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The spatial relationship between pedestrian flows and street characteristics around multiple destinations

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ABSTRACT

Accessibility improvement for pedestrians has received increasing attention in planning. However, pedestrian space is more likely to be designed only for individual streets to secure minimum easiness of walking, and little attention has been paid to developing a street network for pedestrians to walk around multiple destinations on a neighbourhood scale. There is also a lack of empirical analysis of how much pedestrian accessibility would vary depending on the characteristics of streets on routes to specific destinations. This paper is aimed at examining the spatial relationship between pedestrian flows by street type and various street characteristics around multiple destinations in a city centre. First, a literature review summarises what street characteristics should be considered in accessibility analysis for pedestrians. Then, a pedestrian flow model is developed in a way that measures accessibility with street characteristics of origins, destinations, and routes on multi-scales from on-street ones to neighbourhood-scale ones. A multiple regression model is made using data from the West End area in London, in which street characteristics are taken for routes from each street segment to nearby stations and attractions. As a result, this analysis found that the route characteristics to a single nearest station and attraction can account for pedestrian flows well, but route characteristics to multiple nearby stations and attractions do not improve the model fit. These results are more prominent for pedestrianised streets. Their implication may be that these destinations are currently not linked well for pedestrians, and pedestrianisation is required to contribute more to the linkage.

1. Introduction

Improvement of pedestrian accessibility is increasingly expected in transport planning for its contribution to sustainable development through economic, social, and environmental co-benefits. While transport planning has investigated pedestrian accessibility to propose a traffic-calming measure at the city level, urban design has paid more attention to specific design elements to propose pedestrian-friendly built environments at the neighbourhood level. Mixed-use and high-density developments are generally encouraged for the physical design, as in New Urbanism. However, these design elements have not been well-established through empirical analysis [1].

Street design is a critical element of a pedestrian-friendly environment. Many streets have been designed more for cars, as most were constructed during motorisation periods. As a result, the design of on-street pedestrian spaces is typically ignored, that is, sidewalks are set only to secure the necessary space for pedestrian access. Street design is thus increasingly required to improve spaces for pedestrians to move through and stay around [2].

However, these improvements are likely to be introduced only for individual streets. In city centres, increased effort has been made to improve streets to enhance the attractiveness of individual areas as shopping and sightseeing destinations. On the other hand, there is a lack of street improvements to link destinations segregated by heavy traffic despite their spatial advantage of being within walking distance in the city centre. Thus, to improve pedestrian access, strategic approaches to improving links to nearby multiple destinations at a large scale must be emphasised [3].

It is necessary to measure pedestrian accessibility in order to evaluate such street improvements for links around multiple destinations. In traditional transport planning, accessibility measures are established for citywide travel by car and public transport. They account for the ability to reach key destinations with accessibility factors that comprise the characteristics of the origins, destinations, and routes between them [4]. To analyse local accessibility for pedestrians, a similar approach has been discussed in urban design [5], [6].

Nevertheless, existing accessibility measures have limitations in their application to evaluating pedestrian links. Transport accessibility measures is made using origin/destination (OD) travel data, but such

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data are less available for local pedestrian travel. Instead, urban design develops accessibility measures for pedestrians using pedestrian flow volume as an operational and interpretable indicator, in which good accessibility is reflected by higher pedestrian flow. In city centres, where the majority of pedestrians are shoppers, pedestrian accessibility improvement is expected to increase pedestrian flow volume [7].

However, accessibility measures in urban design are heavily focused on the morphological aspects of street networks [8]. In this context, street design would not affect pedestrian accessibility without extensive morphological change of the street network. For instance, the morphology may not be changed by traffic-calming measures, such as pedestrianisation, but the impact of traffic-calming measures on pedestrian accessibility may not be ignorable. It was reported that the observed impacts of traffic calming projects in European city centres contributed to 20%–40% increases in pedestrian flows depending on the spatial scale of the improved areas [9].

This paper conducts an empirical analysis to examine the spatial relationship between pedestrian flows by street type and various street characteristics around multiple destinations in a city centre to improve accessibility measures for pedestrians. The remainder of this paper consists of three parts: literature review, methodology and data collection, and pedestrian flow analysis. First, a literature review is conducted on accessibility measures for pedestrians in transport planning and urban design to summarise appropriate key accessibility factors of street characteristics. Then, a model of multiple regression analysis (MRA) is developed to account for the spatial patterns of pedestrian flow volume on non-pedestrianised and pedestrianised streets, respectively, with street characteristics around nearby stations and attractions in the West End area in London. Finally, the MRA is conducted to examine the contributions of multi-scale street characteristics to pedestrian flows.

2. Literature review

Considering the impact of street characteristics on pedestrian accessibility, we conduct a literature review to determine critical accessibility factors. Although many potential accessibility factors of street characteristics may affect pedestrian behaviour, the purpose of this study is not to develop a detailed pedestrian model and test all possible factors. Instead, this study focuses on extracting major indicators in accessibility measures for pedestrians. In addition, as the factors affecting pedestrian movement may differ depending on the context of an area, attention is paid to the travel of pedestrian shoppers in a city centre.

Conventional measures used to evaluate streets for pedestrians pay significant attention to on-street characteristics, represented by level of service (LOS). While LOS is developed for various road transport users, pedestrian LOS is measured using walking space, as proposed by Fruin [10]. In this measure, walking space is regarded as street capacity for pedestrian flow, in which insufficient capacity decreases LOS for pedestrians owing to crowding. In Fruin's LOS concept, more walking space is recommended for shoppers so they can move around more. Yet, it should be noted that pavement width is positively correlated with pedestrian flow volume [11], but this does not necessarily mean that pavement expansion alone can generate higher pedestrian flow through increased demand for walking.

Early attempts to estimate pedestrian flow volume paid attention to another on-street characteristic, land use. As pedestrian travel has less-specific origins and destinations than other types of transport, land use has been taken into account at a street level as a key variable accounting for pedestrian flow volume in a city centre [12], [13].

On the other hand, an accessibility analysis for pedestrians derived from transport studies considers neighbourhood-scale street characteristics to represent the spatial relationship between origins and destinations. Place-based accessibility measures consist of spatial characteristics of origins, destinations, and routes in pedestrian travel [14], [15], [16]. Talen [17], [18] points out five classes of factors affecting pedestrian accessibility: pedestrian attributes, spatial locations of origins, spatial locations of destinations, destination attributes, and routes attributes between origins and destinations. In these studies, street characteristics of routes are generally measured using the distance between residential origins and commercial destinations. As in traffic flow estimation, the accessibility measure can be applied to estimate pedestrian flow volume in a city centre with distance from individual houses to anchor shops [19]. Although this approach is suitable for a small neighbourhood area, it is too data-intensive for accommodating a large number of visitors from all over the city to a large city centre.

Studies in urban design have developed a simpler approach to pedestrian accessibility measurement, paying more attention to route street characteristics. They hypothesise that street configuration is the most important and sole contributing factor to pedestrian accessibility [20]. Street configuration includes the morphological connectivity of a street network, in which a well-connected street network (e.g. a grid pattern) is more likely to draw people than a less-connected one (e.g. a cul-de-sac pattern). This approach interprets complex street configuration with a simple behavioural principle of pedestrians' preference for more legible routes in a street network. Observation studies have consistently reported that distance is overestimated in complex network layouts [21], [22], [23]. By measuring the connectivity of a street network with the number of changes in direction between street segments, it was proven that street configuration is significantly related to pedestrian flow volume [24]. Configuration analysis has become ones of the most popular approaches to pedestrian accessibility. Pedestrian flow models have also been developed using street configuration indicators and applied to practical street improvement projects owing to their simplicity [25].

However, configurational accessibility analysis does not consider the quality attributes of routes. These route characteristics are accountable only for accessibility improvements from extensive street-network morphological changes. A traffic-calming measure, such as pedestrianisation, does not necessarily change the morphology of a street network. Particularly, the conflict between pedestrians and vehicles must be considered to reflect that route quality affects pedestrian accessibility [26], [27], [28]. Pedestrianisation was reported to increase traffic flows on surrounding streets owing to traffic shifts from the pedestrianised area [29]. This conflict is prominent at intersections with heavy cross-traffic flow caused by longer wait time and higher accident risks, and it may worsen pedestrian accessibility by segregating pedestrian links. Street configuration analyses can be applied to estimate neighbourhood-scale traffic flows on local streets [30], but the impact of the conflict on pedestrian flows have not been analysed with it.

Configuration analysis has another limitation in evaluating pedestrian-link development between multiple key destinations. This limitation is attributed to insufficient consideration to the impacts of specific key destinations for pedestrian accessibility. Although configurational analysis hypothesises that street connectivity to all other streets in the network can account for local land use, key destinations in a city centre are often exogenous and context-dependent. Therefore, explicit consideration to these locations is needed to evaluate potential accessibility improvements in pedestrian links among them.

3. Methodology and data collection

3.1. Pedestrian flow model

In this study, a pedestrian flow model is developed with MRA to capture the contribution of each accessibility factor to overall place-based accessibility for pedestrians on a street segment. The model measures overall pedestrian accessibility using a unit of pedestrian flow volume as an interpretable indicator. In a city centre, accessibility

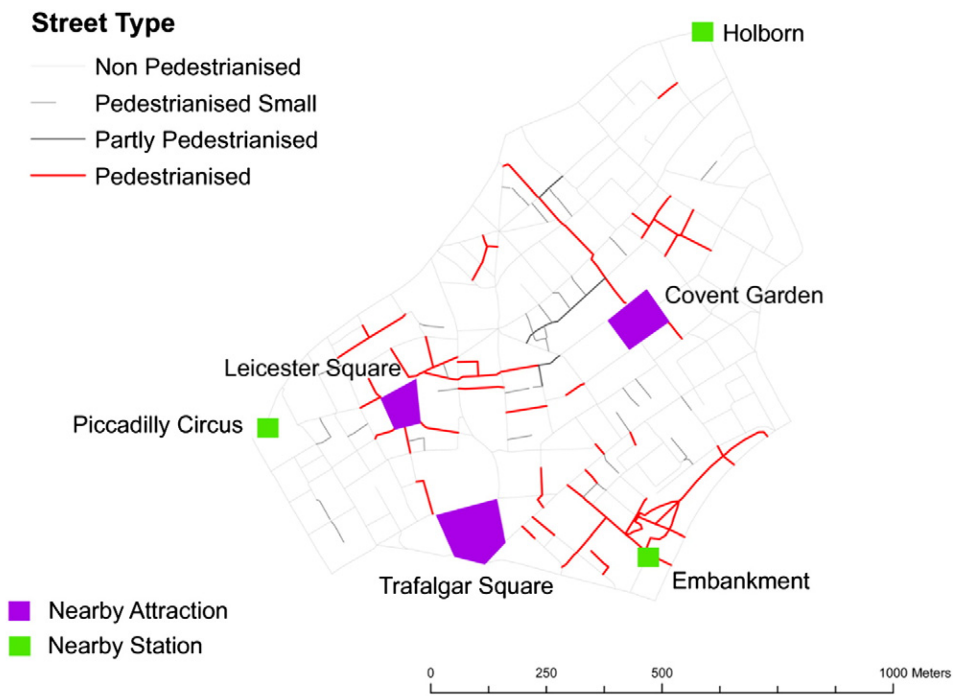

Fig. 1. The case study area of London West End.

improvements for pedestrians may encourage pedestrians to walk longer distances [31]. Such longer walking distances would generate more demand for pedestrians to stay in a city centre distributed into higher pedestrian flows on each street segment according to the spatial pattern of the accessibility factors.

A limitation of this model should first be noted. Correlation of accessibility improvements does not necessarily reflect causality. However, enormous efforts are required to collect data on before and after changes of pedestrian flows in a street improvement project. Thus, this study focuses on key street characteristics identified in the literature review confirming their causal relationships and applies the correlation analysis to examining the effect of each street characteristic on pedestrian flow volume.

The model uses the pedestrian flow volume of each street segment as dependent variables and street characteristics as independent variables. To compare the contribution of a traffic-calming measure to

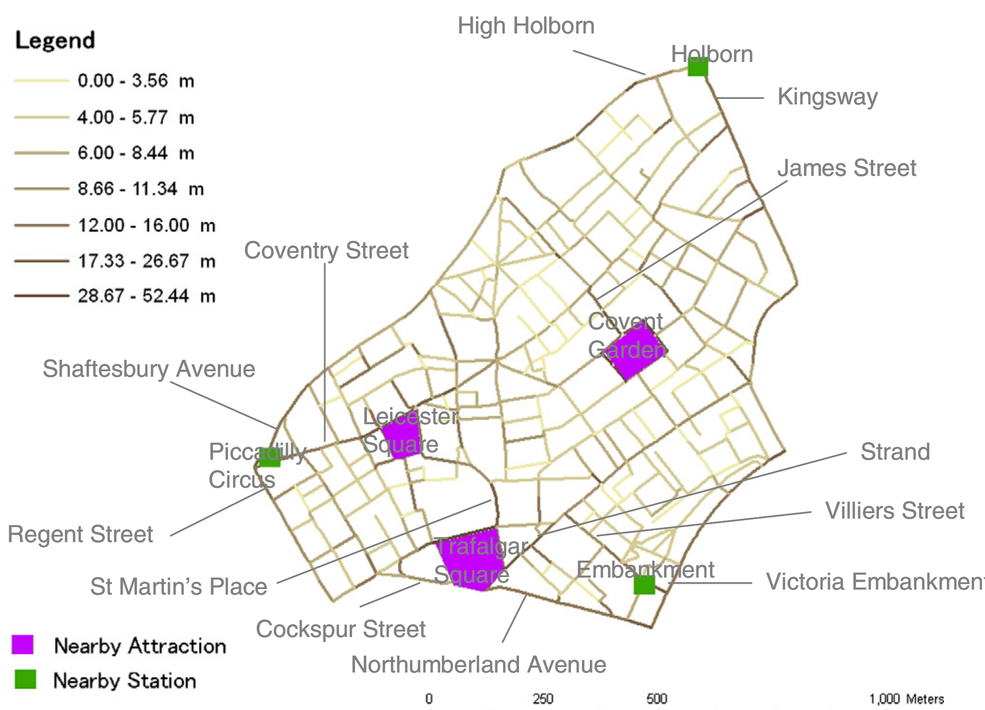

Fig. 2. Spatial distribution of pavement width.

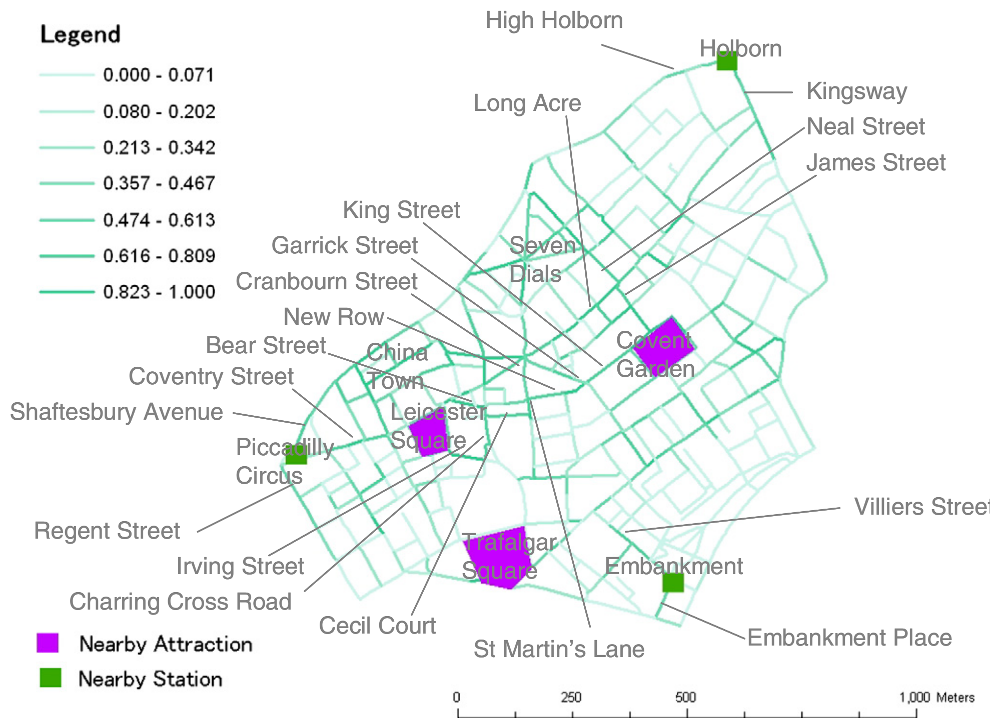

Fig. 3. Spatial distribution of shop coverage.

pedestrian flow volume, the MRA is conducted separately for non-pedestrianised and pedestrianised streets. In addition, the dependent variable is measured based on the logarithmic distribution of pedestrian flows to represent a diminishing marginal increase in pedestrian flow.

The MRA takes a stepwise regression approach by employing the more contributing independent variables. In this analysis, street characteristics on different spatial scales are gradually added to the independent variables to identify their contribution to pedestrian flow volume. The spatial scales of street characteristics are attributed to origins, destinations, and routes respectively in pedestrian travel. Unlike conventional transport analysis, characteristics for pedestrian travel have less specific origins, destinations, and routes. Taking each street segment as an origin, street characteristics of origins are focuses on the quality of an individual street segment. Destinations and

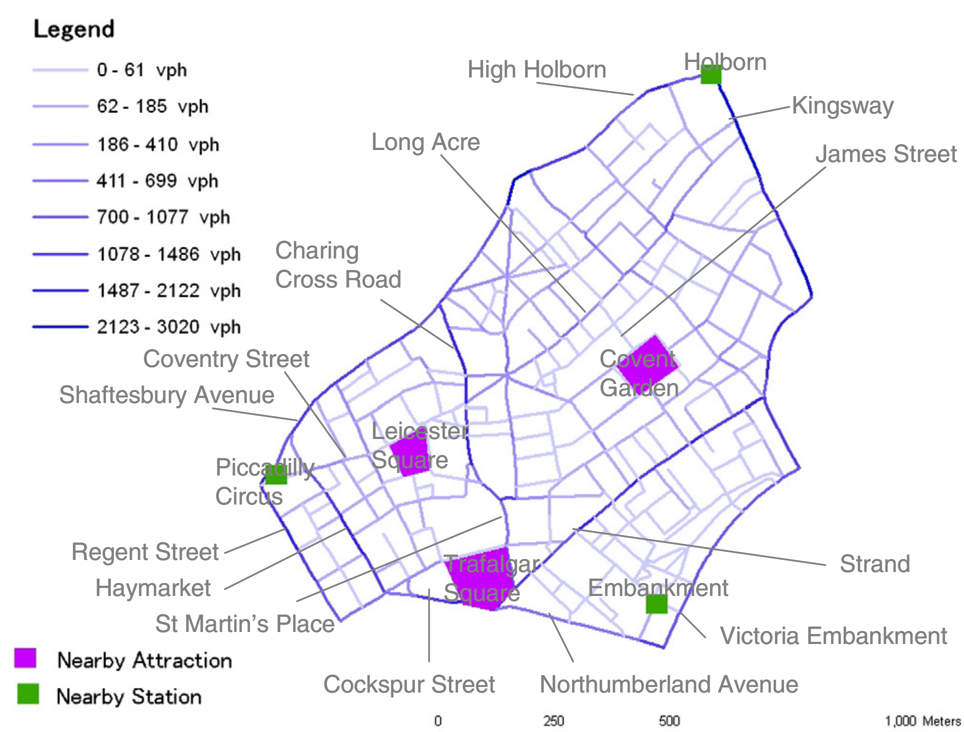

Fig. 4. Spatial distribution of traffic flow.

routes are analysed with neighbourhood-scale street characteristics on routes to key destinations. For key destinations, this analysis chose public transport stations and attractions in a city centre. The route characteristics are further classified from the scale of the nearest destination to the scale of all nearby destinations.

First, the MRA is set up using only origin characteristics such as pavement width and retail land use, as follows:

$$Log(PF_i) = \sum_j \gamma_j \cdot o_{ij}$$

where PF_i is pedestrian flow volume on street segment i, o_{ij} is accessibility factor j of street segment i, and γ_j is the parameter for accessibility factor j.

Then, street characteristics of routes to destinations are added to the MRA. To determine route quality, accessibility factors include not only street configuration and distance along route streets but also pavement width and retail land use there. This analysis of neighbourhood-scale street characteristics starts with routes from each street to the nearest station and attraction, respectively. A wide range of route characteristics may affect pedestrian flow volume indirectly through their impacts on origin characteristics. Therefore, attention is also paid to the correlation between the origin characteristics and the route characteristics. The model thus becomes

$$Log(PF_i) = \sum_j \gamma_j \cdot o_{ij} + \sum_m \lambda_{1m} \cdot rs_{ikm} + \sum_m \lambda_{2m} \cdot ra_{ilm}$$

where rs_{ikm}/ra_{ikm} represents the accessibility factor m of route streets from street segment i to the nearest station k/ attraction l, and $\lambda_{1m}/\lambda_{2m}$ represents accessibility factor m to the nearest station/attraction.

Finally, the MRA tests route characteristics to nearby destinations. Measuring accessibility to a single destination may limit the spatial scale of accessibility improvements to individual streets. The development of a more strategic pedestrian link requires accessibility measures on a neighbourhood scale for all nearby stations and attractions within walking distance. The model form is the same as that for the route characteristics to the nearest destination, but route characteristics are replaced with their averages for all nearby destinations. By comparing the parameters of accessibility factors for the origin, the nearest destination, and nearby destinations, the contribution of multi-scale street characteristics to pedestrian flow volume can be identified.

3.2. Case study area

The case study area of this analysis is the West End area of Central London, United Kingdom. The area is characterised as a large city centre. First, there is proximity to attractions that draw pedestrians. In the West End, several international retail and tourist attractions are located close to each other, such as Covent Garden, Trafalgar Square, and Leicester Square (Fig. 1), which attract visitors wanting to walk around.

Second, there is proximity to public transport stations. The attractions have their own Underground stations (i.e. Covent Garden, Charing Cross, and Leicester Square, respectively), and other nearby Underground stations are situated within walking distance, such as Piccadilly Circus, Embankment, and Holborn. People are less likely to walk between the attractions but more likely to take the Underground to go there, which causes overcrowding in some of the stations, as in Covent Garden.

Third, there is high demand for vehicular traffic. Traffic congestion is serious in Central London, and the high level of road traffic limits pedestrian street space. The dominance of vehicular traffic makes walking less attractive [32], whereas street improvements for pedestrians often causes concerns to car users; thus, street improvements are slow to implement.

Fourth, there is a range of scattered pedestrianised areas, such as squares, courts, and single pedestrianised streets. Leicester Square and Covent Garden both pedestrianised surrounding streets as part of their design improvements in the 1970s. However, pedestrian links between these key destinations in the West End were not developed.

Table 1
Accessibility factors of street characteristics.

	Origin on Street	Route to Nearest Destination		Route to Nearby Destinations	
		Station	Attraction	Station	Attraction
Pavement width	OPW	PWS1	PWA1	PWS2	PWA2
Shop coverage	OSH	SHS1	SHA1	SHS2	SHA2
Street count		SCS1	SCA1	SCS2	SCA2
Street distance		SDS1	SDA1	SDS2	SDA2
Cross traffic		CTS1	CTA1	CTS2	CTA2

3.3. Data collection

This study conducted observation surveys were conducted to collect pedestrian flow volume, traffic flow volume, and land-use data within the study area as primary data for this analysis. The observation survey period was from October 2006 to January 2007. In the surveys, pedestrian and traffic flows were counted at sample points on street segments.

In total, 508 street segments are identified for the 150 streets in the study area, part of which were observed for the surveys. Pedestrians on both sides of the pavement of each non-pedestrianised street, vehicles on the road space of each non-pedestrianised street, and pedestrians on the whole pavement area of each pedestrianised street were counted. Counting was conducted in the random order of street segments for 5 min each at hourly intervals from 14:00 to 18:00 on weekdays. The hourly average count by street segment was converted to pedestrians per hour (pph). In total, 116 street segments were used, which is comparable with previous survey studies [6], [11], [25].

Among the samples, 75 are for non-pedestrianised street segments, and 41 are for pedestrianised ones. The average pedestrian flow on pedestrianised streets is higher than that on non-pedestrianised ones.

Table 2
Descriptive statistics of pedestrian flows and street characteristics.

	All Streets	Non-Pedestrianised	Pedestrianised
	Average (standard deviation)		
Pedestrian flow (pph)	1628 (1632)	1366 (1259)	2090 (2092)
OPW (m)	8.10 (4.49)	7.16 (3.79)	9.76 (5.19)
OSH (percent rate)	0.38 (0.31)	0.32 (0.29)	0.50 (0.32)
SCS1 (streets)	1.20 (0.69)	1.25 (0.66)	1.10 (0.74)
SDS1 (m)	139 (89)	159 (93)	101 (69)
CTS1 (1000 vph)	456 (591)	483 (599)	406 (580)
PWS1 (m)	9.99 (3.51)	9.81 (3.57)	10.30 (3.43)
SHS1 (percent rate)	0.50 (0.19)	0.45 (0.18)	0.59 (0.17)
SCA1 (streets)	2.20 (0.86)	2.31 (0.80)	2.00 (0.92)
SDA1 (m)	128 (75)	143 (76)	102 (66)
CTA1 (1000 vph)	865 (762)	972 (769)	670 (717)
PWA1 (m)	13.90 (5.24)	13.34 (5.80)	14.92 (3.86)
SHA1 (percent rate)	0.48 (0.23)	0.41 (0.22)	0.60 (0.19)
SCS2 (streets)	2.98 (0.49)	3.00 (0.50)	2.95 (0.47)
SDS2 (m)	179 (39)	187 (42)	163 (24)
CTS2 (1000 vph)	1458 (401)	1548 (441)	1293 (244)
PWS2 (m)	9.76 (1.67)	9.73 (1.62)	9.80 (1.78)
SHS2 (percent rate)	0.44 (0.10)	0.41 (0.10)	0.50 (0.09)
SCA2 (streets)	2.46 (0.46)	2.51 (0.46)	2.36 (0.47)
SDA2 (m)	101 (37)	109 (35)	86 (35)
CTA2 (1000 vph)	873 (376)	955 (390)	722 (300)
PWA2 (m)	9.14 (1.58)	8.87 (1.72)	9.62 (1.16)
SHA2 (percent rate)	0.34 (0.10)	0.32 (0.09)	0.39 (0.09)

Table 3
MRA results of the origin characteristics.

	All Streets	Non-Pedestrianised	Pedestrianised
	Coefficient (t values)		
OPW	0.96 (8.62)	1.18 (8.13)	0.77 (4.27)
OSH	1.63 (8.02)	2.00 (7.85)	1.24 (3.46)
Constant	4.42 (18.89)	3.94 (13.44)	4.96 (11.65)
R^2	0.56	0.62	0.43
Sample count	116	75	41

Very high pedestrian flows are mostly observed around stations and attractions. This analysis is conducted to account for the spatial distribution of pedestrian flows with street characteristics of routes to these destinations.

In the study area, there are some partly pedestrianised streets that introduce a pedestrian-friendly pavement design with loose boundaries against the road space. The survey data show that partly pedestrianised streets have higher pedestrian flows per pavement width than non-pedestrianised streets do, but the flows are not as high as those on fully pedestrianised streets. In addition, there is a low level of traffic flows observed on the partly pedestrianised streets. Accordingly, this analysis includes partly pedestrianised streets in the classification of pedestrianised streets, assuming that the road space of a partly pedestrianised street is not included in the measurement of pavement width.

3.4. Measurement of accessibility factors

In terms of the accessibility factor data for origins and routes, this analysis considers 'street count', 'street distance', 'pavement width', 'shop coverage', and 'cross traffic' (Table 1). To collect these data, this study constructed a street network composed of links as street segments divided by intersections. The collected data were included in the links under each street segment. Street counts within routes were also measured to represent the number of directional changes for street configuration. Route characteristics were measured by identifying the street routes with the shortest street count to the key destination.

Spatial data for these accessibility factors were collected from the Ordnance Survey (OS) GIS map. 'Pavement width' was measured by street segment (Fig. 2). The logarithm of pavement width was used in the analysis to represent the decreasing marginal contribution. 'Shop coverage' represents the proportion of shopfronts on a street segment compared to the total street-segment length (Fig. 3). The shopfront length was employed because shops are mostly located on the ground floor in the study area. They were also measured for streets on routes to the key destinations.

The total volume of cross-traffic flows was measured in vehicles per hour (vph) on each route. In order to calculate the cross-traffic volume, the traffic flow volume on each street segment was estimated (Fig. 4), as the pedestrian travel routes cross the entire study area. The MRA was applied to the estimation using the measurement of road connectivity along with road width and shopfront length. The level of connectivity was measured with street counts of routes from each street segment to primary roads and those to the nearest car park. To represent the impact of global connectivity on primary roads, this model introduced a primary-road dummy for through-traffic flows.

Table 4
MRA results of the nearest route characteristics

	All Streets	Non-Pedestrianised	Pedestrianised
	Coefficient (*t* values)		
OPW	0.66 (5.60)	1.13 (7.53)	0.75 (5.14)
OSH	1.43 (7.62)	1.93 (7.49)	1.07 (3.65)
SCS1	−0.48 (−5.17)	–	−0.58 (−4.60)
SCA1	–	−0.13 (−1.36)	–
CTA1	−0.23 (−2.82)	–	–
Constant	5.87 (16.78)	4.36 (10.24)	5.73 (14.99)
R^2	0.64	0.62	0.63
Sample Count	116	75	41

Table 5
Correlation of the nearest route characteristics

	All Streets	Non-Pedestrianised	Pedestrianised
	Highly Correlated Street Characteristics (*R*)		
OPW	PWS1 (0.52)	SCS1 (−0.56)	PWS (0.65) CTA (−0.65)
OSH	SHS1 (0.62) SHA1 (0.55)	SHS1 (0.55)	SHS1 (0.64) SHA1 (0.58)
SCS1	CTS1 (0.51)	–	SDS (0.66) CTS (0.71)
SCA1	–	None	–
CTA1	None	–	–

The descriptive statistics for these data in the study area are shown in Table 2. The route characteristics to the nearby destinations are mostly poorer (more street counts, longer distance, more cross-traffic flow, narrower pavement width, and less shop coverage) than ones to the nearest destination. While the nearest route characteristics are better for the station than for the attraction, the nearby route characteristics are better for the attraction. This reflects the fact that attractions are more compactly located than stations in the study area, which is advantageous for walking around. In comparing pedestrianised and non-pedestrianised streets, pedestrianised streets have not only better origin characteristics but also better route characteristics, which suggests that pedestrianised streets are increasingly located around key destinations. However, as their nearby route characteristics are poorer than the nearest ones, pedestrianised streets are rather located individually around key destinations.

4. Results

4.1. MRA with street characteristics of origins

Table 3 presents the MRA results for all streets and shows that origin street characteristics account well for pedestrian flow and exhibit a high R^2 value. Among the street characteristics contributing to pedestrian flow, high *t* values are seen by both 'pavement width' and 'shop coverage', which are uncorrelated with each other.

In comparing the results between non-pedestrianised and pedestrianised streets, origin characteristics exhibit a higher R^2 value for non-pedestrianised streets than for pedestrianised ones. Thus, the contribution of 'pavement width' and 'shop coverage' to pedestrian flow is smaller for pedestrianised streets, suggesting that individual retail development on pedestrianised streets does not necessarily contribute to increased pedestrian flow.

4.2. MRA with street characteristics of routes to the nearest destination

The model fit of R^2 are improved by the MRA when route characteristics to the nearest destination are added (Table 4). Route characteristics contribute to pedestrian flow with the variables of 'street count to

Table 6
MRA results of the nearby street characteristics

	All Streets	Non-Pedestrianised	Pedestrianised
	Coefficient (*t* values)		
OPW	0.80 (7.44)	1.08 (7.15)	0.71 (4.33)
OSH	1.53 (7.92)	2.00 (8.06)	1.67 (4.77)
SCS2	−0.40 (−3.21)	–	–
PWA2	1.21 (3.24)	0.95 (2.18)	2.86 (3.17)
Constant	3.31 (3.56)	2.09 (2.32)	−1.57 (−0.75)
R^2	0.63	0.64	0.54
Sample count	116	75	41

Table 7
Correlation of the nearby route characteristics

	All Streets	Non-Pedestrianised	Pedestrianised
	Highly Correlated Street Characteristics (*R*)		
OPW	PWS2 (0.51)	None	PWS (0.58) CTA (-0.52)
OSH	SHS2 (0.62) SHA2 (0.63)	SHS2 (0.62) SHA2 (0.52)	SHS2 (0.51) SHA2 (0.71)
SCS2	CTS2 (0.52) SCA2 (0.75)	–	–
PWA2	PWS2 (0.57)	PWS2 (0.63)	PWS2 (0.52) SCA2 (-0.58)

station' and 'cross-traffic to attraction'. The significant contribution of the former may reflect the importance of stations as the nearest travel destinations.

Table 5 shows correlation between street characteristics. The street characteristics in the model are not correlated with each other, but they are correlated with other street characteristics ($R > 0.5$). 'Street count to station' is correlated with 'cross-traffic to station', which may imply a co-benefit of better connectivity. Moreover, origin 'shop coverage' is correlated with 'shop coverage to station' and 'shop coverage to attraction'. This may suggest that on-street shops may be affected by surrounding shops on the route to the nearest destination, where a link of walkable shops is created.

The model fit is significantly improved by route characteristics for pedestrianised streets than for non-pedestrianised ones. 'Street count to station' contributes most to pedestrian flows on pedestrianised streets. Moreover, a wide range of route characteristics for pedestrianised streets are correlated with origin characteristics. These results suggest that route characteristics are critical for pedestrianised streets.

4.3. MRA with street characteristics of routes to nearby destinations

In comparing route characteristics for the nearest destination with those for multiple nearby destinations, the MRA results show that the nearby route characteristics do not significantly improve the model fit (Table 6). Model fit for pedestrianised streets is also worsened using route characteristics for nearby destinations. The result implies that pedestrians are unlikely to walk around multiple destinations and rather walk around each of the individual destinations, particularly on pedestrianised streets.

In terms of the destination type, the attraction contributes more to nearby destinations than to the nearest one. For nearby destinations, 'pavement to attraction' contributes to pedestrian flows for both non-pedestrianised and pedestrianised streets. This may suggest that the linkage to multiple attractions is more meaningful neighbourhood-scale street characteristics to account for pedestrian flows than that to multiple stations.

Moreover, the route characteristics of 'shop coverage' are more highly correlated between the origin characteristics and the route ones (Table 7). This may suggest that on-street shops may be affected by neighbourhood shops on the route to nearby destinations, which can generate an area-wide link of shops. Nevertheless, the poorer model fit may also suggest that the link is not sufficiently developed to contribute to pedestrian flow growth.

5. Conclusions

To develop comprehensive and strategic accessibility measures for pedestrians, this study empirically analysed the spatial relationship between pedestrian flows by street type and various street characteristics around multiple destinations using data on London's West End. The relationship was examined in a way that accounts for pedestrian flow volume with street characteristics, as in pedestrian accessibility composed of accessibility factors. Place-based pedestrian accessibility was measured by classifying accessibility factors into street characteristics of origins and routes to key destinations. Non-pedestrianised and pedestrianised streets were analysed separately to identify the contribution of a traffic-calming measure to pedestrian flow volume.

First, this analysis found that the origin characteristics can account for pedestrian flow volume, but additional route characteristics can do so better. As the nearest destination, stations are the most critical contributor to pedestrian flow. An analysis of the correlation of street characteristics showed that the nearest station and attraction are more likely to be connected individually by shops on pedestrianised streets. Nevertheless, the result that route characteristics affects pedestrian flows on pedestrianised streets more significantly suggests that individual retail development on pedestrianised streets does not necessarily contribute to their pedestrian flow without improving route characteristics for a pedestrian link.

The study also found that route characteristics can have a limited contribution to pedestrian flow volume. Attractions are more important for multiple nearby destinations than stations. Nevertheless, route characteristics for multiple nearby destinations do not particularly contribute to pedestrian flow on pedestrianised streets more than those for the single nearest destination. Despite the lower contribution, the nearby route characteristics are still important accessibility factors to evaluate the level of pedestrian-link development. The result may therefore suggest that the current design of pedestrianised streets is not sufficient to generate a link that contributes to their pedestrian flow growth.

These findings are significant because they provide novel empirical clarification on important accessibility factors used to evaluate strategic pedestrian links between key destinations on a neighbourhood scale in a city centre. Previous analyses of pedestrian accessibility have focused on street configuration without considering route characteristic contributions by destination. The results of this analysis indicate that street configuration is not the sole accessibility factor for pedestrians, but route quality, which includes pavement, shops, and cross traffic, affect pedestrian accessibility. The contribution of routes to key destinations to pedestrian flow is significant, and the levels of contribution depend not only on destination types but also on spatial scales.

This study provides useful empirical evidence of potential street improvements to develop a quality street network for pedestrians on a neighbourhood scale. The lack of knowledge about the effects of neighbourhood-scale street characteristics on pedestrian accessibility makes street improvements to an individual site limited to avoid negative effects on traffic. The results of this study can help identify where and what improvements should take place. This is particularly important for street improvements linking multiple nearby destinations for pedestrians in a city centre. Further research is expected to quantitatively examine the effects of such pedestrian linkages.

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