Examining the geometry of streets through accessibility: new insights from streetspace allocation analysis

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Abstract

This paper describes streetspace allocation analysis, a method that uses street cross-sections to measure footway and carriageway widths and quantify a key parameter of street design citywide. The resulting network-based streetspace allocation metrics are employed on a proof-of-concept study of train stations' service areas in London, applying shortest-path analysis under a place and walking prioritisation approach. Overall, streetspace allocation statistics for London confirm the citywide predominance of space allocated for vehicular transport over pedestrian uses. Whereas a comparison of the current distribution and proposed re-allocation of streetspace on streets near stations allows for the investigation of the effects of streetspace enhancements, which tend to be beneficial by reducing pedestrian movement impedance and extending service areas. The methods presented here can offer valuable analytical capacity for developing new transit-oriented schemes and designing place-based streets that support sustainable transport and sustainable urban development.

Keywords

street networks, urban form, streetspace allocation, street design, London

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Introduction

Transport choices are constrained by physical factors. Despite streets being a fundamental element of urban transport and urban life, comprehensive data about the physical organisation of streetspace is of limited availability for many cities or is structured in a way that makes allocation analysis citywide difficult. Because traffic-oriented planning principles were prevalent throughout the 20th century, cities worldwide are typically dominated by private motorised transport. This illustrates the crucial paradox that more streetspace is reserved for the most space-intense and environmentally-harmful transport mode. Furthermore, motor-vehicles transport networks tend to be continuous and integrated into an extensive connected system, whereas conversely, active travel networks tend to be fragmented making walking and cycling less attractive and convenient transport choices.

A growing body of literature has advocated the benefits of reclaiming streets from cars. Streetspace redistribution has been identified as central for achieving sustainable and more equitable urban environments from social, environmental, health and economic perspectives (Gössling 2020; Sadik-Khan and Solomonov 2016; Carmona et al. 2018; Kenworthy and Laube 1996; Mboup and Warah 2013; Creutzig et al. 2020).

So far, research on the quantification of streetspace has had different approaches and progress. It is either focused on small areas (Gössling 2016; De Gruyter et al. 2022), parking and vehicular circulation space, omitting pedestrian space (Szell 2018), aggregated to administrative areas, (Guzman et al. 2021; Nello-Deakin 2019) or street segments (Lefebvre-Ropars et al. 2021a) with the purpose of providing empirical evidence for the examination of relationships with modal split indicators. Collectively, these studies support the hypothesis that more space is assigned to the private car; the less energy and space efficient transport mode. While important progress in addressing data limitations and processing has been made (Lefebvre-Ropars et al. 2021b; Palominos and Smith 2019; Palominos 2021), the issue of understanding streets as networked elements in which streetspace re-allocations can have a knock on effect in the street system has not been fully addressed. In summary, in the very few attempts to measure streetspace allocation diverse approaches have been adopted and methodological consensus is yet to be developed. In general, either the focus is on small areas or specific transport modes, or street metrics are aggregated for analytical purposes at the expense of losing granularity. The research underlying this paper therefore seeks to present a methodology to derive more comprehensive streetspace allocation information from urban topography street data, addressing a data gap in road centre line representations to allow both a city level streetspace visualisation and street network analysis.

The multifaceted nature of streets brings together conflicting interests for a typically fixed and limited streetspace capacity. Place-based and active travel approaches to the planning and design of streets face the challenge of allocating streetspace for different users with requirements that unfold at diverse scales. For instance, the interest for improving the environmental quality of streets of local businesses coexist with the need to provide the convenient and desirable conditions for short and medium distance trips. Currently, with few recent exceptions (Lefebvre-Ropars et al. 2021b; Nello-Deakin 2019), a major obstacle to conducting streetspace allocation analysis is the lack of critical or reliable data that allows for examining local and strategic urban scales simultaneously. The picture of streets being highly contested gets further complicated with patterns of urban growth coupled with the adoption of emergent mobility technologies which threaten to reproduce private car dominance in many cities worldwide (Sevtsuk and Davis 2019). Ultimately, the allocation of space is a complex socio-economic and spatio-technical process for which streetspace allocation analysis can provide a synoptic and pragmatic picture that takes into account the physical environment of streets at a granular level.

In this paper, we first propose a new methodology that quantifies streetspace allocation using street cross-sections citywide to obtain footway and carriageway widths for all streets in a system. The focus is on quantifying a key and fundamental street design parameter of the total available right-of-way (Scheer 2016). Typically, the streetspace of most existing streets is subdivided by the curb line which determines the spatial capacity of carriageways and footways, and its boundaries are defined by property lines. In cities with a car dominant legacy this appears to be the most common distribution and only recently more complex street layouts have appeared including exclusive designated space for bicycles. For instance, an estimated less than 1% of the total street length in London has designated cycle lanes (estimated from data at (Route Plan Roll 2020)). Therefore, the limitations that result from the incapacity to distinguish between distinct vehicle modes are deemed insignificant. Moreover, there is not reason that impedes the application of streetspace cross-section analysis at a later date provided that the modal distribution data is available.

As proof-of-concept the method is implemented for London and the new data obtained is used to study the impacts of streetspace re-allocation on the streets in walking proximity of train stations. The data is geometrically derived from urban topographic data that is commonly utilised in urban planning and urban design. Then, a cross-section technique, typically used in design to describe the physical characteristics of an environment or an object, is applied to describe the internal geometric characteristics of the streets. Data processing is conducted using free and open-source software and summarised statistically and graphically for Greater London. Next, footway-carriageway relationship citywide is visualised using a bivariate map to understand the citywide pattern of streetspace allocation. Following, the access to train stations is calculated through travel cost analysis of the serviced area. We use streetspace allocation metrics of the current situation and a place-based intervention as a factor of travel impedance to compute shortest paths and compare the reach of both to measure the impact of streetspace re-allocation.

This paper is organised in 4 sections. After the introduction, the following section explains the new methodology for obtaining streetspace allocation metrics and how it is applied for calculating travel impedance. The third section presents the results of the streetspace allocation analysis for London and the comparative analysis of service areas of train stations under the current and proposed streetspace allocation scenarios. In the final section, the research discussion and conclusions are drawn.

Methodology of streetspace allocation analysis

Defining streetspace for spatial analysis

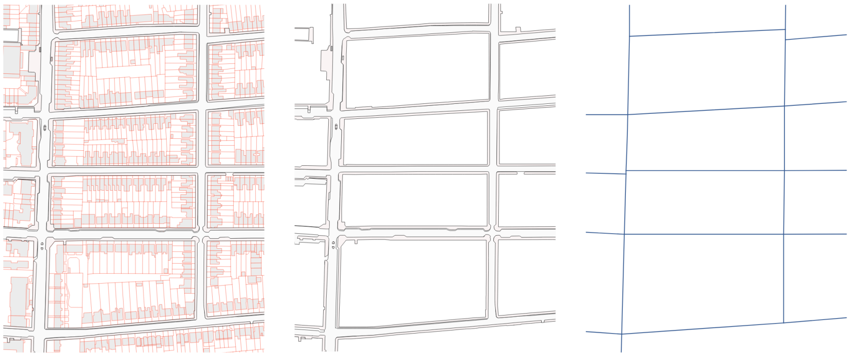
Given that a key aspect of this study is to get a precise and accurate measurement of the street physical environment, it is necessary here to clarify exactly what is meant by streetspace. In studies of urban form the definition of streets traditionally refers to its uses, public nature and shape (Scheer 2016; Kropf 2009; Rapoport 1987). In order to fit with both the theoretical framework of the subject of study and the practicality of accessing meaningful data, this paper defines streetspace as the open space area related to buildings outside the plot boundaries that is mostly used for circulation and occasionally for other activities.

This streetspace definition highlights the limitations of traditional urban planning approaches. Conventionally, the scope of a road plan encompasses interventions over road space (road width, number of lanes, kerb space), often focusing on traffic efficiency. Similarly, land use plans, while relevant to the streetspace social and economic activity, involve decisions over land within private property boundaries. Although these planning instruments can be combined, the planning and design of streetspace often remain outside of their scope (Jones et al. 2007). Therefore, the examination of streetspace allocation metrics over whole urban areas offers analytical insights for urban street planning and design that can be complementary to traditional planning approaches.

Street environment data selection

A close examination of the physical composition of streetspace shows a sub-structure of linear parts that are related to the functional organisation of the street. Most commonly these parts are the footways and carriageways which added together constitute the total street width. Generally, the width of streets, footways and carriageways can be derived from digital urban survey maps that represent the built environment with a high level of detail (see for example the Netherland's countrywide Key Register of Large-Scale Topography (BGT)[1]). The width metrics for each street, however, are not found readily available but need to be derived using tools provided by Geographic Information Systems software.

The lack of readily available street metrics, in addition to the limited access to planimetric and polygonal representations of street features act as a barrier to the comprehensive spatial analysis of streetspace allocation at large scales. Recently, studies have focused on capturing pavement geometries at a detailed scale. These focus on creating a pavement network for routing and enriching OpenStreetMap data (Mobasheri et al. 2018) and on curb regulations by utilising GPS traces and adding curb information to linear curb representations. These approaches while useful for describing the streetspace environment and potentially complementary to the streetspace analysis presented here are however less useful for describing streetspace allocation that enable both carriageway and footway land uses to be analysed simultaneously. For this reason, the appropriate street environment data for streetspace allocation analysis contains polygonal features describing footways and carriageways (often referred to as roadbed) which can be aggregated or matched to a single linear representation as is the case of urban survey maps illustrated in Figure 1 (open data initiatives led by governments are already publishing this kind of data, see for example data for New York City containing sidewalk features[2]). Similarly, large and comprehensive road data sets can be extracted from OpenStreetMap (OSM), but while road features (highways in OSM ontology) have an attribute of the number of traffic lanes, this does not contain information about the open space outside plot boundaries (or total street width) and the traffic lanes value is often missing. This limitation may be overcome in the UK context by using the latest published road data set by the Ordnance Survey which has the average width of the road carriageway for all the road network in the UK, but again it does not contain footway or total street width[3]. Another approach was presented by Etten (2019) in which high quality satellite imagery is used to extract road networks, however the focus is to improve issues of incompleteness and misalignment of OSM road data. Overall, even though there is a wealth of methods and data alternatives to describe the space of the street, these tend to focus on providing routing solutions, thus tend to be linear representations with a clear emphasis on describing vehicular paths of movement. Again, the emphasis on vehicular path descriptions tends to reinforce the imbalance of streetspace allocation. Although less easily available, the consideration of fine scale pedestrian space information as a pertinent variable for transport modelling can help counterbalance the research and institutional emphasis placed on traffic modelling (Batty 2001). However, it can be expected that with the enrichment of platforms such as OSM it will be possible in the near future to



(a) (b) (c)

Figure 1. Street environment data sets:(a) Urban area survey representation of the street environment, (b) streetspace: footways and carriageways and (c) the corresponding RCL representation. Base mapping © Crown Copyright and Database Right (2018). Ordnance Survey (Digimap Licence)

access highly detailed and standardised street environment data sets which would have a positive impact on the replication of the methodology presented here.

Road centre lines (RCL) are a widely available street data set. Essentially, RCL are discrete linear elements representing the two border lines of a road or path that are collapsed into one line drawn in-between at the centre of the road. This type of geometrical abstraction allows the derivation of the street length and the topological structure of the set of streets which is useful for analysing relationships in a street system (connectivity, accessibility, routing, etc.). Nevertheless, the streetspace allocation metrics cannot be derived from RCL data sets. Therefore, it is necessary to create a data generation process to efficiently calculate the streetspace metrics by combining RCL with built environment data sets. As Figure 1 illustrates, the typical representation of streetspace derived from urban area survey and RCL data sources present the data as separated layers of information.

Drawing street cross-section lines

The data generation process follows a similar logic to cross-section drawings. Cross-sections are a representational technique commonly used in architecture to describe physical and spatial relations that are not evident from the plan. The choice of one cross-section as the survey point for measuring streetspace allocation along a street underlies three premises. First, that cross-sections have traditionally been design instruments for establishing guidelines in city planning (Southworth 1997). Second, because street cross-sections are useful representations of the space distribution and they describe an inverse underlying relationship between spaces when re-allocating streetspace (Jones et al. 2007). Third, while setbacks of the property lines that define the boundaries of the street and variations of the curb line that delimit pedestrian and vehicular space might exist within a street segment, particularly in organic street layouts, it is assumed that for most street segments a cross-section sample is accurate enough to represent

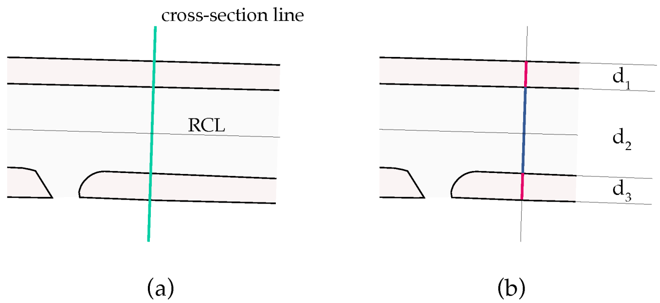


Figure 2. Street data integration: (a) cross-section line overlaid over streetspace data, then (b) carriageway width *d2*, footway width *d1 + d3* and total street width *d1 + d2 + d3* is derived from the intersected segments.

the streetspace allocation of a given street. It is worth mentioning that to overcome this limitation it is possible to increase the density of cross-sections (Lefebvre-Ropars et al. 2021b; Palominos 2021)), however one cross-section is considered sufficient as an average measure to analyse accessibility using street network analysis.

The drawings are generated from two-dimensional plan data that is cut through transversely by a cross-section line that establishes the position where the metrics will be queried (see Figure 2). After the street data is selected, generalized and cleaned the first operation of the streetspace-allocation-metrics generation process is to draw a cross-section line for all the street segments. Recent advances in geocomputation allow the automation this process which will otherwise be excessively time consuming to compute for large urban areas. The analysis was conducted using the R software with the amplified analytical functionalities of packages for spatial analysis (most importantly the sf, sfnetworks, lwgeom and nngeo packages).

Conceptually, the data generation process follows the 'Link and Place' street design framework (Jones et al. 2007). This framework introduces the schematic concept of the link/place trade-off triangle to illustrate the challenge of accommodating the link and place spatial demands within the limits of the often fixed street width. The triangle is based on a scatter plot chart representing the relationship between the link and place dimensions for each street, being the *trade-off* the choice of one dimension over the other as these are inversely related since the spatial envelope that contains both dimensions is typically fixed. Thus, giving priority to either of the dimensions (link or place) would have a knock on impact on the other (see Figure 3 after (Jones et al. 2007)). While the main focus of the 'Link and Place' framework is on the use of streets, the trade-off triangle conceptualisation emphasises the physical characteristics of streets. Link and place are utilised as both to refer to the status of a street as well as its spatial capacity, being the total street width the 'envelope of options' for streetspace allocation. Even though, making a direct connection between link and carriageway space, and place and footway space might seem too simplistic, it is clear that from the design perspective greater spatial capacity assigned to carriageways would aim to address link or movement requirements (the vehicular system), whereas on the contrary greater space allocated to footways would address place-related requirements (the pedestrian system -

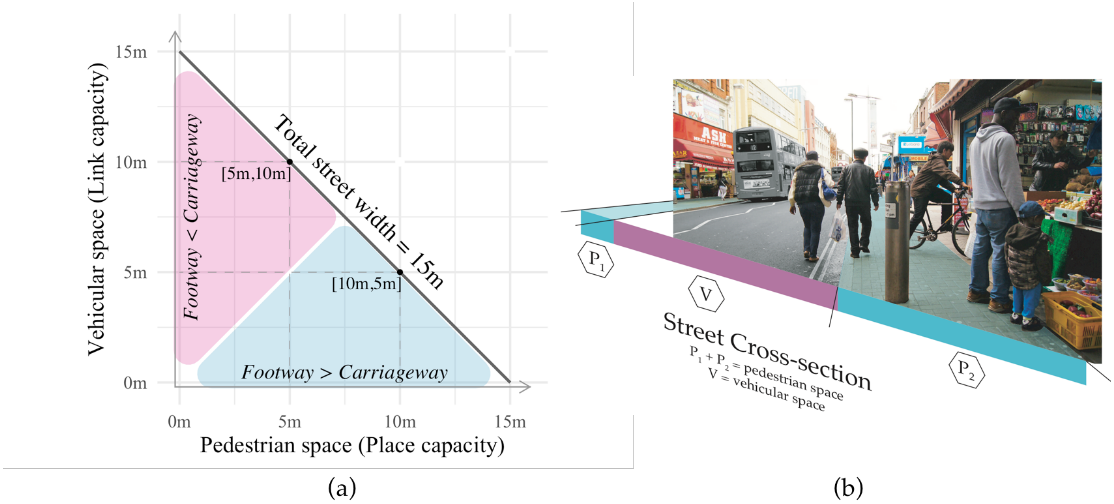


Figure 3. (a) Share-of-Streetspace diagram based on Jones et al., 2007 'trade-off' triangle, (b) Diagram of a street cross-section.

see (Alexander 1965) for a discussion on the necessary overlap of these systems). Importantly, the trade-off triangle allows to illustrate the inverse relationship between the link and place spacial capacity when re-allocating streetspace.

The quality of the streetspace data was verified through an accuracy assessment that checked the discrepancy between a reference data set and the streetspace data. A stratified random sample considering road hierarchy was selected and compared with 'true data' from Google Maps satellite and the OS Mastermap Topography layer. Considering a 5% of tolerance error the overall accuracy test results in a 84.16% confidence level. This result can be considered positive and is similar to other data quality tests of road data sets (Haklay 2010) (for a more detailed explanation of the data quality assessment see section 3.3.3 in (Palominos 2021)).

Access costs to train stations as activity nodes

Worldwide, the design and planning of streets has undergone a shift from car-oriented to people-oriented street environments. While some initiatives are based on counter balancing the negative impacts of private car use and promoting modal split change (Gössling 2020), others go beyond the transport focus arguing that streets are multi-functional urban entities (Alexander 1965; Anderson 1978) and suggest that streets should be considered as drivers of urban prosperity (Mboup and Warah 2013).

As an illustration of this shift, policy guidelines enumerate several negative impacts of high levels of heavy traffic: air pollution, loss of urban public space, accidents, severance, noise and vibration and economic inefficiency and loss of competitiveness of central areas, among others (Directorate-General, E.C.E. 2004; Centre for London 2017). In contrast, it has been reported that place-based street improvements provide considerable value not only to the experience of street users but also to surrounding businesses (Carmona et al. 2018; Sadik-Khan and Solomonov 2016). Notably, associations have been found between the quality of walking amenities and the performance of innovation districts suggesting that face-to-face contacts facilitates innovation (Zandiatashbar and Hamidi 2018). Additionally, it has been implied that, despite how trivial they might be, the sum of many little contacts between pedestrians form the trust of a city (Jacobs 1961) and that pedestrian streets can provide the place for people to rub shoulders which is an "essential social ... 'glue' in society" (Alexander et al. 1977, p.89). Furthermore, the recent guidelines put in place to prevent the propagation of Covid-19 based on social-distancing result in more public and collective space area consumption not only adding pressure to the already contentious and limited streetspace but also suggesting alternative urban futures (Batty 2020) .

Railway and underground stations are conceptualised as 'activity nodes'. The surroundings of stations located in the inner city typically have plenty of amenities and attract substantial pedestrian flows. In like manner, stations with less demand have the potential to do so in the future, by the strategic densification around stations that accommodates city growth with a sustainable approach (Transport for London 2019). As some authors suggest, this approach has been successfully applied worldwide and is referred to as Transit Oriented Development (TOD) (Ibraeva et al. 2020), which is also regarded as sustainability-based (Kenworthy 2006; Weber 2006). Here we make the assumption that the surroundings of railway and underground stations have the potential of concentrating public life, activities and community facilities that mutually support each other.

Streetspace allocation for travel cost calculation

Walking is the most common way to access rail and underground stations. In transport analysis the cost of accessing and departing from stations is conventionally calculated in terms of physical proximity or distance. Coverage or service area analysis allows the evaluation of pedestrian accessibility to stations by finding all accessible streets within a specified distance threshold (Gutiérrez and García-Palomares 2008). The definition of distance and how it is measured is therefore crucial for computing service area analysis. For this study we employ streetspace allocation metrics as a proxy for the quality of street design that influences the cost or impedance of walking along streets surrounding train stations. As a general rule it is assumed that wider carriageways negatively impact the environmental quality of streets through higher presence of motorised vehicles and levels of air and noise pollution. Conversely, wider footways will ease the circulation and social interaction of pedestrians and have the potential of higher environmental quality and pedestrian comfort through the provision of street greenery, shade and street furniture (Transport for London 2019). The weights assigned for shortest path calculations use street *length* as a factor and three of the streetspace allocation variables: *carriageway width (caw), footway width right side (fow1) and footway width left side (fow2)*. For example, a 100 m long street with a 9.5 m wide carriageway and 7 m wide footways has a weight (impedance) of 102.5. The same street with a narrower carriageway (5.5 m) and wider total footway space (11 m) has a weight of 95.5. For shortest path calculations from stations to surrounding streets we used the conventional threshold of 500 meters measured using the network-distance method (Gutiérrez and García-Palomares 2008).

$$weight = length * (1 + \frac{caw}{100}) - (length * \frac{fow1 + fow2}{100}) \qquad (1)$$

For the place-based streetspace re-allocation calculation it is assumed a general re-balancing of streetspace that considers street hierarchy for determining new carriageway widths (see Table 1). Street hierarchy provides a general guidance of street use and context (e.g. presence of retail activity and traffic in main streets) and the proposed widths are based on recommended design standards (Großbritannien 2007). The underlying hypothesis is that less walking impedance will result in larger service areas, however this growth will typically affect the number of crossings and potentially reduced accessibility. Nevertheless, the benefits of extending train stations service areas with a more comfortable pedestrian space is assumed to outweigh the hurdle of additional crossings.

Table 1. New carriageway widths according to street hierarchy.

Hierarchy	Width (m)	Description
Major	5.5	2 lanes (possibly 2 ways)
Minor	4.75	1 lane with parking
Local	2.75	One-way light-traffic

Results: London's streetspace allocation metrics

Following the trade-off triangle concept the square grid heatmaps relating footway and carriageway metrics in Figure 4 (a) and (b) reveal that the majority of streets have more space allocated for carriageways than for footways, as the area above the 50/50 line has higher colour intensity. Also, from Figure 4 (b) it is possible to derive that the typical street in London has a carriageway width of 7.25 m and a total footway width of 4.75 m (n = 7680). It is clear that a unit of a vehicle take more space than a pedestrian, not only due to size but also because of the extra space associated to the speed of movement, so the global predominance of vehicular space could be assumed. However, the street by street streetspace allocation description provides a novel and much richer quantitative description to inform possible street interventions both strategically and locally .

To put it differently, Figure 5 shows the spatial pattern of the carriageway/footway relation with global statistics grouped in two street types according to streetspace balance. It is evident from this visualisation that streets with wider carriageway than footway prevail far and wide. Nevertheless, some concentration of streets with wider footway than carriageway is observable at the city centre. Overall, the grid formed by streets with wider carriageways is by far more comprehensive with 77% of the total street length than the one formed by streets with wider footways which represents 22%.

Before a closer inspection of the basic statistics it is important to notice that as Table 2 shows nearly 2/3 of streets are classified as *Local Road* and these streets also represent 2/3 of the total street length[4]. This is informative to understand that the median values for footway and carriageway portray the measures of a typical 'residential' street with a footway (5.4 m total, or estimated 2.7 m each side) around half a metre above the 2 m minimum recommended, and a carriageway (7.5 m) that can accommodate 2 lanes plus one space for on-street parking or 1 lane and on-street parking on both sides (Großbritannien 2007). Taken together, these metrics suggest that there is an association between the hierarchical classification of streets and their streetspace allocation metrics. From the results it can also be observed that carriageways, footways and total widths show a uni-modal skewed long-tail distribution. This can be explained by the fact that urban street networks are a complex transportation system with efficient

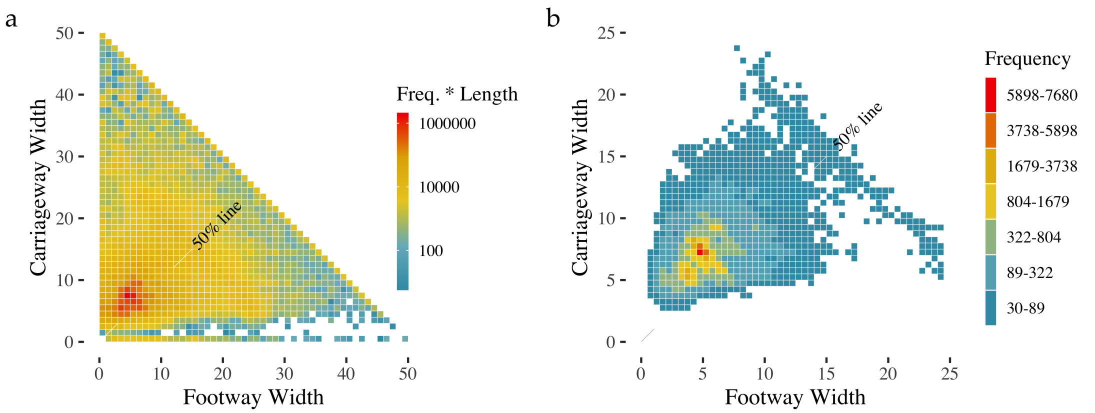


Figure 4. Heatmaps of street frequency according to Footway and Carriageway widths, (a) weighted by length and (b) absolute count detail.

spatial organisation, and that the London street system grew following a space-filling phenomena within a service region constrained by the idea and materialisation of the green belt (Masucci et al. 2013). In London and other European cities that rapidly grew influenced by new transport technologies developed during the industrial revolution, it can be observed that often the construction of major roads precedes minor roads and thus major roads operate as primary distributors. This translates into a street system with few streets with high capacity or width and the majority of streets with low capacity in a hierarchically-nested organisation.

Table 2. Summary of streetspace allocation metrics by designation and hierarchy.

Hier.	Designation	Median width (m)			Relative	
		Total street	Carriageway	Footway	freq.	length
Local	Local Road	12.4	7.3	5.0	**66.2**	67.8
	Shared Use Carr.*	14.1	0.0	14.1	0.1	0.1
Minor	B Road	16.8	9.2	6.9	4.2	3.8
	B Road, Coll. Dual Carr.	28.4	14.9	12.0	0.2	0.1
	Minor Road	15.4	8.2	6.4	12.5	13.5
	Minor Road, Coll. Dual Carr.	29.9	14.9	11.5	0.3	0.2
Major	A Road	21.1	11.2	8.6	10.0	7.6
	A Road, Coll. Dual Carr.	31.1	16.9	11.9	1.4	1.0
	Motorway	30.6	19.4	7.9	0.3	0.7
	Motorway, Coll. Dual Carr.	44.7	35.9	5.8	0.4	1.4
	Primary Road	25.2	13.4	9.5	2.7	2.0
	Primary Road, Coll. Dual Carr.	35.1	21.0	12.0	1.6	1.9

* Shared streets are considered footway space.

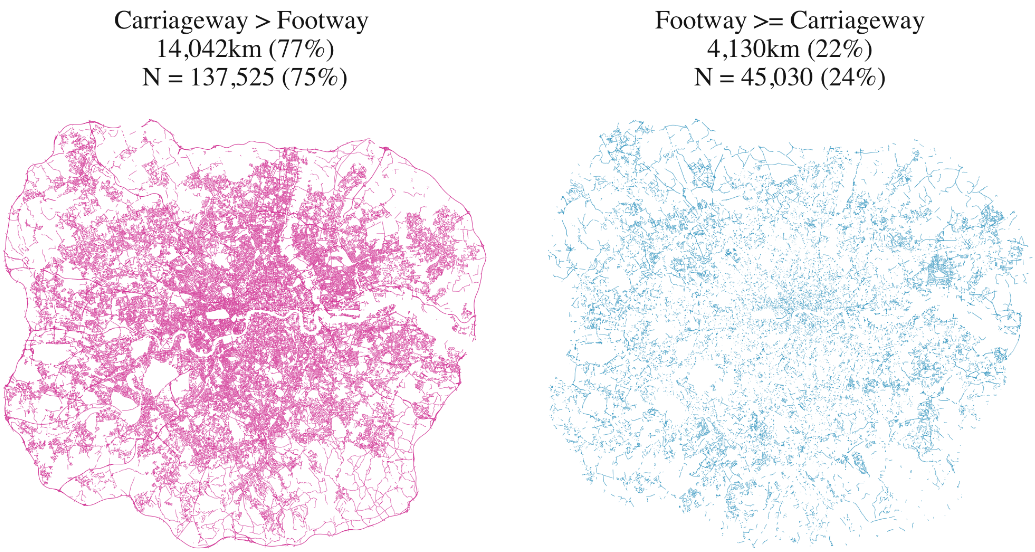


Figure 5. Comparison of streets networks patterns according to streetspace primacy.

The allocation of streetspace is a multi-scalar problem (Appleyard et al. 1981). Strategic scale considerations affect and are affected by design scale factors in a complex way. Certainly, because of urban land ownership structures, street plans have a low rate of change, therefore street redevelopment schemes will most likely operate modifying the pedestrian and vehicular space ratio. To understand how much space is designated to pedestrians and vehicles we visualise these two variables simultaneously using a bivariate thematic map (Eyton 1984). The maps in Figure 6 shows footway-carriageway relationship in the study area and a detailed view of Central London. This visualisation helps analyse street design and streetspace prioritisation at the same time in a quantifiable way. To some extent, the hierarchy of the street system is highlighted, despite the fact that the streetspace allocation in major streets varies from segment to segment portraying the piecemeal street developments and the history and diversity of urban planning paradigms in London.

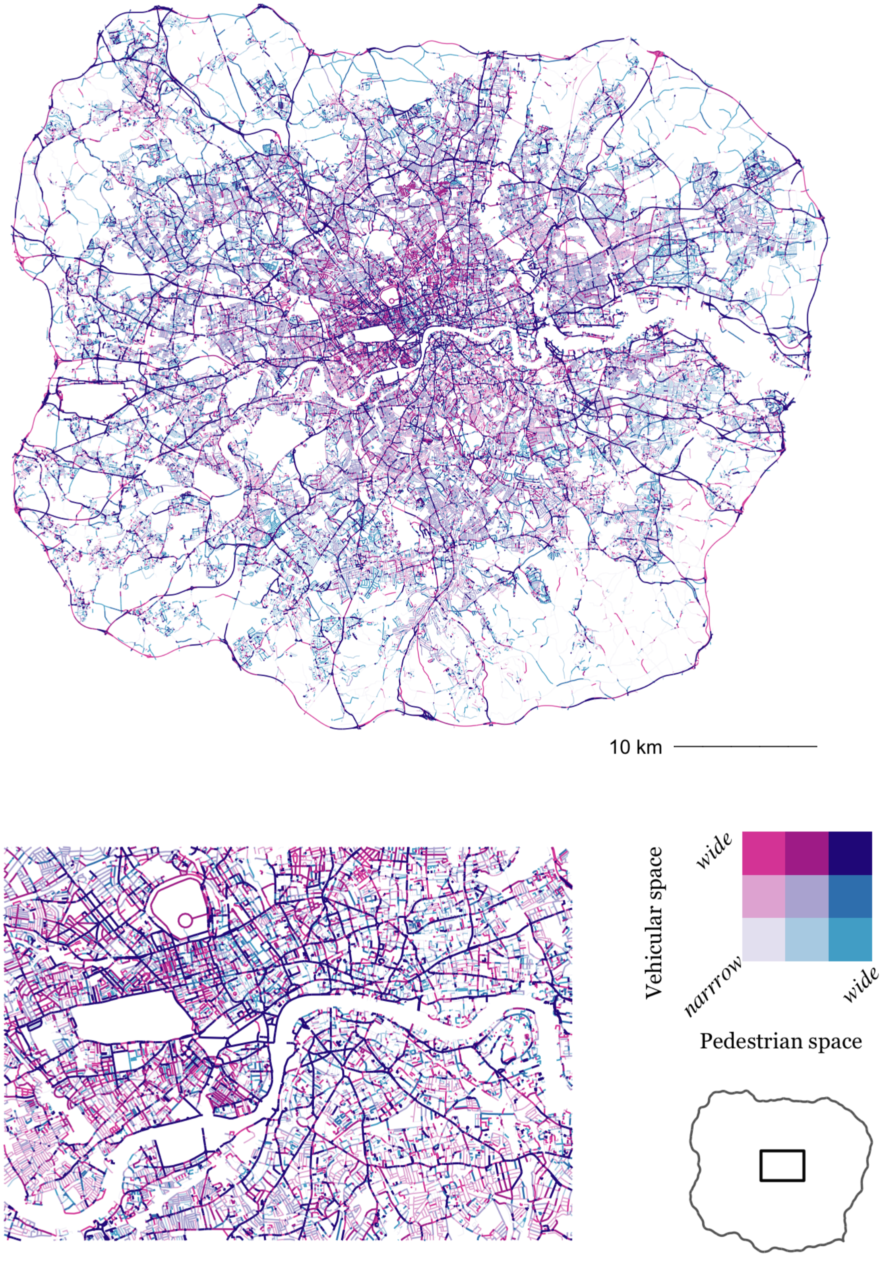


Figure 6. Bivariate representation of streetspace allocation in London. Basemapping © Crown Copyright and Database Right (2018). Ordnance Survey (Digimap Licence).

The impacts of streetspace re-allocation around train stations

In the 517 stations analysed for which the current situation was compared with the proposed streetspace re-allocation, the mean relative change in the aggregated street lengths is 1.1. This indicates a positive impact of streetspace re-allocation by increasing station accessibility and amplifying the serviced area. As expected the varying geometries of streets surrounding train stations hold different potential for streetspace re-allocation (see Figure 7). Stations surrounded by more streets' length of higher hierarchy have the opportunity of greater change, although the relative change does not display a clear relation to the total street length of serviced areas and have an important variation in the relative change with values from 1.9 to 8.3 in the highest 50 stations (panel a in Figure 7). It might appear evident that shortest paths tend to follow main and continuous streets (current situation in red), however, the patterns displayed in panel c in Figure 7 show that subsidiary streets can also be subject of streetspace re-allocation for the improvement of train station accessibility.

Discussion and Conclusion

The study of the physical form of streets offers important insights about the spatial organization and dynamics of cities. From the land-use perspective, street studies are relevant because the space occupied by streets accounts for near an estimated 25% of a city's developed land, and constitute their main transport infrastructure. The designation of streetspace inherited from motorized-transport prioritization is contentious with emergent mobility behaviours and the public space dimension of streets. City officials and active travel advocates are promoting the re-design of streets in a way that acknowledges the prioritisation of non-motorized transport and socio-economic street activity for more sustainable urban development.

While the physical description of the streetspace analysed here is a close representation of the functional organisation of streets, it is still general and could be expanded with complementary street data attributes. For example, a more detailed description of the vehicular space could be obtained by including bus and cycle lanes, speed limits, on-street parking and kerb space use data. Equally, the spatial characterisation of the pedestrian space could be improved by adding street greenery and public life studies data. Street flows data can give a good proxy to study streetspace use dynamics, however, the availability of such data is still limited in both spatio-temporal resolution and geographic coverage.

The cross-section analysis results in a binary simplified relationship between vehicular space and pedestrian space, which is derived from a comprehensive and detailed description of the built-environment. The binary representation of streetspace adopted in this study is not only aimed to fill data gaps but also because it is convenient for a synoptic analysis of street design at a metropolitan scale. But, other features which occasionally have exclusive-use-dedicated-streetspace such as cycle lanes are omitted from the analysis. Even so, the cross-section binary streetspace summary represents the layout of the great majority of streets in London. As such it provides a convenient static representation of the current state. However, while the proposed re-allocation interventions around train stations follow the same binary logic by focusing on the place and walking streetspace (aimed at the station's strategic densification with a sustainable approach), more complex re-allocation scenarios could be developed by accounting for other sustainable transport modes and strategies such as micromobility prioritization (Palominos et al. 2021). It should be acknowledged that streets interventions with a sustainable approach convey a much more complex scenario than changing pedestrian and vehicular space capacity through the

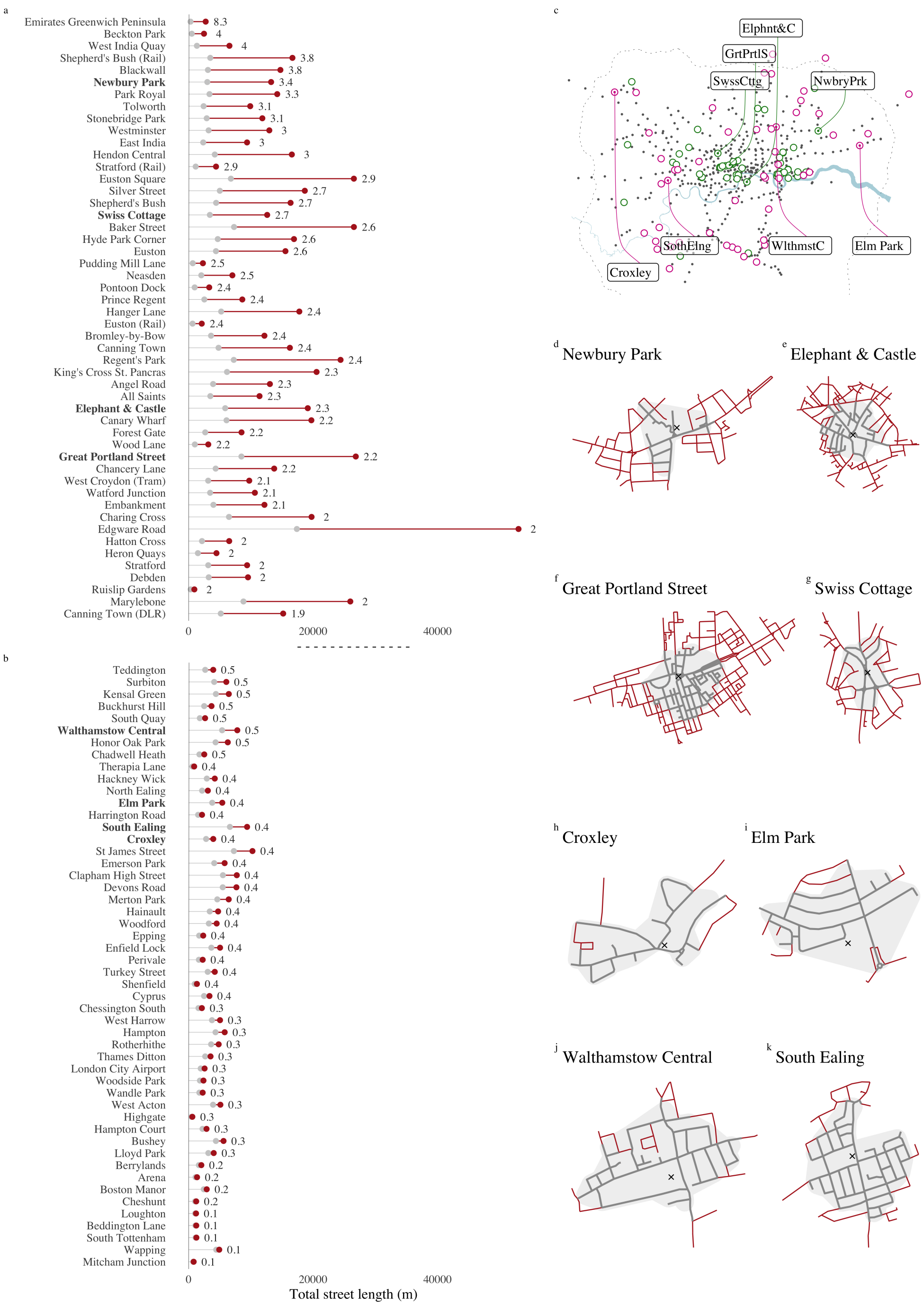


Figure 7. Impact of streetspace re-allocation. Panel (a) and (b) show the 50 highest and lowest relative change of service areas calculated from the difference in aggregated street length (rate annotated, lines lengths in metres). Panel (c) highlights the spatial distribution of stations (highest in green and lowest in pink). Panel (d-g) and (h-k) show a sample of the 4 highest and 4 lowest service areas growth (in red against the current situation in grey) .

modification of the curb line. Additionally, one important factor that could influence walking accessibility to stations is the greater waiting times at junctions which have not been considered in this study due to its assumed dependency on complex technical and social factors. In spite of its limitations, the study adds to the understanding of most streets, built in a different age, and provides a broadly useful reference to understand and explore urban structure at the street resolution.

This paper has described a methodology to generate streetspace allocation metrics: footway, carriageway and total street width for whole urban areas taking into account the networked nature of street systems and applied to London as a case study . This novel data set was computed from existing urban physical environment surveys using geocomputational techniques in open-source GIS software. The method presented is replicable and can be extended over other cities facing similar urban mobility challenges and are spatially organised around motorised traffic. The analysis of the streetspace of whole street systems at a high-spatial resolution can expand street morphology studies in informative ways for transport and urban design practice. Overall, the application of combined spatial research methods including geocomputation and information visualisation provides a method to obtain relevant information that can support street design and planning in a new way and suggests an opportunity to advance in the understanding of streets as places as well as links. The data obtained has been proof-tested on the study of service areas of train stations to provide evidence for streetspace re-allocation interventions.

Previous studies that focus on the quantification of streetspace had made important contributions in providing evidence and new methodologies for highlighting the perceived unfairness of existing patterns of streetspace allocation (Gössling 2016; De Gruyter et al. 2022; Szell 2018; Guzman et al. 2021; Nello-Deakin 2019; Lefebvre-Ropars et al. 2021a). The methodological approach adopted so far is to aggregate data into area geographies for which other transport indicators are available. Whereas the emphasis presented here is placed at the most granular level possible: street segments, while at the same time preserving the topological relationships to amplify the analytical capacity over the street system. While the results of the network-based streetspace allocation analysis follow the typical linear representation and graph modelling of streets applied in street network studies (Marshall et al. 2018), the new analytical technique based on street cross-sections can provide greater insights into understanding the street network structure, the pattern of connections and hence the way the street network functions. These results have important implications for developing mechanisms for determining streetspace allocation that accounts for the many competing streetspace demands of various street user groups (Jones et al. 2007) and contemporary perspectives of streets for transport, streets for sustainability and streets as place (Creutzig et al. 2020). Prior studies that have noted the importance of re-allocating streetspace to protect neighbourhoods from traffic have revealed the mutual connections between metropolitan and neighbourhood scale policies (Appleyard et al. 1981). It can thus be suggested that a citywide streetspace allocation analysis might help better understand the multi-scale implications of re-allocating streetspace.

Some early examples of rethinking the hierarchy of street design are neighbourhood-scale street re-allocation schemes termed super-blocks (Appleyard et al. 1981; Rueda 2018). This in turn are based on the hierarchical organisation of the street system and the identification of environmental areas defined by bordering through-traffic or distributors (Buchanan 1963). However, in order to address the demands of a growing number of mobility alternatives, a more far-reaching and progressive research approach could be adopted through the analysis of larger geographical areas and the exploration of distributors not as traffic channels but as strategic sustainable transport corridors (Palominos et al. 2021). In fact, recent strategic planning responses to Covid-19 in the case of New York (Kimmelman 2020), and the metropolitan-wide pre-Covid-19 but contingent plans announcements in Paris (Reid 2020), already show the viability of these approaches.

With this in mind, examining the geometry of streets appears to be a promising research topic, in the hope that it can provide evidence to scrutinise over-reductionist Modernist practices, offering alternatives for future mobility and urban form adaptation following the principles of sustainable city development.

Notes

1. https://www.pdok.nl/introductie/-/article/basisregistratie-grootschalige-topografie-bgt-
2. https://data.cityofnewyork.us/City-Government/Sidewalk/vfx9-tbb6
3. https://www.ordnancesurvey.co.uk/documents/os-mastermap-highways-network-roads-technical-specification.pdf
4. See p. 39 in https://www.ordnancesurvey.co.uk/documents/product-support/user-guide/os-open-map-local-product-guide.pdf for the OS classification scheme used in the OS Open Map Local data set

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