OPTIMISATION OF STEP-FREE ACCESS INFRASTRUCTURE IN LONDON UNDERGROUND CONSIDERING BOROUGH ECONOMIC INEQUALITY

Eduardo Candela, Corresponding Author*
Ph.D. Candidate
Centre for Transport Studies, Department of Civil and Environmental Engineering
Imperial College London, SW7 2BU, UK
e.candela-garza19@imperial.ac.uk

Jose Javier Escribano Macias, Ph.D.*
Research Associate
Centre for Transport Studies, Department of Civil and Environmental Engineering
Imperial College London, SW7 2BU, UK
jose.escribano-macias11@imperial.ac.uk

He-in Cheong*
Ph.D. Candidate
Centre for Transport Studies, Department of Civil and Environmental Engineering
Imperial College London, SW7 2BU, UK
he-in.cheong08@imperial.ac.uk

Petrina Constantinou
Ph.D. Candidate
Centre for Transport Studies, Department of Civil and Environmental Engineering
Imperial College London, SW7 2BU, UK
petrina.constantinou14@imperial.ac.uk

Arnab Majumdar, Ph.D.
Professor of Transport Risk and Safety
Centre for Transport Studies, Department of Civil and Environmental Engineering
Imperial College London, SW7 2BU, UK
a.majumdar@imperial.ac.uk

Panagiotis Angeloudis, Ph.D.
Reader in Transport Systems and Logistics
Centre for Transport Studies, Department of Civil and Environmental Engineering
Imperial College London, SW7 2BU, UK
p.angeloudis@imperial.ac.uk

* These authors contributed equally

Word Count: 5809 words + 6 table(s) × 250 = 7309 words

Submission Date: October 26, 2021

ABSTRACT

Public transport is the enabler of social and economic development, as it allows the movement of people and provides access to opportunities that otherwise might have been unattainable. Access to public transport is a key aspect of social equity, with step-free access improving the inclusivity of the transport network in particular for mobility impaired population groups. Thus, this study develops a two-step algorithm for determining the optimal allocation of resources for the refurbishment of stations to provide step-free accessibility in pubic transport networks. The first step consists of k-shortest path finding algorithm between every origin-destination pair in the network. The non step-free shortest paths are then fed into the second step of the algorithm, a mixed-integer linear optimization problem that selects the station to be refurbished considering inequality penalties as well as costs, budget and demand constraints. The developed methodology is applied to enhance the accessibility of the London Underground. In doing so, several demographic components, including economic background and disability reported, are parameterised and factored into the determination of the optimal solution. Our analysis produces a 15% increase in step-free trips compared to the current state of the network, as well as a reduction of approximately 60% in existing step-free detour time.

Keywords: Optimization, Mobility, Accessibility, Inclusion, Equality

INTRODUCTION

Public transportation accessibility is a key enabler of social equity in urban and suburban environments. The ability to travel despite not owning a private mode of transportation allows people to access services and opportunities that would otherwise be unreachable to them. Among the many reasons that impede private transport use is physical disability, which requires the development of specific infrastructure that facilitates movement within the public transportation network (*1*).

In the UK, approximately 14% of the adult population (8% of working age) suffers from mobility impairment, meaning that they rely on public transportation for movement (*2*). This proportion is only expected to rise in the coming years given the growing and ageing population in most western countries, as disability prevalence increases with age (*2, 3*). Approximately a fifth of disabled people report having difficulties related to their impairment or disability in accessing transport, which increases to a third for people aged 60 and above (*4*).

The United Nations highlighted the importance of supporting the rights of disabled people through the 2007 Convention on the Rights of Persons with Disabilities, which promotes "the full and equal enjoyment of all human rights fundamental freedoms by all persons with disabilities" (*5*). Likewise, the Mayor of London recently published a report on accessible and inclusive transport that aims to identify the key issues experienced by disabled travellers and propose key solutions (*6*).

A key solution proposed by (*6*) is upgrading existing infrastructure: only 33% of London's Underground stations are classified as step-free by 2021. With 270 stations in total, this means that 180 must be upgraded to allow full step-free access to the network. Such time and capital investment requires strategic planning and a prioritisation scheme that maximises the benefit to the public, yet to date no study has proposed a holistic methodology to strategically plan a network-wide improvement of the public transport step-free accessibility. This is the subject of this paper.

Thus, this paper proposes a data-driven approach for the prioritisation of step-free accessibility in the public transport network. To calculate the optimal allocation of resources for the refurbishment of stations, a mixed-integer linear mathematical model is presented that incorporates the network demand requirements, the estimated costs of upgrades, the demographics of disabilities and economic background. The model also evaluates a two-phase upgrade to increase the inclusivity and accessibility of the network. Thus, the contributions of this paper are as follows:

1. It formalises a novel optimisation problem to prioritise the refurbishment works to improve accessibility of public transport services.
2. It evaluates the need to include the transportation equity.
3. It has implemented the methodology to a realistic case study to demonstrate its usability and scalability.

The following section reviews the relevant literature in the field of public transport accessibility. Next, the mathematical model is presented as well as the formulation and solution method. This model is then applied to a numerical case study based on the London Underground improvement works planned by the Mayor of London. Finally, conclusions and recommendations for future work are provided.

ACCESSIBILITY IN PUBLIC TRANSPORT

In the context of public transportation, accessibility is generally defined as the ability to travel to other areas and use specific services. Good accessibility for a given area is characterized by the provision of greater connectivity, mobility, and job opportunities (*7*). The assessment of accessibility and its effects has been carried out in the context of social inequality and public health (*8*), employment rates (*9, 10*), social exclusion (*11*), and mobility (*12*).

The topic of accessibility for the mobility impaired, and in particular those that require the use of supporting mobility devices, is an under-explored area of research. A recent literature review by (*13*) found only 26 studies on this topic, with 14 of them reporting and analysing the user experiences when using public spaces and public transport, and the remaining focusing on vehicle and station design. In addition, (*14*) designed and developed a survey to obtain the value of disability accessibility in the bus network in Chile, while (*15*) identified the barriers experienced by wheelchair users, expanding upon the findings of earlier studies (*16*).

In assessing the accessibility of public transport, (*17*) propose a gravity-based measurement that quantifies accessibility as a product of the opportunities found in the destination and an impedance function that estimates the inconvenience of travel based on the travel distance. By considering the barriers to mobility and the person's capabilities, the impedance function can be used to model disability accessibility. This approach was used to calculate the disparity between a non-disabled and a wheelchair user in Lisbon.

Of the reviewed literature, only (*18*) seeks to measure and optimise the performance of the transport network in terms of accessibility for people with disabilities. The accessibility measurements are used as inputs to determine prioritisation levels for station improvements. However, their approach can only evaluate a finite number of stations, resulting in limited combination of stations being evaluated simultaneously.

Instead, this paper proposes an network-wide approach to prioritise the provision of step-free access throughout the public transport network. In doing so, we parameterise the need for transport accessibility based on regional demographics. A modified k-shortest path algorithm is developed to find the non step-free origin-destination pairs and its paths. The latter are fed into the mixed-integer optimisation algorithm that returns the optimal selection of stations to be upgraded.

METHODOLOGY

The model presented in this section captures the strategic decision of refurbishing stations within a public transport network. The objective is to reduce the burden of travel of persons with disability through the network, while reducing the inequality gap between different areas of the city. To achieve this, a two-step algorithm is developed consisting on a path finding step, and an optimisation phase as shown in Figure 1.

The path finding phase of the algorithm consists of finding the k shortest paths between all origin-destination combinations in the network, and then only passing the non step-free paths to the optimisation phase. The k-shortest path algorithm is a loop that recursively obtains the next shortest path by extending Dijkstra's algorithm (*19*). In this particular case, it is sufficient to only search for paths with different interchanging stations.

From all the calculated shortest paths, the non step-free paths connecting each origin-destination pair using the network topology and step-free access data are acquired. A step-free path is defined as a path where both the origin and destination nodes are step-free from the street to the train (completely step-free), and all interchanges between lines are also step-free (interchange step-free). Any path that does not possess these properties is thus labeled as non step-free.

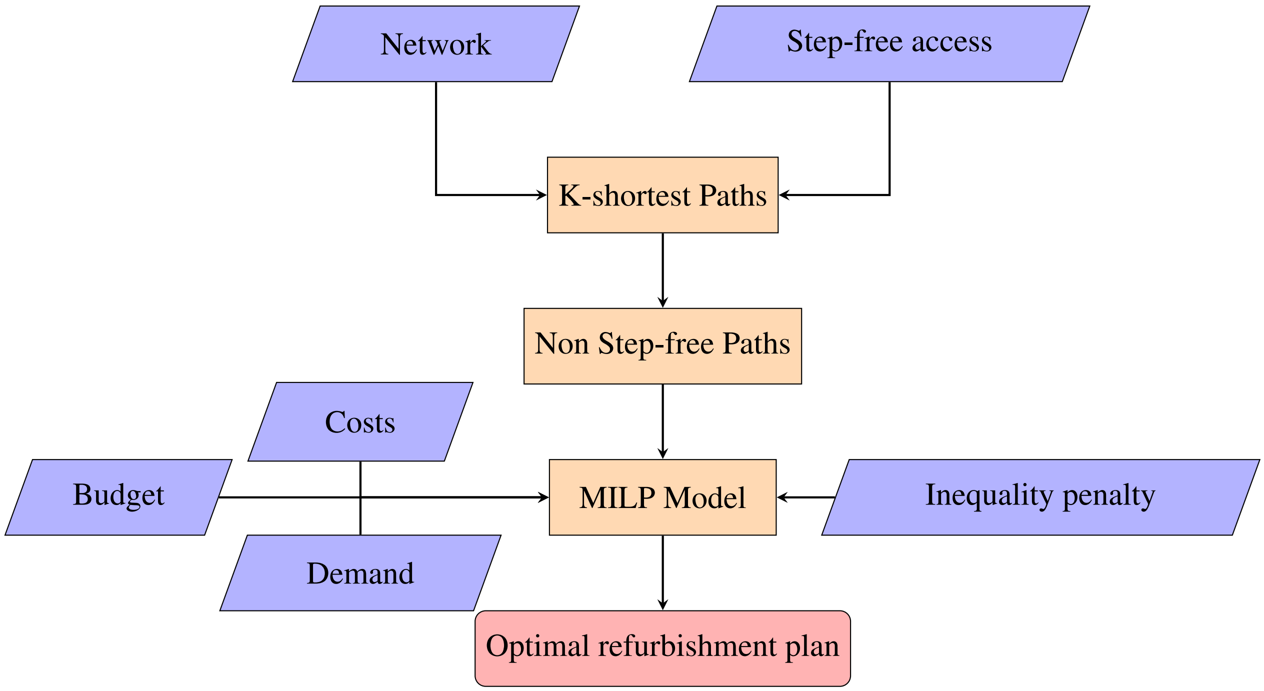


FIGURE 1: Algorithm process flowchart.

These non step-free paths, along with entry and exit data per station and the station refurbishment costs, serve as inputs to the second step algorithm. These are fed into a mixed-integer linear optimisation problem that generates optimal refurbishment plans within a specific budget. The formulation of the problem corresponds to $OP1$, which uses as input the following parameters:

Indices

i, j, n	=	Station
p	=	Path
k	=	Interchange

Sets

OD	=	Set of origin-destination pairs
P	=	Set of paths in O-D pair i, j
K	=	Interchanges in path p
N	=	Set of all interchanges

Parameters

C_i	=	Cost of refurbishment of station i
$D_{i,j}$	=	Demand for travel between stations i, j
$R_{i,j,p}$	=	Number of interchanges for path p between i, j
$S_{i,j,p,k}$	=	Interchange ID
B	=	Budget [£]

Variables

x_i	=	Boolean: station is refurbished
$y_{i,j}$	=	Boolean: travel between stations i, j is step-free
$z_{i,j,p}$	=	Boolean: all interchanges in path p between i, j are step-free
$a_{i,j,p}$	=	Integer: number of step-free interchanges in path p between i, j

($OP1$):

$$\text{Maximise} \quad Z = \sum_{i,j \in OD} D_{i,j} y_{i,j} \tag{1}$$

Subject to:

$$\sum_{i \in N} x_i \leq B \tag{1.1}$$

$$y_{i,j} \leq \sum_{p \in P} (z_{i,j,p}) \qquad \forall i,j \in OD \tag{1.2}$$

$$a_{i,j,p} \leq \sum_{k \in K: n = S_{i,j,p,k}} x_n \qquad \forall i,j \in OD \ \ \forall p \in P \tag{1.3}$$

$$a_{i,j,p} \geq R_{i,j,p} z_{i,j,p} \qquad \forall i,j \in OD \ \ \forall p \in P \tag{1.4}$$

$$R_{i,j,p} - a_{i,j,p} \geq (z_{i,j,p} - 1) R_{i,j,p} \qquad \forall i,j \in OD \ \ \forall p \in P \tag{1.5}$$

$$x_i = \{0,1\} \qquad \forall i \in N \tag{1.6}$$

$$y_{i,j} = \{0,1\} \qquad \forall i,j \in OD \tag{1.7}$$

$$z_{i,j,p} = \{0,1\} \qquad \forall i,j \in OD \ \ \forall p \in P \tag{1.8}$$

$$a_{i,j,p} \in \mathbb{Z}^{+} \qquad \forall i,j \in OD \ \ \forall p \in P \tag{1.9}$$

The objective function is defined by equation (1), which seeks to maximise the number of passengers that are able to complete their trip using only step-free interchanges. Constraint (1.1) represents the budgetary limitation. (1.2) limits $y_{i,j}$ to 0 unless one path exists between the origin-destination pair that is step-free. Constraints (1.3-1.5) remaining constraints ensures $z_{i,j,p}$ is 1 only if all interchanges in path p are step-free. Equation (1.3) calculates the number of step-free interchanges in path p between stations i and j, and constraints (1.4-1.5) set $z_{i,j,p} = 1$ if and only if $a_{i,j,p} = R_{i,j,p}$. The remaining constraints define the variable boundaries: x_i, $y_{i,j}$ and $z_{i,j,p}$ are Boolean, while $a_{i,j,p}$ is a positive integer.

CASE STUDY

London is the capital of United Kingdom and a home to over 9 million residents in 2020 in an area of 1,572 km^2 (*20*). The transport network is run by the local government body and transport authority, Transport for London (TfL), of which the Chair is the Mayor of London (*21*).

The London Underground network is based on a concentric design with over 9 pay fare zones. The network consists of 266 stations on 11 lines that cross all 33 London boroughs and also extends to include a number of stations outside London (*22*), as shown in Figure 2.

The London Underground network is heavily utilised with over 11 million average daily journeys on a weekday in 2018 (*23*). However, the distribution of these journeys is unequal. As an indicative example, although only 0.016% of London population resides in the City of London borough (*24*), it experiences the third highest volume of daily journeys (*23*). A schematic of the demand from and to each station is shown in Figure 3.

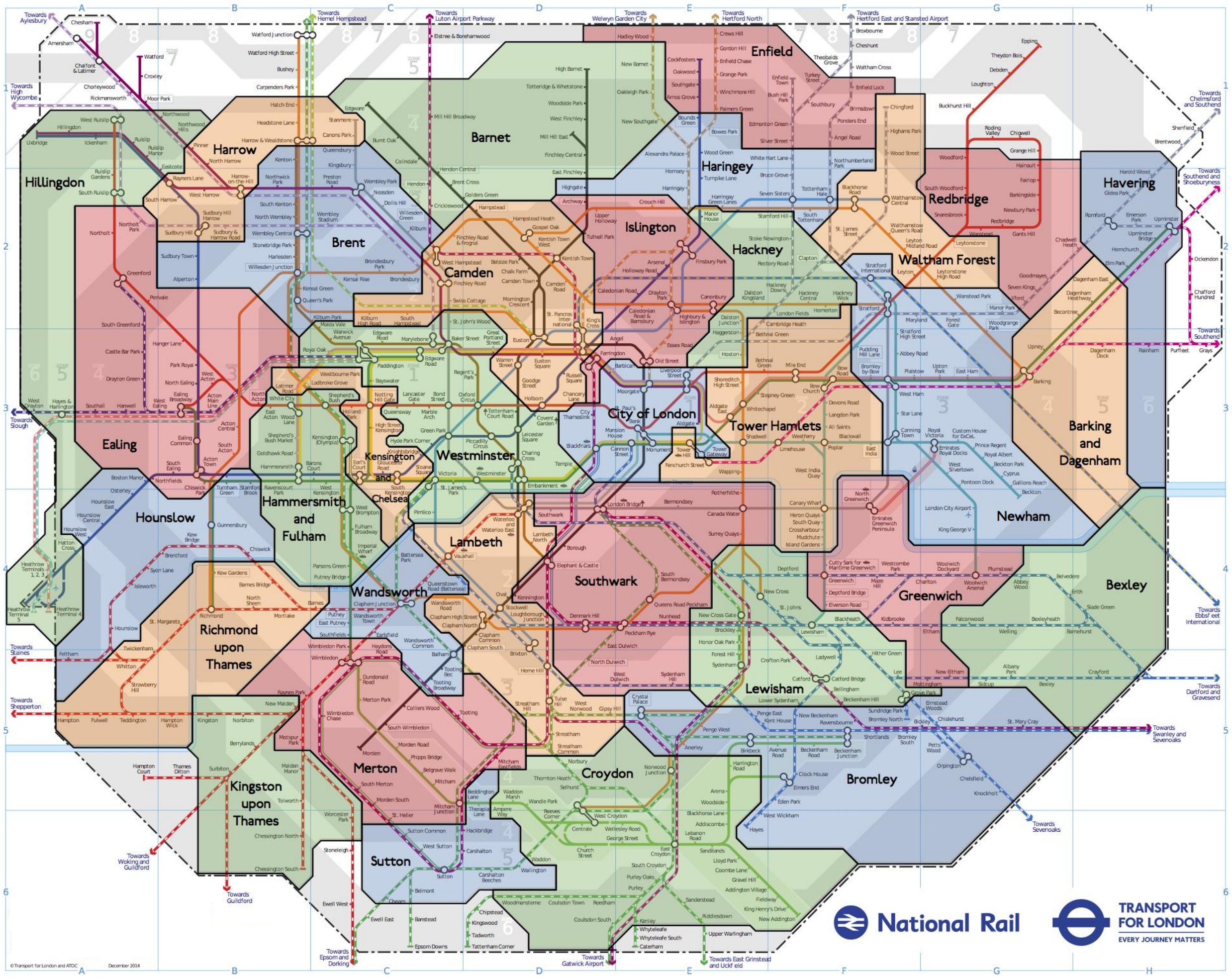


FIGURE 2: London Underground map with overlay of a map of the boroughs (*25*).

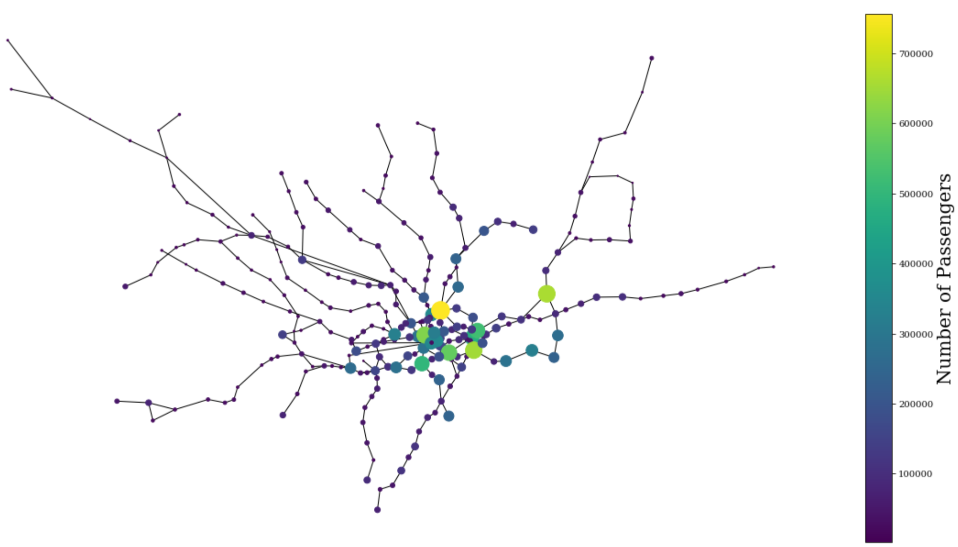


FIGURE 3: Number of passenger entries and exits per station.

The first rail line in the London Underground was constructed in the 1860s with the last station being completed in 2008 (*26*). There are currently two more stations being constructed as part of the Northern Line Extension into west, which are Battersea Power station and Nine Elms station and are predicted to be complete by Autumn of 2021 (*27*). Ten of the central London stations are also being merged with new stations that are being built as part of a new Elizabeth Line (*28*). These have been excluded from the current study, as the opening dates and demand values from and to these stations are currently unknown. The current operating London Underground network has been portrayed based on the original TfL Undergound map (*22*) in Figure 4.

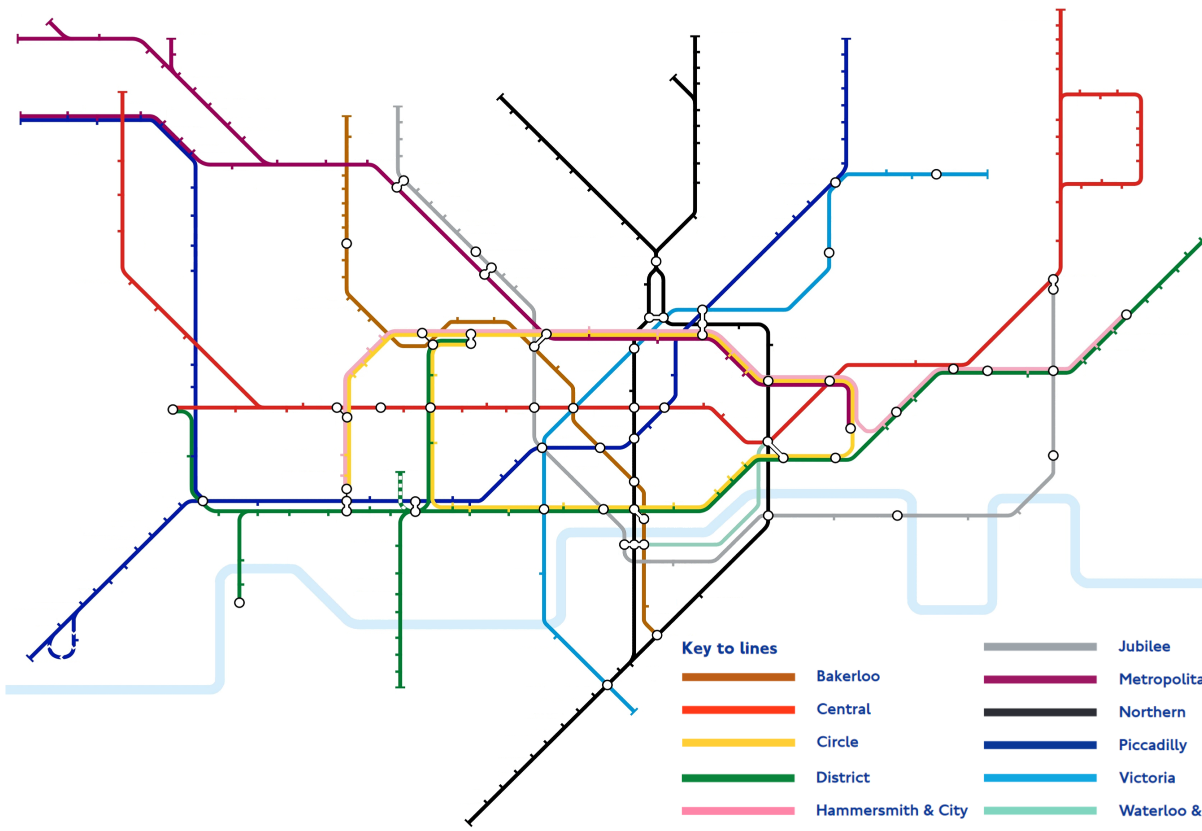


FIGURE 4: London Underground network schematic.

Rail networks that operate within London, such as the Overground, East London Line, TfL Rail, and the Thameslink, were excluded from the study, as they predominantly consist of above ground facilities that do not require an additional step-free access provision or have been already built with lifts as part of their original design.

Due to the current limits of the London Underground network for the users requiring lifts, 98.4% of surveyed wheelchair users in 2019 said that they use the tube less than once a week (*29*). Transport for London (TfL) and the Mayor of London have set out an Action on Equality strategy (*30*) that includes 11 inclusivity objectives, one of which is improving the accessibility of London's transport infrastructure.

The Mayor of London pledged investment of £200 million to upgrade 30 stations to have step-free access with lifts to improve accessibility and have 37% of the London Underground network be classified as step-free (*31*). The stations are still to be fully chosen in phases, but the desired outcome of the Mayor is to cut the additional journey time required by those using the step-free network by 50% (*32*). However, due to the COVID-19 pandemic negatively impacting the revenue for TfL and available capital, no more new step-free access stations are planned (*33*).

Definition of Step-free access

The definition of a step-free access provided by TfL (*34*) refers to a scenario where a passenger can use elevators, ramps or level surfaces instead of stairs and escalators to access trains and can avoid gaps and steps. However, it is not a binary classification, as some stations and interchanges have step-free access only for some lines or some platforms or just between platforms. Thanks to key achievements following the initial investment from the Mayor of London and third party funding of £84m (*33*), in June 2021, TfL stated that there are 84 Tube stations with step-free access (*35*); however, when considering only fully accessible stations with step-free access from road to platform or train on all lines and bounds, only 72 stations qualify.

TfL classifies the different levels of step-free access into four categories: full accessibility, partial interchange step-free accessibility, interchange only step-free accessibility and no step-free access (*36*). A fully accessible station is considered to be one where all the platforms have a step-free access to and from the street. In the case of partial interchange accessibility, only some of the platforms in a station have a step-free access to and from the street. An interchange only accessibility describes a station where step-free access is only possible for specific interchanges, without step-free access to and from the street. The final level describes a station that has no step-free access.

For the purpose of this study, the four levels of accessibility have been simplified into three; namely, a fully step-free, an interchange only and no step-free accessibility. A fully step-free station is one where all the platforms have step-free access to and from the street. An interchange only step-free station is one that allow step-free interchange between lines travelling in the same direction but without step-free access to and from the street. Any station that is unable to support either fully or interchange only step-free accessibility is considered to be a no-step-free access station.

The three levels of accessibility have been used to define a step-free journey for the purpose of this study. A step-free journey is considered to be one where the origin, destination and any required interchanges are all considered to provide step-free access. A journey that requires an interchange should have a fully step-free origin and destination, while the interchange station can either be an interchange only or a fully step-free access station, in order for the journey to be considered as step-free.

Station Refurbishment Costs

While each station is unique and the cost of upgrading the stations to include lifts will vary, an estimate for the station has been made based on historical costs (*37–39*), TfL tender estimates for current and past projects (*40*), and cost savings from standardising lift installation (*41*). For example, the contract for the civil works associated with upgrading seven stations of Burnt Oak, Debden, Hanger Lane, Ickenham, Northolt, Sudbury Hill and Wimbledon Park, excluding lifts and communications, have been contracted for between £10 and £25 million (*42*). For the lift provisions, Otis has won the bid for between £6m and £15m (*40*).

When considering how to estimate the final costs of upgrading each station in average, the upper bound was chosen, based on past Civil Engineering projects often costing more than the initial budget. For instance, the step-free access upgrade of Cockfosters station was tendered between £1 and £5 million, yet close to the opening date, the cost to date was £4.57 million (*37*).

These stations also share similar characteristics: they are above ground and are located in fare zones 3 or higher and are not based near Central London. This allows for lift installation methods to be consistent and cost reduction. This can help increase the absolute number of step-free journeys but not necessarily provide the most step-free journeys or step-free journey time savings. Moreover, stations in zone 2 or zone 1 are much more expensive to upgrade due to the high demands, particularly if they are an interchange, and due to their condition much associated other works need to be carried out simultaneously to refurbish the station. For instance, the contract for developing around South Kensington station in zone 1 including step-free access programme is £25m and £50m (*40*). The refurbishment of Finsbury Park in zone 2 cost £47.8m, although this includes other works and not just the step-free access provision (*39*).

Based on this information, stations have been classified as underground or above ground, as excavating and constructing a shaft would significantly add to the costs, and on the location compared to the fare zone. Construction in central part of London in regions of pay fare zones 1 and 2 would be higher, as the stations are surrounded by high business and sensitive residential areas. As the costs would also depend on the current conditions of the stations, a range of cost has been estimated in line with the tenders, as shown in Table 1.

TABLE 1: Cost estimate of station step-free access upgrade

Station	Zone 3+	Zone 2	Zone 1
Above ground	£5-10m	£10-15m	£15-20m
Underground	£15-20m	£20-25m	£25-30m

For this paper, the average costs within the range have been applied for each station.

Transportation Equity

There are three major types of vertical transportation equity according to Litman (*43*). Horizontal equity is based on egalitarianism, where everyone is treated equally regardless of race, gender, income, and ability. Vertical equity can be based on income and social class. Thirdly, vertical equity can be based on mobility, ability, and needs. These three objectives can be difficult to meet simultaneously, particularly when horizontal equity avoids favoring one group over others, whereas the second vertical equity supports an accessible and inclusive transportation network.

As is the case in many cities, there is a great demographic diversity between the different regions in London. As an indicative example, the City of London borough, which contains the Central Business District, has the highest average income (£99,390) in London. In contrast, the remaining 32 borough only average £35,000 yearly income.

If not taken into account, a horizontal equity objective can skew the transportation network to supply those working and living in the City of London, which compromises of less than 0.2% of the geographical area of London and less than 0.02% of the London population with reported disabilities or children of age below 5 (*24*).

Therefore, four refurbishment strategies are studied in this paper:

1. Horizontal equity (HE): A revised network based on horizontal equity, where every demand is considered equal,

2. Financial Equity (FE): A revised network based on vertical equity regarding income and employment rate with financial penalties applied to the optimisation,
3. Mobility Equity (ME): A revised network based on vertical equity regarding mobility needs and abilities with mobility penalties, and
4. Combined Equity (CE): A revised network based on vertical equity regarding both income and mobility with combined penalties.

In order to incorporate the different equities, the optimisation function was updated to Equation 2.

$$(OP2): \quad \text{Maximise} \quad Z = \sum_{i,j \in OD} D_{i,j} y_{i,j} - p_{economic} \sum_{i,j \in OD} D_{i,j} y_{i,j} BE_{i,j} - p_{mobility} \sum_{i,j \in OD} D_{i,j} y_{i,j} BM_{i,j} - p_{combined} \sum_{i,j \in OD} D_{i,j} y_{i,j} BC_{i,j} \quad (2)$$

The newly introduced parameters are the following:

Indices			Parameters		
economic	=	Penalty parameter p related to income and employment rate	BE	=	Borough specific economic penalty
mobility	=	Penalty parameter p related to disabilities and age below 5	BM	=	Borough specific mobility related penalty
combined	=	Penalty parameter p related to both economic and mobility factors	BC	=	Borough specific combined penalty
			p	=	Penalty parameter and multiplier to borough specific penalty

The borough specific penalties have been determined so that the penalty parameter p is 1 in this study, as $p > 1$ would lead to negative number of passenger completing step-free journeys. Depending on the study of the transportation equity, the p was set to 1 or 0. Calculation of the borough specific penalties for each borough depended on three latest data sources:

- total mean and median annual household income estimate from Greater London Authority from 2012/13,
- number of people with wheelchair, reduced mobility, other disabilities, and of age below 5 from Greater London Authority from 2010, and
- the borough population, employment rate, and borough population without known disabilities from Population Estimates Unit of Office for National Statistics UK from 2019.

To calculate the borough specific economic penalty, the boroughs were ranked by mean annual income, median annual income, and employment rate as a percentage. However, the employment rate is not a true representation of the economic background of the residents in the borough but rather an indication of the labour market, as some may be students, living on investment dividends, or other reasons. Therefore, a weighted average of ratio of 9:9:1 of the mean, median annual income and employment rate was chosen.

As for the borough specific mobility penalty, the boroughs were ranked in terms of the percentage of London population who are people with mobility needs and age below 5. The reason for including population of age below 5 is to take prams into consideration. The combined penalty is the average of the economic and mobility penalty for each borough. For stations outside of London and not belonging to any boroughs, an average of outer London values was chosen. The penalty values for each borough is compared against the travel demand, as shown in Table 3.

The mean of the penalties are lower than one-third, and medians are even lower. A low number of boroughs, such as the City of London, with much higher income are shifting the average of the penalties to be higher. This is also shown by the skewness that particularly economically, the penalties are highly skewed resulting in an even higher skewness in the combined penalties. The travel demand is skewed towards boroughs with more stations and popularity, such as Westminster.

RESULTS

The algorithms described in this paper are executed for the London Underground network and compared against a do-nothing baseline. A budget of £200 million is considered based on the quantity pledged by (*31*). The four refurbishment strategies outlined in the previous section are compared against a baseline case where no improvement is carried out. For a two-phase step-free access upgrade programme, the results present the optimal stations within the budget of £200 million to be upgraded for each phase to provide a more accessible London Underground service.

For the first phase, the solutions for the optimisation of horizontal equity (HE), mobility vertical equity (ME), and combined vertical equity (CE) are the same, and the financial vertical equity (FE) are different. This is partially due to the fact that the combined penalty is mainly influenced by the mobility penalties, resulting in similar trends. The other reason for this result is due to the varying travel demand levels. For example, Westminster has the highest travel demand by over 1 million journeys, and it has a high financial penalty yet an average disability penalty.

The results of the first upgrade are shown in Table 4, indicating that while most refurbished stations are shared by all solutions, the horizontal, mobility and combined equity solutions select Baker Street and Sloane Square, whereas the financial equity solution includes Seven Sisters, South Harrow, Upton Park, and Whitechapel stations.

The second phase solutions share the same six stations, particularly those with high travel demand, but the horizontal equity then also includes Holborn, Whitechapel, Seven Sisters, and Upton Park. The vertical equity solutions share the same two stations of Baker Street and Colindale, but the FE solution replaces Finchley Road and Sloane Square with Bethnal Green and Ealing Common. The solutions of ME and CE are the same. The results of the second upgrade are shown in Table 5.

The refurbishment locations of the first and second upgrade are shown as an overlay on OpenStreetMap (*44*) in Figure 5a and 5b, respectively. These show that some of the stations of the second phase of upgrades are further away from the centre of London. For example, Camden Town station is selected in all equity strategies and resides in Zone 2, experiencing the second highest volume of journeys from and to the station.

TABLE 3: Resulting penalties for each borough.

Borough	Borough specific economic penalty, *BE*	Borough specific mobility related penalty, *BM*	Borough specific combined penalty, *BC*	Travel demand from and to, *D*
Barking and Dagenham	0.027	0.472	0.249	103,696
Barnet	0.301	0.027	0.164	251,691
Bexley	0.208	0.378	0.293	No Tube
Brent	0.107	0.269	0.188	329,278
Bromley	0.363	0.238	0.300	No Tube
Camden	0.399	0.402	0.401	1,149,468
City of London	0.907	1.000	0.954	764,530
Croydon	0.215	0.000	0.107	No Tube
Ealing	0.191	0.216	0.204	230,456
Enfield	0.095	0.005	0.050	53,695
Greenwich	0.193	0.208	0.201	118,367
Hackney	0.160	0.340	0.250	30,976
Hammersmith and Fulham	0.399	0.552	0.476	446,472
Haringey	0.202	0.343	0.273	259,866
Harrow	0.225	0.405	0.315	123,449
Havering	0.202	0.308	0.255	25,548
Hillingdon	0.197	0.173	0.185	170,093
Hounslow	0.169	0.310	0.240	106,039
Islington	0.309	0.452	0.381	575,340
Kensington and Chelsea	0.797	0.603	0.700	576,998
Kingston upon Thames	0.379	0.584	0.482	No Tube
Lambeth	0.263	0.124	0.193	709,813
Lewisham	0.209	0.181	0.195	No Tube
Merton	0.365	0.539	0.452	134,331
Newham	0.026	0.258	0.142	632,157
Redbridge	0.187	0.286	0.236	130,512
Richmond upon Thames	0.624	0.526	0.575	53,815
Southwark	0.241	0.119	0.180	669,176
Sutton	0.286	0.481	0.384	No Tube
Tower Hamlets	0.169	0.373	0.271	542,644
Waltham Forest	0.125	0.288	0.207	192,313
Wandsworth	0.486	0.226	0.356	188,908
Westminster	0.523	0.335	0.429	2,369,585
Outside of London	0.242	0.312	0.277	81,394
Mean	0.288	0.333	0.311	324,135
Median	0.220	0.311	0.263	152,212
Standard Deviation	0.192	0.195	0.175	452,181
Skewness	1.527	0.919	0.171	2.864

TABLE 4: Upgraded stations in the first phase based on solutions.

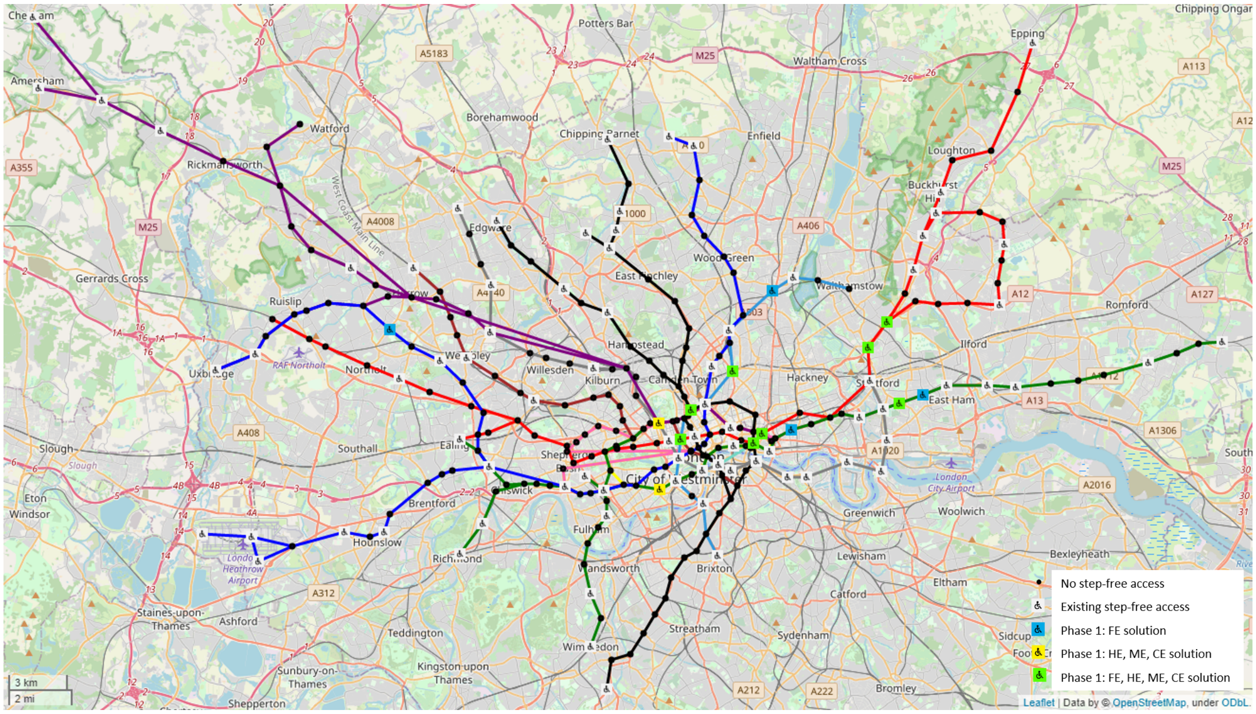
	Horizontal Equity, HE	Financial Equity, FE	Mobility Equity, ME	Combined Equity, CE
First Phase: Stations Upgraded	Bank & Monument Euston H&I* Leyton Leytonstone Liverpool Street Oxford Circus Plaistow Baker Street Sloane Square	Bank & Monument Euston H&I Leyton Leytonstone Liverpool Street Oxford Circus Plaistow Seven Sisters South Harrow Upton Park Whitechapel	Bank & Monument Euston H&I Leyton Leytonstone Liverpool Street Oxford Circus Plaistow Baker Street Sloane Square	Bank & Monument Euston H&I Leyton Leytonstone Liverpool Street Oxford Circus Plaistow Baker Street Sloane Square
Costs	First Phase: £200 million			

* H&I - Highbury & Islington.

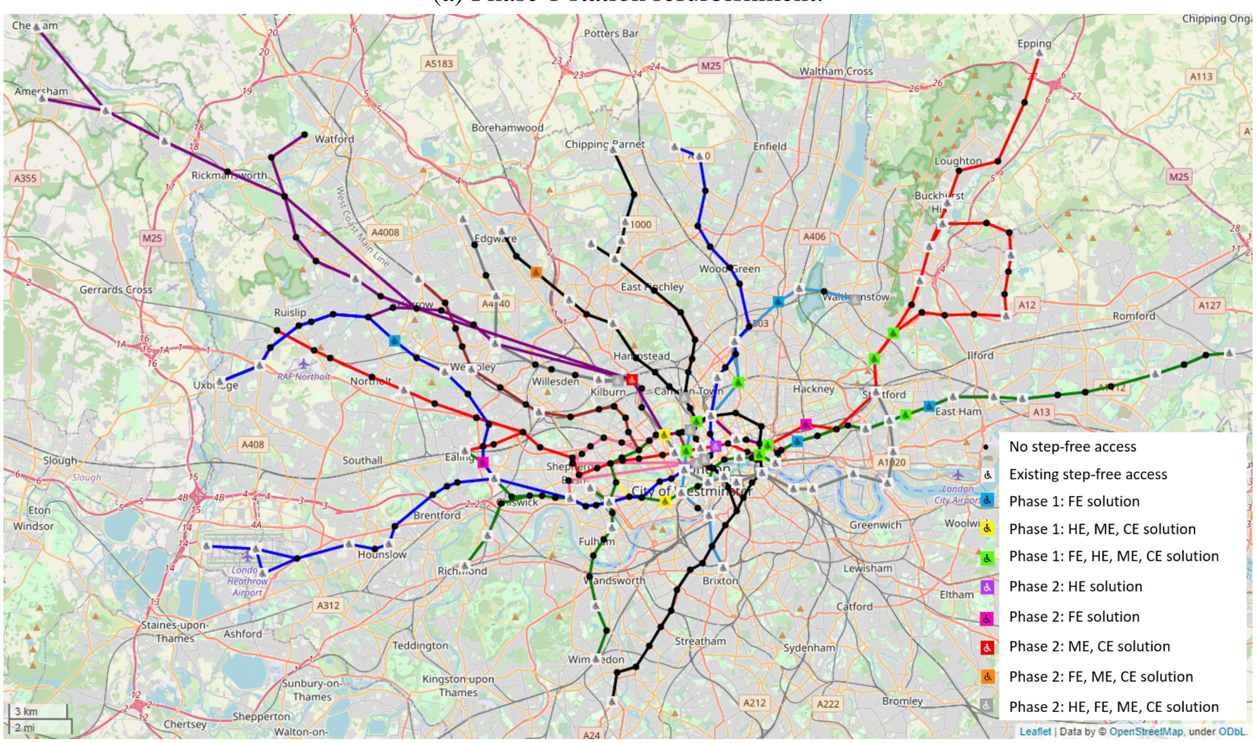
TABLE 5: Refurbished stations in the second phase following the first phase of upgrades.

	Horizontal Equity, HE	Financial Equity, FE	Mobility Equity, ME	Combined Equity, CE
First Phase	HE	FE		
Second Phase: Stations	Camden Town Leicester Square Piccadilly Circus Walt. Central* Warren Street West Hampstead Holborn Whitechapel Seven Sisters Upton Park	Camden Town Leicester Square Piccadilly Circus Walt. Central Warren Street West Hampstead Baker Street Colindale Bethnal Green Ealing Common	Camden Town Leicester Square Piccadilly Circus Walt. Central Warren Street West Hampstead Baker Street Colindale Finchley Road Sloane Square	Camden Town Leicester Square Piccadilly Circus Walt. Central Warren Street West Hampstead Baker Street Colindale Finchley Road Sloane Square
Costs	Second Phase: £200 million			
	Total for both First and Second Phase: £400 million			

* Walt. Central - Walthamstow Central.



(a) Phase 1 station refurbishment.



(b) Phase 2 station refurbishment.

FIGURE 5: London Underground network showing the proposed step-free access stations for the different refurbishment strategies.

In order to quantify the benefits of each solution, five key performance indicators (KPIs) have been defined:

1. Expected new trips: the estimated demand for step-free trip that is serviced after refurbishment.
2. Percentage time savings: the improved travel time to existing step-free paths, and
3. Step-free paths: the percentage difference of step-free routes created compared to the all the non step-free routes available,
4. Optimal step-free path: the percentage of step-free routes that are equal to non step-free counterpart,
5. Total daily step-free trips.

Figure 6 show the aggregated results for the complete London Underground network, where KPIs 1 and 2 are presented in Figures 6a and 6b, respectively, KPIs 3 and 4 are shown in Figure 6c, and Figure 6d presents KPI 5. A baseline is calculated using the current step-free capabilities of the underground network, while the other metrics correspond to the different inequity refurbishment strategies by first and second upgrade phase: Horizontal Equity first and second phases (HE-1, HE-2); Financial Equity (FE-1, FE-2); Mobility Equity (ME-1, ME-2); Combined Equity (CE-1, CE-2).

Figure 6c shows that, in its current state, the London Underground Network only provides approximately 5% of all available routes. By upgrading 10 stations, the percentage of step-free paths increases to 12% and to 10% in the FE case. Approximately a third of these paths are the shortest possible in the network. Further development would improve the number of step-free paths to approximately 16% (with 60% of them being optimal) for the HE case, and marginally lower percentages for the rest of the refurbishment strategies.

The two phased refurbishment strategy is expected to provide approximately 400,000 additional daily trips in the HE and FE cases, and 350,000 in the ME and CE cases (see Figure 6a). In contrast, all strategies should generate close to 250,000 new trips per day in the first phase. This represents an increment in new trips 15% step-free trips in the first upgrade phase compared to the current baseline, while the second upgrade phase adds between 5-10% step-free trips, depending on the selected inequity strategy (see Figure 6d).

In terms of journey time, Figure 6b shows that the FE case is the worst performing strategy, reducing journey time by 60% after two phases, while this is achieved in a single phase by the other strategies.

The results show an improvement in the overall London Underground network. To evaluate the impact on the boroughs, eight boroughs were chosen based on their rankings of the three penalties and demands, as shown in Table 6.

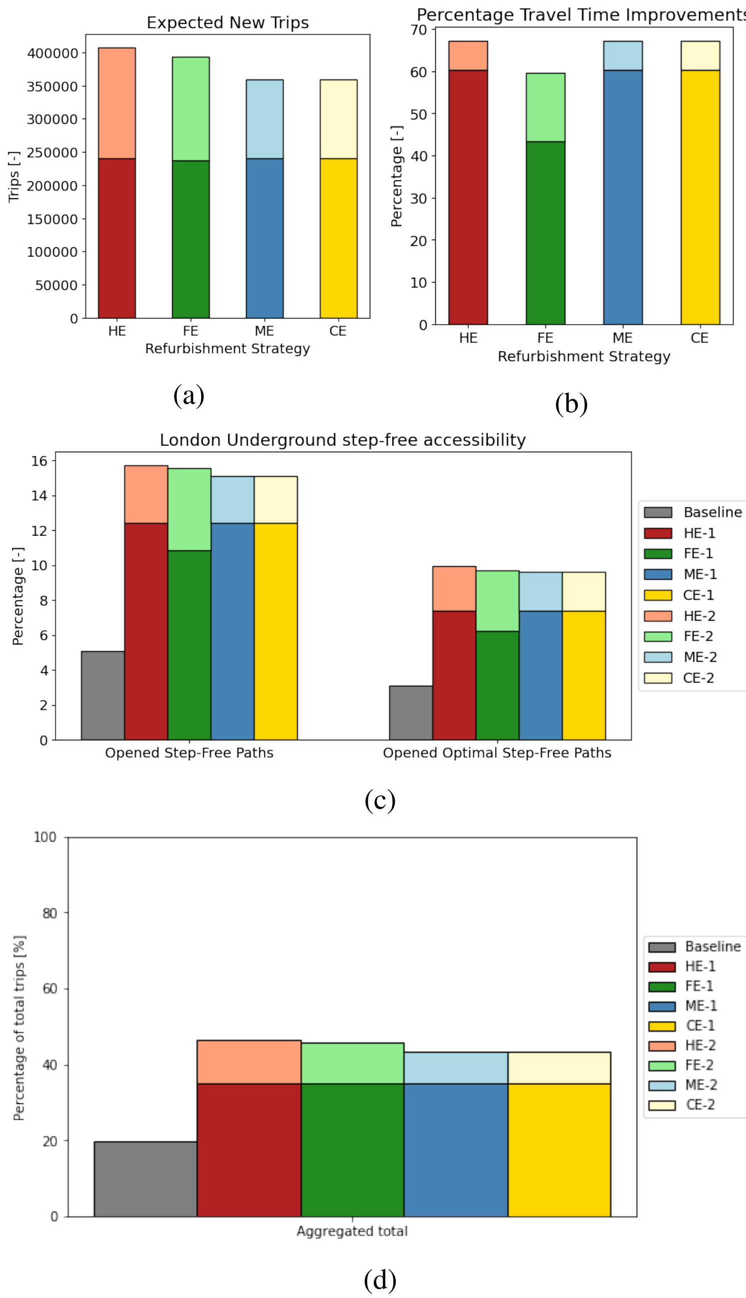
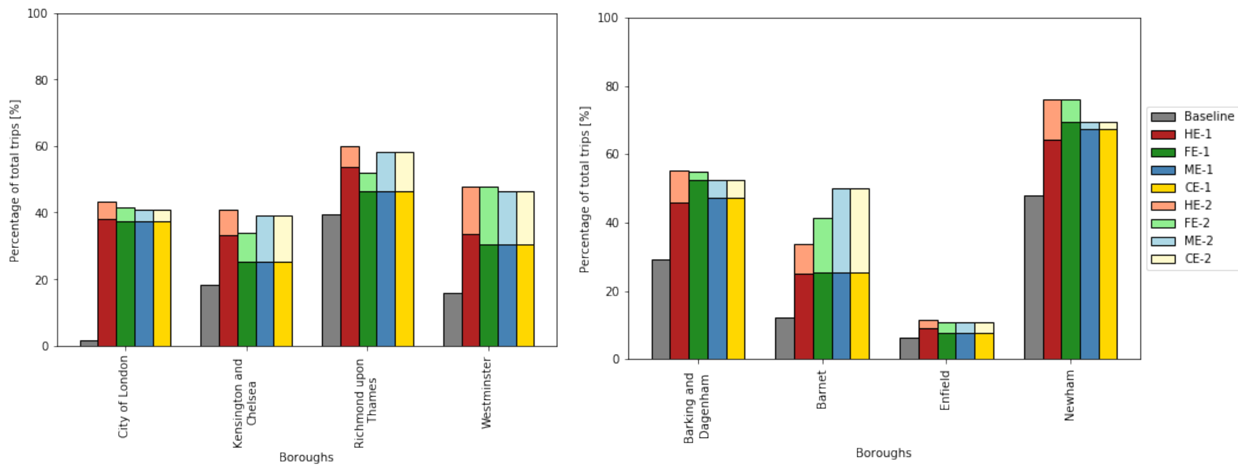


FIGURE 6: Improvement of step-free accessibility in the London Underground network: a) new step-free trips expected, b) percentage travel time savings of existing step-free trips, c) percentage step-free paths in the network, and d) percentage of step-free trips for different refurbishment strategies.

TABLE 6: London borough result analysis.

Borough	Financial Equity, FE	Mobility Equity, ME	Combined Equity, CE
Barking & Dagenham	2nd lowest income and employment rate		
Barnet		Highest number of people with disabilities and children under 5	
City of London	Highest income and employment rate	Lowest number of people with disabilities and children under 5	Highest combined penalty
Enfield		2nd highest number of people with disabilities and children under 5	Lowest combined penalty
Kensington and Chelsea	2nd highest income and employment rate	2nd lowest number of people with disabilities and children under 5	2nd highest combined penalty
Newham	Lowest income and employment rate		2nd lowest combined penalty
Richmond upon Thames	3rd highest income and employment rate		3rd highest combined penalty
Westminster (Highest demand)	4th highest income and employment rate	Average	5th highest combined penalty

To analyse the impact of the refurbishment strategies at a borough level, the different percentages of step-free trips are presented in Figure 7 for some boroughs of interest: the richest and poorest ones. It can be observed that the largest increase in step-free trips as a result of the interventions suggested by this model correspond to the City of London, which is expected due to its centrality and high transit. When comparing between inequity strategies, the percentages of step-free trips are larger for the horizontal equity (no penalty) solution in the richer boroughs, while for the poorer boroughs the opposite usually happens for the financial, mobility and combined inequity penalties (except in Enfield, which can be explained due to its low demand). This trend confirms the expected effect of adding inequity penalties to the optimisation model, particularly with the first upgrade phase.



(a) (b)

FIGURE 7: Total step-free trips grouped by boroughs of interest: a) boroughs with higher income and lower number of reported disabilities; b) boroughs with lower income and higher number of reported disabilities.

DISCUSSION AND FUTURE WORK

The results reported show that significant improvements can be made to the accessibility of the London Underground network using the framework developed in this study. Governmental organisations and transport management companies can utilise this framework to assess and improve their accessibility policies and plan strategic improvements in their networks. This fits with the recent efforts by the London authorities towards equality and equity in their public transport systems.

However, the presented method contains several limitations. The refurbishment costs were estimated based on historical data and mapped to the stations according to the its location and whether the station is above or underground. While a standardised refurbishment approach has progressively reduced lift provision of several stations, these were located exclusively above ground and in lesser densely populated areas. Estimating refurbishment costs for central London stations is significantly more difficult as the latest figures also include additional works beyond step-free access provision. Thus, producing more accurate costs based on the station characteristics would improve the results derived from the framework developed.

A further cost not considered in this study involves the construction time, and the time the station will stop being functional for. For example, refurbishment works in South Kensington station cause the closure of the Piccadilly line access, so the resulting detour costs should also be accounted by the model. This also represents an important hurdle towards implementing the proposed framework, as simultaneous refurbishment works in several central London stations would significantly impact commuters' journey time and travel time.

However, estimating refurbishment work impact on the users requires the consideration of other forms of public transport which may be used as a replacement while a particular connection remains inactive. Thus, further work should seek to include these aspects as part of mathematical formulation. For example, the number of works carried out simultaneously within a single line or borough could be limited for each phase of construction, and other public transport should be added to provide realistic alternatives for users.

While the original objective function (1) is modified to include equity considerations in the form of financial opportunities to travel and mobility needs in equation (2), the topic of accessibility and its effects in terms of equality is a topic area that requires further exploration. However, the reasons for reduced mobility are numerous and are not limited to the lack of wheelchair access. Visual, hearing and intellectual impairment have specific needs and solutions to consider, and incorporating these aspects requires the development more complex objective functions that will comprise further work.

Another note on the objective function, the demand considered is estimated based on existing entry-exit passenger counts and adapted to step-free demand based on the proportion of people with mobility disability. One issue with this approach is that there is no information on the actual route passengers take to achieve their journey. Our methodology mitigates this by proposing a set of k paths and seeking to ensure that at least one of the provided paths is step-free.

Another limitation relates to the fact that the mobility impaired will not utilise stations without step-free access, so they are not represented in the dataset as it currently stands. Therefore, we approximate the step-free demand based on the demand patterns of the rest of the population, which may not be the case as the majority of the mobility disability group consists of persons aged 60 or more and the Underground demand mainly fluctuates based on commuter behaviour. A four-stage transport model specific for this population group would provide more indicative demand quantities.

CONCLUSION

Public transport system, in particular underground and train networks, are essential for mobility in most larger cities in the world. The improvement of public transport can positively impact urban and suburban environments in many aspects, such as traffic flow, connectivity, air quality, quality of life, among others. Therefore, the democratisation of public transport should be a priority to policy makers and infrastructure designers.

This study focuses on step-free accessibility in underground and train networks, which is a key enabler of social equity in metropolitan areas. Unfortunately, the number of possible step-free journeys are usually low, and need to be urgently increased in many places around the world. Extremely efficient refurbishments and upgrades in transport systems need to be planned and executed due to limited resources and high refurbishment costs associated with infrastructure improvements. Hence, mathematical optimisation techniques should be used for optimal refurbishment planning.

A novel two-step method is presented for the optimal selection of stations to be upgraded to step-free, which usually involves adding infrastructure such as lifts and ramps to stations. In the first step, the k shortest paths between all origin-destination pairs are calculated, and from those only the non step-free paths are kept. In the second step, a Mixed Integer Linear Problem is formulated to maximise the total number of step-free trips. The problem takes as input the non step-free paths from the first step, together with parameters for average travel demands, station refurbishment costs and available budget. Moreover, in order to increase fairness and equality in the decision making process, zone inequality penalties are added to the optimization model to derive various inequity refurbishment strategies.

Finally, for illustrating and validating the presented method, a case study of the London Underground network is provided. Two sets of upgrade recommendations are generated, one taking into consideration inequity (financial, mobility and combined) between city boroughs, and one only maximising overall trips (horizontal equity). Setting the refurbishment budget to the £200 million the Mayor of London recently pledged for step-free access infrastructure, and using real data for travel demands, refurbishment costs, and borough demographic information. On average, the recommended refurbishment strategies lead to an increase in step-free trips by approximately 20%, and a reduction of total step-free travel time by 60%. An additional analysis is conducted by considering a second refurbishment stage of another £200 million, which leads to an increase in step-free trips by approximately 8%, and a reduction of total step-free travel time by 10%.

ACKNOWLEDGEMENTS

The authors would like to thank UK Research and Innovation funded EPSRC, Lloyd's Register Foundation, and the President's Scholarship Programme funded by Imperial College London.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: P Angeloudis, E Candela, JJ Escribano Macias, H Cheong, P Constantinou; data collection: JJ Escribano Macias, H Cheong, P Constantinou, E Candela; analysis and interpretation of results: E Candela, JJ Escribano Macias, H Cheong, P Constantinou; draft manuscript preparation: E Candela, JJ Escribano Macias, H Cheong, P Constantinou. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Antipova, A., S. Sultana, Y. Hu, and J. P. Rhudy, Accessibility and transportation equity. *Sustainability*, Vol. 12, No. 9, 2020.
2. Office for National Statistics, *Family Resources Survey 2014/15*. Department for Work and Pensions, 2016.
3. McCurdy, C., *Ageing, fast and slow When place and demography collide*. Resolution Foundation, 2019.
4. Gilhooly, M. L., K. Hamilton, and M. O'Neill, *Transport and Ageing : Extending Quality of Life for Older People Via Public and Private Transport*, 2002.
5. United Nations, *Convention on the rights of persons with disabilities*, 2007.
6. London Assembly, *From Step-free to Stress-free: Accessible and inclusive transport in London*. Greater London Authority, London, UK, 2020.
7. Saif, M. A., M. M. Zefreh, and A. Torok, Public transport accessibility: A literature review. *Periodica Polytechnica Transportation Engineering*, Vol. 47, No. 1, 2019, pp. 36–43.
8. Basagaña, X., M. Triguero-Mas, D. Agis, N. Pérez, C. Reche, A. Alastuey, and X. Querol, Effect of public transport strikes on air pollution levels in Barcelona (Spain). *Science of the Total Environment*, Vol. 610-611, 2018, pp. 1076–1082.
9. Johnson, D., M. Ercolani, and P. Mackie, Econometric analysis of the link between public transport accessibility and employment. *Transport Policy*, Vol. 60, No. June 2016, 2017, pp. 1–9.
10. Grisé, E., G. Boisjoly, M. Maguire, and A. El-Geneidy, Elevating access: Comparing accessibility to jobs by public transport for individuals with and without a physical disability. *Transportation Research Part A: Policy and Practice*, Vol. 125, No. March 2018, 2019, pp. 280–293.
11. Mackett, R. L. and R. Thoreau, Transport, social exclusion and health. *Journal of Transport and Health*, Vol. 2, No. 4, 2015, pp. 610–617.
12. Mugion, R. G., M. Toni, H. Raharjo, L. Di Pietro, and S. P. Sebathu, Does the service quality of urban public transport enhance sustainable mobility? *Journal of Cleaner Production*, Vol. 174, 2018, pp. 1566–1587.
13. Unsworth, C., M. H. So, J. Chua, P. Gudimetla, and A. Naweed, A systematic review of public transport accessibility for people using mobility devices. *Disability and Rehabilitation*, Vol. 0, No. 0, 2019, pp. 1–15.
14. Peña Cepeda, E., P. Galilea, and S. Raveau, How much do we value improvements on the accessibility to public transport for people with reduced mobility or disability? *Research in Transportation Economics*, Vol. 69, No. July, 2018, pp. 445–452.
15. Velho, R., Transport accessibility for wheelchair users: A qualitative analysis of inclusion and health. *International Journal of Transportation Science and Technology*, Vol. 8, No. 2, 2019, pp. 103–115.
16. Jolly, B. D., M. Priestley, and B. Matthews, *Secondary analysis of existing data on disabled people ' s use and experiences of public transport in Great Britain*. University of Leeds, 2006.
17. Vale, D. S. and M. Pereira, The influence of the impedance function on gravity-based pedestrian accessibility measures: A comparative analysis. *Environment and Planning B: Urban Analytics and City Science*, Vol. 44, No. 4, 2017, pp. 740–763.

18. Ferrari, L., M. Berlingerio, F. Calabrese, and J. Reades, Improving the accessibility of urban transportation networks for people with disabilities. *Transportation Research Part C: Emerging Technologies*, Vol. 45, 2014, pp. 27–40.
19. Eppstein, D., Finding the k shortest paths. *SIAM Journal on computing*, Vol. 28, No. 2, 1998, pp. 652–673.
20. Population Estimates Unit of Office for National Statistics UK, *Mid-Year Population Estimates, UK, June 2020*. Available from: https://data.london.gov.uk/dataset/londoners-reduced-mobility, 2021, [Accessed 26th July 2021].
21. TfL, *Board Members*. Available from: https://tfl.gov.uk/corporate/about-tfl/how-we-work/corporate-governance/board-members, 2021, [Accessed 24th July 2021].
22. TfL, *Tube map*. Available from: https://content.tfl.gov.uk/standard-tube-map.pdf, 2021, [Accessed 24th July 2021].
23. TfL, *TfL Rolling Origin and Destination Survey*. Was available from: https://data.london.gov.uk/dataset/tfl-rolling-origin-and-destination-survey, 2018, [Accessed 10th October 2020].
24. Annual Population Survey - Office of National Statistics UK, *Annual Population Survey: Working-age employment and disability*. Available from: https://data.london.gov.uk/dataset/employment-rates-by-disability, 2020, [Accessed 24th July 2021].
25. Maggiolo, S., *Filling a void*. Available from: http://blog.poormansmath.net/filling-a-void/, 2015, [Accessed 20th July 2020].
26. TfL, *A brief history of the Underground*. Available from: https://tfl.gov.uk/corporate/about-tfl/culture-and-heritage/londons-transport-a-history/london-underground/a-brief-history-of-the-underground, 2011, [Accessed 24th July 2021].
27. TfL, *Northern line extension*. Available from: https://tfl.gov.uk/travel-information/improvements-and-projects/northern-line-extension, n.d., [Accessed 21st July 2021].
28. Crossrail, *Central and South East Stations*. Available from: https://www.crossrail.co.uk/route/stations/, n.d., [Accessed 20th July 2020].
29. Mayor of London and TfL, *Travel in London: Understanding our diverse communities 2019*. Available from: http://content.tfl.gov.uk/travel-in-london-understanding-our-diverse-communities-2019.pdf, 2019, [Accessed 21st July 2021].
30. TfL, *Action on Equality: TfL's commitments to 2020*. Available from: http://content.tfl.gov.uk/action-on-equality-tfls-commitments-to-2020.pdf, 2016, [Accessed 24th July 2021].
31. Mayor of London and London Assembly, *Mayor's £200m investment boosts Underground step-free access*. Available from: https://www.london.gov.uk/press-releases/mayoral/mayors-200m-investment-in-step-free-access, 2016, [Accessed 26th July 2021].
32. Mayor of London and TfL, *Guidance for Borough Officers on Developing the Third Local Imlementation Plan*. Available from: https://content.tfl.gov.uk/lip3-guidance-for-borough-officers-preparing-lip3-2018.pdf, 2018, [Accessed 21st July 2021].

33. Mayor of London and TfL, *Transport for London Financial and Sustainability Plan*. Available from: https://content.tfl.gov.uk/financial-sustainability-plan-11-january-2021.pdf, 2021, [Accessed 21st July 2021].
34. TfL, *Wheelchair access & avoiding stairs*. Available from: https://tfl.gov.uk/transport-accessibility/wheelchair-access-and-avoiding-stairs?intcmp=5344, n.d., [Accessed 24th July 2021].
35. TfL, *Step-free access*. Available from: https://tfl.gov.uk/travel-information/improvements-and-projects/step-free-access?intcmp=1954, n.d., [Accessed 21st July 2021].
36. TfL, *Step–free data specification for lrad-v2.xml*. Available from: https://content.tfl.gov.uk/step-free-data-specification-for-lrad-v2.pdf, 2021, [Accessed 24th July 2021].
37. TfL, *FOI Request Detail - Cost of Lift and Step Free Access at Cockfosters*. Available from: https://tfl.gov.uk/corporate/transparency/freedom-of-information/foi-request-detail?referenceId=FOI-1356-2021, 2020, [Accessed 21st July 2021].
38. D&D Rail Limited, *Project: Acton Town Station – Step Free Access & Modernisation Project*. Available from: https://www.ddrail.com/projects/acton-town-station-step-free-access-modernisation-project/, n.d., [Accessed 21st July 2021].
39. What Do They Know - Freedom of Information, *Accessibility at Finsbury Park Station - TfL Ref: FOI-0963-1415*. Available from: https://www.whatdotheyknow.com/request/accessibility_at_finsbury_park_s, 2014, [Accessed 21st July 2021].
40. TfL, *Contracts greater than £5,000*. Available from: https://tfl.gov.uk/corporate/publications-and-reports/contracts-greater-than-5000, 2021, [Accessed 24th July 2021].
41. Mayor of London and London Assembly, *Huge boost for accessibility as further 13 stations to go step-free*. Available from: https://www.london.gov.uk/press-releases/mayoral/further-13-stations-to-go-step-free, 2018, [Accessed 21st July 2021].
42. Crossrail, *Central and South East Stations*. Available from: https://www.crossrail.co.uk/route/stations/, n.d., [Accessed 20th July 2020].
43. Litman, T., *Evaluating Transportation Equity*. World Transport Policy & Practice, The address of the publisher, 2002, pp. 50-65.
44. OpenStreetMap, *OpenStreetMap*. Available from: https://www.openstreetmap.org/, 2021, [Accessed 21st July 2020].