Identifying and Characterising Active Travel Corridors for London in Response to Covid-19 Using Shortest Path and Streetspace Analysis

Nicolas Palominos, Duncan A Smith, Sam Griffiths

Abstract

Covid-19 related restrictions have forced public transport services to operate with less capacity. In response, trips are channelled to walking and cycling. We use shortest-path analysis to identify all street-level connections between all rail and underground stations in inner London. We are able to identify the critical pathways which show a long tail distribution and a radial/cellular spatial pattern. We visually compare this network with the existing cycling network, and explore two scenarios of street interventions in 8 critical pathways using streetspace cross-section analysis. The methods presented here can offer valuable analytical capacity for developing new cycling and walking schemes and designing place-based streets that are more appropriate to control virus propagation.
Keywords: micro-mobility; street networks; street design; urban transport

1 Introduction

Worldwide, city authorities and transport agencies are implementing fast emergency streetspace reorganisation strategies in response to the Covid-19 pandemic [5]. The Department for Transport in the UK launched a statutory guidance for network management in response to Covid-19 [2], which includes recommendations for real-locating road space to people walking and cycling and other measures to discourage

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the use of cars, such as e-scooters trials and a 'fix your bike' voucher scheme [3]. The transport and public space management has at least two specific new requirements to prevent virus propagation. First, the movement of people has social-distancing restrictions resulting in more street area consumption, and second it is desirable to provide alternatives to mass public transport to avoid the general overcrowded environment of such systems. Both have triggered urban interventions resulting in the reallocation of streetspace for walking and cycling [4].

Despite the efforts by city authorities, a problem they face is the limited comprehensive understanding of how streetspace is allocated citywide, how streetspace provision relates to streetspace demand and how these relate to variations in travel behaviour, weakening the understanding of the effectiveness of the streetspace safe-distancing measures. In addition, because actual streetspace and street networks were mostly designed to satisfy the demands of car traffic, the alternative solutions proposed should be sufficiently attractive with equal levels of convenient connectivity and high environmental quality to effectively counterbalance car travel choice and produce a mode shift towards active travel. The picture gets further complicated by the effects of the extra streetspace demand at the neighbourhood scale for which streetspace reorganisation has also appeared as a solution (e.g. High Streets pavement-widening and low-traffic neighbourhoods). If street interventions fail it is likely that car usage will increase, accentuating well-known health impacts associated with air and noise pollution, traffic injuries and sedentary lifestyles.

Streetspace allocation is a key street design parameter especially relevant in circumstances where the available space is scarce and demand is high as it is expected when rail transport operates with less capacity (e.g. an estimated 15% for London). The analysis of streetspace can be informative in several ways; fine-grain and enhanced urban analytics for monitoring and understanding the impacts of streetspace interventions, and for the proposition of alternative scenarios that guide future interventions for sustainable healthy cities.

From multiple perspectives, there are significant arguments to reclaim streets from private cars and prioritise people in the design and planning of streets. Moreover, it is clear that travel patterns can substantially change through the changes in road capacity and streetspace allocation. Given the current demands for healthy transport modes, in this chapter, we investigate the potential streetspace re-allocations needed to create a micro-mobility network which prioritises space for active travel and public transport. Forthcoming sustainable transport policies provide the setting for the analysis. These are the expansion of the Ultra Low Emission Zone in London for 2021 (ULEZ 2021, see Fig. 1), and the target to have 80% of trips done by foot, cycle or public transport by 2041 [26].

Given the study area, we assume the intensity of usage of places from transport data with railway and underground stations conceptualised as 'activity nodes' [16]. Then, we identify the critical pathways of connections between these places using shortest-path network analysis. Finally, we present a descriptive analysis of two optimal network scenarios applying the street metrics developed in previous work on quantifying streetspace in London [19].

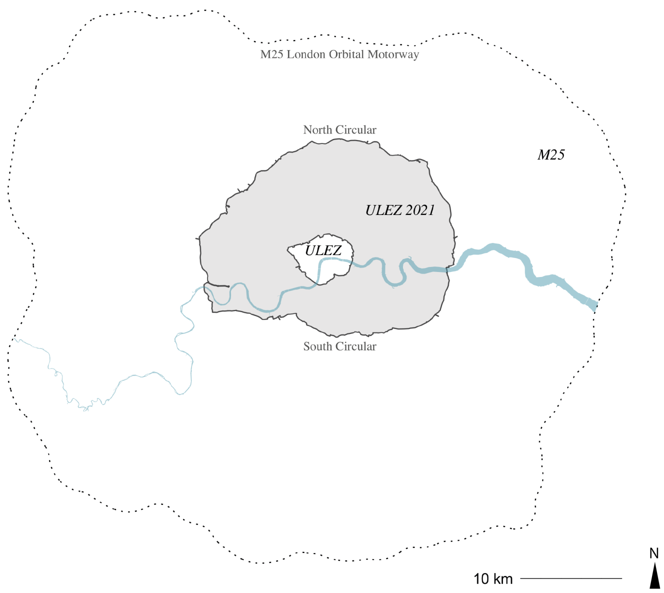

Fig. 1: Boundaries of Ultra Low Emission Zones and M25 zone organised as concentric rings.

The analysis is conducted by creating a pathways model connecting all railway and underground stations at the street level. The street segments contained by the pathways represent 30% of the total street length, and show a big variance of carrying load (or transport 'flow' as defined by [20]). Moreover, a selection of 8 pathways has 38% of aggregated carrying load, although these correspond to just 2% of the total street length within the ULEZ 2021. Because the shortest-path calculations are a factor of network centrality analysis, some associations can be made with regards to the type of streets that constitute the network of pathways.

At a higher spatial resolution, the analysis of two reallocation of streetspace alternatives show that although the streetspace has considerable variations along pathways, there is sufficient space for vehicular and pedestrian uses to coexist. Also, the impacts of narrowing carriageways are relatively more beneficial to footway space than disadvantageous for carriageway space.

The following sections begin with an overview of relevant indicators related to streets and street usage. Then follows a brief descriptive analysis of the street network in the study area and the nodes definition. Next, we present the methodology for generating a micro-mobility network and analyse the results. At last, we conclude with a summary and a discussion of the key findings.

2 Street use and transport general trends and facts

This section includes a review of key indicators related to the street ecosystem and general transport indicators for London. Commonly these indicators are presented in reports prepared by the metropolitan transport authority Transport for London (TfL) and other think tanks specialised in urban issues. The indicators cover a wide range of domains from the built environment to air pollution and are presented without any particular organisation as most of them relate to two or more domains (transport, health, economy, etc.).

While Covid-19-related street measures are noteworthy in number and extent, the design and planning of streets have already been shifting from car-oriented to people-oriented towards more sustainable cities. Some initiatives are based on counter balancing the negative impacts of private car use and promoting a modal split change [6], others go beyond the transport focus arguing that streets are multi-functional urban entities [7, 8] and suggest that streets should be considered as drivers of urban prosperity [9].

In general, street network studies reduce the complexity of the space of the street by using a linear representation to facilitate network-based structural investigations of the street systems [8]. For example, spatial configuration analysis is a well-known approach in urban morphology for the study of street patterns using road centre line street representations. Findings of this approach include important associations between configurational metrics and street social and economic activity [23, 24, 25], among others. Nevertheless, the analysis of physical metrics that are fundamental attributes impacting the way a street functions, such as the footway and carriageway widths, are often overlooked. The focus on streetspace allocation in combination with street level connectivity presented here is a concrete contribution not only for expanding street network studies and the insights these can bring into street planning and design but also for other realms of sustainable urban design noted as relevant at multiple scales from local initiatives to the country-level industrial strategy. Moreover, the methods presented here can offer valuable analytical capacity for developing new cycling and walking schemes and designing place-based streets that are more appropriate to control virus propagation and promote a green post-pandemic recovery. A key aspect for promoting active travel is to make this kind of trips more convenient, attractive and less costly. We suggest that identifying the most direct and shortest routes for active travel prioritisation can bring important benefits for urban transport without disrupting bus services but on the contrary creating exclusive circulation corridors.

Shortest-paths analysis has been studied elsewhere to highlight the tree-like structure of transport modes [21] and to model route choice behaviour of ride-hailing services [22]. Nevertheless, the analysis presented here has the purpose to examine and prescribe new street morphologies for future urban mobility. This considers assuming a street network in which active travel modes are prioritised with direct and fast routes at the expense of modes that are less efficient and have a greater environmental impact such as the car. This proposal of promoting walking, cycling and micro-mobility aims to absorb the trips of public transport services that are operating with less capacity due to social distancing restrictions, while at the same time controls an increase in car travel.

The streets of London carry the majority of the daily trips which are mainly done by active and sustainable modes (walking, cycling and public transport). In 2018 this accounted for 63% of trips. This modal share would require a 0.7 annual increase approximately to reach the Mayor's 80% target by 2041. In more detail, the period between 2000 and 2018 shows a decline of private transport from 48% to 37%, a small increase of 1% in walking starting at 24% and a bigger increase of 9% in public transport starting at 27%. The 36% of public transport share is composed by 22% and 14% of the trips done by rail/underground and bus respectively [26]. This is relevant from a street environment perspective as all public transport trips typically include a short walk at the beginning or end of trips. As an illustration, for the calculation of the Public Transport Access Level (PTAL) a value of 12 minutes walk is used by TfL. However, the streets of London are not only crucial for transport purposes but also have an important role as the main public space of the city occupying an estimated 80% of the total surface of public space [27].

From the economic perspective, a number of reports for London suggest greater value of pedestrian-oriented streets. For example, it has been demonstrated that pedestrians spend 65% more than drivers on average per month. Moreover, improvements on the street environment, including pavement widening, add significant value to private property [28, 13]. This can be explained by the negative impacts of motorised traffic on the environmental quality of streets. For example, in London, motorised road transport is a relevant contributor to air pollution generating emissions that are harmful to human health (14% of nitrogen oxides and 56% of particulate matter less that 2.5 microns in diameter)[18].

As an illustration for modal shift towards sustainable transport, 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 [10, 11]. In contrast, it has been reported that place-based street improvements provide considerable value not only to street users but also to surrounding businesses [12, 13]. Notably, associations have been found between the quality of walking amenities and the performance of innovation districts, suggesting that face-to-face contacts enables innovation [14]. Additionally, it has been implied that, despite the trivial they might be, the sum of many little contacts between pedestrians form the trust of a city [15] and that pedestrian streets can provide the place for people to rub shoulders which is an "essential social 'glue' in society" [16]. In the United Kingdom, one of the key areas of the Government's Industrial Strategy, Future Mobility, was reformulated with emphasis on the role of urban design and planning and the need to develop new street design standards to optimise sustainable and low environmental impact travel systems [17].

Overall, it is possible to observe in London a trend of car use decline and greater awareness of the social, economic and environmental benefits of pedestrian-oriented street environments. This situation has already been recognised by public authorities and research groups in London [11, 18, 29, 31, 30].

3 Streets and nodes of the Ultra Low Emission Zones

In this section we analyse the streetspace designation metrics of the current 2020 and proposed Ultra Low Emission Zones (ULEZ), and introduce a definition of 'activity nodes' within the ULEZ 2021. Both ultra low emission zones are graphically represented in Fig. 1. The current 2020 ULEZ corresponds with the Congestion Charge zone (Euston Rd., City Rd., Tower Bridge Rd., Kennington Ln., Vauxhall Bridge Rd. and Park Ln.), and the 2021 expansion is defined by the North and South Circular roads. The charts in Fig. 2 show the central tendency of streetspace allocation measures for the M25, ULEZ 2021 and ULEZ 2020 zones, which are quite revealing in several ways. First, it can be seen a very regular pattern in the relation between zones for all streetspace designation measures. Second, that the ULEZ has the highest values for all streetspace metrics and the M25 zone has the lowest with a striking exception for footways where the ULEZ 2021 has the lowest values. Finally, the chart shows a decline trend of total streetspace from centre to periphery and the overall predominance of carriageway streetspace over footway streetspace across all zones, which is consistent with the description presented in [19], that was conducted using a different approach.

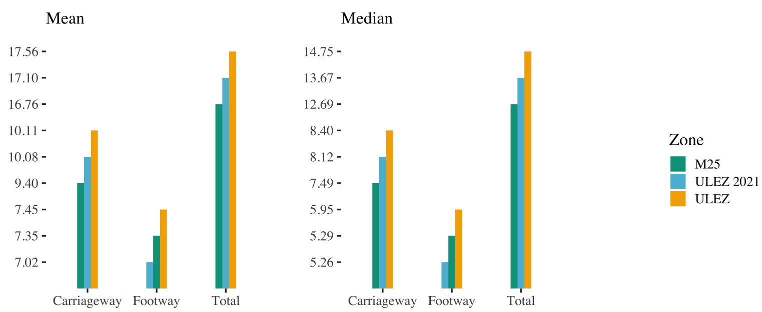

Fig. 2: Central tendency comparison of streetspace metrics between the zones within the M25 Orbital, the current 2020 ULEZ (Congestion Charge Zone) and the planned ULEZ 2021

For the purpose of defining 'activity nodes' within the ULEZ 2021, 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 ('activity nodes' is proposed as a pattern by [16]). The surroundings of stations located in the inner city already have plenty of amenities and attract an important number of people. In like manner, stations with less demand have the potential to do so by the strategic densification around stations that accommodates city growth with a sustainable approach [33]. As some authors suggest this approach has been successfully applied worldwide and is referred to as Transit Oriented

Development (TOD) [32]. With this in mind the ULEZ 2021 has plenty of potential 'activity nodes'. Fig. 3 shows the dispersion of stations in the current 2020 and proposed ULEZ, which number increases with the ULEZ extension in 266 stations from 37 to 303.

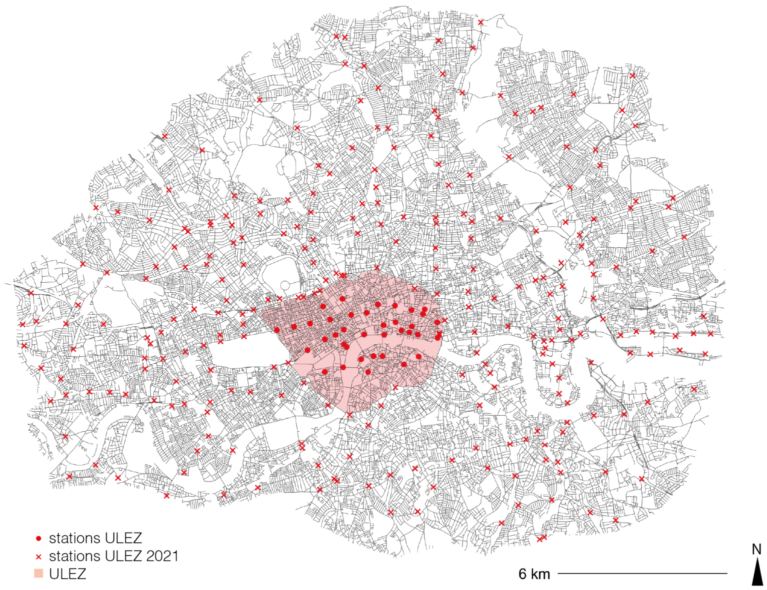

Fig. 3: Railway and underground stations in the ULEZ 2021

4 A street level micro-mobility network

Having defined what is meant by 'activity nodes', we will now move on to present the methodology for generating a street level micro-mobility network. Micro-mobility comprises a smaller kind of urban mobility in two forms: the size of the vehicle and the trip range. This type of mobility has disseminated in many cities worldwide supported by platform technologies that allow a convenient 'as-needed' flexible transport solution, usually for short and medium distance trips. The most common types of vehicles are e-scooters, dockless bikes and station-based bikes (such as the cycle hire scheme operating in London since 2010), which have a small physical footprint and weight, although they have a limited passenger capacity. Still, micro-mobility has the potential for both increasing the access and adding options to public transport (as a first mile/last mile solution), and for replacing short-distance car trips [34, 35].

Before proceeding to define the micro-mobility network, it is important to discuss the implications of prioritising streetspace for active travel and public transport framed under a people-oriented street design approach. In the context of scarce physical streetspace, the incorporation of a new type of vehicle intensifies the existing competing demands for urban space. For example, micro-mobility vehicles occupy extra streetspace for both parking and circulating. Parking has been the focus of attention of public authorities to solve the additional streetspace clutter that this vehicles generate when parked inappropriately (e.g. the designation of parking areas for dockless bikes). Circulating is not yet fully admitted (e.g. electric scooters in the UK), nevertheless micro-mobility vehicles have greater competitive advantages because they are more space-efficient than private cars (see Table 1). In addition, it could be argued that with an adequate management micro-mobility vehicles can allow greater social contact and community connections.

	Standing/Parked		Speed		Travelling	
unit	sqm	sqf	kph	mph	sqm	sqf
Pedestrian	0.5	5	5	3	2	20
Micro-vehicle	1	11	25	16	7	70
Bicycle	2	20	16	10	5	50
Bus Passenger	2	20	48	30	7	75
Automobile	37	400	48	30	139	1500

Table 1: Per-person travel space requirements for different modes. Source: National League of Cities, 2019; Tice, 2019

As previously stated, micro-mobility, active travel and public transport are different types of transport solutions that have similar objectives. In addition, we have defined activity nodes that are actual and potential attractive destinations. Assuming that the intensity and diversity of activities of the nodes is complex to define and a matter in constant evolution and adaptation, the micro-mobility network is created by connecting all nodes through the shortest-paths, in order to create the conditions for an integrated public transport system that optimises travel distance using the actual street infrastructure (see Fig. 4). Essentially, this network provides the convenient and desirable conditions for short, medium and long trips Also, it can potentially enable multi-modal integration and maximise the efficiency of streetspace in concordance with sustainable urban goals. It would be expected that the paths which are most intensively used could gradually turn into 'promenades' of mixed-use activity such that the remaining in-between areas are at short distance from lively and vibrant streets and centres ('promenade' is proposed as a pattern by [16]).

From the design perspective it is important to highlight that the shortest-path type of structure for transportation purposes is far from being the optimal for construction (see discussion from a network perspective in [36]). Yet, the alternative proposed here adopts such structure to prioritise the convenience of users by optimising

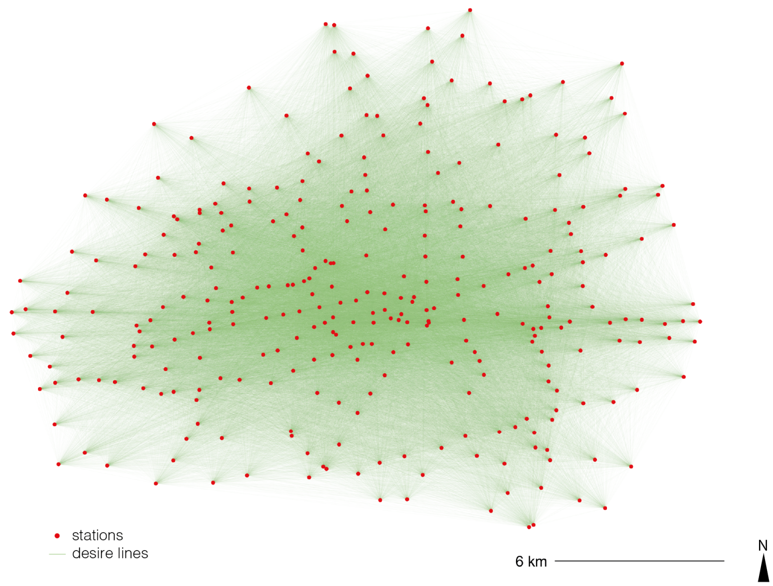

Fig. 4: Complete graph connecting stations: node-to-node shortest-paths (n = 45,753)

travel distance and at the same time optimises construction by utilising preexisting infrastructure.

The map in Fig. 5 shows the structure of the micro-mobility network highlighting the street segments that concentrate the greater number of through-routes and the travel pathways these form. It is possible to observe a cellular/radial spatial pattern that coincides with some the actual cycling infrastructure. Fig. 6i shows the current cycle lanes which are fully or partially segregated, on-carriageways or shared lanes (e.g. bus lanes). Some of these cycle lanes are also part of the designated cycle routes, which are part of executed, ongoing and future investments. Overall, however, this visual comparison shows that the connectivity and complexity of the modelled network are much greater than the observed reality of the cycling network.

Having discussed the methodology to construct the network, the next sections address the descriptive analysis of the network and travel pathways and the potential streetspace re-allocations needed to create a micro-mobility network.

4.1 Cycling infrastructure and missing links

The growth of cycling trips in recent years has been accompanied by investment in new and upgraded infrastructure. In this section we analyse with more detail the

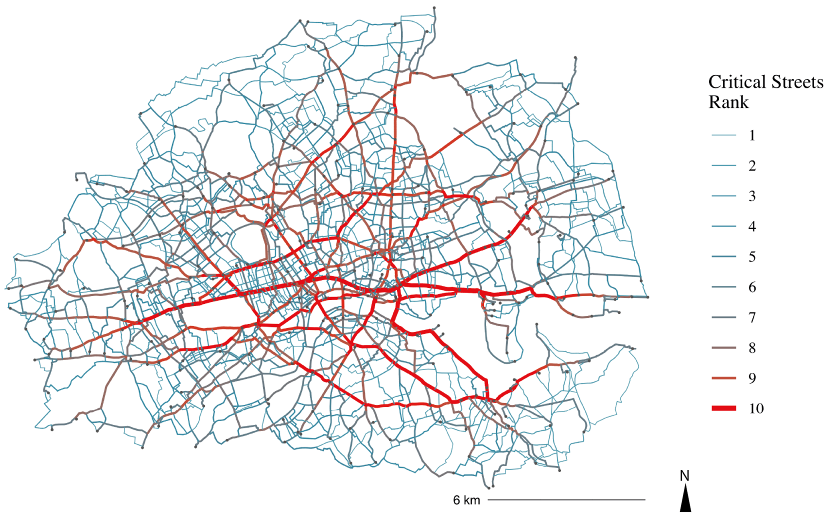

Fig. 5: Critical streets ranked according to shortest-paths through-routes

cycling infrastructure illustrated in Fig. 6i, and we compare it with the core critical streets network in Fig. 5. As can be seen, there is an overlap between the critical streets with higher rank and the provision of cycling infrastructure (e.g. some of the radials like Kingsland Rd, Edgware Rd and the Victoria Embankment). To identify the core critical streets we selected the segments at the highest 20% of through-routes, which corresponds to 4.513 street segments with values from 490 up to 7031 traversing shortest-paths (see Fig.6ii).

Cycle Lane Type	Physically segregated (a)	Signs and markings (b)	Shared on carriageway. No priority (c)
True	Segregated Partially Seg. Stepped	Mandatory Advisory Priority	Shared On carriageway
False	On park On waterside		Priority

Table 2: Description of cycle lane types from TfL survey

The 5 cycle lane types in Fig. 6i provide a general description of the quality of the cycle lanes that occupy part of the street. The cycle lane types were generated from the cycling infrastructure documentation published by TfL (see database schema at

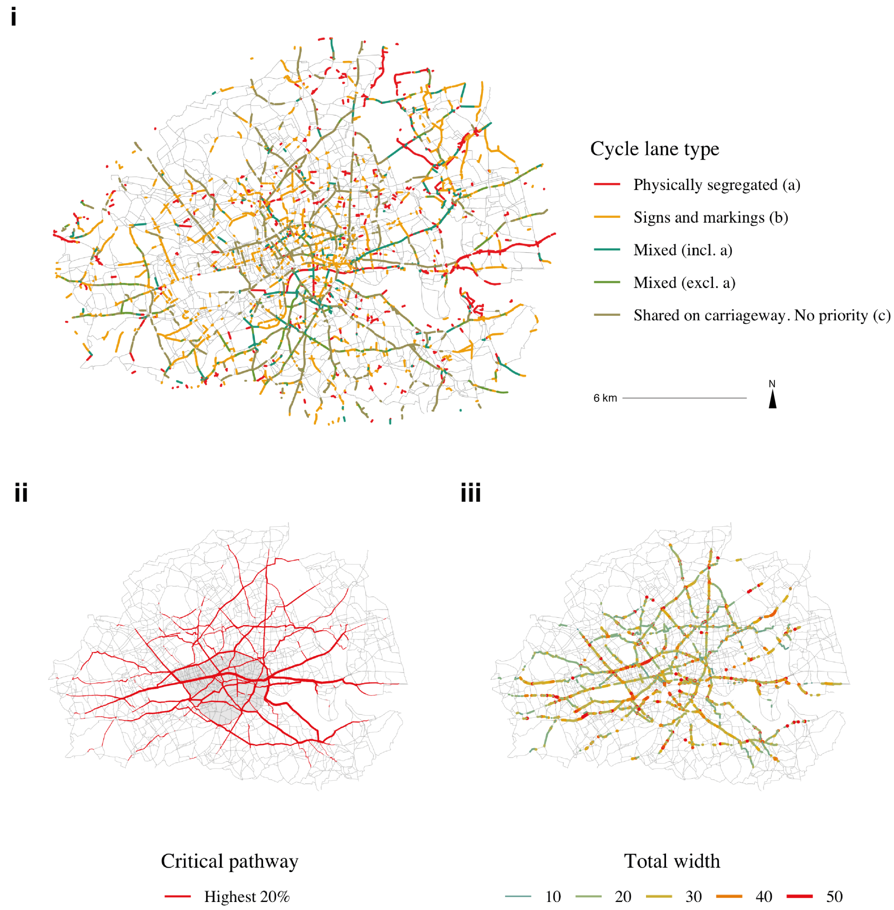

Fig. 6: Cycling infrastructure and missing links: (i) Cycle lane types, (ii) Core of critical streets, (iii) Difference between *ii* and *i* classified by total street width (*i* is excluding *c*). See figures in Table 3. Data source: (i) https://cycling.data.tfl.gov.uk/

https://cycling.data.tfl.gov.uk/). Table 2 describe the attributes of 3 cycle lane types and Fig. 7 shows real-world examples. The 3 cycle lane types information was joined to the streetspace road centre line representation (RCL) resulting in street segments with mixed cycle lane types (2 additional). Because physically segregated lanes could be considered of the highest standard (type *a*), the mixed cycle lane types were defined with reference to these.

From Fig. 6i and ii and the breakdown in Table 3 it is possible to observe the main characteristics of the existing cycling lanes. Near 64% of the cycling street network only has indicative cycling infrastructure (Signings and markings (*b*) and

	Physically segregated (a)	Signs and markings (b)	Mixed (incl. a)	Mixed (excl. a)	Shared on carriageway. No priority (c)	Total length
Cycle lanes (km)	85.60	177.70	47.10	33.30	117.20	460.90
pc	0.19	0.39	0.10	0.07	0.25	1.00

	Total length
Critical pathway (km)	261.3

total width breaks (m)	(0,10]	(10,20]	(20,30]	(30,40]	(40,50]	Total length
Missing connections (km)	2.5	76.3	68.0	31.5	5.7	184.0
pc	0.01	0.41	0.37	0.17	0.03	1.00

Table 3: Summary of Figure 6

(a) Physically segregated

(b) Signs and markings

(c) Shared on carriageway

(d) Mixed (excl. a)

Fig. 7: Examples of cycle lane types. Images source: https://cycling.data.tfl.gov.uk/

Shared on carriageway with no priority (*c*)). Although, the spatial pattern described by them is of continuous lines similar to some of the critical pathways in Fig. 6ii. The same could be observed from the physically segregated cycle lanes (type *a*), however, these are both shorter (29%) and scattered with some continuity in Central London (Victoria Embankment) and the radial connections towards the East, plus isolated radials in the north-eastern part of the study area.

The missing links illustrated in Fig. 6iii are obtained from the difference between the core critical pathways and the existing cycling lanes (excluding Shared on carriageway with no priority (*c*). It is possible to observe that an important part of the critical pathways network would need to be build or enabled to create the continuous paths. The visualisation shows the total street width of the missing connections to estimate the easiness to fit in formally designated road space for cycling or micro-mobility. Additionally, it is possible to observe the stretch of critical streets without any cycle lane infrastructure but that have the potential to create a continuous route. The general piecemeal pattern might be the result of street retrofitting investment strategies, which despite the existence of a general plan of designated cycle routes, lacks the adequate infrastructure and continuity of a purposefully constructed cycling/micro-mobility network. Nevertheless, the construction of a continuous network has the constraints imposed by the scarcity of streetspace represented by the total street width available. The bottom of Table 3 shows the breakdown according to total street width illustrating that most streets segments needed to complete the critical core are relatively narrow (10-20 m), reflecting the challenges of streetspace reallocation.

4.2 General patterns of the street-level travel pathways

We have argued that the design approach for the construction of the network optimises the utilisation of the existing streets. The figures in Table 4 show that the total street length of the ULEZ 2021 is around 4,784 km. , and that 30% of the total street length is needed to create the network. However, the street segments have a varying carrying load represented by the total number of through-routes along them (see Fig.5). This can be observed in the distribution of routes per street segment which shows a left skewed distribution. This means that there are many streets that are part of few travel routes and a few critical street segments that are traversed by many travel routes (see Fig.8).

	Km	Perc
Total ULEZ 2021	4784	100
Network	1434	30

Table 4: ULEZ 2021 and Network total street length

The carrying load metric for each street segment is useful to measure the relative importance of the different pathways. To compare pathways we define a rate of critical pathway importance P by adding the carrying load of all street segments in the pathway S and dividing it by the total number of street segments or edges E in the pathway to control by pathway length

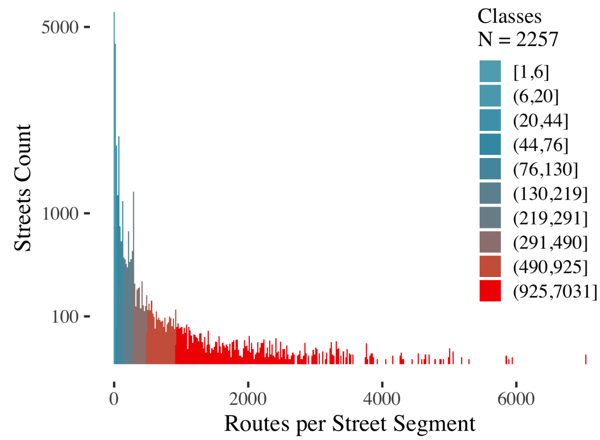

Fig. 8: Street segments-pathways distribution

$$P_{ij} = \sum \frac{S_{ij}}{E_{ij}} \tag{1}$$

Variable	Min	Q1	Median	Q3	Max	Mean
Carrying Load (S)	145.0	73308.0	181291.5	371886.8	1213439.0	255723.3
Number of segments (E)	3.0	113.0	177.0	249.0	524.0	185.2
Critical Pathway (P)	5.6	613.9	1046.2	1680.4	4771.5	1226.5
Pathway length in km	0.1	6.6	10.2	14.3	28.2	10.7

Table 5: Pathways metrics summary

Table 5 presents the results obtained from the descriptive statistical analysis of the pathways. Because of the location and spread of the activity nodes, the pathway length and total number of segments (E) show a considerable range with maximum values more than 200 bigger than minimum values. Similarly, the carrying load (S) has maximum values 8000 times bigger than minimum values, which is useful to identify important travel routes as this measure could be assimilated with a measure of aggregated betweeness centrality. Also, this can favour strategic approaches for selecting significant pathways for intervention, which would have a greater impact for the whole network. The 10.7 km mean value of pathway length reveals that under appropriate street-infrastructure conditions a one way average commute could take 25 min. on an electric micro-vehicle and 35 min. riding a bike.

The critical pathway metric is better understood looking at the spatial pattern. Fig. 9 b show the pathway with maximum critical pathway value P, at the city centre (Cornhill, Leadenhall St, Aldgate High St.), representing the thoroughfare with the highest density of traversing routes. The pathways in colour red on Fig. 9 d

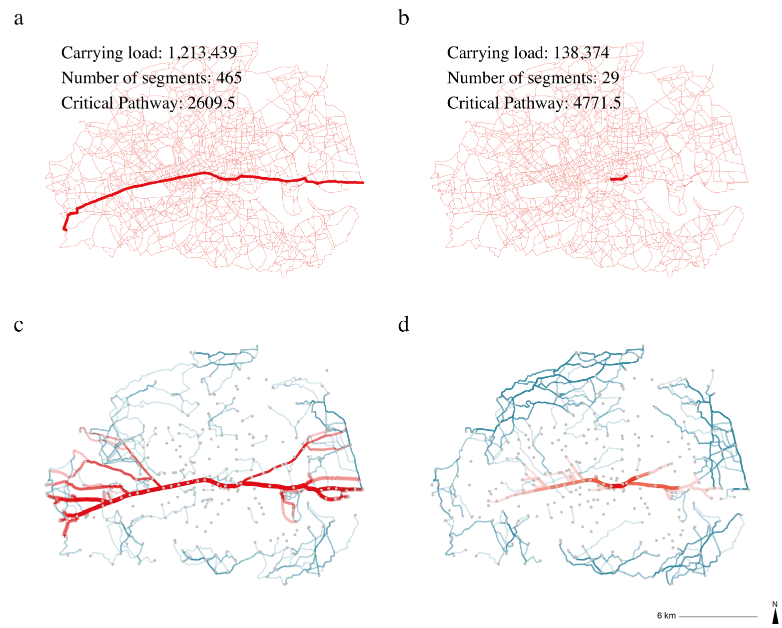

Fig. 9: Spatial pattern of pathways carrying load *S* and critical pathway *P*. Panels a and b are the maximum values of *S* and *P*, and panels c and d show the top (red) and bottom (blue) 1% values of *S* and *P*. Stations represented in light grey.

correspond to the highest 1% values of *P*. Interestingly, along the West extension there appear a series of branches towards the North which correspond with relatively short pathways adjacent to the main East-West thoroughfare, which get high *P* because of their proximity to the pathway with highest *P* (Southhampton Row, Gower St., Tottenham Court Rd and Cleveland St.). Fig. 9 c shows a pattern of longer branches in red representing the highest 1% values of *C*, which can be defined as long and high-density pathways connected to the centre. For Fig. 9 c and d, the pathways in blue are the lowest 1% values, where it is possible to identify peripheral and few central pathways. Overall, it stands out the total lack of important pathways South of the river. This result is somewhat counter-intuitive, because some of the pathways in the South also traverse the main thoroughfare (see Fig. 5), yet longer routes are needed and also the concentration of nodes is much bigger in the North (see for example the sequence of stations in light grey in Fig. 9 c), therefore the overall carrying load is greater (e.g. *S* value of all top 1% pathways in Fig. 9 c is over 1 million).

4.3 Selection of critical pathways that conform the micro-mobility network

A number of strategies could be adopted to select the pathways out of the more than 40 thousands. For example, a balance between Northern and Southern areas of the city could be desirable, or a focus on areas with higher potential urban growth. It is clear from the pathway analysis that the intervention on the East-West pathway in Fig. 9 would represent an impact for an important number of pathways. However, the geographical balance between different areas within the ULEZ 2021 is missing from this analysis.

In order to identify pathways that could complement the East-West main thoroughfare, we decomposed the critical streets map in Fig. 5 into 20 groups classified by the rank of their streets segments frequency and presented cumulatively (see Fig. 10).

This sequence resembles a pattern of urban growth where by comparative analysis it is possible to identify the formation of critical pathways. For the reasons we discussed above the first pathway to be generated is the East-West thoroughfare. Then, a branch to the South-East follows and a bifurcation of the main thoroughfare in diagonal in a North-East direction (from panel 2 onward). Also, on the first panels it is possible to observe the formation of a pathway in diagonal towards the North-West (represented with more clarity in panel 4; for reference this corresponds to Edgware Road). In panel 16 a dozen of pathways form a network with an extensive geographic coverage. From these, for the sake of simplicity, we selected the 8 pathways represented in Fig. 11 which contain the pathways with the maximum S and P, and most of the pathways highlighted in the rank visualisation which are connected together and form a network.

The criteria for pathways selection is to avoid overlapping between paths while at the same time to connect stations sufficiently separated so that the 8 pathways network has a considerable geographic coverage of the ULEZ 2021. Table 6 shows a summary of the pathway metrics for the 8 pathways network. The metrics can be compared with the summary of the whole network in Table 5. As can be seen, most of the P values are close to the whole network mean (1226,5), although there are 2 notable exceptions which correspond to pathways with a South-North direction and a trajectory that crosses rather than overlaps with the centre (Westferry-South Tottenham and Clapham Common-White Hart Lane). Importantly, the S values are mostly above the general median (181291.5) except for Westferry-South Tottenham. The total street length of the 8 pathways network is 96 km approximately, many times smaller than the whole network (1434 km), yet it concentrates near 38% of the aggregated carrying load.

A closer inspection of the pathways characteristics can be done by looking at the streetspace designation metrics. Table 7 presents an overview of total street, footway and carriageway widths. Overall, figures show that on average the selected pathways have considerable designated footways and carriageway streetspace. However, because of the piecemeal street improvements across the history of London,

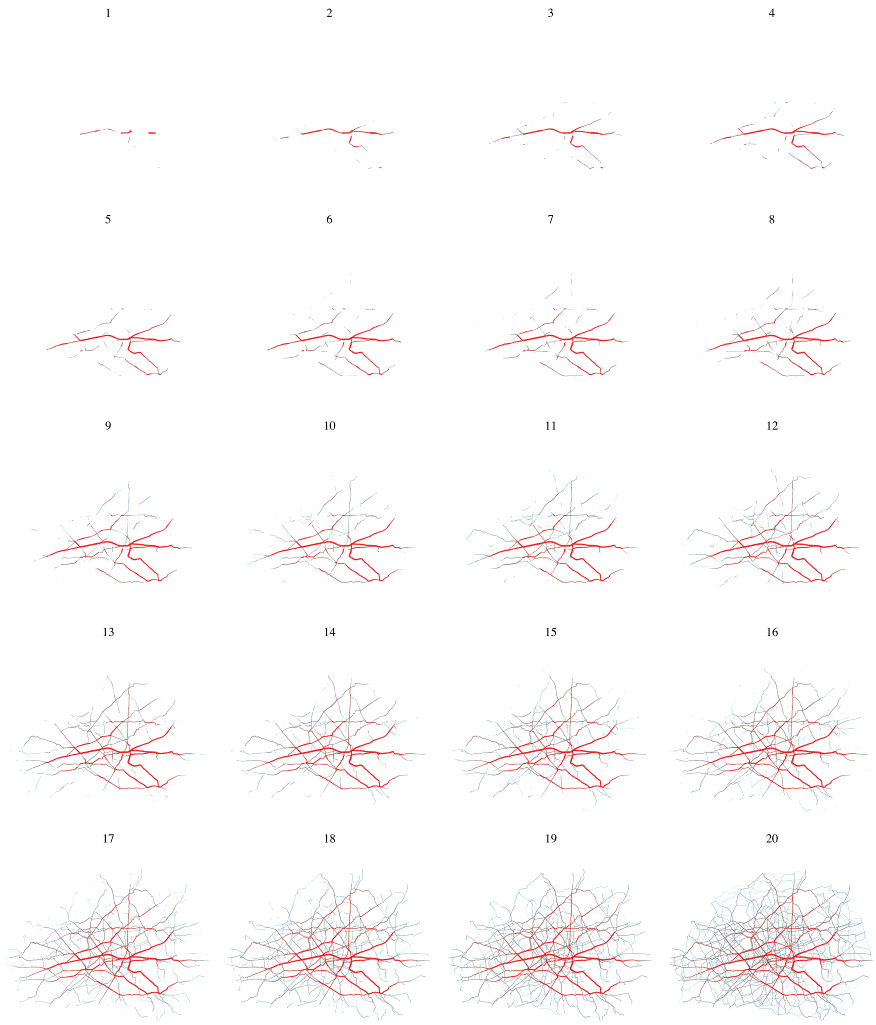

Fig. 10: Cumulative critical streets sequence according to street carrying load

it is possible to anticipate that there will be important variations in the streetspace designations metrics along the pathways.

Before the quantitative examination of possible scenarios to re-allocate streetspace, it worth visualising what do we mean by this. We assumed that the prioritisation of active travel and public transport implies reducing carriageway space to a minimum width that allow the circulation of buses. The carriageway width is assigned for two scenarios: the demarcation of one and two lanes (3.5 and 7 m width respectively).

Fig. 12 illustrates the variations of the streetspace designation metrics for the two scenarios in a sample of 60 street segments from the Aldgate East-Bow Church

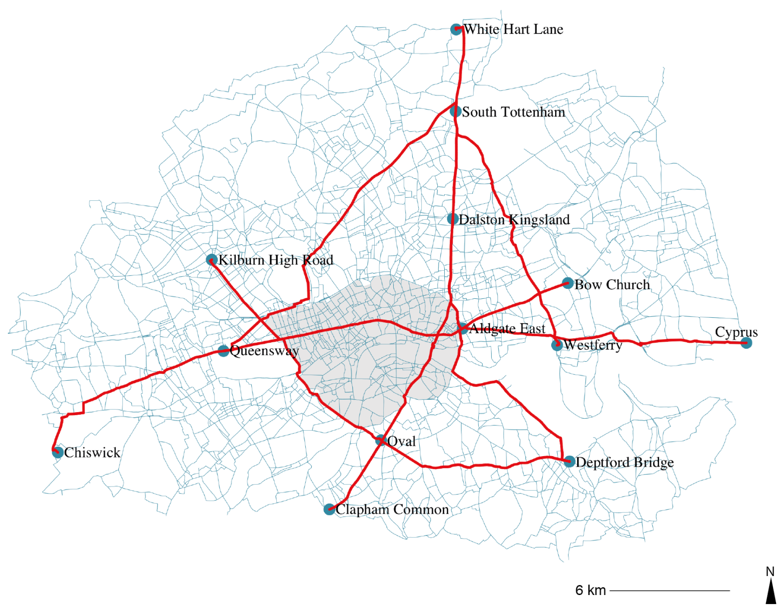

Fig. 11: Network of 8 selected pathways

from	to	Total length (m)	S	E	P
Chiswick	Cyprus	25696	1214066	467	2600
Deptford Bridge	Dalston Kingsland	10892	435321	195	2232
Clapham Common	White Hart Lane	17934	330986	350	946
Queensway	South Tottenham	12801	239540	203	1180
Kilburn High Road	Oval	8890	225359	161	1400
Aldgate East	Bow Church	3854	211983	77	2753
Oval	Deptford Bridge	6695	195528	119	1643
Westferry	South Tottenham	9181	122143	176	694

Table 6: Eight pathways network metrics summary

pathway. From the chart, it can be seen that by designating a fixed carriageway it is possible to uniform the otherwise chaotic sequence of street cross-sections. Accordingly, this allow to identify places along the pathway with greater potential or challenge for active travel prioritisation. While the indication of designated town centres provides clues to estimate streetspace demand, the addition of other variables that reflect the complexity of street usage would enrich this analysis (e.g. street markets, bike stations, bus stops, etc). Nevertheless, the multiple dissection of the pathway serves as a baseline that presents key geometrical information of the streets environments that compose the pathway.

The 8 pathways network scenarios are summarised in Table 8. To measure the variance between the actual, two lanes and one lane scenarios, we calculated a

from	to	Total street width mean	Footway width mean	Carriageway width mean
Aldgate East	Bow Church	30.2	14.4	15.7
Clapham Common	White Hart Lane	26.8	11.0	15.8
Oval	Deptford Bridge	24.8	9.6	15.1
Chiswick	Cyprus	27.8	11.2	16.6
Kilburn High Road	Oval	29.3	11.1	18.3
Queensway	South Tottenham	25.0	10.4	14.6
Westferry	South Tottenham	24.7	9.6	15.1
Deptford Bridge	Dalston Kingsland	25.4	10.1	15.3

Table 7: Eight pathways streetspace designation metrics summary

total approximate area by multiplying actual and proposed street widths by the street length. What is interesting about the data in this table is that the carriageway variance for both proposed scenarios are very similar, reflecting the modular nature of street design with regards to vehicular space. The opposite is true for pedestrian space which is the 'left-over' space after the carriageway has been determined. Also, since the positive and negative values can be seen as gains and loses of space, the figures reflect that the proposed scenarios entail a gain of 73% and 109% footway space on average for the two lanes and one lane scenario respectively, and a loss of 51% and 75% of carriageway space. This last measures are consistent with the figures in Table 7 that show a carriageway total mean of 15 m approximately which could fit 4 lanes.

Overall, because footways widths are smaller than carriageway widths, on the whole the relative gains surpass the losses. In other words, on streets such as the ones forming the selected pathways, changes of the streetspace designation metrics like the studied here, can have a relatively greater impact for the footway space than for the carriageway space.

	Actual total app. area (sqm)		Two lanes				One lane			
Pathway	Footway (fo)	Carriageway (ca)	fo	var	ca	var	fo	var	ca	var
Ald_Bow	55160	55829	84008	0.52	26981	-0.52	97498	0.77	13490	-0.76
Cla_Whi	184071	266856	325389	0.77	125538	-0.53	388158	1.11	62769	-0.76
Ova_Dep	58183	89514	100829	0.73	46868	-0.48	124263	1.14	23434	-0.74
Chi_Cyp	264531	366850	451512	0.71	179868	-0.51	541447	1.05	89934	-0.75
Kil_Ova	89563	143317	170651	0.91	62228	-0.57	201766	1.25	31114	-0.78
Que_Sou	116806	171064	198263	0.70	89607	-0.48	243066	1.08	44804	-0.74
Wes_Sou	77411	125812	138954	0.80	64269	-0.49	171088	1.21	32134	-0.74
Dep_Dal	99214	145390	168361	0.70	76244	-0.48	206483	1.08	38122	-0.74
Mean	118117	170579	204746	0.73	83950	-0.51	246721	1.09	41975	-0.75

Table 8: Summary of pathways two lane and one lane scenarios

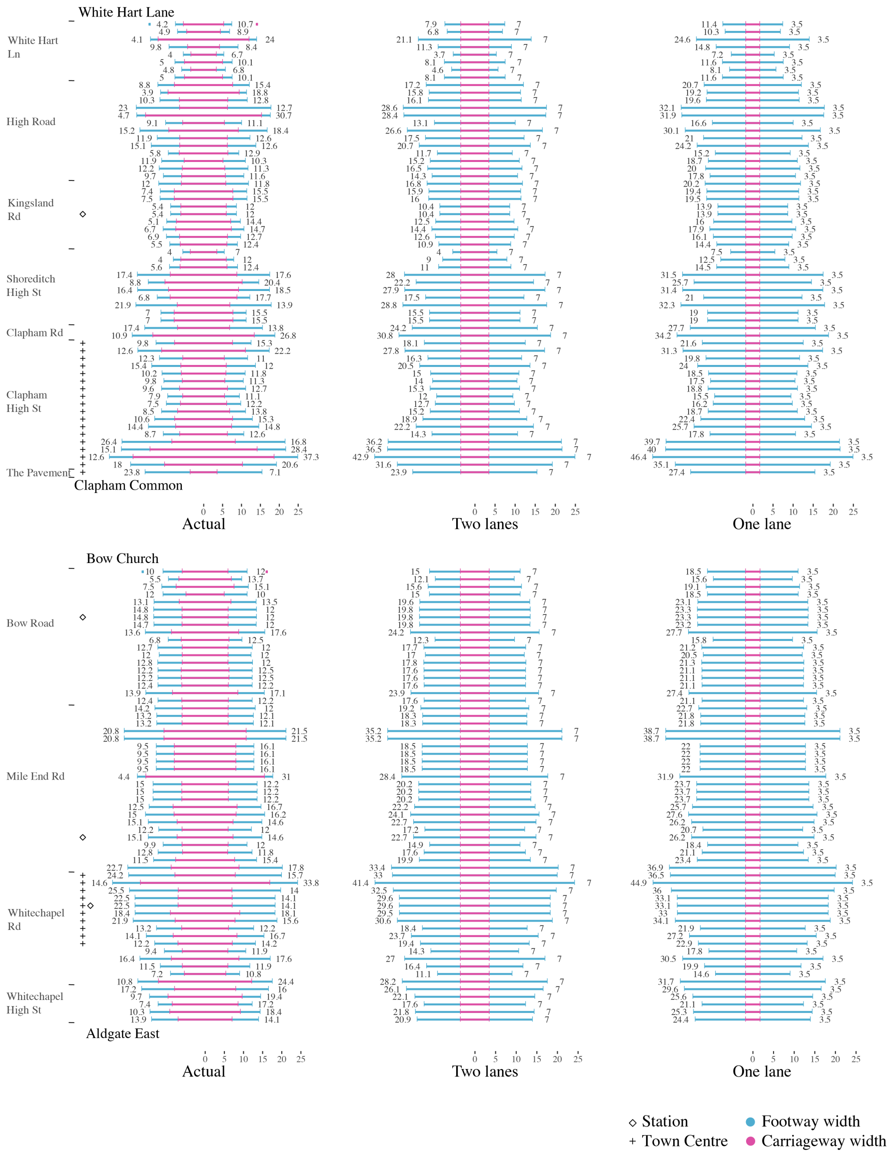

Fig. 12: Pathway anatomy: Multiple dissection of selected pathways and micro-mobility scenarios (sample of 20 segments at the start, middle and end of paths)

5 Summary and discussion

In this chapter we have presented a method to analyse the street network of central London and proposed alternative scenarios for the conformation of a micro-mobility network that prioritises active travel and public transport. The method covers from the definition of a structure of routes to a fine-grain characterisation of street segments, and is inspired by well-known strategies of rail infrastructure optimisation (e.g. user-oriented and construction-oriented design). This considers proposing a completely connected active travel network in which direct and fast routes are prioritised for active travel modes at the expense of modes that are less efficient and have a greater environmental impact. However, because the construction of a network from an ordinary number of points results in a high number of connections (over 40 thousands in this case), the problem of pathways selection arises. The analysis could be further refined with the purposeful selection of certain nodes, to reduce the number of pathways or to focus on certain areas. For example, it would have been possible to identify key amenities of public interest such as schools or hospitals. In fact, this is not far from the solutions that some cities have implemented in the context of the Covid-19 pandemic. This include from pavement widening and the delimitation of car-free zones to setting up temporary cycle lanes to control public transport overcrowding and ease the compliance of social-distancing recommendations [5]. In London the Covid-19 crisis accelerated ongoing policies of streetspace reclamation that are more adequate for promoting sustainable transport travel [1]. Notably, all these solutions correspond to urban planning schemes that revolve around the idea of reclaiming streetspace from private cars.

The shortest-path analysis of the central area of London, showed that only 30% of the actual street length is used to connect all railway and underground stations through the shortest route. The pathway length frequency distribution is normal and pathways have an average length of 10.7 km. Although, the number of routes traversing street segments (carrying load) has a left skewed distribution with maximum values 8000 times bigger than minimum values. The method combining shortest-path with streetspace analysis can be useful for both planning active travel prioritisation strategies and Covid-19 pandemic street management measures to keep cities functioning. In the meantime, street use will continue evolving in response to the pandemic and transition to long-term recovery while mass transit operates with less capacity.

The visual comparison of transport networks illustrate both the endurance of historic networks but at the same time the difficulties of constructing connected and complex networks, despite the use of existing streets (e.g. dispersion and disconnectedness of the current cycle network). Additionally, the spatial visualisation of the street segments carrying load distribution in small multiples, resembles a pattern of urban growth that allow to identify the formation of critical pathways.

Moreover, the multiple dissection of pathways reveals the variations of streetspace designation metrics along a route at high spatial resolution. Street reallocation interventions visualised in this manner allow to understand the positive impacts of narrowing carriageways for increasing the public value of streets (i.e. healthier street environments), while still keeping space for motorised-traffic like buses. This, in addition to the fact that only some streets are needed to connect all stations, reinforces the idea that small interventions on few streets at the city and street levels can have a big impact.

Other known approaches to traffic management consist of the definition of a neighbourhood unit that group together minor streets surrounded by major streets. This same concept was developed by Buchanan as the 'environmental areas' from which through-traffic was excluded and instead it was channeled through the perimeter streets forming the city corridors [37]. Such strategies have had real-world applications in the area of Barnsbury in London and in some areas of Barcelona under the name of 'superblocks' [38]. However, even though these approaches favour the creation of good quality pedestrian environments, they operate in an inward-like manner as opposed to the strategy presented here, were the street enhancements are done on the main corridors of the city.

Because the analysis presented here is based in shortest-path and streetspace analysis, some associations were found with the analysis of previous research (see [19, 39]). First, it was possible to identify the central streets of the system, which in this case has a clear East-West pattern at the North side of the river. Second, a hierarchy of streets with a central-periphery pattern which correspond to 30% of of the total street length inside the ULEZ 2021. Third, a left skewed long tail frequency distribution of routes per street segment, similar to centrality distribution. Finally, from urban planning perspective, the simultaneous examination of the strategic and design scales of the street system allows for a more comprehensive analysis and overview of interventions.

Similarly, some associations could be drawn with preexisting and existing transport networks. For example, the correspondence of the 8 pathways network with the former tramways network, the current cycling infrastructure and bus route network and the Roman roads. Fig. 13 demonstrate the slow rate of change of some pathways over time. That is the case, for example, of the Clapham Common-White Hart Lane pathway, starting at Clapham Road in the South a continuing along Kingsland Road in the North, following the same trajectory of part of a tramway route and a Roman road (to Chichester in the South and to York in the North). Similar juxtapositions can be found for the rest of the pathways in the 8 pathways network (e.g. Seven Sisters Road, Edgware Road, Whitechapel Road, etc). Certainly, the 8 pathway structure is partially contained by the cycling routes, yet that is only because the majority of the cycling routes represented in Fig. 13 share the streetspace with bus lanes. In addition to this, the piecemeal-like pattern of the actual cycling routes reflect the difficulties of transforming the space of the street from car priority to bicycle priority.

In the last section of this chapter, we analysed the pathways in more detail looking at the streetspace designation metrics of a subset of the shortest-paths network. It was not a surprise to find that the pathways are formed by relatively wide streets with more space assigned to the vehicular part. The pathways anatomy visualisation of multiple cross-sections offers an alternative more detailed perspective of the streetspace designation metrics variations along a route. Also, we studied two possible scenarios for prioritising active travel and public transport through the reallocation of carriageway space. These show that by reducing carriageway space to minimum functional standards can have a significant increase of streetspace for place-based street improvements and space-efficient modes of travel. Given the current social distancing restrictions and the decreased capacity of mass transit services

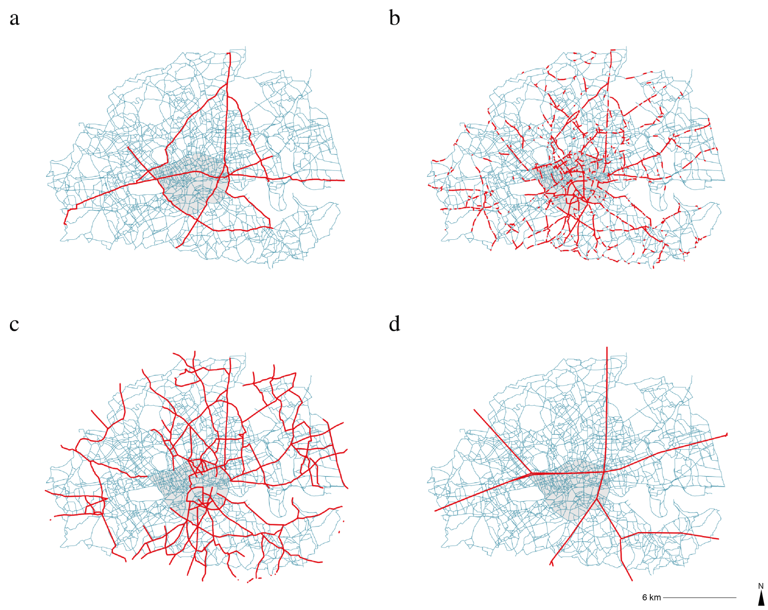

Fig. 13: Transport network comparison. (a) is the 8 pathways network, (b) cycle lanes (segregated and shared with bus lanes), (c) former tramways (mid 1900's) and (d) Roman roads diagram. Data sources: b: https://cycling.data.tfl.gov.uk/, c: http://sharemap.org/public/Trams_in_London, d: https://darmc.harvard.edu/data-availability

due to the Covid-19 pandemic, these street interventions should have a positive effect for both controlling virus propagation and encouraging a sustainable and healthy recovery [4].

6 Data accessibility

Data for the cycling infrastructure analysis are available online from TfL's Cycling Infrastructure Database. Metrics of streetspace designation metrics are available from Zenodo: https://doi.org/10.5281/zenodo.3783807

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