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Designing an E-Bike City: An automated process for network-wide multimodal road space reallocation

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ABSTRACT

Effective and timely decarbonization of urban mobility requires systemic changes to transportation systems. High-quality cycling networks are seen as one of such measures and multiple scholars have developed automated approaches for a quick generation of such interventions. However, a common shortcoming is that they mostly ignore the tradeoffs and dependencies in allocating scarce road space to different modes. In this paper, we introduce an automated process for generating alternative multimodal transport networks within the boundaries of existing road space. Based on the user's configuration, the resulting networks can prioritize separated cycling infrastructure, dedicated lanes for public transport, or a dense provision of on-street parking spaces. Also, the prioritization and the resulting designs can follow a variety of design principles, such as one-way streets, or impermeable superblocks. The outputs can be visualized on a map and used in common transport simulation toolkits. A case study in Zurich is used to demonstrate the process on a real-world network and discuss the results. The underlying software package SNMan (Street Network Manipulator) is available as open-source software and can be utilized by researchers and planners to envision alternative urban mobility futures in any place in the world.

1. Introduction

Car-centric transportation systems have played an essential role in generating economic benefits through accessibility gains (Axhausen et al., 2011). However, the need to rapidly decarbonize the transport sector (IPCC, 2022) challenges this paradigm. Purely technical solutions such as electric vehicles will likely not be able to reduce carbon emissions quickly and strongly enough (de Blas et al., 2020; Gebler et al., 2020; Cox et al., 2018). Most likely, a combination of technical and systemic innovations, involving the geography of transportation will be needed (Raubal, 2020).

In earlier work (Ballo et al., 2023), we proposed the 'E-Bike City', envisioning an urban transport system based mainly on public transport and small vehicles such as bicycles and e-bikes. Discussing such urban mobility future further requires tangible designs and impact assessments. To create such designs in a reproducible way, we need a robust algorithm for generating city-wide cycling-oriented network designs, while respecting the limited road space, as well as the dependencies within networks of lanes for motorized traffic and public transport. However, the vast majority of existing methods for designing cycling networks in cities (Paulsen and Rich, 2023; Mahfouz et al., 2023; Szell et al., 2022; Steinacker et al., 2022; Liu et al., 2022; Castiglione et al., 2022; Akhand et al., 2021; Zhu and Zhu, 2020; Natera Orozco et al., 2020; Caggiani et al., 2019; Guerreiro et al., 2018; Mauttone et al., 2017; Duthie and Unnikrishnan, 2014) does not account for the trade-offs in road space allocation. To our knowledge, only two approaches consider the limited road space but either do not provide scalability beyond small network examples (Mesbah et al., 2012), or are not yet able to consider the real-world interdependencies within multimodal transport systems (Wiedemann et al., 2024), such as public transport routes, access to buildings, and parking needs. In this paper, we address this gap by introducing an automated process for generating network-wide road space reallocation schemes in real cities, while considering the limited road space, as well as dependencies within the transport networks. The

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resulting designs can be visualized, evaluated with a set of metrics, or used as an input for traffic simulation toolkits. We use a case study in Zurich, Switzerland for demonstration. The process is implemented in a Python software package and made available open source, together with all data needed for reproducing the case study.

Section 2 summarizes previous work, Section 3 explains the conceptual design approach guiding the process, Section 4 shows the underlying methods, and Section 5 shows results from the case study in Zurich. Section 6 discusses the findings and the limitations, and Section 7 concludes the paper.

2. Previous work

2.1. Cycling network design

Studies that introduce cycling network design algorithms can be divided into five groups. The first entails the generation of networks in real-world scenarios, using greedy algorithms. Szell et al. (2022) ’grow’ cycling networks by connecting a set of arbitrary points of interest using greedy triangulation, defining the order of implementation, and routing the connections onto the existing street network. Steinacker et al. (2022) generate bike lane networks that optimally facilitate trips in a bike-sharing system. They use an inverse network formation, where, initially, all edges have bike lanes and are subsequently removed, while prioritizing those whose removal has the smallest adverse effects on the cycling trips. Natera Orozco et al. (2020) generate additions to existing cycling networks to improve their connectivity by adding short missing pieces.

The second group focuses on prioritization within a set of possible cycling infrastructure projects. Paulsen and Rich (2023) use a novel technique of mapping the potential benefits predicted for individual origin-destination pairs onto the network and identifying the contributions of individual additions. Then, they prioritize them to maximize the net present value, while considering the future benefits and construction costs. Mahfouz et al. (2023) present another integrated approach for prioritizing cycling facilities, that involves cycling demand prediction, route calculation, and network analysis.

The third group (Liu et al., 2022; Zhu and Zhu, 2020; Caggiani et al., 2019; Guerreiro et al., 2018; Mauttone et al., 2017; Duthie and Unnikrishnan, 2014) uses optimization techniques to find networks of cycling facilities that maximize the benefits for cyclists (e.g., maximizing cycling infrastructure length) while minimizing the construction cost.

The fourth group deals with less conventional approaches: DBSCAN clustering of GPS points from micromobility vehicles to identify potential corridors (Castiglione et al., 2022), and using Physarium-inspired growth mechanisms (Akhand et al., 2021).

And lastly, the fifth group addresses the trade-offs within limited road space. Wiedemann et al. (2024) allocate parts of the road space either to cycling lanes or general travel lanes and generate a Pareto frontier of travel times for cyclists (adjusted by comfort factors) and travel times for drivers (affected by detours after removing travel lanes). Mesbah et al. (2012) utilize a bi-level optimization, consisting of a genetic algorithm and a traffic assignment that produces an estimate of the resulting travel times for both cyclists and drivers. Along similar lines, Burke and Scott (2016) propose a framework to incorporate the disruption of motorized traffic by removing travel lanes. They use a Network Robustness Index (Scott et al., 2006) to measure how critical a link is to overall traffic flow. It is calculated by performing a traffic assignment and calculating the resulting travel time changes for all trips. However, the traffic assignment in both, Mesbah et al. (2012) and Burke and Scott (2016) involves a relatively high computational cost, thus substantially limiting the feasible network size and the number of design iterations.

2.2. Network capacity

Loder et al. (2019) have analyzed the amount of motorized traffic that can be handled by urban networks. They have estimated a regression model that explains the form of the Macroscopic Fundamental Diagram (MFD), which shows the maximum trip production in vehicle-km per hour. It uses four network measures as inputs: road network density, betweenness centrality, intersection density, and bus production density. The maximum trip production of motorized traffic is increased by higher road network density, lower average betweenness centrality, lower intersection density, and lower bus production density. While this model does not include any consideration of cycling, it allows a quick approximation of how different network variations affect the motorized traffic, without the complexity of carrying out a traffic assignment.

2.3. Economic analysis

Transport investments and policy decisions are commonly assessed using a cost-benefit analysis (CBA). Comprehensive CBA studies related to cycling infrastructure (Rich et al., 2021; Li and Faghri, 2014; Sælensminde, 2004) typically consider the construction and maintenance cost, personal travel cost savings, travel time savings, health care cost reduction, crash cost and the benefits of reduced emissions. Sælensminde (2004) additionally considers the cost reductions for transporting school children, as well as the reduction of parking costs. Other CBA studies (Chapman et al., 2018; Wang et al., 2005; Brey et al., 2017) consider parts of these aspects. Zani et al. (2023) conducted a CBA for different cycling interventions in complex urban environments in Zurich. They focus on the challenge of properly quantifying the costs and safety benefits of each intervention. Rich et al. (2021) conclude that higher usage of e-bikes leads to worse (yet still favorable) cost-benefit outcomes due to lower health benefits and higher crash costs, which are not fully compensated by higher travel time savings.

2.4. Representing cycling comfort

The user benefits of cycling infrastructure in comparison to mixed traffic can be quantified using route choice models. Meister et al. (2023) have estimated a recursive logit model from 4’432 cycling trajectories in Zurich. Expressing the resulting parameters in a Value of Distance (VoD) space shows the users’ perception of individual route attributes in units of distance. The authors report median VoD indicators of −0.36 for bike paths and −0.66 and bike lanes: Compared to mixed traffic, using cycling infrastructure is perceived equivalently to reducing the distance by 36 and 66 % respectively. The authors argue that the higher valuation of bike lanes over bike paths is likely a result of forced choices in Zurich’s network. In this paper, we use the mean of the above two values for all types of cycling infrastructure: −0.51. Using the VoD indicators allows us to convert the benefits into distance and travel time that can be used in other methods such as shortest-path routing.

Similar studies in other cities have also derived VoD indicators of cycling infrastructure relative to mixed traffic: Prato et al. (2018) report −0.249 for bicycle paths and lanes in peak hours in Copenhagen. Another study in Copenhagen (Jensen, 2019) shows VoD indicators of −0.044 for roads with bicycle lanes and −0.231 for roads with bicycle paths. Broach et al. (2012) have found ’distance values’ of −10.8 % to −26 % in Portland, OR. Hood et al. (2011) report average ’marginal rates of substitution’ of 0.49 (bike lanes) and 0.57 (bike paths) in San Francisco, corresponding to VoD (as defined above) of −0.51 and −0.43. Overall, the findings in Meister et al. (2023) in Zurich are in a similar range.

2.5. Preparation of street network data

Processing street networks relies on accurate and standardized data sources. OpenStreetMap (OSM) provides open geodata that is available globally in a consistent format, unlike official data which is fragmented and often not easily accessible. As of 2017, OSM covered the entire road network in more than 40 % of countries, mostly in the developed world, but including also several developing nations as well. Globally, it covered 83 % of all roads and was found to be superior to global datasets used by the World Bank (Barrington-Leigh and Millard-Ball, 2017). The Python package osmnx (Boeing, 2017) provides a convenient toolbox for extracting the data and performing basic geospatial operations. It provides a data structure for storing the street networks in a Street Graph, built on top of the networkx package (Hagberg et al., 2008), where each street is represented as one or more edges with geometries and attributes. It also provides a set of basic simplification tools that remove most interstitial nodes (with degree=2)[4] that are not intersections and consolidate multiple nodes representing a single intersection. However, osmnx lacks a data structure to store the allocation of road space and determine the total road widths. Also, its embedded simplification algorithm does not provide satisfactory results in the dense urban network of Zurich.

Berg et al. (2022) introduce the General Modeling Network Specification[5] (GMNS) framework for storing information about traffic lanes. Originally intended for studies on autonomous driving, it is a comprehensive relational data model with multiple tables, similar to the widely used General Transit Feed Specification (GTFS).

3. Conceptual approach

Based on the concept presented in Ballo et al. (2023), we model a hypothetical transformation that reallocates a large part of the road space to cycling, while maintaining a high-quality public transport service, and guaranteeing basic access for motorized traffic. The goal is to test the overall potential for change and illustrate the embedded trade-offs. The reallocation happens within the existing road space. No new streets are added and the pedestrian infrastructure remains unchanged. To widen the redesign possibilities, all existing traffic lanes, except those dedicated to public transport are ignored and subject to new organization. The new distribution favors cycling to the maximum extent possible while considering the needs of other modes: Public transport must be able to operate along its given routes and every residential location must be still reasonably reachable by motorized traffic. Finally, the resulting network must have hierarchies, where major streets channel through traffic while local streets serve only for access, similar to the 'Superblocks' paradigm (Eggimann, 2022; Rueda, 2019). Fig. 1 shows an illustration of the design principles.

4. Methods

4.1. Nomenclature and abbreviations

The nomenclature used in this paper is derived from four-step transportation models (Schnabel and Lohse, 2011), choice modeling (Meister et al., 2023; Ben-Akiva and Lerman, 1985), and the Python libraries networkx and osmnx. Parts of the nomenclature were adjusted to avoid using the same symbols for different meanings.

G	Street Graph
L	Lane Graph
A	Access Graph
u, v, k	Edge indices: node from, node to, key
i, j	Residential location, Parking lane
$p_{req,i}$	Required parking spots at a residential location i
$p_{cap,j}$	Capacity of a parking lane j
a_{ij}	Number of parking spots assigned between a residential location i and a parking lane j
s_i	Parking surplus (positive) or shortage (negative) at residential location i
n	Iteration step
$c_{uvk,mode}$	Generalized cost of traversing the edge uvk for a mode
l_{uvk}	Length of the edge uvk
VoD_x	Attribute x converted into the Value-of-Distance space
BC	Normalized Edge Betweenness Centrality
car lanes	Lanes for motorized traffic
bike lanes	Lanes for micromobility
PT lanes	Dedicated lanes for public transport
parking lanes	Lanes for on-street parking
OSM	OpenStreetMap

(continued on next column)

(continued)

4.2. Data acquisition

The raw street network data is acquired from OSM using osmnx with relevant traffic-oriented tags[6] and stored in a Street Graph (G). In addition, we use data sources specific to the context of Zurich: existing on-street parking spaces,[7] a digital elevation model,[8] public transport routes,[9] as well as a disaggregated version of the Swiss Statistical Population (STATPOP) dataset,[10] representing each permanent resident as a point. While a digital elevation model is available globally,[11] the other datasets may not be available for the given context. However, enriching the data model with these sources is optional and the process can be run without them, with the following limitations: Without a public transport routes dataset, the resulting network may conflict with the existing routes. Without an on-street parking dataset, any potential of repurposing space through a reorganization of on-street parking would be ignored. Without a population dataset, parking cannot be redistributed accurately based on nearby residents. Finally, in places with less detailed road tags, e.g., the number of lanes, the resulting street network will have less accurate road widths, thus having a lower accuracy in representing the road space usage potentials. Nevertheless, even with these limitations, users may still produce at least a proof of concept. They may distribute parking based on other data such as building footprints or business locations. For public transport routes, users may rely on relations in OSM (if available) or digitize the routes manually.

4.3. Data model and preparation

The primary data structure is an extended version of the directed Street Graph (G) from osmnx. In addition to the original format, each edge is extended with an attribute that contains a representation of its lanes, with a simplified data structure adopted from the GMNS format. For representing the lanes in a human-readable format, we use the following encoding: [lane type][direction][status (optional)][width (optional)]. Possible lane types are M (car lane), L (bike lane), H (highway lane), T (PT lane), R (parking lane), and X (mixed cycling and pedestrian path). Possible directions (relative to the directed edge) are <

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[4] In graph theory, the 'degree' of a node refers to the number of edges that are attached to it.

[5] https://github.com/zephyr-data-specs/GMNS

[6] bridge, tunnel, layer, oneway, oneway:bicycle, ref, name, highway, maxspeed, service, access, area, landuse, width, est_width, junction, surface, lanes, lanes:forward, lanes:backward, cycleway, cycleway:both, cycleway:left, cycleway:right, bicycle, bicycle:conditional, sidewalk, sidewalk:left, sidewalk:right, foot, psv, bus, bus:lanes, bus:lanes:forward, bus:lanes:backward, vehicle:lanes:backward, vehicle:lanes:forward, busway, busway:right, busway:left, footway

[7] https://data.stadt-zuerich.ch/dataset/geo_oeffentlich_zugaengliche_strassenparkplaetze_ogd

[8] https://www.swisstopo.admin.ch/en/height-model-swissalti3d

[9] https://data.stadt-zuerich.ch/dataset/ktzh_linien_des_oeffentlichen_verkehrs_ogd_

[10] https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/erhebungen/statpop.html

[11] For example, the US SRTM dataset: https://doi.org/10.5066/F7PR7TFT

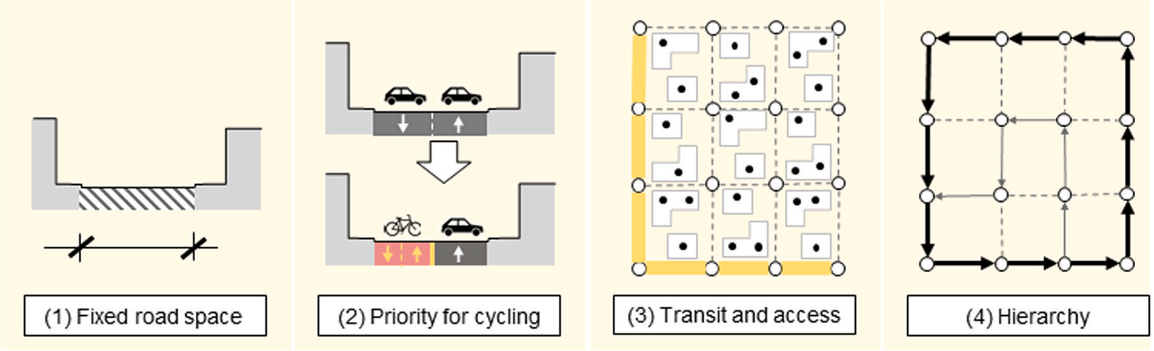
(1) Fixed road space
(2) Priority for cycling
(3) Transit and access
(4) Hierarchy

Fig. 1. Design principles.

(backward), > (forward), - (both directions), and? (to be defined in the redesign process). The status represents whether the lane is already final or yet to be edited. It can have the values * (fixed), / (optional), or ! (to be determined by an algorithm). The ? direction, as well as the / and ! status, are used throughout the rebuilding process (see Section 4.8) to keep track of lanes that can still be removed or changed, and those that cannot be altered anymore. Outside of the rebuilding process, all lanes have a * (fixed) status and a set direction. The last position, the width, is in the units of the projection used, typically in meters. If the status and width are missing, we assume the lane to be fixed and have the default width. The lanes are separated by | to represent the entire road space allocation on a street. As an example, L<*2.5 | T<*3 | M>*3 | L>*2.5 represents a street with two separated 2.5-meter cycling paths (one backward and one forward), a dedicated PT lane in the backward direction, and a regular car lane in the forward direction. It is a string representation of the object-oriented data structure in Python, that can be easily viewed and edited in GIS software.

Default lane widths used in this paper were measured on satellite images of existing streets in Zurich: 3.0 m for standard car lanes, 4.5 m for short bidirectional car lanes on residential streets, 1.5 m (half of a car lane) for standard cycling lanes, 2.5 m for mixed pedestrian and cycling tracks, and 2 m for parking lanes. During the rebuilding process, the preferred cycling infrastructure consists of two lanes per direction, thus resulting in a width of three meters, if the available space permits.

The initial lanes are reconstructed based on tags from OSM. Since there is no information about the actual lane widths in OSM, we use the default values described above. The total width of every road is determined by the sum of its lane widths. The OSM tags are used as follows: The highway tag provides information about road hierarchies, lanes shows the number of car lanes and dedicated PT lanes, oneway defines the directionality of the lanes, psv represents access by public transport and service vehicles, and maxspeed provides the maximum speed. On some roads, vehicle:lanes:forward, vehicle:lanes:backward, bus:lanes:forward, and bus:lanes:backward provide explicit information about the order and directions of car- and PT lanes. Otherwise, it is implied from the previously mentioned tags. Finally, bicycle defines the usability of roads and paths by cyclists, e.g., pedestrian paths with cycling allowed, and the tags cycleway:left, cycleway:both, as well as cycleway:right, are a source of information about the presence and type of cycling infrastructure. For the exact implementation, refer to the source code.[12]

For routing and calculation of graph measures using standard tools in the networkx library, we convert G to a Lane Graph (L) – a secondary representation where each lane is a separate directed edge, with cost attributes for each mode. L offers the benefit of being routable but in contrast to G, it introduces a redundancy of multiple edges representing the same physical street axis. Therefore, we continue to use G as a primary data structure and convert to L (and back to G) only for those steps where it is needed. Fig. 2 illustrates the difference between these two data structures.

4.4. Simplification

Next, we simplify the network acquired from OSM such that every street section between intersections is represented by one edge and every intersection by one node. Before the simplification, the largest intersections in Zurich have up to ~100 nodes and some streets are represented by 2–5 parallel edges. The process is an extension of the simplification provided by osmnx, and is described in the next paragraphs. Fig. 3 illustrates the difference between the original and the simplified network using the two algorithms.

The existing simplification tools in osmnx provide two steps: Elimination of (some) interstitial nodes with degree=2, and merging complex intersections. The nodes in intersections are merged using a combination of geometric buffers and weakly connected components. A buffer with a globally defined radius is added around every point and all touching buffers are merged. Within each resulting geometry, all nodes are sorted into weakly connected components (WCC),[13] and those in the same WCC are merged into one node. Its location is the center of gravity of the original node geometries.

However, this approach has several shortcomings that are crucial for the network in Zurich: First, and overall, it is focused solely on edges and does not consider their allocation of road space. Thus, the merged edges

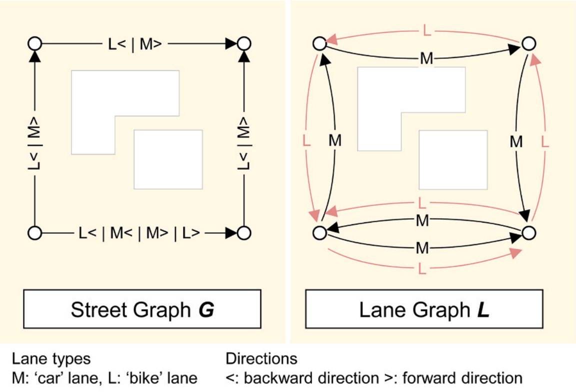

Fig. 2. Network data structures.

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[12] snman/space_allocation.py/_generate_lanes_for_edge()

[13] A 'weakly connected component' is a set of nodes in a directed graph were a path exists between any two of them. All edges can be passed in both directions, in contrast to a 'strongly connected component' where each edge can only be passed in its direction.

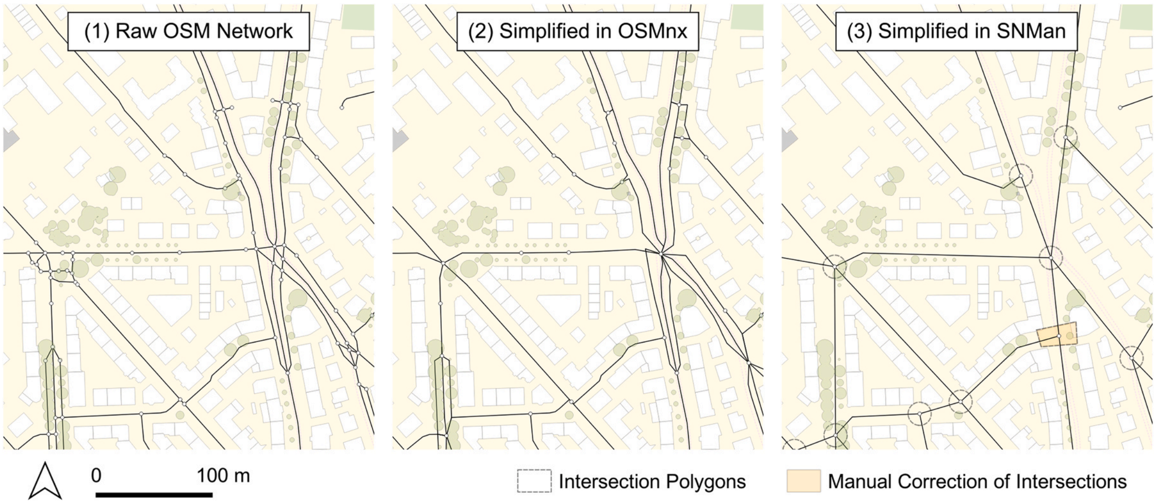

Fig. 3. Comparison of network simplification algorithms.

only maintain their tags as lists of original values but there is no data structure for managing lanes when edges are merged or separated. Second, it fails to merge all parallel edges and does not distinguish between those representing the same street and physically separated parallel streets. Third, its strict WCC condition in merging intersections does not allow proper treatment of wide streets with multiple parallel edges where side streets are often attached only to some of the main street edges. Fourth, it does not allow to exclude certain streets from the simplification process, such as highways where complex interchanges are difficult to simplify properly without losing important information. Finally, the process does not provide a way to manually correct the intersection extents in cases where the algorithm fails to provide satisfactory results. To overcome these limitations, we add the following extensions to the process.

First, we extend the process for merging consecutive and parallel edges by a logic that maintains a consistency of the road space allocation data. Whenever parallel edges are merged, their lane lists are merged as well. When consecutive edges are merged, the lanes of the longest one are kept and all other lane lists are discarded. Similarly, we add a logic for treating the tags, maintaining the highest value (e.g., highest maxspeed or highest highway tag), rather than storing all values in lists.

Second, we use Hausdorff Distance[14] (HD) to distinguish between parallel edges of the same street and parallel streets. If the HD of two parallel edges is more than 30 m, they are not merged, even if they share the same pair of nodes. This allows to keep parallel streets separate, instead of merging them and creating streets with an unrealistically high number of lanes, which would otherwise happen in residential areas of Zurich. We also run the entire simplification process multiple times to catch all merging opportunities that arise from the later steps.

Third, we add two steps for properly merging intersections on large streets with multiple parallel edges. In one step, we add an interstitial node to each edge passing through an intersection polygon, if both of its endpoints lay outside of the polygon. In the other step, we create artificial connections between the nodes within intersections if they are at the same physical level (based on the layer tags of their adjacent edges). This modification avoids splitting the intersections on major streets into multiple nodes and thus allows also to properly merge all of their parallel edges into one.

Fourth, we add a possibility to exclude some nodes and edges from the simplification.

Fifth, we modify the intersection merging process by adding a manual override of the automatically determined intersections. We take a polygon layer input and superimpose its features onto the automatically detected intersection polygons. This way, manual corrections are possible in cases where the simplification is not satisfactory and can be applied automatically to every network generated in the future.

And lastly, we create an iterative process consisting of the original osmnx functionalities, as well as the extensions introduced above. The topology simplification is repeated multiple times to catch any secondary simplification potentials that appear later:

1. Topology simplification, run three times:
    a. Label each node and edge whether it should be left unchanged during the simplification process.
    b. Create the intersection geometries using a buffer of 10 m, as typically used in literature (Barrington-Leigh and Millard-Ball, 2020; Boeing, 2021), superimposed by a layer of manually drawn polygons.
    c. Split edges passing through intersection polygons.
    d. Add connections between intersection nodes on the same physical level.
    e. Consolidate intersections using the previously generated polygons.
    f. Merge consecutive edges.
    g. Merge parallel edges.
2. Simplify the edge geometries.
3. Remove all nodes and edges outside of the largest WCC.

4.5. *Enrichment*

Next, we enrich the Street Graph G with additional data sources. We extend the node attributes with elevation data and calculate a grade value for each edge. We match public transport routes to the street network using Leuven Map Matching (Meert and Verbeke, 2018). Similarly, we match individual parking spaces provided by the official datasets to their respective streets and convert their counts to an approximate number of parking lanes.

4.6. *Representing the comfort of cycling*

Since reallocating road space to dedicated cycling infrastructure impacts cyclists mainly through comfort, the resulting change in generalized cost must be represented in the shortest path calculations. For that, we adjust the corresponding cost $c_{uvk,\ \mathrm{cycling}}$ using the VoD indicators estimated in Meister et al. (2023), such that:

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[14] the longest distance between any point along the geometry of street X and its closest counterpart on street Y, originally defined in Hausdorff (1914)

$$c_{uvk,\mathrm{cycling}} = l_{uvk} * \left[1 + \mathrm{VoD}_{\mathrm{infra}}(\mathrm{infra}_{uvk}) + \mathrm{VoD}_{\mathrm{grade}}(\mathrm{grade}_{uvk})\right]$$

For $\mathrm{VoD}_{\mathrm{infra}}$, we assume -0.51 if dedicated cycling infrastructure is present and 0 otherwise. $\mathrm{VoD}_{\mathrm{grade}}$ is 0.55 for $2\% < \mathrm{grade} \leq 6\%$, 3.11 for $6\% < \mathrm{grade} \leq 10\%$ and 4.33 for $10\% < \mathrm{grade}$. Cyclists can use general travel lanes but the link cost is lower on cycling lanes. On the other hand, motorized traffic cannot use cycling lanes.

Car trips are affected primarily by the detour length. VoD Indicators for driving comfort would be theoretically possible but we leave them out for the sake of focus and simplicity. For car trips, the cost of each link is equal to its length:

$$c_{uvk,\mathrm{car}} = l_{uvk}$$

Other comfort-related aspects such as additional stops or turns are ignored for both, cycling and car trips. Travel time changes due to congestion would need to be evaluated using an assignment model. For comparability of the resulting average shortest paths in Section 5.3, we report the values both with and without VoD indicators.

4.7. Network constraints

To guarantee network connectivity, ensure sufficient access to buildings by cars, and maintain a high quality of public transport, we enforce three constraints throughout the rebuilding process: (1) Every residential location must obtain a guaranteed number of on-street parking or loading spaces within a given distance. (2) The network cannot be disconnected, with two sub-conditions: (2a) All parking spots must be accessible by having a parallel car lane on the same street, and (2b) The number of strongly connected components[15] cannot increase. This means that we cannot remove a car lane if it would increase the number of isolated car lane networks and nodes with no car access. And, finally, (3) the network must allow the operation of all existing public transport routes (except minor neighborhood and night-time services). Fig. 4 illustrates the constraints.

The *access to residential locations* is ensured using an Access Graph (A). It establishes a connection between each pair of residential location i and on-street parking lane j within a given radius. Every residential location has a defined number of required parking spots $p_{req,i}$, based on its number of residents. On the other hand, each parking lane has an estimated capacity $p_{cap,j}$ based on its length. To keep track of under- or overprovision of parking spots, we use a gravity model of traffic distribution (Schnabel and Lohse, 2011) to assign the number of parking spots a_{ij} for every pair of a residential location and a parking lane. The same process can be used for commercial locations as well. The gravity model is fixed at the side of the parking lanes, thus concentrating any surplus or shortage of parking at the side of the residential locations (e.g., positive means that residents at location i have more parking than necessary):

$$s_i = \sum_j a_{ij} - p_{req,i}$$

In each step n of the rebuilding process, parking lanes can only be removed if the sum of all instances of parking shortage (where $s_i < 0$) does not increase:

$$\sum_i \min(s_{i,n+1}, 0) \leq \sum_i \min(s_{i,n}, 0)$$

To *maintain connectivity*, we enforce two conditions: First, all nodes of the graph must be strongly connected for cyclists. Second, all parking lanes must have at least one parallel car lane for access and this car lane must be part of a strongly connected graph for cars. Each car or cycling lane can only be removed if none of these conditions are violated.

To *maintain the operation of public transport*, every street with tram or bus routes must allow their passage in each route direction. Removal of travel lanes is only allowed if it does not lead to a violation of this condition.

4.8. Network design

We apply a reversed network formation process, adapted from Steinacker et al. (2022), consisting of five steps: First, we (1) Generate complete wish lists of lanes for all streets. Then, we perform the following reduction steps until the total width of the assigned lanes on each street does not exceed its available width: (2) Removing parking lanes, (3) Removing car lanes, (4) Removing bike lanes, and (5) Adjusting lane widths to fill the available street width. Fig. 5 illustrates the steps on a small street network. The process is carried out on a Lane Graph. Thus, when referring to 'lanes', we also refer to their corresponding edges in the Lane Graph. The resulting Lane Graph is then converted back to a Street Graph to maintain the primary data structure. In the following paragraphs, we describe the algorithms used in each step.

The *wish lists of lanes* are generated such that every street provides the most desirable travel options for every mode in each direction: One car lane, two bike lanes (for a comfortable double width), as well as a lane for on-street parking. Depending on the planner's aims, the wish lists can be set differently for each road hierarchy and each lane in the wish list can be either fixed (not removable throughout the later steps) or optional. Similarly, the lane widths can be set differently for each road hierarchy or depending on the maximum speed. Simultaneously, we construct an Access Graph, connecting residential locations with suitable parking lanes, as described in Section 4.7.

Second, we *remove parking lanes* as long as the necessary parking provision is not violated. We follow the order of largest excess width (the difference between available street width and the sum of lane widths). All parking lanes whose removal would violate the constraints in Section 4.7 are marked as fixed and the algorithm is finished once all parking lanes are fixed.

Third, we *remove car lanes*, following the order of their normalized edge betweenness centrality[16] (BC). Removing those with the lowest BC first results in permeable networks that favor smaller detours for the through traffic, while using the opposite order creates less permeability. Like in the previous step, lanes whose removal would violate any of the constraints are marked as fixed. The algorithm is finished once all car lanes are fixed.

Fourth, we *remove bike lanes* on all streets whose allocation still exceeds the available width. The order in which individual bike lanes along a street are removed is controlled by minimizing the increase in cycling cost between its nodes (sum of cost differences in both directions). With this logic, one-way streets for car traffic will favor contraflow cycling facilities.

Finally, the *lane widths are adjusted* such that they fill out any spare street width, after the removal of lanes with discrete widths. On streets with bike lanes, the spare width is filled out by widening them. In other cases, all other lanes are widened proportionally. Same-direction cycling lanes are consolidated into wider paths and all lanes are rearranged according to a pre-defined order.

4.9. Customization

The process described above is implemented such that users can generate a vast variety of custom designs. Individual steps can be reordered, their inputs can be replaced, or custom algorithms can be

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[15] The 'number of strongly connected components' represents the number of subnetworks that are disconnected from each other. Refer to footnote 10 for 'strong' and 'weak' connectivity.

[16] A measure for the importance of an edge: Number of shortest paths in a graph passing through the given edge, normalized by the overall graph size. We use the implementation in networkx.edge_betweenness_centrality()

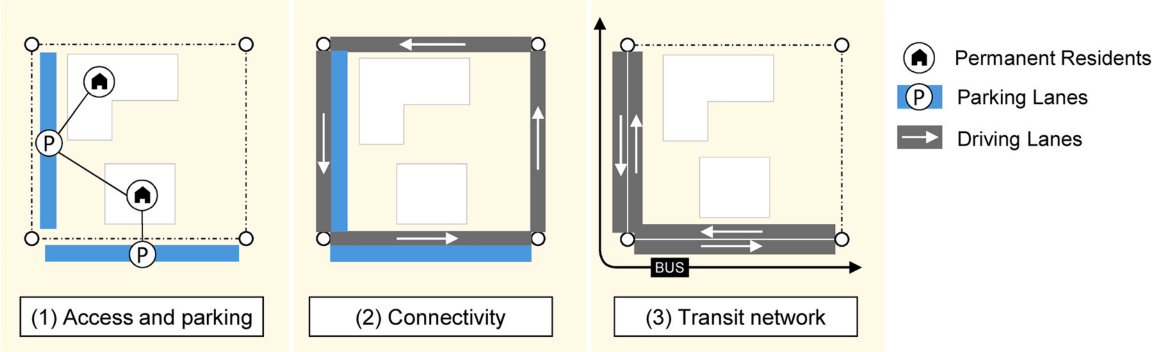

Fig. 4. Constraints during the rebuilding process.

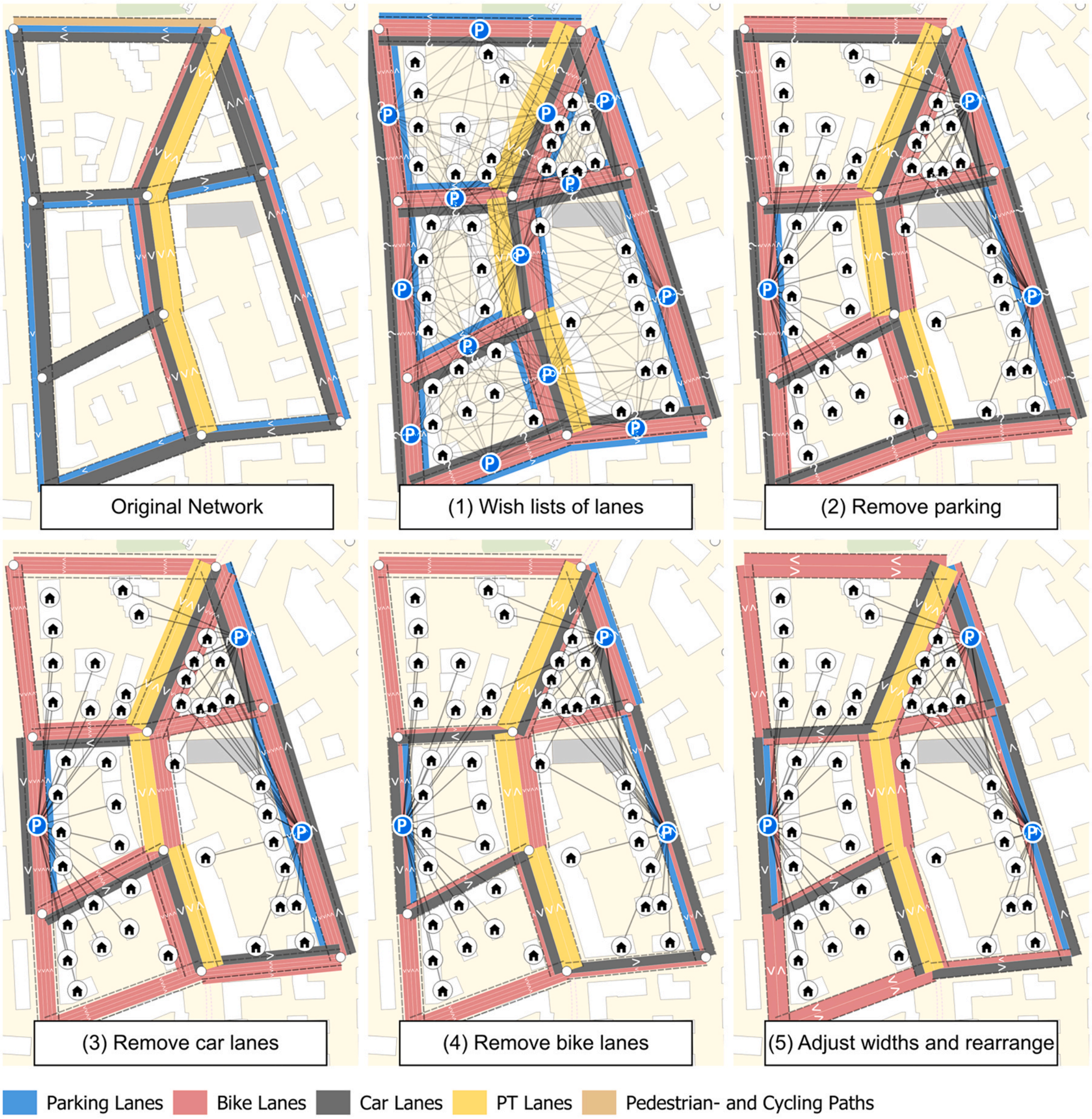

Fig. 5. Five steps of the network redesign process.

provided for individual steps. The process can be run in steps, for individual parts of the network separately, each with a different design configuration – allowing to combine multiple design strategies in the same resulting network. Users may also match polylines with manual overrides of the existing road space allocations onto the network or impose specific future road space allocation on individual streets during the redesign process. The functions for creating the lane with lists, as well as for carrying out the lane removal can be replaced by custom

Table 1
User inputs for generating different designs.

Input	Values	Design outcomes
Rebuilding regions	Custom polygons, to be applied in a given order	Network hierarchies and neighborhoods with different design rules
Street hierarchies to include	Highways, main roads, local roads	All or only some street hierarchies are included in the rebuilding process
Street hierarchies to fix	Highways, main roads, local roads	Some street hierarchies are left unchanged
Parking mode	By need (by gravity model), as existing, or no parking	On-street parking is allocated according to the given mode
Parking needs	Walking radius and maximum number of residents per parking spot	Number of resulting on-street parking spaces in the parking mode ’by need’
Public transport mode	PT lanes along every PT route (mandatory or optional), PT lanes as existing, or no PT lanes	PT lanes are allocated according to the given mode
Car lanes mode	Separated by direction or bidirectional	Types of resulting car lanes
Order of car lane elimination	Lowest BC or highest BC	Permeability or ’Superblocks’
Custom function for generating the lane wish lists	A function.	Desired allocation of space on every street
Custom functions for eliminating parking, car lanes, and bike lanes	Functions.	Custom optimization for different network structures, travel times, access, etc.
Custom overrides of lane wish lists on individual streets	Polylines with the desired wish lists	The resulting design may have specific lanes on some edges, while the rest of the network is arranged automatically, according to the constraints.

implementations. Table 1 shows an overview of user inputs that can be used for customizing the designs. See Section 5 for an exemplary application to Zurich.

5. Case study in Zurich

5.1. Description

As of 2024, the City of Zurich, Switzerland had a population of 443’037 inhabitants, an area of 91.9 km^2, and roughly 1.9 Million inhabitants living within its entire metropolitan region (City of Zurich, 2024c). The number of registered cars was 134’601 and remained nearly constant since 2002 (City of Zurich, 2024b) while car ownership decreased from 388 to 318 cars per 1’000 residents (City of Zurich, 2024a). Its relatively narrow streets and high density of PT services pose heavy restrictions on the construction of cycling facilities. Additionally, the cantonal constitution currently limits any measures that would reduce the capacity of cantonal roads, which entail a large portion of major streets within the city. In this case study, we apply the process presented above to propose a network-wide reorganization of road space allocation in favor of cycling. We consider the functional constraints related to public transport and access but ignore the current legal restrictions.

5.2. Design considerations and process

The redesigned network should substantially increase the length and width of cycling facilities while maintaining the quality of public transport and guaranteeing basic car access for every residential location. Further, car traffic should be concentrated on a network of main streets, while minimizing the traffic volumes in residential areas. On-street parking facilities should be reduced mainly to short-term loading zones and parking for the disabled. The access to parking spaces should be guaranteed within a similar walking distance as public transport stops.

The transport network after simplification has approximately 5’000 nodes and 7’000 edges within the municipal area of Zurich. To maintain a hierarchy of permeable main streets and low-traffic neighborhoods, we partition the network into one region with all main streets (OSM highway tags primary, secondary, and tertiary), and 60 neighborhoods between the main streets. All motorways are ignored and left unchanged. For the main streets, we prioritize the removal of car lanes by lowest betweenness centrality, while for the neighborhoods, we do the opposite to discourage the through traffic. In all regions, we fix the existing PT lanes but let all other lanes be determined by the process. We provide basic car access, with at least one parking spot per 60 residents within a radius of 200 m from each residential location. This is roughly one-sixth compared to today’s number of parking spaces (46’282 parking spaces, 9.6 residents per space). However, we have ignored any parking spaces on private ground and in large garages, thus the effective proportion of parking spaces removed is substantially smaller. For simplicity, we focus on residents as users of the parking spaces and ignore the other groups (e.g., businesses, tourists, etc.). The radius of 200 m is similar to the typical max. crow-fly distance to public transport stops.

5.3. Results

The run time was 7 h 39 min on an 11th generation Intel Core i7 processor, without parallelization. Fig. 6 shows a comparison of the network before and after rebuilding. Table 2 shows the resulting metrics for all streets within the city of Zurich, except highways and pedestrian infrastructure.

The road space has been substantially reallocated, increasing the share of cycling infrastructure by a factor of 4.5, from 12.1 % to 54.3 %. On the other hand, the proportion of space for general travel lanes has decreased by almost one-half, from 66.6 % to 35.1 %. The space for on-street parking was reduced by more than two-thirds, from 14.3 % to 3.8 %. In alignment with the original design goal to maintain the quality of public transport, space allocated to PT lanes has remained unchanged. The total road space grew slightly. This is due to a shortcoming of the reversed network generation process that, in some cases, results in bidirectional car traffic (and larger total lane width) on today’s one-way residential streets.

The cost of the average shortest path for cyclists (considering the VoD indicators for comfort and grades) has decreased by 24.1 %. Without considering the VoD indicators, the average shortest path remained nearly unchanged which can be explained by a high permeability of the current Zurich’s network, allowing cyclists to use almost all links in both directions. The reconfiguration does not make cycling trips substantially shorter but it reduces their generalized cost through higher comfort. On the other hand, the average shortest path for cars increased by 35.7 %, as a result of the many one-way and cycling-only streets.

The normalized average betweenness centrality grew by 157.5 % for cars and decreased by 3.5 % for bicycles. According to the model by Loder et al. (2019), both, the decreased total lane area (proportional to total lane length), as well as the increased betweenness centrality lead to lower network capacity for cars. On the other hand, slightly lower betweenness centrality and more road space usable by cyclists increases the capacity for this mode. However, accurate statements about the overall capacity change can only be made with a traffic simulation.

5.4. Plausibility checks and violations

The rebuilding process was developed iteratively, with several rounds of manual plausibility checks. These included the resulting road typologies, shortest paths between important origin/destination pairs, and violations of the design constraints (street widths, parking access, connectivity, and public transport). Most design issues could be resolved

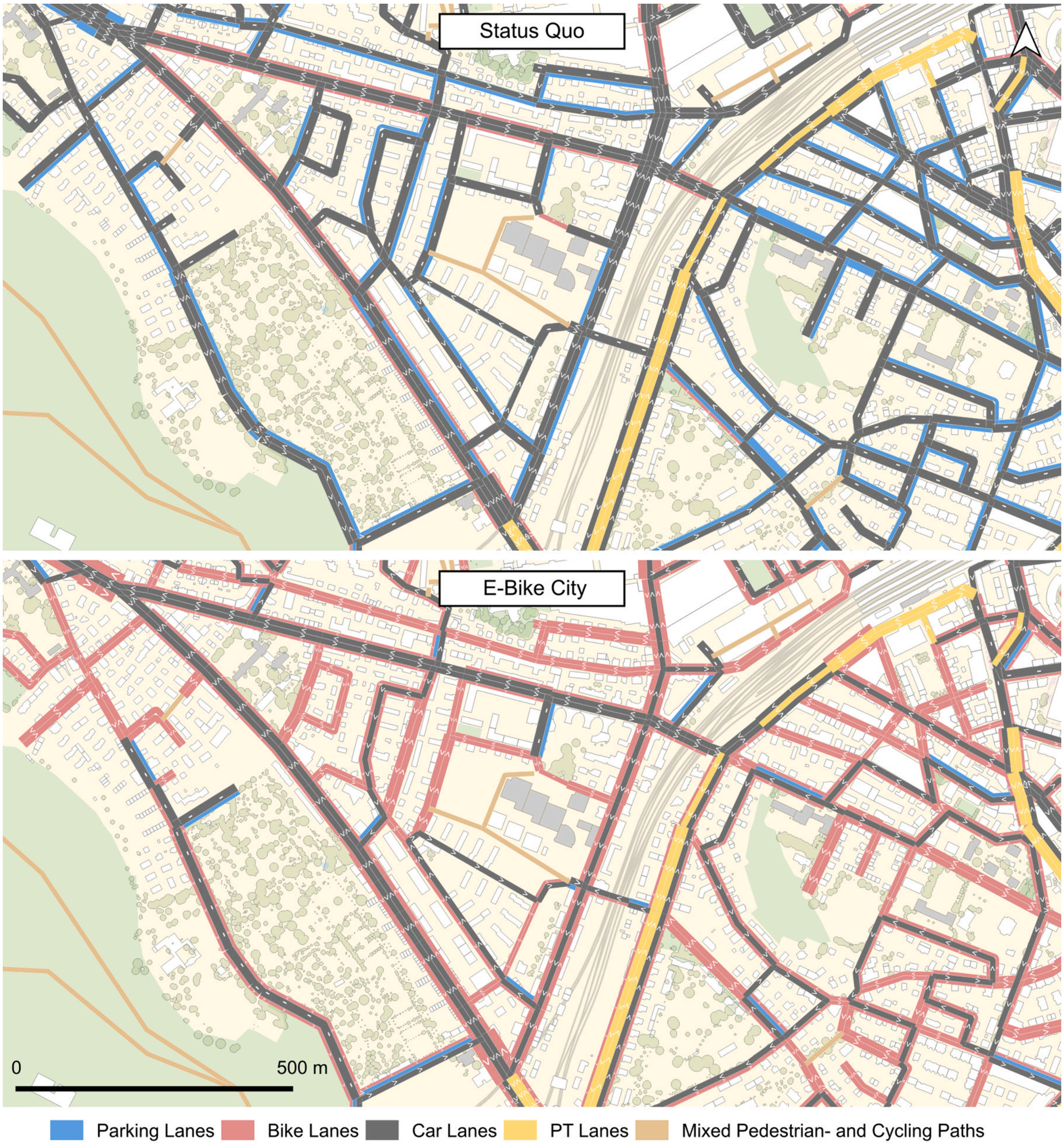

Fig. 6. Network previews (see supplementary material for the full network).

Table 2
Network indicators.

Metric		Status Quo		E-Bike City		Change
avg shortest path for cars	km		5.463		7.412	+35.7 %
avg shortest path for bicycles	km		5.391		5.334	−1.1 %
avg shortest path for bicycles with VoD indicators	km		4.824		3.661	−24.1 %
avg normalized betweenness centrality for cars	-		0.00506		0.01303	+157.5 %
avg normalized betweenness centrality for bicycles	-		0.00367		0.00354	−3.5 %
road space general travel lanes	km^2	(66.6 %)	3.7564	(35.1 %)	2.0257	−46.1 %
road space parking	km^2	(14.3 %)	0.8040	(3.8 %)	0.2188	−72.8 %
road space PT lanes	km^2	(7.0 %)	0.3962	(6.9 %)	0.3962	+0.0 %
road space cycling infrastructure	km^2	(12.1 %)	0.6816	(54.3 %)	3.1340	359.8 %
total road space	km^2		5.6382		5.7747	+2.4 %

by adjusting the algorithms, changing the user inputs (see Table 1), manually resolving simplification errors in the network, or correcting errors in the OSM data. However, two issues have not been resolved yet: First, one-way streets are occasionally converted to two-way traffic despite missing space, and second, the routing of car lanes through the neighborhoods results in implausible detours in some cases. Nevertheless, the extent of the width violations is relatively small (2.4 % of the total road space) and has little practical relevance: It applies mainly to residential streets, usually with short lengths and low traffic volumes so bidirectional traffic is possible even with smaller than usual widths. Similarly, improving the implausible routing of car lanes through neighborhoods would make the automatically generated network plan more visually appealing but would have little impact on the results presented in this paper or a future impact assessment. In any case, any plans for actual implementation would have to be scrutinized and improved with manual adjustments if necessary.

6. Discussion

The results show that a substantial reallocation of road space to cycling infrastructure is possible, while still providing a connected network for other modes. Essential car trips are still possible, although with detours and longer access and egress distances. The remaining on-street parking spaces, centralized at a few locations in every neighborhood, still provide space for short-term loading, pick-up, and drop-off, as well as parking for persons with disabilities. Personal electric vehicles, such as e-wheelchairs or electric carts may help to overcome the last couple of hundred meters for deliveries or for those who are unable to walk. An appropriate design of the cycling infrastructure would allow unchanged access for emergency and utility vehicles. However, the transformation is only possible with a substantial reduction of capacity and parking for motorized traffic, as well as a redefinition of the minimal access standard to buildings by cars. For such a future to be viable, the small modes, together with public transport must be attractive enough to trigger a substantial decrease in car ownership.

In the network design, we have considered many real-world needs but some aspects have still been left out: First, we have not made any changes to the pedestrian spaces. Second, the parking provision was controlled by only rudimentary assumptions about the maximum number of residents per parking spot, as well as the maximum distance from every address. Third, in the assessment, we have considered the VoD indicators only for cyclists and neglected any changes in speed and comfort for drivers. And lastly, the simplification used has removed detailed information about the intersections, such as the available infrastructure, or turn restrictions.

7. Conclusions and further work

While the accessibility growth in the last seventy years was driven mainly by adding large infrastructures, in this paper, we have turned the attention to merely reorganizing the usage of existing streets. The process we have introduced enables researchers and planners to quickly test alternative urban mobility paradigms at any scale, from closing down a neighborhood street to reorganizing road space in entire cities. The outputs can serve as starting points for discussions about future urban transport policies. Together with appropriate metrics, they may help illustrate and quantify key trade-offs, such as the one between the provision of convenient on-street parking, the perceived cost of cycling, and dedicated bus lanes. Planners and communities can work on top of these outputs to create final designs, adding all local details that have not been considered in the automated process, such as exact street and intersection designs, detailed access needs of individual buildings, or rerouting public transport services.

Future work should focus on two directions: Improving the design and assessing the impacts. The first, and most important improvement should integrate mathematical optimization (Wiedemann et al., 2024) and cost-benefit analyses (Rich et al., 2021; Paulsen and Rich, 2023; Zani et al., 2023) in the design process to deliver results with better performance and more flexible goals. Second, it should include aspects beyond mere traffic considerations, such as pedestrian spaces, mitigation of urban heat, or stormwater resilience by allocating parts of the street space to a wider set of functions. Such extension would also need to consider ways of increasing the level of detail in the network data, as well as improving the simplification algorithm to deal with the complexities of pedestrian networks. Third, future work may improve the data and assumptions used for the provision of parking, such that also the needs of businesses, or residents in neighborhoods with different parking alternatives are considered. Also, the provision of bicycle parking at major destinations should be considered. Fourth, further development of the simplification process may retain more information about infrastructure in intersections that is currently lost. And, finally, the design process should also consider transition aspects, with the possibility to generate intermediate stages of implementation.

On the impact assessment side, future work should build a comprehensive traffic simulation for the proposed scenario. In Ballo et al. (2024), we show the first steps toward an agent-based traffic simulation and accessibility analysis that shows the changes for different population groups. Further work should also focus on a CBA to create a closed end-to-end process, starting with different network design concepts and ending with easily comparable CBA metrics. Other future work may also refine parts of the assessment process, with VoD and travel time metrics for different bicycle types, cycling facility variants, as well as for cars.

In summary, we have contributed to a discussion about future transport policy directions by introducing a process to quickly envision different city-wide road space allocation schemes. We hope it will inspire fellow researchers and policymakers to explore the potential and implications of projects that merely reallocate road space, instead of building new infrastructures.

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Lukas Ballo: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Martin Raubal:** Writing – review & editing. **Kay Axhausen:** Writing – review & editing.

Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jcmr.2024.100048.

Data Availability

The latest version of the SNMan (Street Network Manipulator) software introduced in this paper is available open-source: https://github.com/lukasballo/snman.

The exact code together with the data used in this paper is available here: https://zenodo.org/doi/10.5281/zenodo.13621694.

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