



The potential of implementing superblocks for multifunctional street use in cities

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The Barcelona superblock has been proposed as a sustainable urban neighbourhood transformation strategy in cities. Superblock design reduces space assigned to cars to enable alternative uses for improving liveability and sustainability. Here, the potential for superblock transformation is systematically quantified and evaluated for cities with varying urban forms and densities. A superblock consists of nine (3 × 3) urban city blocks, including interior and exterior streets. Miniblocks, consisting of four (2 × 2) blocks, are proposed as a less-disruptive strategy to initiate urban transformation on which superblocks can build. A geospatial network-based approach is developed to find locations for introducing multifunctional streets. For possible site prioritization, the identified locations are evaluated concerning the potential disruption to traffic. The analysis reveals that the potential for superblocks and miniblocks, as well as their disruption effect, varies considerably across cities and is affected by the urban layout. For some cities, over 40% of the street network is potentially suitable for integrating superblock or miniblock design, providing opportunities for city-scale transition towards more sustainable and liveable cities. A grid-like layout in cities is not a sufficient condition for high superblock potential, and cities with irregular street layouts can show high transformation potential as well.

Pursuing sustainable urban design approaches in today's cities is necessary as cities face manifold challenges due to climate change, urban heat, flooding and air or noise pollution¹. The COVID-19 pandemic intensified the discussion on how to transform cities and neighbourhoods to be more liveable, resilient and sustainable and has triggered the rethinking of public urban spaces^{2–4}. Unconventional concepts such as tactical urbanism, multifunctional streets and superblocks are being envisioned, where more space is assigned, for example, to urban greening, pedestrians or cycling zones^{5–7}. Encouraging walkable neighbourhoods by reducing car-based dependencies is envisioned to improve health and urban liveability^{8–10}. Superblocks (*superilles*) were prominently proposed in Barcelona^{11,12} as an innovative and unconventional urban transformation strategy to create pedestrian-centric neighbourhoods¹³ and have since become an integral part of Barcelona's climate commitment strategy to reduce transportation emissions and address urban heat islands¹⁴. The Barcelona superblock forms an urban unit made up of nine (3 × 3) urban blocks with interior and exterior streets and is characterized by enabling a transformation of the interior streets for new shared urban uses (Fig. 1a)¹⁵. In Barcelona, a speed limit of 10 or 20 km h⁻¹ was applied to interior streets, and they were altered so that superblocks cannot be crossed by car, thus preventing through traffic¹³. Superblocks do not only redefine urban mobility by shifting the modal split towards public transportation, cycling or fostering walkability but have also the intention to improve urban green infrastructure and biodiversity by establishing urban corridors traversing the city¹⁶. The long-term vision in Barcelona is to transform individual neighbourhoods and bring about transformation at the larger scale by repeated superblock implementation across the city¹⁷. For such a superblock-based urban regeneration strategy, an average increase in life expectancy of almost 200 days due to reduced urban heat, air and noise pollution levels was estimated in the case of implementing 503 superblocks across Barcelona¹⁸.

Despite the promising potential benefits of the Barcelona superblock design, it has received only limited attention in research, even though cities are independently exploring how superblocks could be implemented^{19,20} and the European investment bank is financing urban regeneration with superblocks²¹. A systematic quantification of the potential for superblock design across different cities is currently lacking. The potential for implementing superblocks given the street network topology for different urban morphologies is equally unclear. The principal aim in this article is to address this knowledge gap and to provide a first exploration of the potential of the superblock concept with the help of automated geospatial analysis for different cities while considering impacts on urban mobility. Considering mobility is essential as banning traffic from one area in a city will typically affect the remaining parts of a street network, and the implementation of superblocks is challenging in cases involving considerable disruption to traffic. In this work, a data-driven geospatial methodology for automatic detection of superblock potentials is developed and applied for a range of cities with various shapes and sizes. In addition, the suitability of superblock potentials concerning traffic flow exposure is assessed with the help of a network flow algorithm. Because urban morphology varies substantially across cities, the superblock concept first needs to be conceptually transferred to different urban morphologies.

Barcelona superblock design in different cities

Barcelona was extended in the nineteenth century following an urban development plan based on chamfered square urban blocks with a side length of around 113 m (ref. ²²). Some Barcelona districts (for example, Eixample) are characterized by a grid-like street network and therefore represent a perfect model for superblocks. Other parts of Barcelona have an irregular typology with urban blocks not following a grid plan. Urban blocks act as the fundamental spatial organization of a city and can be described as the land area defined by the street network, whereby urban blocks vary in size and shape

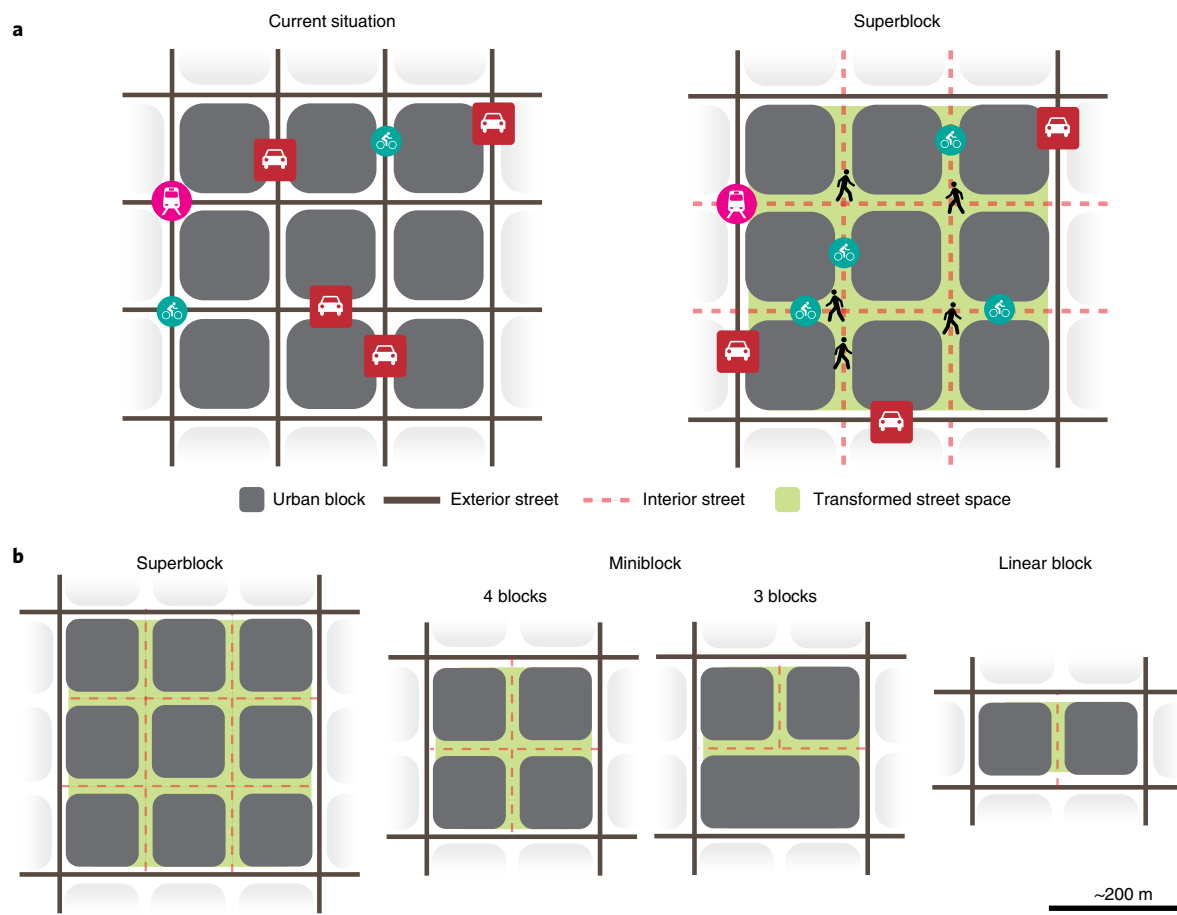


Fig. 1 | Schematic of superblock design. **a**, Barcelona superblock adopted from the urban mobility plan of Barcelona. Superblock design is characterized by exterior streets surrounding urban blocks and the transformation of interior street space. **b**, The superblock design is further developed into similar urban configurations such as miniblocks or linear blocks.

across the world^{17,22–24}. Exploring the Barcelona superblock strategy in different cities is promising as many cities are facing similar challenges. Although the urban morphology varies between cities^{25–27}, an often common element is the presence of dense urban structure surrounded by higher-order, exterior streets, such as the sikkak system in Arab countries²⁸ or the hutongs in China²⁹. The spatial dimension of the area surrounded by the superblock can differ, and typologies have been proposed to characterize internal street layouts³⁰. However, there is no common use of the superblock terminology. In the case of the much larger and functionally different Chinese superblock, for example, removing gates and opening the interior streets is proposed (in contrast to the Barcelona model)³¹. In this work, the term ‘superblock’ is used as intended for the Barcelona case, and careful replication and contextualization is necessary.

Cities may not always form large urban blocks or may show heterogeneous urban layouts. To address this, different superblock design elements are delineated from the Barcelona superblock concept with which analogous street transformation strategies can be envisioned, most importantly, the mini-superblock (miniblock) (Fig. 1b). Miniblocks follow the same logic as superblocks; that is, they include exterior and interior streets but are made up of 2×2 or 1×2 urban blocks and form a lighter and geometrically smaller version of a superblock. A superblock consists of four overlapping miniblocks. An even greater reduction to a linear block could be conceived, where only a single street is bordered by two blocks. Adaptations of the Barcelona superblock may, however, not provide

the same functionality. Ecosystem services of implemented alternative street-use measures may not perform equally well for a range of different criteria³². Whereas, for example, one intention of the superblock is to create multifunctional and independent neighbourhoods or foster walkability, this may be possible only to a lesser degree with miniblocks. It may be more difficult to have key destinations for daily living within the boundary of the miniblock to establish independent communities, or the public street space available for exercising, daily interchange, leisure and so on may be smaller^{12,28}. However, including the miniblock enables broadening the analysis as, otherwise, potentially only very few sites with urban layouts identical to Barcelona are identified.

Geospatial modelling and network analysis

For each street, the suitability for superblock design is assessed on the basis of urban characteristics and the street network topology. The developed geospatial and network analysis for the identification of superblocks and miniblocks relies on a graph-based representation of the street network, which is downloaded and processed from OpenStreetMap, a commonly used volunteered geographic information data source³³.

Structural diversity and density are two key urban characteristics for evaluating the suitability of superblocks³⁴. Streets with low population density values are excluded from the analysis (Table 1) as superblocks are typically proposed for high-density neighbourhoods. High-density areas are most exposed to negative effects

Table 1 | Criteria used for identifying superblocks and miniblocks

Criteria	Superblock		Miniblock	
	G_0	G_1	G_0	G_1
Interior street loop length				
Minimum (m)	427	213	n/a	n/a
Maximum (m)	640	1,280	n/a	n/a
Exterior street length				
Minimum (m)	1,280	640	853	427
Maximum (m)	1,920	3,840	1,280	2,560
Total number of interior street nodes				
Minimum number of nodes with degree ≥ 4	3	3	0	0
Minimum number of nodes with degree ≥ 3	1	1	1	1
Minimum length of interior streets (m)				
Minimum length of interior streets (m)	n/a	n/a	427	213
Maximum length of interior streets (m)				
Maximum length of interior streets (m)	n/a	n/a	640	1,280
Minimum building footprint coverage (%)				
Minimum building footprint coverage (%)	30	30	30	30
Minimum population density (inhabitants ha ⁻¹)				
Minimum population density (inhabitants ha ⁻¹)	100	100	100	100

The formulae for calculating the values are provided in Methods. G_0 represents a scenario with a geometric dimension of a superblock with an overall length of 400 m, where a 20% uncertainty range is assumed to obtain the minimum and maximum values. The degree of a node indicates the number of neighbouring edges of a node on a graph. Building footprint coverage, street nodes and population density values are kept constant.

resulting from urban concentration, and therefore alternative street use is potentially most pressing³⁵. Another rationale for focusing on high-density areas is that a high urban concentration means that alternatives to car-based mobility are potentially more feasible. Information related to structural diversity is difficult to obtain as data such as working spaces are typically not freely available. To include non-residential areas in the analysis, the building footprint coverage is used to approximate overall imperviousness. If the footprint building coverage is below a threshold (Table 1), a street is considered unsuitable. This approach thereby follows the same hypothesis as in other studies¹⁹: in case of currently high availability of sealed land and little urban green, the transformation of a street is more beneficial and of higher priority^{19,36}.

A range of network indicators have been proposed to describe urban form and street network layouts^{27,37}, which are used for identifying superblocks and miniblocks. The local edge connectivity measure and the node degree are found to be highly useful for analysing street network segments. The local edge connectivity measure describes the minimum number of edges that must be removed to disconnect a considered edge from a network. Edges with a local connectivity value of one are considered unsuitable and removed as these are typically cul-de-sac or network elements, which do not follow the logic of superblocks. The degree of a node (the number of edges that are incident to a node) is used to locate street network nodes that could form part of superblocks or miniblocks. Furthermore, the lengths of the exterior (circumferencing) and interior streets are used for geometric characterization. A superblock typically contains a network cycle of four nodes with a degree value larger than or equal to three. Miniblocks are identified with network nodes with a degree larger than or equal to three, where the encompassing exterior streets need to fulfil length criteria.

For detecting exterior streets, a shortest-path algorithm is applied to determine the shortest route that connects all neighbours of the superblock nodes. Table 1 summarizes all applied criteria for the identification of superblocks and miniblocks.

For analysing the street network typology and locating potential superblocks, spatial geometry scenarios (G_j) are considered (Methods). Key geometric indicators of the Barcelona superblock (termed v_0) are varied with a geometric deviation factor f . A scenario G_j includes indicator values v in the range $\left(\frac{v_0}{1+f}, v_0 \times (1+f)\right)$. The

Barcelona superblock is considered to have an overall dimension of $400 \times 400 \text{ m}^2$ (G_0), whereby an additional uncertainty of $\pm 20\%$ of the dimension is assumed to consider slightly different spatial dimensions. Resulting properties for a deviation where the minimum block width is half and the maximum block width twice the size of the Barcelona block (G_1) are provided in Table 1, which are further used for the presented analysis. Urban configurations up to this value are here still considered as comparable in terms of urban characteristics such as walkability, urban streetscape or the reachability for urban mobility. The scenario parameter G_j allows easy adaptation to the search to fit a desired geometry. The sensitivity of G_j is shown in Fig. 2, which reveals that the simulated total street length of superblocks or miniblocks increases for higher values. Such an increase in streets fulfilling the respective geometric criteria is to be expected with increasing deviation. The detected street percentages, however, level off from a value of G_1 onwards. The selected value of G_1 used here includes a considerable geometric deviation from the Barcelona superblock. Therefore, the obtained simulation results reflect a generous estimate.

Superblock and miniblock potential

The developed methodology is applied for a selection of smaller and larger cities (Methods). Figure 3 shows the processed street network and modelled street classification. The classified streets may provide multiple options for superblock implementation, particularly if the street network is grid-like and various options exist for placing the superblock. For the miniblock classification, urban configurations consisting of three or four blocks are combined (Fig. 1). All simulated potential superblock and miniblock options and street classifications are available for download. Figure 4 summarizes the statistics of the street network classification. The pedestrian street class includes living and pedestrian streets as defined by OpenStreetMap and provides an estimation of already transformed streets to be car-free or where low-speed limits apply. These streets are not further analysed as, in these locations, either urban transformation strategies (including superblocks) have already been applied or they require alternative strategies (for example, historic town centres with a distinct urban form). When comparing the absolute lengths of the street types across the case studies (Fig. 4a), several points need to be noted. First, the choice of the $5 \times 5 \text{ km}^2$ case-study area extent, which was centred on the city centre, determines which streets are considered and affects the street distribution. Second, the local geography affects the overall length as, for example, large water bodies reduce the urban area and thus street length. Third, OpenStreetMap is user generated, which means that the classification or completeness needs to be considered and may differ³⁸.

The relative classification results across the selected cities are compared in Fig. 4b. The large streets typically comprise around 20–30%. The share of pedestrian streets is typically only a few percent, except for some cities such as Barcelona. The street network that could potentially be considered for implementing superblocks ranges from a few percent (for example, Atlanta) to over 40% (for example, Mexico City). The potential for miniblocks generally follows the same pattern, and unless the city has a highly grid-like structure, miniblock potentials are detected more frequently. For some cities (for example, London), the potential for transforming

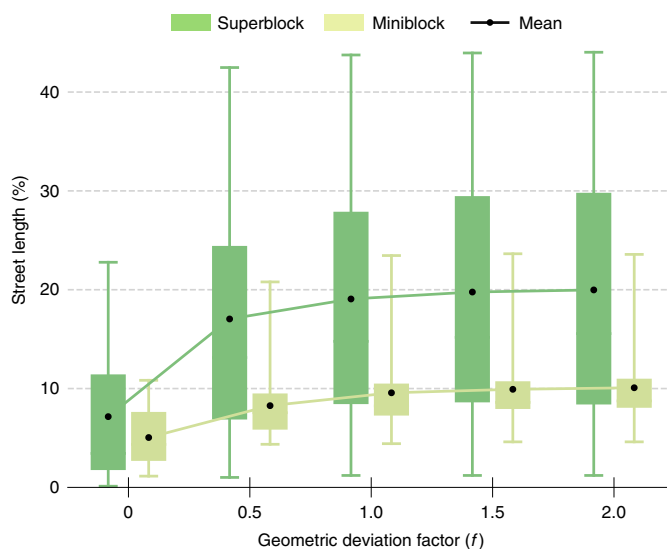


Fig. 2 | The relative street network length classified as superblocks or miniblocks is modelled for different f values for each case-study city. The f value indicates the geometric deviation from the Barcelona superblock. Whereas the analysis is sensitive to the parameter f , the classification levels off at G_1 . Box plots depict the full value range across all cities, and the mean classification results are plotted as lines.

larger neighbourhoods as intended with superblocks is smaller: the street network fulfils the topological criteria fewer times, and superblocks would oftentimes be too large or be intersected by primary, secondary or trunk streets. However, despite having a lower superblock potential, there is nonetheless potential for miniblock transformation with a combined potential of superblock and miniblock of ~12.7% of total street network length. The identified potential for superblocks in Figs. 3 and 4 consequently is highest in cities having similar layouts to Barcelona, such as Madrid or Mexico City. However, even though some cities have a grid-like city structure (for example, Atlanta), the simulated density (either population density or building coverage) is not sufficiently high for superblocks or miniblocks. The same holds for other cities such as Warsaw, where many buildings are surrounded by large green open spaces.

Identified superblock and miniblock implementation opportunities serve as an upper limit estimation, as in the case of actually turning interior streets into multifunctional use, other streets would need to serve as exterior streets. These streets would need to be removed as suitable candidates, thus reducing the potential following implementation, particularly for grid-like city layouts. As there are multiple options of implementing superblocks or miniblocks, all simulated options are here provided without proposing a concrete design.

Disruption simulation of urban mobility

To link superblock design to car-based urban mobility, the importance of each street concerning traffic flow is assessed. Detailed traffic flow simulation modelling approaches could be used for this analysis, which is, however, challenging to set up for a large number of cities. Alternatively, manifold studies have investigated the resilience or importance of a single network element for different network types, including the street network³⁹. Typically, the street hierarchy provides a first and important indication of its importance. Ref. ²⁷, for example, described the criteria continuity, connectivity and depth to build a street hierarchy. Although street hierarchy typically is higher for larger streets, street size is not the only indicator of its importance: large streets may be less critical

in the case where traffic could easily be rerouted. The availability of redundancy and alternative routes are thereby essential when evaluating the disruption due to the removal or reconfiguration of an individual street. Therefore, the importance of a street needs to be assessed with help of the street network with network indicators to differentiate street hierarchy or the criticality of a single street network element^{40,41}. For this study, available user-generated information on the street hierarchy is used for excluding large streets, which are not considered suitable for superblocks or miniblocks due to their critical importance for traffic. In addition, the importance of each street is assessed with the help of a network flow algorithm, the Edmonds–Karp algorithm, which is a flow-based algorithm and a special implementation of the Ford–Fulkerson algorithm. The algorithm has been applied in different research fields and for various network types, including traffic flow simulation^{42,43}, and is commonly used for analysing the resilience of networked infrastructure. The algorithm requires information on the flow capacity for each network edge, that is, information on the maximum amount of flow that can pass through each edge. Different models have been proposed to estimate street flow capacities for changing conditions. These models typically aim to identify critical quantities where traffic flow changes and traffic jams occur. Traffic flow depends on the street type, network layout, topography, user behaviour, weather and so on⁴⁴. For this study, the flow capacity for each street is set with help of the street classification and the number of lanes provided by OpenStreetMap, thus only considering relative flows. The number of lanes serves as a proxy for network capacity; that is, the simplifying assumption is made that capacity is directly linked to the number of lanes. As lane information is not consistently available in OpenStreetMap, missing lane numbers are estimated with the street hierarchy. For all interior streets classified as potential superblock or miniblock locations, the street network disruption indicator (NDI) is calculated (Methods).

Figure 5 shows the absolute and relative street lengths of all superblocks and miniblocks, categorized into a low, medium or high NDI class. The presented categorization enables the evaluation of the modelled potentials in Fig. 4 and can serve to identify the least-disruptive sites. When comparing the absolute street lengths, the same considerations need to be made as mentioned previously; that is, the relative street categorization allows better comparison between the case studies. The prevailing street network typology of cities strongly affects how disruptive superblock interventions are, which is revealed by the considerable variation in calculated NDI values: the streets falling into the lowest NDI class, which is considered to have the least disruption effect, ranges between ~39% and ~74%. For Paris, Barcelona and Budapest, higher percentages of the identified superblock and miniblock sites have higher NDI values. For cities that already have a higher share of pedestrian streets, the availability of streets with low NDI values tends to be lower. The analysis reveals that across cities with a high share of streets having low NDI values such as London, Cairo and Bangkok, there is high potential to transform neighbourhoods with only limited impact on traffic flow. Other cities such as Paris and Berlin have less-favourable network topologies, where the superblock implementation is comparatively more disruptive. Identified superblock or miniblock potentials in cities with more grid-like urban layouts are not necessarily less disruptive, even if currently only very few pedestrian zones exist. For Mexico City, for example, a high superblock potential was modelled, of which, however, sites are oftentimes considered as having a considerable street network disruption effect.

In the case of implementing superblock design, the network flow changes and traffic would need to be rerouted. Such a dynamic interplay was not considered here. Calculated NDI values, therefore, provide only a first estimate on the current exposure of superblock

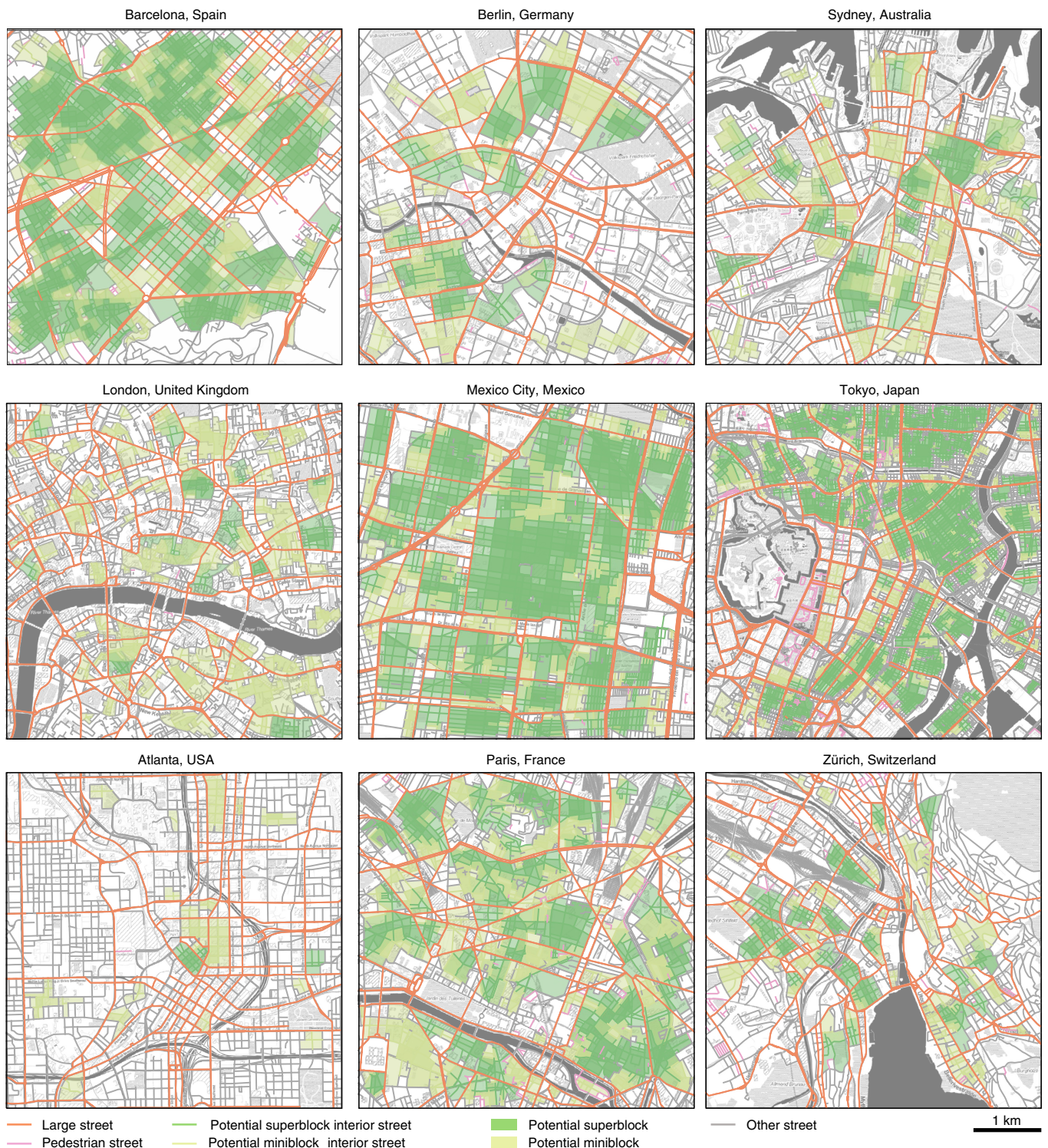


Fig. 3 | Modelled classification of the street network for selected cities. Potential superblock or miniblock locations are coloured in green. The suitability for superblock design is evaluated on the basis of density criteria, street network geometry and street network topology. The deviation of the modelled superblocks and miniblocks is minimum half and maximum twice the size of the Barcelona superblock width (G_s , Table 1). Different shadings in green result from overlapping blocks. Map data © OpenStreetMap contributors.

or miniblock sites to urban mobility, thereby assuming that transforming streets with high traffic flow is potentially most disruptive. Detailed studies would need to accompany concrete implementation plans, including detailed traffic simulations that consider unique properties of streets and local constraints.

Discussion

This investigation provides a first estimate of superblock and miniblock potentials across different cities and how disruptive identified potential sites are concerning traffic flow. Superblock design crucially frees up urban space from car-based mobility by assigning

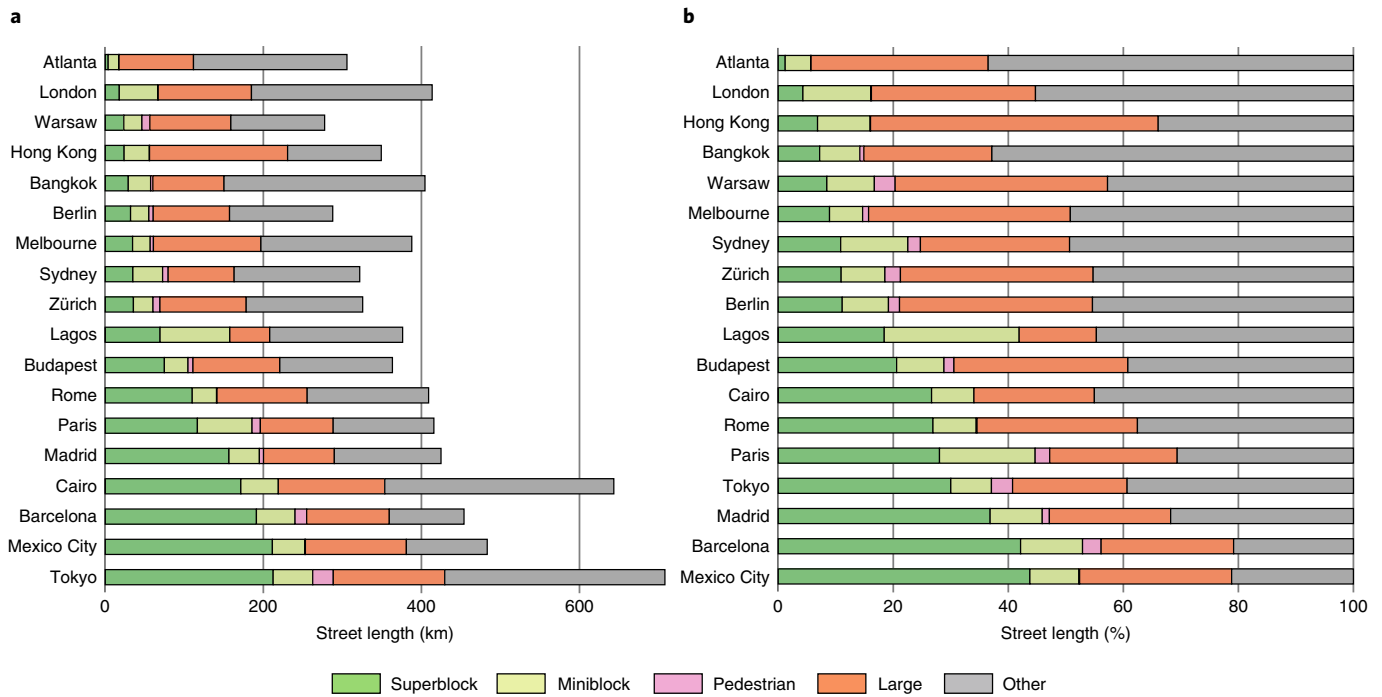


Fig. 4 | Comparison of the modelled absolute and relative street types for the case-study cities. a, Absolute street types. **b**, Relative street types. The calculations are for a 25 km² extent for each city. Calculated superblock and miniblock potentials represent upper limits.

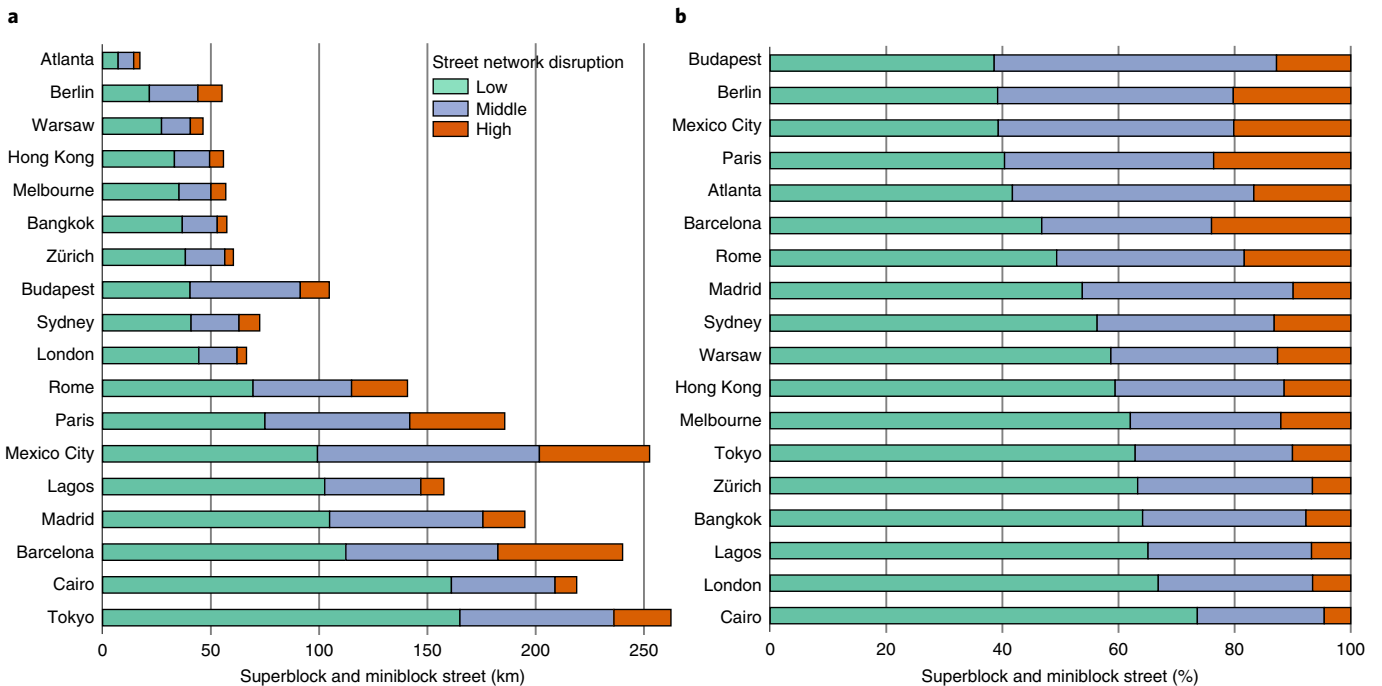


Fig. 5 | Absolute and relative lengths of all street networks modelled as either superblocks or miniblocks. a, Absolute lengths. **b**, Relative lengths. The streets are categorized on the basis of the calculated network disruption indicator (Methods) into a low ($\leq 5\%$), a middle ($>5\text{--}\leq 15\%$) or a high ($>15\%$) network disruption category.

novel uses to street spaces such as urban greening or pedestrian zones. This analysis offers insights on opportunities for cities to tackle several of the challenges they are increasingly faced with such as climate change, noise and air pollution, urbanization and limited availability of urban green space⁴⁵. The introduced geospatial

data-driven methodology for the automatic detection of superblock design opportunities can be easily applied to different cities or geographical extents and the methodological assumptions changed to adapt the analysis. The approach could similarly be extended for other urban design strategies that, for example, focus on transforming

cul-de-sac streets. The share of the existing street network simulated to be suitable for implementing superblock design was found to range for some cities from a few percent of the street network (for example, Atlanta, London and Hong Kong) to a considerable share above a third of the street network for other cities (for example, Mexico City, Madrid and Tokyo). Even if only few superblocks were identified, the transformation potential of streets is still notable when also considering miniblocks. Miniblocks are found where the urban layout complicates the implementation of a superblock but still offers opportunities for street transformation at smaller scales. Notably, a grid-like urban street layout does not automatically mean high implementation potential for superblocks due, for example, a lack of dense and compact urban form. The validation of the modelled superblock opportunities is challenging as local knowledge is required, and the concrete implementation and street conversion potentials are highly disputed. The implementation depends not only on the personal vision for cities but also on the political will for urban transformation or on how future urban mobility will evolve, particularly related to autonomous vehicles, which are anticipated to result in a considerable change to urban form^{46,47}.

Substantial differences were found not only in the quantitative simulation of superblock design potentials but also concerning traffic flow disruption. The identified superblock and miniblock locations can be prioritized with the help of the calculated network disruption indicator. Urban transformation could be more challenging concerning traffic disruption for cities that have already considerably transformed streets and that have a high number of pedestrian streets. Implementing miniblocks may be a less-disruptive strategy to start or further expand urban transformation. Because superblocks essentially consist of multiple miniblocks, miniblocks are an opportunity to initiate city transformations on which superblocks could build¹⁷.

The presented simulation results serve as a starting point for urban neighbourhood transformation by superblocks or miniblocks and provide crucial inputs to city planners, particularly for locating and prioritizing the most promising sites for alternative street use. This information is particularly relevant for the ongoing discourse surrounding densification⁴⁸, urban rewilding⁴⁶ and the transformation of parking spaces⁴⁹. When implementing superblock design, improving alternative transportation modes is vital to enable inter-metropolitan commuting, and changes to the urban street network may require amendments to the existing public transport system¹⁵. Superblock design, however, goes beyond traffic calming measures and aims towards an integrated urban transformation strategy to improve urban sustainability at the city scale. Implementing superblocks must therefore not be done in isolation¹². The identified sites need to be further assessed and evaluated concerning opportunities to improve the connectivity of green infrastructure across a city with green axes, reduce pollution, integrate superblocks into public transport, foster walkability or achieve optimal urban heat mitigation. To this end, further integrated modelling efforts are required³⁶. It is also necessary to account for a wider range of considerations, including social change related to gentrification¹⁴. Follow-up studies to the presented generic and data-driven approach for individual case-study cities should integrate further local constraints in more detail.

The analysis reveals considerable potential for transforming urban streets with superblocks or miniblocks in high-density areas to improve urban liveability and reduce environmental stresses. The simulation results can serve as a basis for further exploration of sustainability impacts of different superblock scenarios at city scale in various cities. It needs to be noted, however, that superblock design represents only one urban design strategy among different strategies to achieve more sustainable cities and neighbourhoods.

Methods

Case-study selection. The case studies are chosen to include different cities around the globe that are commonly used for urban studies⁵⁰. From the 18 selected case-study cities, 12 cities are part of the C40 cities initiative, which aims to lead the way in urban sustainability. The selection ranges from large cities strongly following a grid street plan (for example, Mexico City and Tokyo) to smaller cities that are not dominated by a grid-like urban layout (for example, Zürich). This selection is not exhaustive, and comparatively more European cities are analysed. Barcelona is considered to test the methodology for the city where the superblock concept originates. The presented analysis can, however, be applied to further cities and is merely constrained by data availability.

Street network data processing. The case-study extent for each city is 25 km², for which the street network is downloaded with the help of Overpass API⁵¹ and represented as graphs with edges and nodes. For the graph-based algorithms and geometric processing steps, the python packages networkX⁵² and shapely⁵³ are used. The downloaded raw data are processed in several steps to obtain more accurate street length estimations. First, network nodes that are within a 15 m distance of each other are clustered to obtain a simplified network. This street network abstraction particularly reduces the complexity of street intersections. Second, closed detached rings (loops) and isolated subgraphs are removed from the street network as well as long (>300 m) tunnels and streets intersecting buildings. Further network cleaning is conceivable, depending on the case-study context, such as removing elevated streets. Third, very small network edges not forming part of longer streets are removed as they typically represent driveways (Supplementary Information section 2). The street network was not re-designed by extension. For example, the street network connectivity was not increased by adding new streets, which could potentially help to design more superblocks or miniblocks.

Before searching for potential superblocks or miniblocks on the street network, the street network nodes are classified into higher- and lower-level nodes. Whenever a node forms part of an intersection (degree ≥ 3), the node is classified as a higher-level node. A lower-level node forms part of a street (edge) between two higher-level nodes. Typically, the street between two higher-level nodes consists of multiple lower-level nodes and edges as the streets are typically not perfectly straight. The lower-level nodes are considered for calculating distances on the street network and creating the blocks. However, when checking for the network topology criteria to identify superblocks and miniblocks, only the higher-level street network is considered. This differentiation is necessary as otherwise, superblocks and miniblocks often would not be identified on the street network due to the lower-level nodes (Supplementary Information section 1).

Street hierarchy. The complexities surrounding superblock implementation are higher for streets that are essential to urban mobility. Contributors to OpenStreetMap can classify streets and assign different attribute labels to define a street network hierarchy. On the basis of the provided street hierarchy, the assumption is made that streets labelled as primary, secondary and trunk streets are not suitable for superblock design. Similarly, streets that form part of a trolleybus or tram route are excluded as potential superblock locations. For this analysis, all footways and private streets are ignored. Streets categorized as pedestrian or living streets are considered to be already not centred on car-based mobility and are ignored as the focus here is on transforming streets that are currently focused around car-based mobility.

Calculation of population density and building coverage. To go beyond relying on street network characteristics for detecting superblock design, density values are calculated for the entire street network. For each network node, average density values are calculated considering a radius of 100 m and then averaged per edge by averaging the density values from the starting and end nodes. Alternatively, the population density could be calculated by buffering the street network edges. The population density calculation is based on population data provided by the Center for International Earth Science Information Network and Meta⁵⁴, which are population estimates based on satellite data and census data at a ~30 m resolution. With the help of OpenStreetMap building footprints, the building footprint coverage is calculated first for every node on the street network considering the same radius of 100 m. Second, the average building coverage per edge is calculated by averaging the value from the start and end node of each edge.

Detecting superblocks and miniblocks on the street network. The street network forms the basis for locating potential superblock and miniblock candidates. Before searching potential candidates, the street network is characterized by street type, population density and building coverage as outlined in the previous two paragraphs for narrowing down the search. Then, the street network is first cleaned for cul-de-sac street elements, and the degree of all street network nodes is calculated. Second, all nodes with degree ≥ 3 are filtered as they could potentially be part of interior street intersections of superblocks or miniblocks. From this reduced filtered street network, all network cycles are identified as they could potentially be an interior street loop of a superblock. Isolated nodes with degree ≥ 3 not forming part of a network cycle or interior street loop of a superblock are

further evaluated as a potential miniblock. Third, to find the exterior streets, all neighbouring nodes of the considered node(s) are identified, and a shortest-path algorithm is applied on the network where the considered nodes are removed to connect all the neighbouring nodes. If no path is found, the street network typology prevents the design of a miniblock or superblock. For miniblocks, all neighbours of the single node (single interior street intersection) are selected. Similarly, for superblocks, all neighbouring nodes not forming part of the interior street loop are connected along the shortest-path route to form the superblock polygon. If no path is found, or the path crosses a bridge, the node is not further considered. Finally, the geometric properties of the identified potential superblocks or miniblocks are checked to determine whether all the boundary conditions are fulfilled. In case a potential superblock does not fulfil the boundary conditions, the conditions for fulfilling a miniblock are tested. Table 1 lists all conditions, and the geometric scenario calculation is outlined in the next section.

Geometric scenario calculation. The geometry of the superblock is calculated on the basis of the assumed 400 m length of the Barcelona superblock (l_{BCN}) consisting of three individual blocks (block side length $l_{block} = \frac{l_{BCN}}{3}$). When identifying superblocks (S) or miniblocks (M), the following boundary conditions for the exterior street length (l_{ext}), interior street length (l_{int}) and length of the interior street loop or ring (r) (for superblocks only) need to be fulfilled:

$$j_{ext,max}^M = (8 \times l_{block} \times z \times (1 + f)) \quad (1)$$

$$j_{ext,min}^M = \left(\frac{8 \times l_{block} \times z}{1 + f} \right) \quad (2)$$

$$j_{int,max}^M = (4 \times l_{block} \times z \times (1 + f)) \quad (3)$$

$$j_{int,min}^M = \left(\frac{3 \times l_{block} \times z}{1 + f} \right) \quad (4)$$

$$j_{ext,max}^S = (12 \times l_{block} \times z \times (1 + f)) \quad (5)$$

$$j_{ext,min}^S = \left(\frac{12 \times l_{block} \times z}{1 + f} \right) \quad (6)$$

$$r_{int,max}^S = (4 \times l_{block} \times z \times (1 + f)) \quad (7)$$

$$r_{int,min}^S = \left(\frac{4 \times l_{block} \times z}{1 + f} \right) \quad (8)$$

where f denotes the deviation factor and z incorporates an uncertainty of $\pm 20\%$ of the Barcelona superblock and takes a value of 0.8 (min) or 1.2 (max). Example values for G_0 and G_1 are provided in Table 1.

Street NDI. The Edmonds–Karp algorithm is applied to assess the importance of each network edge concerning traffic flow across the street network. This approach is inspired by ref. ⁵⁵, where artificial ‘super’ sinks/sources are introduced. Super sinks/sources enable extending a network by adding a single node that feeds all the sources or drains all the sinks⁵⁶. The following steps are performed to assess the street network edge criticality. In a first step, four supernodes are projected in each direction to the network and placed outside the street network extent. Then, 100 helper nodes are equally distributed along a straight axis on each side of the network extent. An auxiliary linking edge is established between each helper node and the supernode. An additional linking edge is next added between each helper node and the closest node on the street network. A visualization and a more detailed explanation of this step are provided in the Supplementary Information section 3. In a second step, the Edmonds–Karp algorithm is run consecutively for each direction between opposing super sinks and super sources. The resulting flows of each simulation run are summed and averaged for each edge (i) to obtain the average flow (f_i^{avg}) per edge. The average edge flow is then normalized (f_i^{norm}) with the calculated maximum average flow value of the network:

$$f_i^{norm} = \frac{f_i^{avg}}{\max_j(f_j^{avg})} \quad (9)$$

To consider local as well as regional network impacts, these outlined steps are performed on a raster with a resolution of 2.5 km as well as for the entire case-study area. The calculations on the raster provide local flows (f_i^{norm}) as outlined in the preceding. As the overall analysed city extent is 25 km², local flows are calculated across four regional cells across the city. In addition to these local flows, the same calculation is performed once for the entire case-study area using the 5 × 5 km² as the input for the flow calculations in equation (9). This calculation using the entire

street network reflects flows at a higher geographical level and is termed F_i^{norm} . In a third step, the two calculations are equally weighted and combined into a single indicator (NDI) to calculate the relative importance of each edge concerning traffic flow:

$$NDI_i = \frac{f_i^{norm} + F_i^{norm}}{2} \quad (10)$$

Edges with high NDI are edges that are critical to the street network; edges with low NDI have a low disruption potential as they do not form part of a critical network element and alternative paths exist for rerouting traffic. Calculating the NDI provides an approximate indication of the street disruption of a network towards urban mobility. The NDI is further used to derive classes indicating the street network disruption (low, middle, high). As identical geographical extents have been selected across our case studies, the obtained NDI values are comparable.

Data availability

The classified streets, including calculated NDI values and all simulated superblocks and miniblocks for the geometric scenario G_1 , are available for download as shapefiles or GeoJSON files: <https://doi.org/10.5281/zenodo.4562462>.

Code availability

The workflows and code used are available from the corresponding author upon reasonable request.

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Author contributions

The author confirms sole responsibility for the entire study.

Competing interests

The author declares no competing interests.

Additional information

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