In many old cities, the options for radical change to the overall network structure are limited, at least in the short term. Even for a new system, station design is often the result of an "architectural competition," with the emphasis on aesthetic qualities rather than the functionality of the building. This may result in contrasts between high-quality concourses and basic platforms (MIMIC, 1999). In many countries, operators have only limited control over stops and stations (Iseki and Taylor, 2009).

The third explanation is closely related to the second, and involves the lack of analytical tools to understand transfer behavior and evaluate transfer improvements. This is largely due to the nature of transfers. Many aspects of transfers that seem important to passengers are difficult to quantify, and individually they may have only a marginal effect. A typical analytical approach is to compile laundry lists of positive and negative attributes. However, this approach fails to consider the relative importance among these attributes and between them and other traditional time and cost factors. It also fails to differentiate them across different transfer facilities (Horowitz and Thompson, 1994; Kittelson and Associates, 2003; Evans, 2004; see Iseki and Taylor (2009) for summary). Furthermore, there are theories and models concerning "modal choice" for specific modes, but methods to explain why people mix modes and how they use (or, often, do not use) different combinations at different times are less developed (Horowitz and Thompson, 1994; MIMIC, 1999).

This paper focuses on the last issue, the transfer assessment. The purpose is twofold: first, to better understand transfer behavior and its importance to public transport; second, to better assess system-wide transfer performance and demonstrate the potential benefit of making improvements. The next section summarizes existing assessment methods. Section 3 proposes a new method based on path choice, and the remaining sections apply the method to the London Underground (LUL).

2. Transfer assessment

Transfer assessment is usually done in two ways: measuring personal transfer experience from the user's perspective and inventorying the transfer supply from the operator's perspective.

2.1. Experience assessment

Transfer experience can be divided into three components: transfer walking, waiting, and the transfer penalty, a purely psychological aspect of transfers that is affected by the transfer environment (Ortuzar and Willumsen, 2004). Each component has distinct policy implications. Transfer walking is defined by network and station design, transfer waiting is determined by service operation and management, and the transfer penalty is affected by a broad range of factors, including safety and security, ease of way-finding during transfers, availability of escalators, weather protection, seating availability, lighting, air conditioning and ventilation, and concessions on the platforms.

Experience assessment has traditionally focused on transfer time while ignoring other important factors such as environment, organization, and information (U.S. FTA, 1996; Clever, 1997). For example, many studies have examined timed transfers despite the fact that transfer waiting time is only a portion of the entire transfer experience, and the approach is valid only for low-frequency services (Abkowitz et al., 1987; Guihairea and Hao, 2008; Shafahi and Khani, 2010). In contrast, there are surprisingly few quantitative studies of the impact of fares and ticketing on transfer experience, even though their significant effects are widely acknowledged (GUIDE, 1999). This reflects operators' traditional reliance on travel time savings,

[4] For a list of transfer-related projects by the European Commission, please see Footnote 1.

rather than travel quality and ambience, to justify transfer investments. This bias has led to a low priority on transfer improvements relative to other objectives (GUIDE, 1999).

The second issue in experience assessment is that transfers are often defined inconsistently by different studies (Wardman, 2001). A transfer can be defined as a dummy variable or by the number of transfers, without separate transfer time variables (Alger et al., 1975; Han, 1987; Gleave, 1981; MVA, 1991; Toner and Wardman, 1993). The transfer variable may encompass the entire transfer experience, but it does not differentiate among the three components. Transfer time is sometimes incorporated into a consolidated travel time variable, so the dummy or number of transfer variables reflects the premium cost of transfers over travel time (Wardman, 1983; Oscar Faber TPA, 1993). A few studies separate transfer walking and waiting from the dummy or number of transfer variables (Hunt, 1990; Parsons Brinckerhoff Quade and Douglas Inc., 1993 (which included only transfer waiting); Liu et al., 1997; CTPS, 1997; Wardman et al., 2001; Guo and Wilson, 2004, 2007). In this case, all three components of the transfer experience could be estimated separately.

The third problem in experience assessment is the reliance on mode choice models and stated preference (SP) in analysis. For example, among the 47 transfer assessment studies identified by Wardman (1998), 37 are based on SP data. SP data allows greater freedom in defining the choice context, alternatives, and attributes (Bradley and Bovy, 1986), but the choice situation presented by SP data is usually uni-dimensional (e.g., number of transfers) or bi-dimensional (transfer time or cost). In other words, SP data is unable to provide variability for the diverse transfer environments sufficient to support thorough transfer estimates (Bovy and Stern, 1990). Mode choice models are relatively easy to calibrate, but they only reflect travel attributes by distinct modes. Therefore, transfers at different stations and movements must be consolidated in order to provide single mode-based estimations. Another issue with mode choice is that it is hard to separate the (non)preference for transfers from mode preference, which often results in a biased estimation.

The above problem leads to a natural outcome: most studies produce an average assessment for the entire system. However, a typical public transport network – even a relatively small one – offers a very large number of possible transfer locations (GUIDE, 1999). There are more than 600 transfer stops/stations in Greater London identified by Transport for London's (TfL) transfer plan. Even within the Underground network, transfers occurred in 191 out of 307 stations (TfL, 2004). To an operator, an average system-wide value offers little help in selecting problematic stations and prioritizing investments. Therefore, the experience assessment method is seldom referenced in stop/station design or operations (Smart et al., 2009). Instead, "rules of thumb" and qualitative approaches are often employed.

2.2. Supply assessment

The supply assessment inventories and ranks all aspects of transfer supply, including station design, social environment, and service management. In Europe, the supply assessment is often based on input from experts, and it compares the perceived importance and performance of transfer facilities to identify the gaps in transfer supply by facilities (MIMIC, 1999; TfL, 2002). In the US, supply assessment tends to involve a broad range of stakeholders, such as passengers, officials, and neighborhood residents, and it becomes a public participation process (US DOT, 1994; Smart et al., 2009).

Supply assessment normally provides a long list of factors proposed by experts or various stakeholders that are presumably important to all transfer facilities (Vuchic and Kikuchi, 1974; Hoel et al., 1994; Horowitz and Thompson, 1994; Smart et al., 2009). These factors are normally ranked or weighted in ordinal measures without any real meaning. They cannot be converted into monetary values to support the cost-benefit analyses.

Another common drawback of the supply assessment is that it often targets individual facilities and does not compare their *relative* importance and performance. This is understandable; it is nearly impossible to address a long list of factors for all transfer facilities, especially in a large, multimodal network. For example, MIMIC (1999) applied this method to only seven transfer facilities in seven European countries, and PIRATE (1999) looked at fourteen sites in six European countries.

The best example of the supply assessment is the Interchange Plan, conducted by Transport for London for more than 600 transfer facilities in London (2002). The Plan calculated two values for each facility: policy value and quality value. Policy values were based on scores for 20 policy objectives identified in the Mayor's Transport Strategy (GLA, 2001). Physical quality values were estimated using a Mystery Shopper Survey (MSS), which assessed appearance (lighting, graffiti, litter and cleanliness, etc.), accessibility (stairs, escalators, lifts, etc.), environmental quality (level of draft, shelter availability, etc.), security (CCTV, ease of crossing roads), information (signs, announcements, etc.), and staff (presence and helpfulness of staff). Each factor was given a weight, and a Quality Gap index between the policy and the quality values was developed. A station with a high Quality Gap, or high policy value but poor physical quality, ranks high on the list of priorities for investment. The 2002 Interchange Plan is the most comprehensive supply assessment of transfers that the authors have identified. Transfer investments are guided by policy priorities and the evaluation criteria is straightforward. However, the process is costly and time consuming, and the results are still unable to quantify the extent of the problem and to justify the benefit of transfer investments.

In summary, although experience and supply assessments are helpful in understanding transfer behavior and the current conditions of a transfer facility, they do not provide useful tools to guide specific transfer investments on where to invest (which facility), how to invest (which aspect), and how much to invest (quantitative justification of the investment). As a result, transfer facilities often develop in an unplanned manner, and most improvements in the facilities come about opportunistically or when the budget allows for change (MIMIC, 1999). A transfer project conducted by the European Commission stated:

> It was becoming clear that those who plan, design, build and manage Interchanges were "flying blind" when it came to defining the needs of public transport users and others. At an early meeting of the consortium, one partner observed that he received detailed instructions for building a supermarket than for a new Interchange, for which commonly his clients had few ideas of their own except that it had to cater for a given number of vehicles per peak hour. (PIRATE, 1999, page 4).

This paper proposes an approach that combines the merits of both experience and supply assessment methods while avoiding their drawbacks. The approach is based on path choice modeling using revealed, not stated, passengers' preferences.

3. Methodology: path choice

Path choice models have a unique attribute: they are able to retain the location and movement information of a transfer. Because all transfer components (walking, waiting, and environment) are movement specific, they could be specified and modeled separately in path choice models. Therefore, transfer assessment could be done not only for the whole system, but also for a particular station and a transfer movement. This method allows the comparison across many stations and between movements in the same station, in terms of both the transfer cost and the benefit of improvements, in a quantitative way. In other words, it is able to prioritize transfer facilities and transfer investments. Other transfer supply attributes, such as way-finding easiness, platform width, seat availability, crime rate, etc. can be easily incorporated in the framework. Path choice is also less likely to contaminate the transfer assessment because, when modeled in a single mode network, the mode preference will not be mixed with the (dis)preference to transfers. Below describes the approach in detail.

3.1. Transfers and path choice

According to the time allocation theory (Jiang and Morikawa, 2004), transfer cost comes from two sources: the opportunity cost of extra time or money spent on transfers that otherwise could be spent on work or leisure, and the disutility of the transfer itself, the transfer penalty. The transfer cost C is a function of three factors:

$$C = f(time, fare, penalty). \tag{1}$$

In practice, transfer time and penalty might interact with each other. The penalty could affect the time coefficient or be a separate term. For example, the estimation of transfer walking time might be affected by the number of turns and availability of escalators along walk path. The more environmental variables are defined and included, the more likely this effect is to be controlled.

Because most transfer attributes (transfer time and environment) are specific to station and movement, the transfer cost is likely to vary across stations and between movements at the same station. For example, at Green Park station in London, transfer from the Victoria Line northbound to the Jubilee Line is quite convenient, involving one change in level and a short walk. However, transfers at the same station from the Piccadilly to Jubilee Lines are formidable, involving several changes in levels and a long walk. Therefore, Eq. (1) is revised to reflect such variation:

$$C_{ij} = f(time_{ij}, fare, penalty_{ij}) \tag{2}$$

where C_{ij} is the transfer cost for transfer movement j at station i.

For each pair of intersecting services, there are normally eight possible transfer movements. For a large transfer station with multiple service lines, the transfer movements within the station can be quite complicated.In a public transport system, a path is defined as a unique sequence of entry, transfer, and exit stations. Different services following the same sequence are treated as the same path, because they differ only in waiting times not transfers. Under this definition, a unique path always corresponds to a particular movement at a transfer station. In mathematical form, it is

$$L = s(entry, transfer_1, \ldots, transfer_i, \ldots, transfer_n, exit) \tag{3}$$

or

$$L = s(entry, movement_{1j}, \ldots, movement_{ik}, \ldots, movement_{nm}, exit) \tag{4}$$

where L is a unique path, s is a sequence, i is the number of transfer stations ranging from 0 to n, j, k, m are corresponding transfer movements at the 1st, ith, and nth transfer stations. Note j, k, m refer to a particular movement, not a set of movements at a transfer station.

Suppose a passenger has multiple paths from an entry to an exit station in a rail network, the passenger is assumed to choose the path with the highest utility (Ben-Akiva and Lerman, 1985). The utility for path L is a function of all path attributes:

$$U_L = f\left(ivt_L, wt_L, wk_L, fare_L, servis_L, \sum_{i=0}^{n} C_L^i\right) \tag{5}$$

where ivt_L, wt_L, and wk_L are the in-vehicle time, initial waiting time, and non-transfer walking times between station entrances and platforms for path L, respectively. $fare_L$ is the non-transfer fare cost for path L. $servis_L$ refers to all other service quality attributes on path L, such as reliability and crowding.[5] $\sum_{i=0}^{n} C_L^i$ is the total transfer cost from n transfers on path L. Because there is no alternative specific constant in Eq. (5), the transfer penalty, often specified as a transfer dummy variable, will not be contaminated by mode preferences.

However, path choice modeling is technically more challenging than mode choice modeling (Bovy and Stern, 1990). Unlike mode choice modeling, where options (car, subway, bus, etc.) are usually clear, it is hard to know what the path options perceived by a traveler are. RP data record only the final decision but nothing on other options considered. Analysts have to generate the path options, and unfortunately, there is no perfect solution to this problem. In this research, we used a method called the labeling approach developed by Ben-Akiva et al. (1984) to generate the path choice set.

3.2. Path choice set generation and the labeling approach

Oft-cited methods to generate path choices include kth shortest path (Dijkstra, 1959; Gallo and Pallottino, 1988), link elimination and penalty (Azevedo et al.,1993; Park and Rilett, 1997), branch and bound (Friedrich et al., 2001), labeling, and simulations (Sheffi and Powell, 1982). The labeling approach is chosen because it meets four requirements fairly well: applicability to public transport networks, theoretical basis, reasonable size of choice set, and simplicity in application.

For example, compared to road networks, public transport networks have scheduled discrete services, which impose constraints on travelers' travel choices (Wilson and Nuzzolo, 2004). The network usually comprises fewer links, but each link is critical to network performance. The kth shortest path and link elimination methods, developed primarily for road networks, may disconnect these critical links and cause infeasibility in a public transport network. The branch and bound method tends to produce unrealistically large choice sets. The simulation methods require high computational effort, especially for large networks. In an empirical test comparing these methods, the labeling approach yielded the best results (Bekhor et al., 2006). For more detailed discussion of this method, see Ramming (2002) and Fiorenzo-Catalano (2007).

In the labeling approach, a label defines a set of weighs for travel attributes. An algorithm then finds a path that minimizes the generalized cost based on the weights. When one travel attribute is weighted very heavily, the algorithm will find a path with the least value of that attribute. For example, a label with walking time weight of 100, compared with normal values of 2–3, will find the minimum walking time path. In other words, a label represents a personal preference for a particular travel attribute, or a combination of multiple attributes (Guo, 2008).

How labels should be developed depends largely on the analyst's own judgment. In this research, one label is created for each travel attribute to find a path that either minimizes or maximizes that attribute. Then, different combinations of attribute weights are tested. These labels are tested against two criteria. Defining C_r to be the set of paths chosen by passengers, C_g^i the set of paths generated by label i, and C_{rg}^i the overlap set between C_r and C_g^i, the two criteria can be written as:

$$B_1^i = \frac{C_{rg}^i}{C_r}, \quad \text{and} \quad B_2^i = \frac{C_g^i}{C_{rg}^i} \tag{6}$$

B_1^i is the *effectiveness* measure for label i, indicating the percentage of chosen paths covered by label i. B_2^i is the *efficiency* measure, reflecting how many paths are generated by label i in order to cover one chosen path.

A good label should have a high value of B_1 but a low value of B_2. A low B_1 value suggests that the generated choice sets do not match the actual decisions, while a high B_2 value indicates that the label generates too many alternatives that passengers are unlikely to consider in reality. In this research, B_1 is defined to be larger than 50%, i.e. a label has to cover at least half the chosen paths, and B_2 to be less than seven, based on the psychological theory that a human being can comprehend and compare up to seven alternatives (Miller, 1956; Hoogendoorn-Lanser, 2005).

Although there is no way to determine whether the generated paths are indeed options considered by passengers when they make decisions, the validity of the generation approach can be tested with two values: the coverage rate (B_1) of the label based on weighting factors used by the public transport system, and the percentage of correct prediction by the developed path choice model. Both values are calculated in the following sections (65% and 80%), and the results validate the labeling approach.

4. Case study: London Underground

The London Underground (LUL) offers an excellent case for this research. Transfers are critical to LUL's performance. About 44% of trips involve at least one transfer between LU lines on a typical weekday, 87% of which are a first transfer, and 12% are a second transfer on a journey. Transfer activities are concentrated in a small number of major stations: the top 14 stations account for more than 60% of transfers. Oxford Circus is the largest transfer station with 110,000 transfer trips per weekday. At Baker Street Station, about half of the passengers make transfers (TfL, 2008).

Being one of the largest and most complex subway systems in the world, LUL offers ample path options for many origin and destination station pairs. Based on an origin–destination (OD) survey, 25% of the surveyed ODs have more than two

[5] In the London Underground, reliability can be measured as the excess travel time and the percentage of service cancelled due to accidents and overcrowding at the *line* level. Each link has a built-in crowding factor, which is just the extra travel time over free flow. Unfortunately, the TfL network model, RailPlan (2006), does not provide separate these time values. These factors are not included in the empirical analysis because of the lack of this type of data, and the consequence on model estimation is discussed in Section 7.

Table 1
Path attributes descriptive statistics.

Path attributes (min)		Average	Max	Min	Standard deviation	Sources
In-vehicle	RODS paths	17.9	55.5	1.5	8.3	RailPlan
	Generated paths	21.1	88.6	1.0	10.5	RailPlan
Entry within station	RODS paths	1.8	6.6	0.2	1.0	RailPlan
	Generated paths	2.1	7.1	0.1	1.3	RailPlan
Exit within station	RODS paths	2.6	7.1	1.0	0.9	RailPlan
	Generated paths	2.8	8.6	1.0	1.6	RailPlan
Initial waiting	RODS paths	2.2	16.6	1.0	1.6	RailPlan
	Generated paths	2.6	30.2	1.0	1.9	RailPlan
# Stations	RODS paths	9.7	28.0	1.0	4.1	RailPlan
	Generated paths	11.7	43.0	1.0	5.6	RailPlan
# Transfer	RODS paths	0.95	2	0	0.33	RailPlan
	Generated paths	0.97	3	0	0.36	RailPlan
Transfer waiting time	RODS paths	1.7	30.2	0	1.8	RailPlan
	Generated paths	2.1	30.2	0	2.1	RailPlan
Transfer walking time	RODS paths	1.6	10.1	0	1.2	RailPlan
	Generated paths	2.2	13.7	0	2.2	RailPlan
Escalator[a]		0.38	1.00	0	0.49	Station inventory Direct enquiry Field survey
Stairs[a]		43	378	0	55.72	Station inventory Direct enquiry Field survey
Horizontal distance[a]		45.68	292	0	58.15	Direct enquiry
Ramp length[a]		12.80	154	0	25.44	Direct enquiry
Even transfer[a]		0.50	1.00	0	0.50	Direct enquiry field survey

Note: $N = 3564$ for RODS paths, and 8126 for generated path.
[a] $N = 1044$ transfer movement directions for both RODS and generated paths.

paths chosen by passengers. A few OD pairs are well connected by a large number of chosen paths, for example, 13 paths from Waterloo to King's Cross.

LUL is also the world's oldest subway system with the first service operating in 1863. Many of the transfer stations and connections have been constructed when new lines were connected to the existing network – the latest addition being the Jubilee Line in 1999. Therefore, the network possesses diverse transfer environments with respect to station design, platform connections, and technology. Such variability facilitates the assessment of transfer cost.

The main data source used to identify travel paths in the LUL network is the Rolling Origin and Destination Survey (RODS). It is conducted annually by Transport for London [(TfL) or its predecessor organization London Transport] and records the access, transfer, and egress stations, access/exit modes, purpose and frequency, ticket type, and traveler's gender and age for more than 250,000 trips between 1998 and 2005.

The main data sources for travel time attributes is RailPlan, an EMME/2 based network model developed by TfL to model public transport users in the AM peak period in London and the South East of England (RailPlan Modeling User Guide, 2006). In the model, each link is assigned a specific time value. For track links, the value is from the Underground 2001 working timetable. Dwell time is treated as a uniform value for all stations. For walk links, the value is calculated based on an average walking speed adjusted by the type of walking: level walking, escalator, stairs, or lift.

The main data sources for the transfer environment are the Station Inventory Database (TfL, 2006), Direct Enquiry Database, and field survey by the authors. Station Inventory Database is developed by the Underground, which records the design characteristics of 273 stations such as station and platform types, facilities (escalators, lifts, waiting rooms, etc.), amenities (clocks, help points, toilets, information, commercial, phone, etc.), and accessibility in terms of number of stairs, escalators or lifts between platforms, ticketing halls, and streets. However, the database does not cover all transfer paths at transfer stations.

Direct Enquiry Database is developed by a non-profit organization[6] in London to facilitate disabled access to a variety of activities including transportation, key attractions, pharmacy, post office, etc. The database describes, in text and diagram, every segment of all transfer paths at all Underground stations including ticket gates, level walking, ramp, escalator, lift, door, etc.

The two datasets provide most information needed to describe the transfer environment. When there was ambiguity for a particular station or transfer path, the authors conducted four field surveys to collect data in January and June 2007 and January and May 2008. Only attributes for 23 major transfer stations and 1044 transfer movements for both RODS and generated paths are used for this study.

Based on these data sources, travel time and transfer environment variables are developed for each surveyed path. The former includes entry/exit walking time, initial waiting time, in-vehicle time, and transfer walking and waiting time. Entry/exit time refers to walking time between a platform and a station entrance or exit. The latter initially includes 16 different factors, but only five of them were found to be statistically significant in the final models. They are escalator availability,

[6] http://www.directenquiries.com/londonunderground.aspx.

Table 2
Path choice generation based on default LUL network.

Ranking[a]	Revealed paths C_R = 13,295	Generated C_L	Overlap C_{RL}	Additional RODS paths captured	Additional unique paths generated	Effectiveness $B_1 = C_{RL} \div C_R$ (%)	Efficiency $B_2 = C_{RL} \div C_L$ (%)
1	Default value, *A*	10,252[b]	8633	8633	10,252	64.9	84.2
2	Min initial wait	9471	8354	224	1021	62.8	88.2
3	Min # transfers	9284	8303	250	501	62.4	89.4
4	Min transfer time	9285	8057	72	496	60.6	86.8
5	Combination 3	9284	7940	125	584	59.7	85.5
6	Combination 1	9285	7936	226	826	59.7	85.5
7	Default value B	9284	7868	15	202	59.2	84.7
8	Combination 5	9284	7833	77	608	58.9	84.4
9	Default value C	9284	7822	245	753	58.8	84.3
10	Combination 4	9284	7773	55	403	58.5	83.7
11	Min transfer wait	9284	7571	65	634	56.9	81.5
12	Combination 2	9284	7457	37	653	56.1	80.3
13	Combination 6	9284	7355	44	637	55.3	79.2
14	Combination 7	9284	7270	35	337	54.7	78.3
15	Combination 8	9284	7097	1	221	53.4	76.4
16	Min Delay Time	9284	7046	17	414	53.0	75.9
17	Combination 9	9284	6347	98	1050	47.7	68.4
Total				10,219	19,592[c]	76.9	52.2

[a] Ranking is based on the effectiveness measure B_1.
[b] Pathfinder algorithm in TransCAD can find multiple paths.
[c] Distinct generated paths from all 17 labels.

number of stairs, horizontal distance, ramp length and a dummy variable on whether the two transfer platforms are at the same level. Service reliability and crowding should matter for path choice (Rietveld et al., 2001; Liu et al., 2004), but are not included due to the lack of data at the path level. Fare is not included because transfers within the Underground are free, and there is little variation of fares among different paths between the same OD.[7] Table 1 lists the descriptive statistics and data sources for all variables for both RODS and generated paths.

5. Model development

This section explains the choice set generation results, model specification, and model development sequence.

5.1. Path choice set

Not all RODS OD pairs and paths can be used to generate alternative paths. OD pairs with very few trips and paths with more than two transfers on a journey are excluded because most of them are subject to coding errors. Paths with a small share (⩽10%) of trips between an OD are excluded because many of them could be caused by station closure, service disruption, etc., Finally, 9284 RODS OD pairs, corresponding to 13,925 RODS paths, are selected. The labeling approach is then applied to these OD pairs on two versions of the LUL network: the default RailPlan network, and a map-based network. In the latter, the link length is the map distance, instead of the actual distance.

More than 80 labels were applied with 17 of them satisfying the effectiveness and efficiency criteria. The cumulative coverage rate of 13,295 RODS paths is 77% on the default network, and 75% on the map-based network. Table 2 lists the labels and their performance. Fig. 1 summarizes the generation process. It indicates that when more labels are applied, more RODS paths are generated (solid lines), but new labels become increasingly less efficient and effective (dotted lines) until they reach one of the two thresholds.

These results compare nicely to some prior studies. In Ramming's research (2002) for a road network, for example, the coverage rate is 72% for a combined labeling method, 60% for multiple-path algorithm, and 50% for a simulation method. The study by Bekhor et al. (2006) reached similar results. Another recent study by Fiorenzo-Catalano (2007) achieved a coverage rate of 78% but for a much simpler multimodal network along a corridor, using a combined simulation and labeling approach with randomized link attributes and personal preferences. Both studies used more sophisticated generation methods than those used in this research. The label based on default weight factors alone covers 65% of RODS paths, which further confirms the effectiveness of the generation approach and the overall process.

OD pairs can be grouped into three categories based on the generation result: a single generated path, multiple generated paths but no RODS path(s), and multiple generated paths with at least one RODS path. OD pairs in the first two categories are not usable for choice modeling because we do know neither the choice set nor the decision – which path is actually chosen by a passenger.

[7] Fares are different only when a path passes through different fare zones, which, though not impossible, is rare in the Underground network because of the lack of ways to bypass Central London.

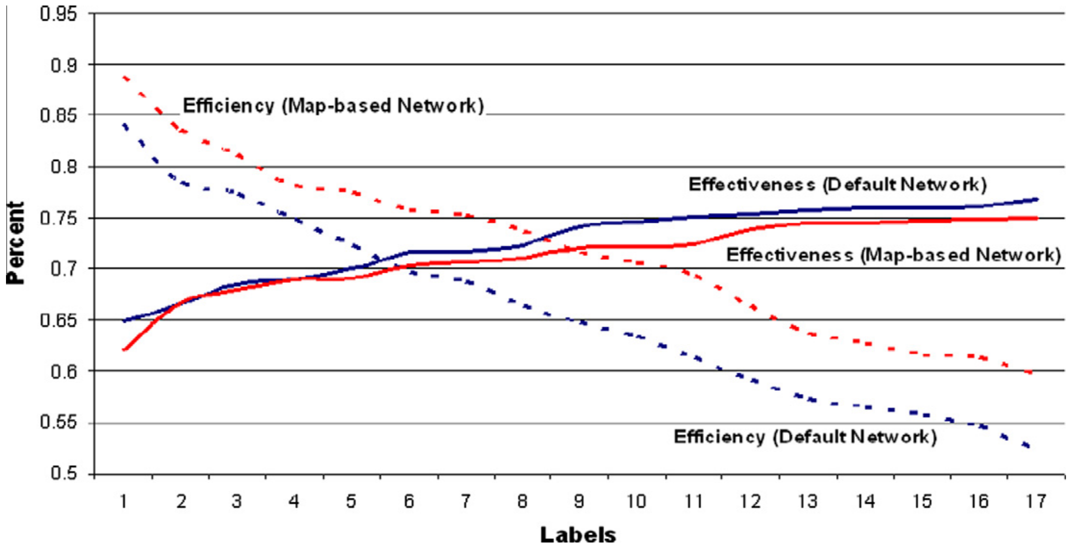

Fig. 1. Process of path choice set generation. *Note*: percent refers to the accumulative percent of adopted labels.

The final path choice set for model estimations includes 2969 RODS ODs, corresponding to 3564 RODS paths and 25,036 RODS trips. For these OD pairs, 10,391 path options are generated. In other words, one RODS OD on average has 3.5 feasible paths. The choice set size varies from OD pairs to OD pairs, ranging from two to six. The attributes of all generated paths are extracted from the same data sources described previously. They tend to have larger averages and standard deviations than those only from RODS paths, which is our expectation.

5.2. Model specifications

Model specification is affected by path correlation. Path options often overlap with each other to different extents because they start at the same origin and end at the same destination. In a public transport network, two paths could share the same link segment, the same transfer station, or the same service line, all of which could contribute to the correlation between paths.

Various models have been proposed to control for the path correlation, including multinomial logit (MNL) (Menghini et al., 2010), C-Logit, Path-Size Logit, Cross-Nested Logit, Mixed Logit, and Probit (Ramming, 2002). This research adopts the simpler model specification, MNL, to handle the problem for two reasons. First, there is little evidence that more sophisticated models perform better than simpler ones. Actually, the opposite might be true if the assumptions of sophisticated models are too strong (Bhat and Pulugurta, 1998). Secondly, and more importantly, overlapping path segments often start or end at a transfer station. Controlling for the path overlap (correlation) might affect the estimation of transfer variables in an uncertain way. A safe alternative is to specify transfer attributes to partially control the path correlation. It might not be ideal, but it is still a reasonable approach for this study.

This decision is examined in a prediction test based on the later-defined MNL models after all coefficients are estimated, a process described in the following section. The dataset is split into two parts, each having half the observations from the original dataset. The split is based on odd versus even access station code numbers, so it is a random selection. Next, one half dataset is used for estimation using the best model specification. Then the results are used to predict the path choice for the other half dataset (Footnote 2). The prediction test found 80% an average probability of correct prediction for a complete path, and 91% for trips. This suggests that the MNL model specification works well in estimating travelers' path choice decisions, at least in the LUL network.

Within the MNL structure, the transfer cost for path L, $\sum_{i=0}^{n} C_L^i$, can be represented by four different specifications in the path utility function (Eq. (5)). They are

$$\sum_{i=0}^{n} C_L^i = f(n) \tag{7}$$

$$\sum_{i=0}^{n} C_L^i = f\left(n, \sum_{i=0}^{n} station_{1i}, \ldots, \sum_{i=0}^{n} station_{ki}, \ldots, \sum_{i=0}^{n} station_{mi}\right) \tag{8}$$

$$\sum_{i=0}^{n} C_L^i = f\left(n, \sum_{i=0}^{n} station_{1i}, \ldots, \sum_{i=0}^{n} station_{ki}, \ldots, \sum_{i=0}^{n} station_{mi}, \sum_{i=0}^{n} time_i\right) \tag{9}$$

Table 3
Model estimation results.

Variables models	Model 1 (Eq. (7)[a])	Model 2 (Eq. (8))	Model 3 (Eq. (9))	Model 4 (Eq. (10))
Base path attributes				
Entry/exit walking	−0.395 (−12.6)	−0.382 (−11.2)	−0.288 (−9.0)	−0.247 (−7.3)
Actual in-vehicle time	−0.452 (−22.1)	−0.498 (−22.7)	−0.554 (−21.1)	−0.571 (−20.1)
Initial waiting	−0.516 (−11.0)	−0.436 (−8.1)	−0.362 (−7.4)	−0.367 (−6.9)
# of transfers	−2.217 (−13.5)	−2.457 (−12.7)	−2.270 (−11.6)	−1.874 (−8.5)
Station variables				
Baker St.		−0.342 (−1.9)	−0.512 (−2.8)	−0.685 (−3.4)
Bank/monument		−0.608 (−3.2)	−0.638 (−3.0)	−0.679 (−2.5)
Bond St.		1.454 (5.5)	1.198 (4.4)	1.077 (3.8)
Earl's court		2.186 (6.6)	1.417 (3.9)	1.668 (4.0)
Embankment		−0.119 (−0.3)	−0.301 (−0.9)	−0.197 (−0.6)
Euston		−0.401 (−1.8)	−0.462 (−2.0)	−0.516 (−2.0)
Green park		0.644 (3.9)	0.763 (4.0)	0.353 (1.5)
Holborn		0.669 (3.3)	0.620 (2.8)	0.569 (2.5)
Leicester Sq.		0.814 (2.6)	−0.120 (−0.5)	0.418 (1.3)
London bridge		0.116 (0.31)	0.096 (0.2)	0.602 (1.3)
Oxford circus		0.917 (5.8)	0.592 (3.3)	0.565 (2.6)
Paddington		−2.013 (−5.0)	−1.896 (−4.7)	−1.999 (−5.1)
Piccadilly circus		0.137 (0.44)	−0.516 (−1.7)	0.252 (−0.8)
Victoria		0.339 (1.7)	−0.060 (−0.3)	−0.251 (−1.2)
Warren St.		−1.675 (−4.7)	−1.523 (−4.3)	−1.205 (−3.1)
Waterloo		−0.836 (−−3.6)	−0.501 (−2.1)	−1.592 (−4.6)
Westminster		0.093 (0.4)	0.249 (0.9)	0.158 (0.6)
Transfer times				
Transfer walking			−0.322 (−8.9)	−0.299 (−7.7)
Transfer waiting			−0.197 (−4.6)	−0.176 (−4.4)
Transfer environment				
Total transfer stairs				−0.0038 (−3.2)
Total horizontal distance				0.0021 (1.1)
Presence of escalator				0.935 (3.9)
Ramp length				0.009 (5.6)
Same-level transfer				0.827 (4.4)
Adjusted, $\rho 2$	0.504	0.543	0.579	0.592

[a] The equation specifies the utility function of transfer not the entire path; numbers in parentheses are t statistics.

$$\sum_{i=0}^{n} C_L^i = f\left(n, \sum_{i=0}^{n} station_{1i}, \ldots, \sum_{i=0}^{n} station_{ki}, \ldots, \sum_{i=0}^{n} station_{mi}, \sum_{i=0}^{n} time_i, \sum_{i=0}^{n} design_i\right) \tag{10}$$

where n is the number of transfers; k refers to a particular transfer station; m is the number of transfer stations in the dataset (17 in this study); $station_{ki}$ is a dummy variable (1 if the nth transfer occurs at station k); $time_i$ is the transfer time (walking and waiting) for the transfer movement corresponding to path L at station i; $design_i$ refers to a transfer environment attribute for the transfer movement at station i that corresponds to path L.

The equations measures the transfer cost at different levels. Eq. (7) captures the system wide average cost of one transfer without specifying the factors that contribute to that cost. Eq. (8) captures the variation of the transfer cost across station. Eq. (9) divides the transfer cost into two parts: the transfer penalty captured by n and $station_{ki}$, and the transfer time captured by $time_i$. Eq. (10) further explains the origins of the transfer penalty through the environmental attributes for a transfer movement. Since $time_i$ and $design_i$ are transfer movement specific, Eqs. (9) and (10) not only explain the source of transfer cost, but also measure the variation of the cost across transfer movement. They represent the definition of transfer cost in Eq. (2).

Four types of models (Models 1–4) are estimated based on the equations with the results presented in Table 3 and summarized below.

6. Transfer cost assessment

In Model 1, all four non-transfer variables are significant at the 5% level with the expected signs. The more a path takes in terms of entry, exit, in-vehicle, or initial waiting time, the less likely that path is to be chosen by travelers. On average, one transfer is perceived by the typical Underground passenger as equivalent to 2.217/0.452 = 4.9 min of in-vehicle time. This value is the system average across all transfers at all Underground transfer stations for both the first and second transfers. According to LUL, there are about 1.4 million transfers in the network on a typical weekday. Assuming that the value of time is \$16.6 (£10.6) per hour[8] (RailPlan Modeling User Guide, 2006), the total transfer cost to passengers on a typical weekday is

[8] Using the current rate (on August 25, 2010): £1 GBP = \$1.56 US

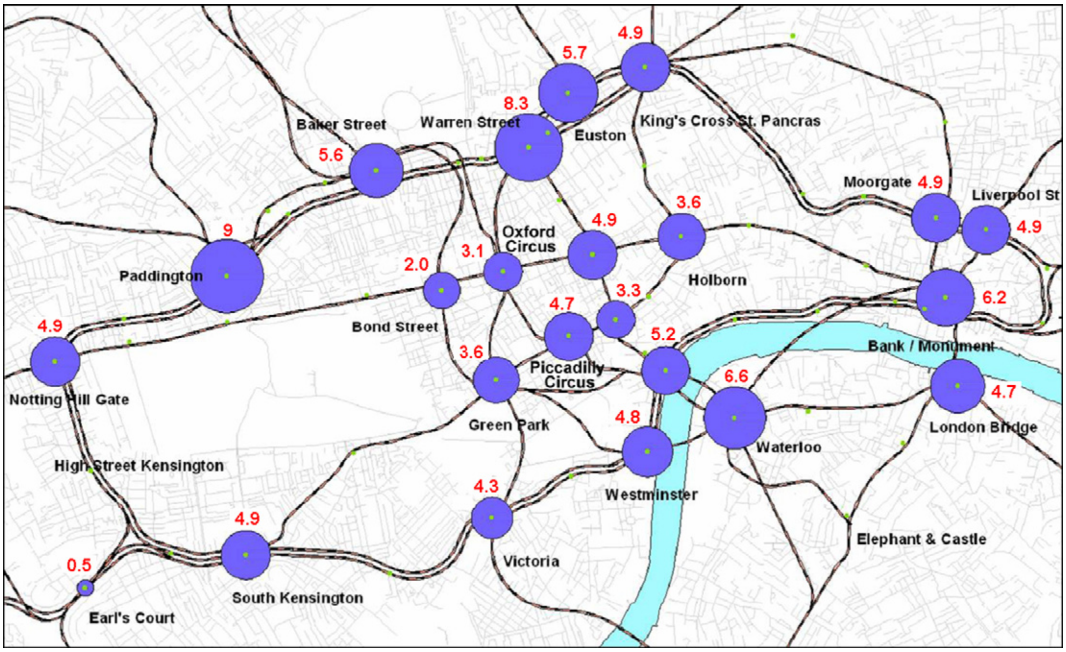

Fig. 2. Average perceived transfer cost at selected underground stations. *Note*: values include influence form transfer walking and waiting; units are minutes of in-vehicle time.

about of $1.9 million. Assuming that there are 240 typical weekdays and 125 weekends and holidays a year, the transfer cost to passengers is about $573 million per year (based on the 2006 currency rate).

This is the perceived disutility of transfers by passengers who decided to transfer, not taking into account latent LUL trips which are not made because of the inconvenience of transfers. The real cost might be much larger. In other words, LUL passengers perceive a cost of more than $573 million per year for transfers in the system.

Model 2 estimates the average transfer cost for 17 major LUL transfer stations (six other stations were included in the specification, but they were insignificant in the final model specification). The 17 station dummy variables capture the unique station effect relative to a base, which is 2.457/0.498 = 4.9 in-vehicle minutes for all other transfer stations. As expected, Model 2 finds a large variation of average perceived transfer cost across stations. The worst transfer stations are normally some of the largest, most complex, National Rail terminal stations including Waterloo, Paddington, and Euston. The best transfer stations all have simple transfer environments and heavy use, such as Earl's Court, Bond St., Leicester Sq., Oxford Circus, and Victoria. One transfer at Paddington, the worst transfer station has an average perceived cost of 9 min, while one transfer at Earl's Court, the best transfer station, has only 0.5 min. Fig. 2 shows the average transfer cost at all these Central London transfer stations.

Next, the average perceived transfer cost is multiplied by the number of transfers at each station to estimate the total transfer cost by station. The ranking is different from that of the average transfer cost. For example, the worst station is now Baker St., with a weekday cost of $170,312 and an annual cost of almost $42 million, about 7.4% of the total perceived transfer cost on the system. The best station, Earl's Court, has a total annual cost of $2.8 million, 0.5% of total system transfer cost. The results of Model 2 suggest a way to prioritize transfer-related investments.

In Model 3, after transfer times are included, their effect on the transfer cost is captured separately from the number of transfers and station variables. The latter two now capture the transfer penalty over and above the transfer times. In other words, Model 3 is able to compare two different sources of the transfer cost. The contribution of transfer times to the perceived transfer cost is calculated by multiplying the average transfer times by station with the weights of transfer times (0.58 for transfer walking and 0.36 for transfer waiting in Model 3). Its average value is then compared with the average perceived transfer cost. The result suggests that the transfer times contribute on average 32% of the transfer cost, and the transfer penalty contributes the rest 68%.

A sensitivity test is conducted because the coefficients of transfer time variables are relatively small compared to most other studies. It might be caused by the small variation of transfer times defined in the RailPlan network (RailPlan Modeling User Guide, 2006). The sensitivity test used weighting factors = 1.0 and 1.14, the default value in RailPlan, for both transfer waiting and walking. The contribution of the transfer penalty decreased to 49% and 53%, while the station ranking remained the same. In summary, the transfer penalty contributes at least half of the transfer cost at the 17 targeted stations. The highest shares come from Warren St. (59–80%) and Piccadilly Circus (59–77%). Efforts that focus only on reducing transfer times at these stations might be ineffective in improving the overall transfer experience.

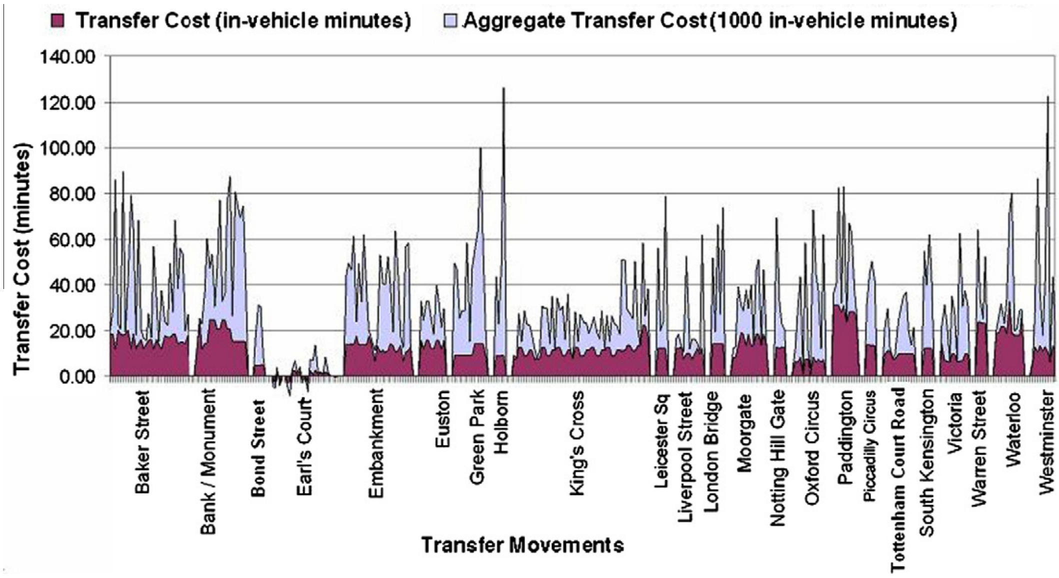

Fig. 3. Average and aggregate transfer cost by transfer movement.

Model 4 explains why some stations have a higher transfer penalty than others. Among the five environmental variables included, four are significant at the 5% level, while the fifth (horizontal distance) is insignificant. Obviously, the four variables only capture a portion of the transfer penalty because the number of transfers and most station variables are still statistically significant. In Model 4, after the transfer walking time is controlled for, the total number of stairs adds an additional burden to the transfer experience, while all the other attributes tend to reduce that burden. The presence of an escalator, the longer ramp, and being a same-level transfer improve the transfer experience.

The result implies that when two transfer platforms are side by side at the same level and connected with horizontal tunnels or ramps, the transfer experience might be much better than with a vertical connection by stairs, even if the walking time is similar. A possible explanation is that the former is likely to eliminate barriers to walking, reduce directional turns, and offer simple way-finding, at least in the LUL network. Certainly, the cost of construction must also be taken into count. In the LUL case, about 15% of transfer paths do not involve a change of level.

Following the same process in Model 2, the average transfer cost by movement is calculated using the same method as in Model 3. Results again confirm large variations in the transfer cost across transfer movements. The variation is even greater when the number of transfer trips is taken into account. Fig. 3 shows the average transfer cost and the total cost on a typical weekday for 303 transfer movements at the targeted stations in the LUL network.

Note several transfer directions at the Earl's Court Station show a negative value, which implies that transferring along these directions actually has a positive utility. However, this does not mean that some passengers prefer transferring even when it is not necessary—it is probably caused by the tradeoff between (1) riding the first but not direct service train and then transferring at Earl's Court where more direct services are available, and (2) waiting for the direct service train. This often occurred between the Wimbledon and the Edgware Road branches of District Line. RODS data indicated that among 1009 passengers who traveled from the Wimbledon branch to the Edgware Road branch, 24% actually transfer at Earl's Court despite direct service being available. Because the waiting time is simply calculated based on the combined headways, our models are unable to control for this first train effect, and therefore may instead "assign" a positive value to the transfer station.

During the model development, the explanatory power as indicated by the adjusted ρ^2 increases significantly from 0.504 (Model 1) to 0.543 (Model 2), 0.579 (Model 3), and finally 0.592 (Model 4).

7. Discussion and conclusion

This study assessed the perceived transfer cost and differentiated that cost by source and location (stations and platforms), taking into account both the operators' service and the passengers' experience. The results show a tremendous cost imposed by transfers in a public transport system, and suggest that improving transfer experience could significantly benefit public transport. The results also provide a useful tool for an operator to use for evaluating, e.g., through a formal cost-benefit analysis, potential transfer improvements, in terms of where to invest (which facility), how to invest (on which aspect), and to what extent (quantitative justification of the investment), which was not available through previous studies.

Furthermore, the results may still under-state the severity of the problem and the potential benefit of improvements for three reasons. First, the London case study targets subway-to-subway transfers, which have the most convenient type of transfer in a public transport system. Average transfer cost between subway and bus, or between subway and commuter rail is likely to be much larger (Guo and Wilson, 2007). Second, the London Underground is operated close to capacity in peak periods and directions. Overcrowding is a big problem in many parts of the system. Many passengers may decide to transfer in order to avoid overcrowding, but those transfer decisions might appear unreasonable from the perspective of minimizing transfer times. In other words, if overcrowding is not controlled for, which is the case in this study, path choice model will "think" that these transfers are actually favored by passengers, thus under-estimating the transfer cost. Lastly, transfer improvements could benefit all passengers not just transferring passengers.

Despite its merits, the path choice approach also has its limitations as applied to transfer analysis. First, the model is sophisticated when applied to many OD pairs in a large network.[9] Path choice set generation can be time consuming, and path choice correlation might be difficult to resolve. Secondly, the approach is limited in terms of generalization. It can best be used for large and complex networks with multiple paths between many OD pairs. It might not be applicable to most medium and small public transport systems. The method is also less applicable to a system with little variation in their transfer environments, such as the Metro system in Washington, DC. For small or medium sized systems, a simpler, partial path choice model could be applied (Guo and Wilson, 2004).

The third limit is true for all modeling approaches—it is difficult to incorporate many transfer environment attributes in model estimation. It is partly a data collection problem, and partly a modeling problem – many of these attributes are correlated and/or insignificant in a statistical sense. Both are illustrated by this study. In this aspect, marketing research to detail customers' evaluation of a large set of environmental attributes might be a valuable supplement to the modeling based approach (Horowitz and Thompson, 1994; TfL, 2002; Taylor et al., 2009).

Constrained by the third limit, the solutions proposed to reduce the transfer cost are still crude and relatively simple. In addition to transfer walking and waiting, only five environmental variables are included. It is far from clear how passengers perceive the environment along their transfer path. This study is just a starting point for this investigation.

In conclusion, transfers can impose a tremendous cost on public transport systems. Although the cost cannot be completely eliminated, it could be significantly reduced by better facility design and service planning. The transfer cost comes from three different sources: transfer walking, transfer waiting, and transfer environment. All require distinct solutions, e.g., network design for transfer walking, service control for transfer waiting, and station and interior design for transfer environment. The solutions differ dramatically in implementation frequency, investment scale, and responsible agency. However, they cannot be performed in isolation because they all affect the same transfer experience. Integrated transfer planning is required for public transport systems.

Notes:

1. More substantial work is done in Europe. Since 1998, a series of programs have been conducted by the European Commission to better understand the concept and practice of transfers:
   - PIRATE (Promoting Interchange Rationale, Accessibility and Transfer Efficiency, 1999) compared two valuation approaches on transfer facilities: evaluation and planning and aimed at providing guidelines to make transfer improvements.
   - MIMIC (Mobility Intermodality and Interchanges, 1999) developed an evaluation approach by scaling the perceived importance and the perceived performance of various factors of a transfer facility. By comparing the two, an index could be developed to guide where action should be taken.
   - GUIDE (Group for Urban Interchanges Development and Evaluation, 2000) focused on information, fares and ticketing, funding, organization, and the evaluation of investments at both network-wide and facility level.
   - INTERCEPT (INTERmodal Concepts in European Passenger Transport, 2001) focused on the transfers between public transport and alternative modes (car, taxi, or bike).
   - EU_SPIRIT (European System for Passenger Services with Intermodal Reservation, Information and Ticketing, 2001) focused on providing a user-friendly, internet-based, multi-modal information system, enabling travelers to plan their journey across Europe from departure point to final destination.

2. $$\mathrm{Pr}edict = \frac{\sum_{n}\sum_{i} P_n(i) * C_n(i)}{N} \tag{11}$$

where $P_n(i)$ = the calculated probability of observation n choosing path i, $C_n(i) = 1$ if path i is chosen by observation n, 0 otherwise N = number of observations.

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[9] Most developed path choice models for public transport are based on a simple network, e.g., a corridor or a conceptual network. The authors have not identified any similar empirical studies for a large public transport network.

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