Designing an E-Bike City

An automated process for network-wide multimodal road space reallocation

Working Paper

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Publication date:
2024-06

Permanent link:
https://doi.org/10.3929/ethz-b-000679713

Originally published in:
Arbeitsberichte Verkehrs- und Raumplanung 1881

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

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ACKNOWLEDGEMENTS

Thanks to Sven Ruf for testing the early developments of `snman`.
Thanks to Jeppe Rich and Mads Paulsen for hosting Lukas Ballo at DTU and providing feedback on early approaches for this work.
Thanks to Wannes Meert for answering questions about the usage and adaptation of the Leuven map-matching algorithm.

FUNDING

Internal funds of Prof. Kay W. Axhausen, ETH D-BAUG lighthouse project grant, EnergieSchweiz, and Swiss Federal Office of Energy.

CONFLICTS OF INTEREST

None.

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4’951 words + 6 figures + 2 tables

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 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 or modes and follow a variety of design principles. 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 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.

KEYWORDS

Cycling network design; SNMan; E-Bike City; Decarbonization; Multimodal transport networks

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 transport 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. However, making cycling attractive to a wide audience requires the provision of cycling infrastructure that is separated from motorized traffic. 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; Mesbah et al., 2012) does not account for the tradeoff in road space allocation between cycling, motorized traffic, and public transport. Considering this aspect, as well as the overarching topologies of the resulting transport networks is crucial in cities with limited road space and highly connected public transport systems.

In this paper, we present a flexible automated process for designing network-wide road space reallocation schemes, such as the E-Bike City, while simultaneously considering the needs of all other modes of transport. In contrast to the existing approaches, our method can be used to model multimodal road space reallocation schemes in dense cities. The resulting network can visualized, evaluated with a set of metrics, or used as an input for traffic simulation toolkits. The process is implemented in a Python software and available open source. We use a case study in Zurich, Switzerland for demonstration.

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 concludes the paper.

2 PREVIOUS WORK

2.1 Design processes and evaluation

Steinacker et al. (2022) have proposed an algorithm for proposing new bike lanes. It reverses the network formation by starting with a full cycling network and iteratively removes links from it, based on a set of indicators. However, like most other approaches, it does not account for tradeoffs in the usage of limited road space. Burke and Scott (2016) propose a framework to incorporate the disruption of motorized traffic by removing travel lanes through the introduction of a Network Robustness Index (NRI). The NRI considers the total effect on the level of service in the network for motorized traffic. It is calculated by performing a traffic assignment and calculating the resulting travel times for all trips.

This process requires that the demand is known and traffic assignment must be repeated each time a link is changed, leading to high computational cost.

To evaluate urban transport networks without the complexity of traffic assignment, Loder et al. (2019) have estimated a multi-regression model that explains their performance using a set of simple measures: road network density, betweenness centrality, intersection density, and bus production. They show how these four measures impact the shape of the Macroscopic Fundamental Diagram (MFD). The maximum trip production is increased by higher road network density, lower average betweenness centrality, lower intersection density, and lower bus production density.

2.2 Preparation of street network data

Processing street networks relies on accurate and standardized data sources. OpenStreetMap (OSM)[1] provides open geodata, available globally in a consistent format, in contrast to official data that is fragmented among local authorities. 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 OSM data in a street graph, built on top of the `networkx` package, where each street is represented as a directed edge, with a set of attributes. It also provides a basic simplification tool that removes most nodes with degree=2 and consolidates intersections using a buffer. However, `osmnx` does not provide any structures to determine road widths or to work with actual road space allocation, represented by lanes. Also, its embedded simplification algorithm does not provide satisfactory results in dense urban networks.

Berg et al. (2022) introduce the General Modeling Network Specification[2] (GMNS) framework for storing information about road networks, including their 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).

2.3 Representing cycling comfort

The benefits of cycling infrastructure, as opposed 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 admit that the higher valuation of bike lanes over bike paths is counterintuitive. It is likely a result of forced choices created by the spatial constellation of Zurich’s network. In this paper, we use the mean of the above two values for all types of cycling infrastructure: -0.51.

Multiple similar studies were performed in other cities as well. Prato et al. (2018) report mean VoD indicators of -0.249 for bicycle paths/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

[1] https://osm.org/
[2] https://github.com/zephyr-data-specs/GMNS

Portland. 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. However, the VoD indicators used should be adjusted based on the city where the road space reallocation process is applied.

3 CONCEPTUAL APPROACH

Based on the concept presented in Ballo et al. (2023), we model a transformation that reallocates a large part of the road space to cycling, while maintaining a high-quality public transport service. The entire transformation happens within the existing road space – no new streets are added and the pedestrian infrastructure remains unchanged. To widen the redesign possibilities, the existing allocation is ignored and subject to new organization. However, to avoid negative impacts on public transport, existing tram and bus lanes are retained within the process. 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 reachable by motorized traffic, with a guaranteed supply of on-street loading zones and parking within a given radius. 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). Figure 1 shows an illustration of the design principles. The process can be modified for modeling scenarios according to other sets of design principles.

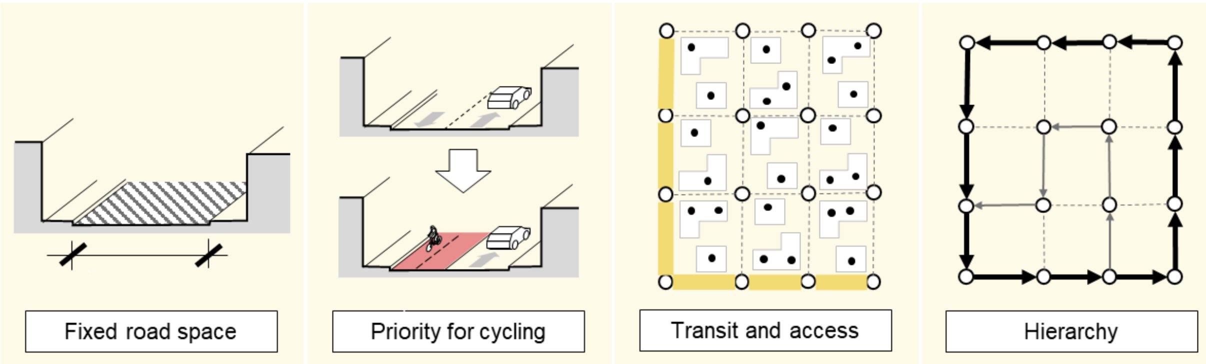

Figure 1: Design principles

4 METHODS

4.1 Nomenclature

G	Street graph
u, v, k	Edge indices: node from, node to, key
L	Lane graph
A	Access graph
i, j	Residential location, Parking lane
p_i	Required parking spots at a residential location i

p_j	Capacity of a parking lane j
a_{ij}	Number of parking spots assigned between a residential location i and a parking lane j
p'_i	Parking surplus (positive) or shortage (negative) at residential location i
k	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	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

4.2 Data acquisition

The raw street network data is acquired from OSM using the `osmnx` package with relevant traffic-oriented tags[3], and stored in a street graph (*G*). In addition, we use data sources specific to the context of Zurich: existing on-street parking spaces[4], a digital elevation model, public transport routes[5], the official land survey dataset of Canton Zurich[6] as well as the Swiss Statistical Population (StatPop) dataset[7]. However, enriching the data model with these sources is optional and the process can be run also in places where such data are not available.

4.3 Data model and preparation

The primary data structure is an extended version of the street graph (*G*) from `osmnx`. In addition to its original form, each edge is extended with an attribute that contains a representation of its lanes, with a data structure adapted from the GMNS format. The lanes are reconstructed based on the attributes acquired from OSM, with assumed widths (3 m for standard travel lanes, 4.5m for bidirectional travel lanes, and 1.5 m for standard cycling lanes):

- `highway, lanes, oneway, psv,` and `maxspeed` for information about car and public transport (PT) lanes and their directions
- `vehicle:lanes:forward, vehicle:lanes:backward, bus:lanes:forward,` and `bus:lanes:backward` for PT lanes and their directions

[3] `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`

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

[5] https://data.stadt-zuerich.ch/dataset/ktzh_linien_des_oeffentlichen_verkehrs__ogd_

[6] https://www.stadt-zuerich.ch/geodaten/download/10016

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

- `bicycle`, `cycleway:left`, `cycleway:both`, and `cycleway:right` for bike lanes

For routing and calculation of graph measures using standard tools in the `networkx` library, we convert *G* to a secondary representation “Lane Graph” (*L*) where each lane is represented as a separate directed edge, with cost attributes for each mode. Figure 2 illustrates the difference between these two data structures.

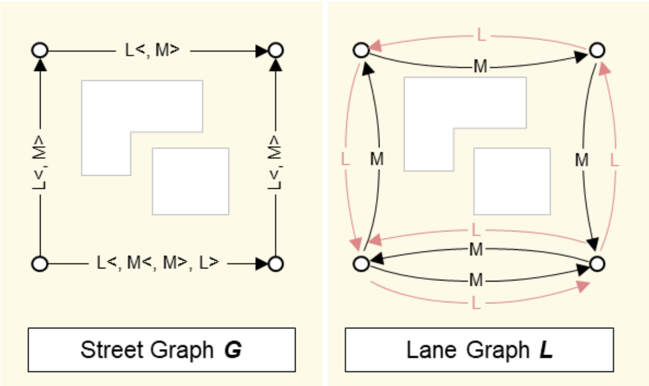

Figure 2: Street graph and lane graph

4.4 Simplification

Next, we simplify the network such that every street is represented by one edge and every intersection by one node. Before the simplification, the largest intersections in Zurich contain up to ~100 nodes and many streets are represented by 2-5 parallel edges. Figure 3 illustrates the difference between the original and simplified network with an example. The process is an extension of the simplification tools provided by `osmnx`, described in the next paragraphs.

Figure 3: Street graph from OSM data before and after simplification

At first, we detect the spatial boundaries of intersections. All nodes with a degree ≥ 3 are grouped using unions of 10-meter buffers as is common in the literature (Barrington-Leigh and Millard-Ball, 2020; Boeing, 2021). Second, we split edges passing through the intersection polygons. This step is crucial for properly simplifying one-sided intersections of large streets with multiple OSM edges and smaller side streets. Third, we group nodes within each intersection polygon using weakly connected components. This step allows to maintain the separation of disconnected parts of intersections, e.g., due to being on different physical levels. However, to include nodes that have been created in the second step, we add artificial connections between different weakly connected components if they are on the same physical level, based on the `layer` OSM tag. In the fourth step, consecutive edges are merged. Chains of edges and degree=2 nodes are merged into single edges. To prevent creating false connections, edges that do not permit car traffic are treated separately from those that do. OSM tags, as well as the list of lanes, are copied from the longest edge in each chain. The final step merges all sets of close parallel edges, i.e., sharing the same pair of start node *u* and end node *v*, as well as the same `layer` tag, and having a Hausdorff Distance (the longest distance between any point along the geometry of street X and its closest counterpart on street Y, originally defined in Hausdorff (1914)) of less than 30 meters. Parallel streets whose geometries are further apart, remain separated. The OSM tags are copied such that the highest road hierarchy and highest maximum speed are maintained. This step discards any physical separations (medians, trees) and treats the sum of all available road spaces as one entity.

The above steps are repeated until all possible simplifications have been made. Finally, the geometries of all resulting edges are slightly simplified to eliminate any sharp turns produced by attaching the merged edges to the consolidated intersections. Cases, where the intersections have been detected incorrectly, are corrected using a manual input of intersection boundaries. Errors related to wrong map data were corrected directly in the public OSM database.

4.5 Enrichment

Next, we enrich G with additional data sources. 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, e.g., two for parallel parking on both sides of the street.

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 $c_{uvk,\text{cycling}}$ using the VoD indicators estimated in Meister et al. (2023), such that:

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

For $\text{VoD}_{\text{infra}}$, we assume -0.51 if dedicated cycling infrastructure is present and 0 otherwise. $\text{VoD}_{\text{grade}}$ is 0.55 for $2\% < \text{grade} \leq 6\%$, 3.11 for $6\% < \text{grad}e \leq 10\%$ and 4.33 for $10\% < \text{grade}$. 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 decided to ignore them. For car trips, the cost of each link is equal to its length:

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

Other comfort-related aspects such as additional stops or turns are ignored for both, cycling and car trips. Travel time changes due to congestion need to be evaluated using a traffic simulation (see section 6). 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/loading spaces within a given distance. (2) The network must remain connected, with two sub-conditions: (2a) All parking spots must be accessible by having a parallel travel lane that is part of a strongly connected graph with all remaining travel lanes. (2b) All nodes in the network must be part of a strongly connected graph for cycling. And finally, (3) the network must allow the operation of all existing public transport routes, except neighborhood and night-time busses. Figure 4 illustrates the constraints.

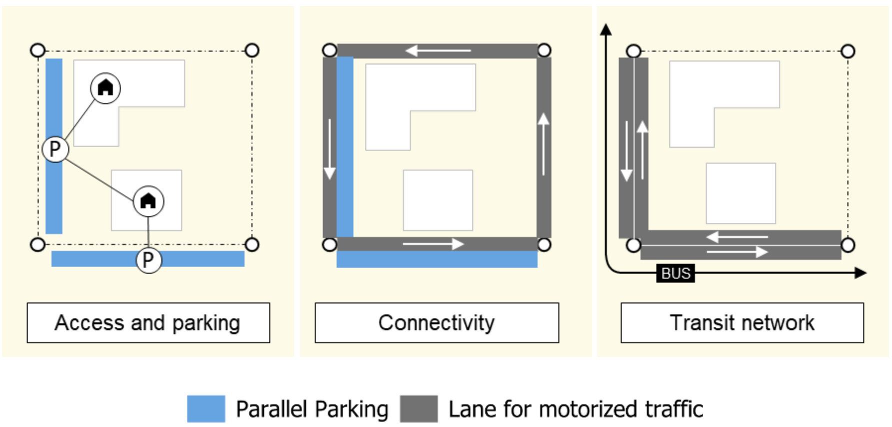

Figure 4: Constraints during the rebuilding process

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_i, e.g., based on its number of residents. On the other hand, each parking lane has an estimated capacity p_j based on its length, divided by 5 meters. 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, concentrating any surplus or shortage of parking at the side of residential locations (e.g., positive means that residents at location *i* have more parking than necessary):

$$p'_i = \sum_j a_{ij} - p_i$$

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

$$\sum_i \min(p'_{i,k+1}, 0) \leq \sum_i \min(p'_{i,k}, 0)$$

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 direction. Removal of travel lanes is only allowed if this condition is met.

4.8 Network design process

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. Figure 5 illustrates the steps on a small street graph. In the following paragraphs, we describe the algorithms used in each step.

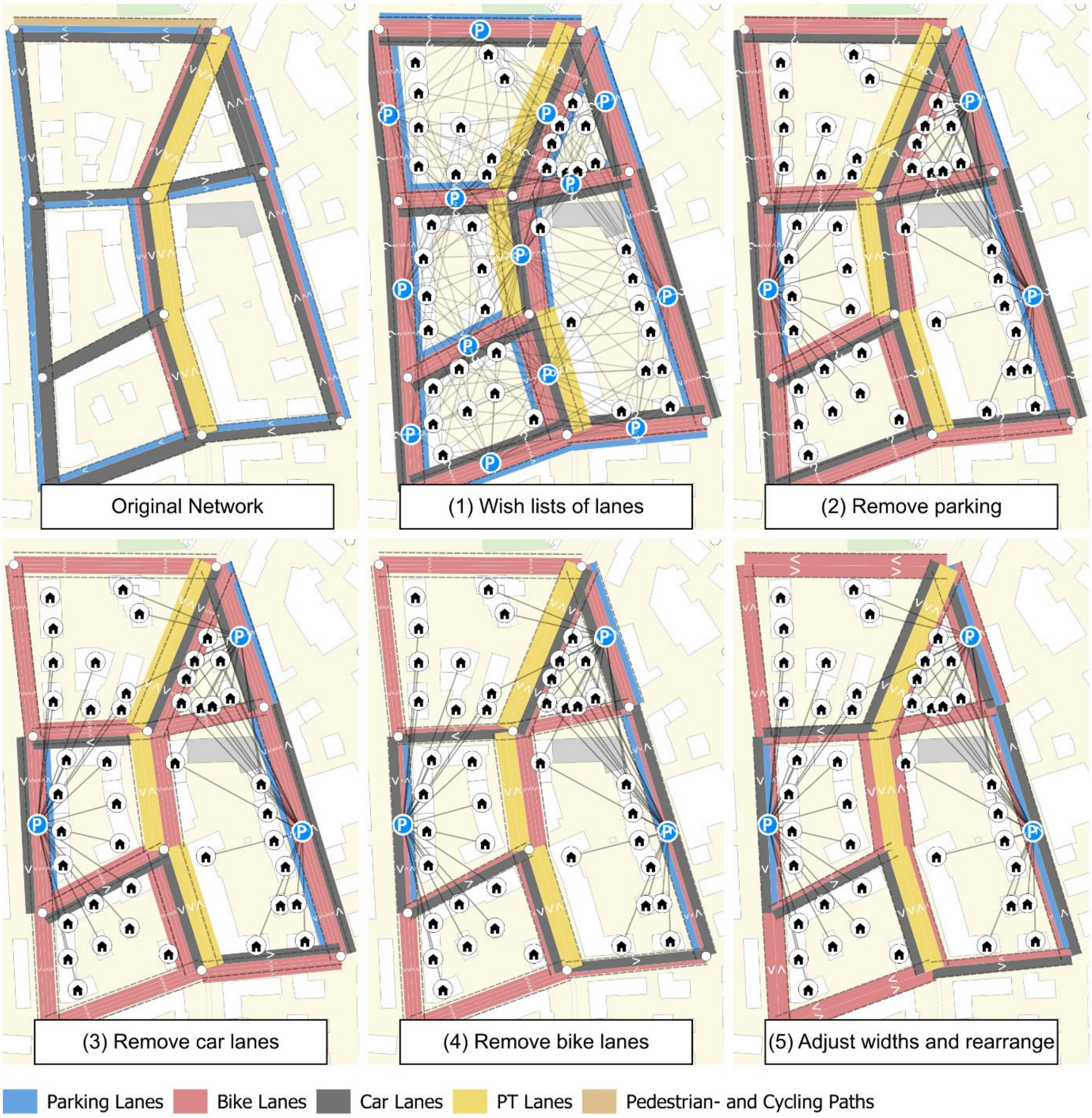

Figure 5: Network design steps

The *wish list of lanes* is generated such that every street provides the most desirable travel options for every mode in each direction: One car lane, two bike lanes (for double width), as well as a lane for on-street parking. Depending on the planner's aims, each lane in the wish list can be either fixed (not removable throughout the later steps) or optional. Car lanes on streets with bidirectional traffic may be separated by direction or one wider lane may be shared by traffic in both directions. 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 supply 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 betweenness centrality (BC). Removing those with the lowest BC first results in permeable networks, favoring through traffic while using the opposite order creates impermeable ones. 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 has excess 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). As a result, streets with one-way car traffic favor contraflow cycling lanes.

Finally, the *lane widths are adjusted* such that they fill the available street width. On streets with bike lanes, the spare width is filled by widening them. In other cases, all other lanes are widened proportionally. Same-type cycling lanes are consolidated into wider paths and all lanes are rearranged according to a pre-defined order. This allows a more realistic visual representation and easier manual checks before the resulting network is used for traffic simulations.

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 provided for individual steps. The process can be run for individual regions of the network separately, each with an individual design configuration, allowing for a combination of multiple design principles in the same scenario. Table 1 shows an overview of user inputs that can be used for customizing the designs. In Section 5, we show an exemplary application for Zurich, Switzerland.

Table 1: User inputs for generating different designs

Input	Values	Design outcomes
Rebuilding regions	Custom polygons, with order of application	Network hierarchies, locations with different design rules
Street hierarchies to include	Highways, main roads, local roads	Different street hierarchies included in the access calculations
Street hierarchies to fix	Highways, main roads, local roads	Different street hierarchies included in the rebuilding scheme
Parking mode	By need (by gravity model), as existing, no parking	Allocation of space for on-street parking
Parking needs	Walking radius and max. number of residents per parking spot	Number of resulting on-street parking spaces in "by need" parking mode
Public transport mode	PT lanes along every PT route (mandatory or optional), PT lanes as existing, no PT lanes	Allocation of space for PT lanes
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 "Superblock"
Custom function for lane wish lists	A Python function for generating the wish list for every street	Desired allocation of space on every street
Custom functions for eliminating parking, car lanes, and bike lanes	A Python function for eliminating car lanes	Optimization for different network structures, travel times, access, etc.

5 CASE STUDY IN ZURICH

5.1 Description

As of 2024, the municipality of Zurich, Switzerland has a population of 443'037 inhabitants, an area of 91.9 km2, and roughly 1.9 Million inhabitants living within its entire metropolitan region (City of Zurich, 2024). Its relatively narrow streets and high density of PT services pose heavy restrictions on the construction of cycling facilities. In this case study, we apply the process presented above to propose a network-wide reorganization of road space allocation in favor of cycling.

5.2 Design goals and process

The redesigned network should massively improve the attractiveness of cycling while maintaining the quality of PT, 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 on residential streets.

The transport network after simplification has approximately 5'000 nodes and 7'000 edges within the municipal area of Zurich. To maintain a network hierarchy of permeable main streets and low-traffic neighborhoods, we partition the network into one region with all main streets (OSM tags `primary`, `secondary`, and `tertiary`), and 60 neighborhoods between the main streets. For the main streets, we prioritize the removal of car lanes by lowest betweenness centrality, while for the neighborhoods, we do the opposite to avoid 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 one parking spot per max. 60 residents within 200 meters of each residential location. For simplicity, we leave out on-street parking spaces for other purposes (e.g., businesses, train stations, taxi stands) but in theory, they could be allocated using the same process.

5.3 Results

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

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%)	0.3962	(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%

The road space has been substantially reallocated, increasing the share of cycling infrastructure by factor 4.6, 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 due to a limitation of the reversed network generation process that, in some cases, results in bidirectional car traffic on today's one-way streets, thus over-allocating their road space. However, the magnitude of this effect is small and can be ignored for the sake of simplicity.

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 oneway and cycling-only streets. In addition, the crow-fly access distance to the closest on-street parking spot is up to 200 meters.

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 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 (the sum of the road space for general travel lanes and cycling infrastructure) increases the capacity for this mode. However, the change in overall capacity (in terms of total trip production across all modes) needs to be evaluated in a simulation.

ACKNOWLEDGEMENTS

Thanks to Sven Ruf for testing the early developments of `snman`.
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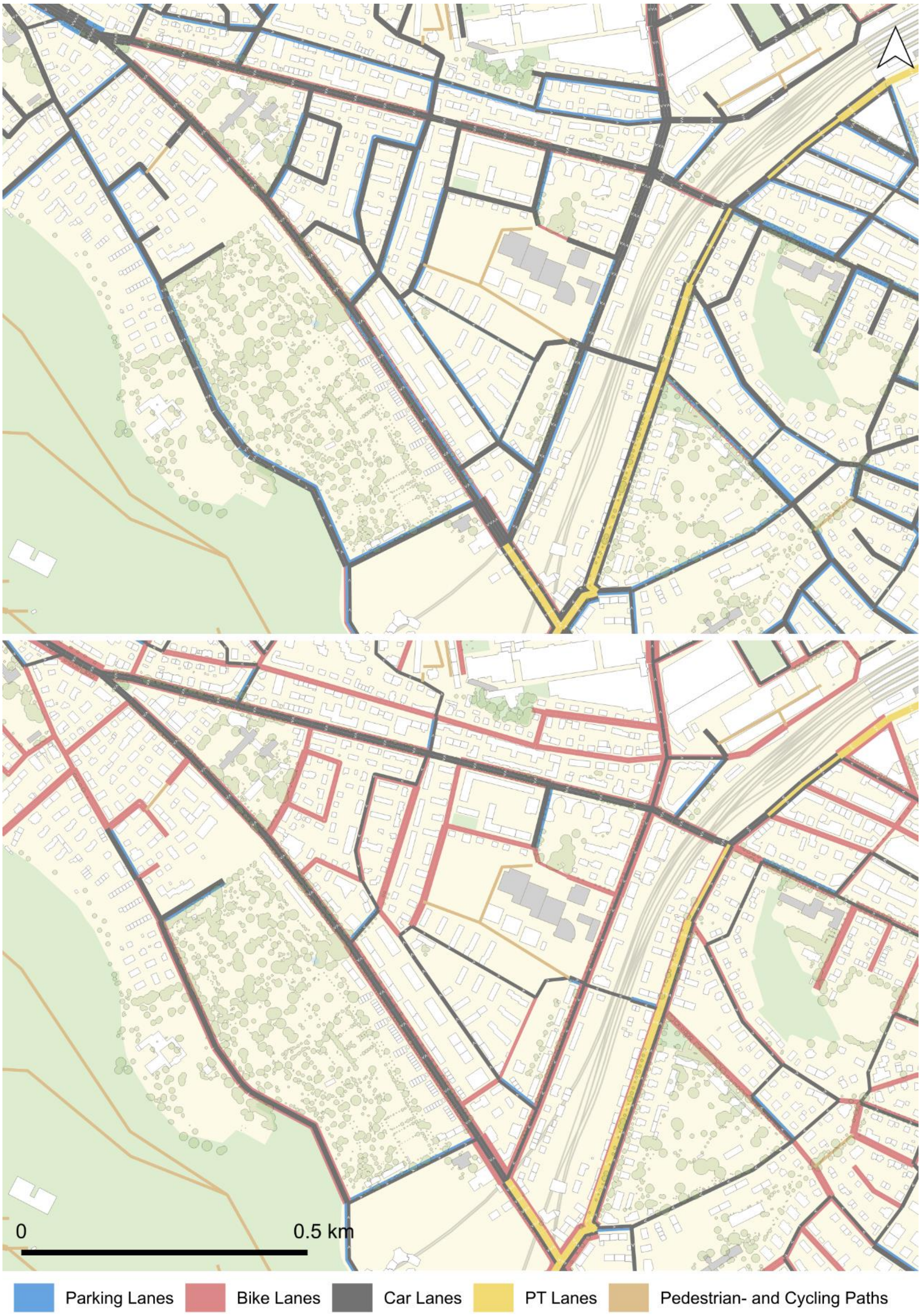

(see supplementary material for the complete network)

Figure 6: Network previews, top: Status Quo, bottom: E-Bike City

6 CONCLUSIONS AND FURTHER WORK

Our process enables researchers and planners to quickly model and test alternative urban mobility paradigms at any scale, from small neighborhoods to entire cities. The outputs can serve as starting points for discussions about future urban transport policies. Together with appropriate metrics, they may also illustrate and quantify key tradeoffs, 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.

Further development of the process for reallocating road space may include additional aspects of sustainable urban development such as adding green spaces, improving pedestrian infrastructure, or increasing resilience for disruptions during extreme weather events. It may also be extended to consider further needs, such as needed access to garages, or parking spaces for businesses. Another further development should focus on creating designs with better performance (e.g., in terms of average shortest paths) by using demand data and integrating advanced mathematical optimization algorithms, such as the work by Wiedemann et al. (2024).

The case study has illustrated that massive improvements in safety and comfort for cyclists are possible even in a place with highly restricted road space if its allocation is rethought thoroughly. However, strong changes are necessary in the organization of motorized traffic, and further studies are needed to show the resulting magnitude of mode shifts and accessibility levels. Future work should include a precise impact assessment of the changes, allowing policymakers to understand the costs and benefits of the E-Bike City and similar future scenarios produced by this process. A particular area of interest is exploring the structural changes in accessibility that would be produced and their evaluation from an equity perspective.

The software presented in this paper is published as part of the open-source Python project `SNMan` (Street Network Manipulator): https://github.com/lukasballo/snman. To access the code used in this paper, refer to the *journal_paper* branch.

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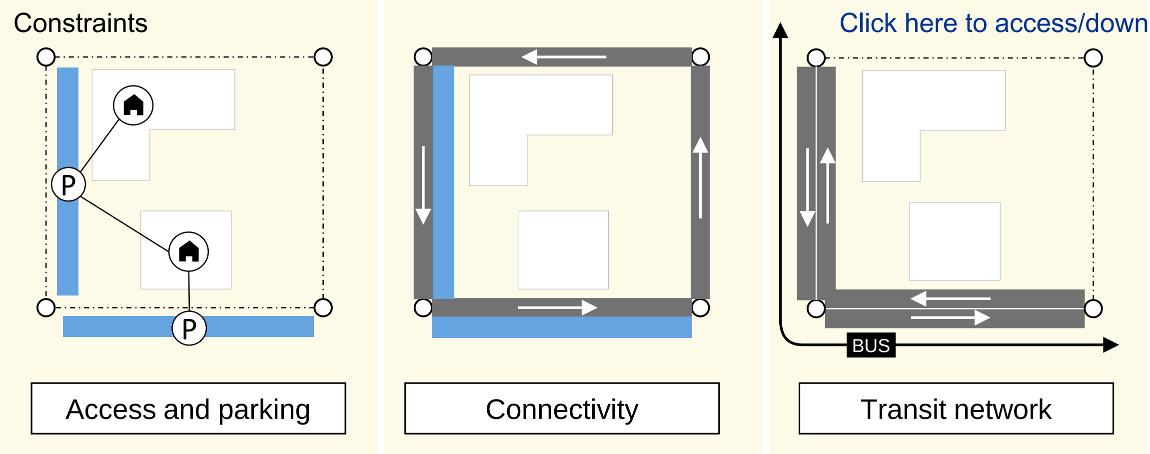
Constraints
P
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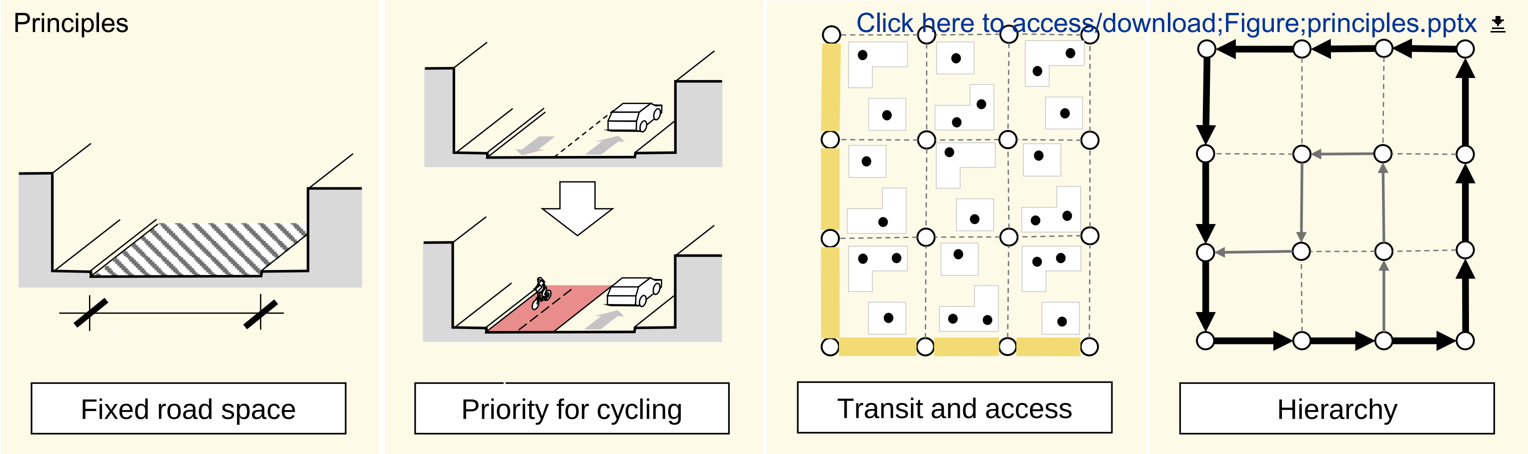
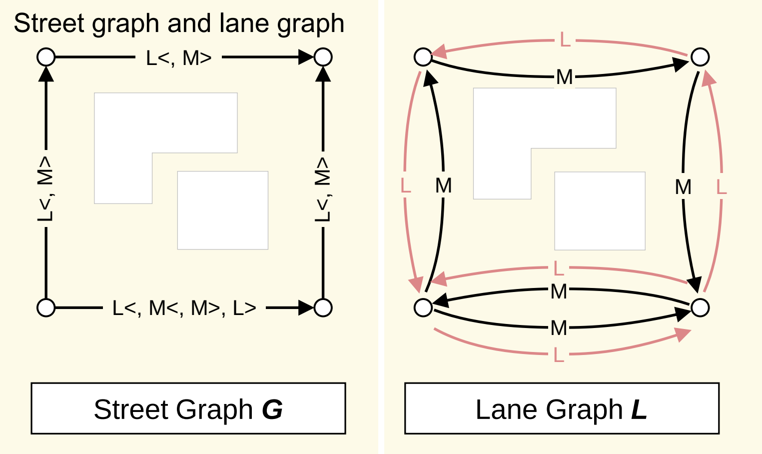
Access and parking
Connectivity
BUS
Transit network


Principles
Fixed road space
Priority for cycling
Transit and access
Hierarchy



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Rebuilding steps

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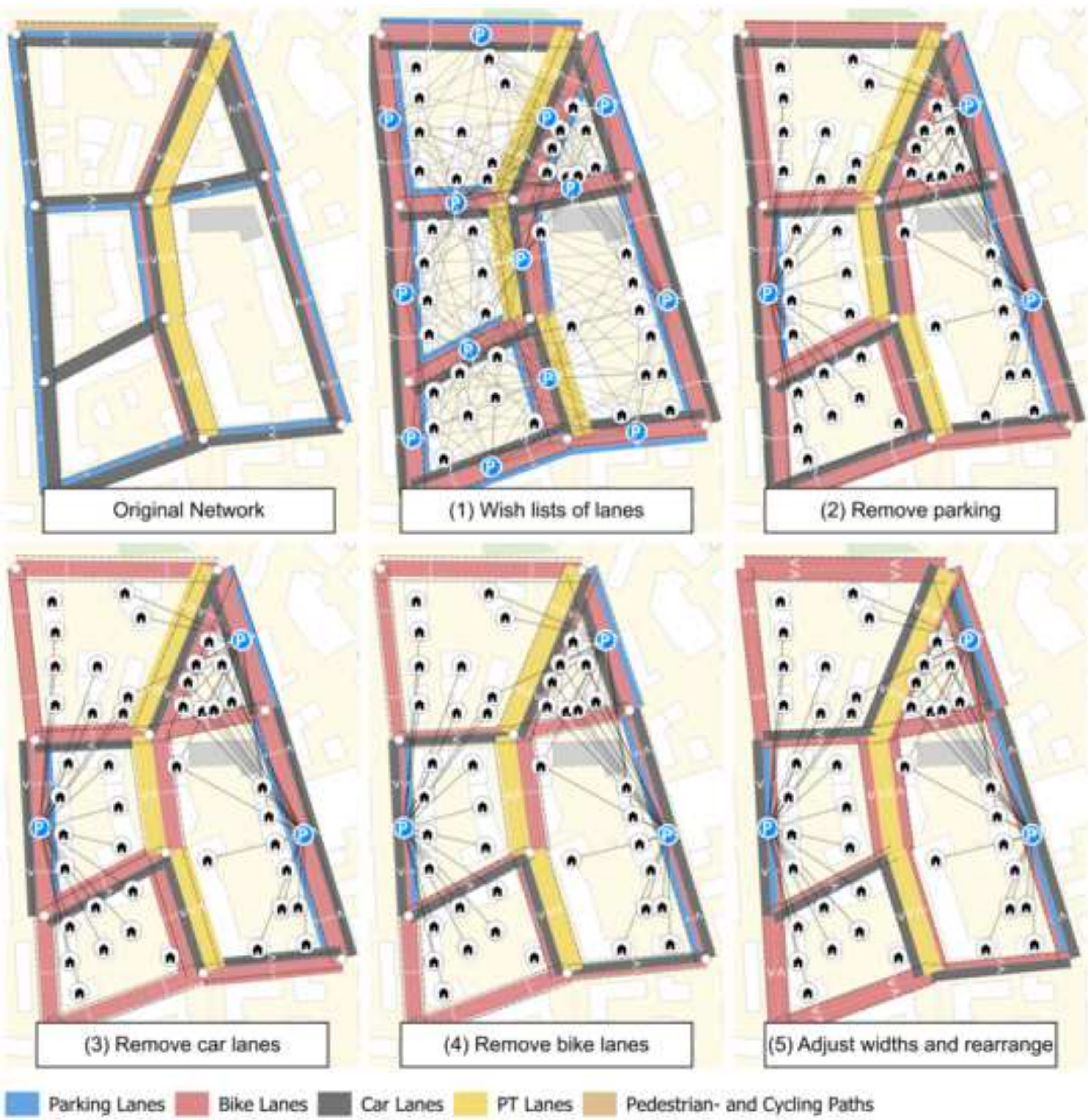

Network previews

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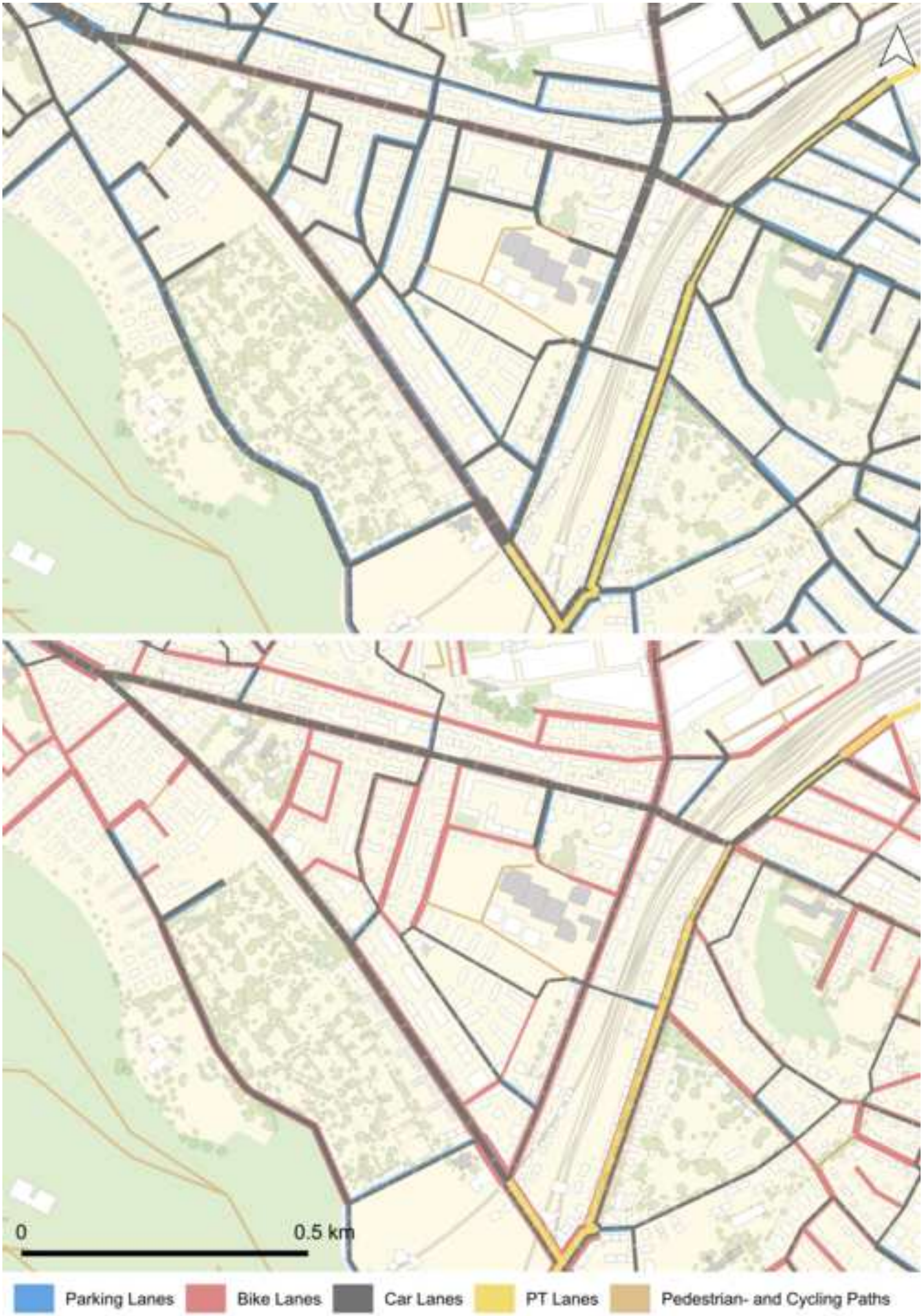

Simplification