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A case study in Zurich

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Modeling Sustainable Mobility Futures Using an Automated Process of Road Space Reallocation in Urban Street Networks. A Case Study in Zurich.

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ABSTRACT

Transport policy research must explore different more or less radical mobility futures that would be able to rapidly reduce the carbon footprint of transport. In this paper, we present a method for modeling one such future by focusing on the allocation of road space between different modes of transport. In a case study for Zurich, Switzerland, we apply the method to reshape the street network allocating the maximum possible proportion of road space to cycling infrastructure, while still allowing access for motorized traffic. Multiple design rules are applied: Ensuring the reachability for motorized traffic, guaranteeing the routes needed by the present public transit services, and maintaining street hierarchies. The resulting network shows many single-lane one-way streets, with generous infrastructure for cycling.

We use Value-of-Distance indicators from route choice models to represent the benefits created by the added cycling infrastructure. In a descriptive analysis of the present and the rebuilt street network, we show that the overall length of the cycling infrastructure can be increased by a factor of three while reducing the average distances perceived by cyclists by 20%. On the other hand, the average shortest path for motorized traffic would grow by 36%, its network of lanes would become less redundant and its capacity would decrease.

A Python implementation is available as open-source software. The networks generated by the software can be used as input in common transport modeling tools for impact assessment studies.

Keywords: urban transport; e-bike city; road space allocation; street networks; sustainability

1. INTRODUCTION

Mobility is one of the largest contributors to climate change [1] but reducing its carbon footprint is difficult. Besides technical challenges, transport policy is caught in a dilemma between several contradicting goals [2], [3]: While radical decarbonization would increase the private cost of transport, low-cost transport, and growing accessibility are important drivers of economic growth [4]. Simultaneously, innovations like electrification or autonomous driving will reduce the generalized cost of private car use [5], [6], inducing more traffic and urban sprawl [7]. Trying to navigate between these contradicting goals, policymakers tend to opt for incremental optimization with smaller measures rather than tapping into larger sustainability potentials.

As a way out of this dilemma, [8] calls for exploring different mobility futures, with tangible plans for transport in real cities – in particular, "car-reduced" futures, leveraging behavior change to reduce the negative externalities of transport. [9] proposes the paradigm of 15-minute cities, where trips are short and active mobility takes a large mode share. [10] shows a practical example of how similar ideas could be implemented in the grid of Barcelona, using "superblocks".

Unlike other modes of transport, active mobility is associated with positive externalities [11], i.e., growing volumes of walking and cycling produce external benefits. It also provides 7-13x more capacity on the same road space compared to private motorized vehicles [12]. However, little work has been done so far to study whether it could be the basis of citywide transport, apart from relatively marginal cycling infrastructure programs. In [13], we have introduced a more specific car-reduced future to be developed and tested: The *E-Bike City*, a transport policy based on the primacy of sustainable modes such as cycling and transit. As an initial hypothesis, it assumes to allocate ~50% of road space to cycling and other forms of micromobility, supported by a well-functioning public transit network. Unlike more radical "cycling utopias", e.g. [14], [15], the concept would aim for a balanced approach, allowing for a mix of modes like today, only with a different distribution of capacity and generalized costs.

In this paper, we present a novel process for designing and testing alternative scenarios of road space allocation (such as the E-Bike City) in existing street networks. It is demonstrated with Zurich, Switzerland, a city of 450'000 inhabitants with an area of 88 km^2 within a metropolitan area of about 1.5 million. The street network data is acquired from OpenStreetMap (OSM) and enriched with local datasets. We identify the maximum potential for reallocating road space to dedicated cycling infrastructure and use a series of graph measures to show the consequences for the network performance.

The rest of this paper is structured as follows: Section 2 elaborates on the background and existing literature. Section 3 describes the methods and workflows used. Section 4 shows the results and discusses them. Finally, section 5 concludes the paper with suggestions for future work.

2. BACKGROUND

2.1 Optimal cycling network design

Automated approaches for generating cycling networks enjoy growing interest. [16] starts with important network nodes, searches for the best paths to connect them with dedicated cycling infrastructure, and creates an optimal order in which the infrastructure should be implemented. Similarly, [17] generates networks of cycling infrastructure by using the demand data from public bike-sharing systems and deciding which links would provide the highest benefits. [18] focuses on optimizing the use of financial resources by identifying small gaps in existing cycling networks where targeted improvements produce the highest benefits. These methods aim for finding the most suitable routes for new cycling infrastructure, considering comfort and construction costs. However, they do not include the tradeoffs of reallocating limited road space to cycling or other modes.

2.2 Network design approaches

A systematic design of alternative networks on existing streets requires a principle for deciding how the road space should be reallocated. While cyclists can use most lanes for motorized traffic (with reduced comfort), drivers cannot use dedicated cycling infrastructure. Therefore, the design principle must provide a way to ensure connectedness for motorized traffic, while maximizing the space for cyclists.

The *Superblocks* paradigm assumes that a basic network of main streets remains accessible to motorized (through) traffic, forming large blocks while all local streets are dedicated primarily to active mobility [10]. It has been originally proposed for the 19^{th}-century grid in Barcelona, grouping the existing street blocks into larger “superblocks”. The resulting network provides long straight streets both for drivers as well as cyclists and pedestrians. [19] has tested the same approach for other cities. While in principle feasible, its implementation in cities with irregular street patterns requires that most (direct) main roads remain dedicated to motorized traffic, while micromobility would have to use less direct local roads.

Different methods from graph theory offer further design alternatives. A *Minimum Spanning Tree* (MST) provides the minimum subset of edges for motorized traffic, needed to maintain the reachability of all nodes [20]. However, its definition as an undirected graph would not allow one-way streets. In cities with many two-lane streets, each street would either be for active modes or motorized traffic only. It would create a system of cul-de-sac arrangements for motorized traffic, creating a strong concentration of traffic on key streets and intersections. A further alternative is a *Minimum Equivalent Graph* (MEG), which is defined by the minimum subset of edges to maintain the reachability of nodes in directed graphs [21]. Unlike MST, it allows for one-way streets and loops, thus creating streets with space for both motorized and active modes and not enforcing cul-de-sacs. Similarly, the *Transitive Reduction* (TR) also minimizes the number of edges (or the sum of their weights) but ignores the edges that already exist in the original graph [22]. However, it potentially creates edges where there are no existing streets.

2.3 OpenStreetMap data acquisition and simplification

OSM provides open geo data, available globally in a consistent format. The Python package `osmnx` [23] provides tools for downloading the data, performing basic geospatial operations, and exporting it to commonly used data formats. It uses a custom data structure, built on top of the Python `networkx` package to store the street network data as a directed graph. Besides the graph itself, `osmnx` also stores the exact geometry of each street and each node. It also provides basic network simplification tools, such as reducing nodes with degree=2 or consolidating intersections by using simple buffers.

2.4 General modeling network specification (GMNS)

GMNS is a standard for modeling street networks both at a level of streets and intersections, as well as individual lanes [24]. Besides a basic model of nodes and edges, it provides a data structure to store information about lanes and their attributes. While originally developed for studies on autonomous driving, it can also be used for representing the allocation of road space on streets. An open-source Python package `osm2gmns` [25] enables the conversion of open geo data from OSM to the GMNS data format.

2.5 Indicators

[26] develops a comparison of cities around the world using a series of graph measures such as the total length of streets, node count, circuity, or average node degree. [27] studies differences in the structure of urban networks using the orientation of streets. The work of [28] introduces a Python toolkit `momepy` for analyzing urban morphologies. [29] analyze global differences in urban sprawl using a street network disconnectedness index, capturing the difference between networks with redundant and well-connected street networks and those dominated by cul-de-sac arrangements. [30] study the factors influencing the capacity of urban street networks. They identify four measures of road networks that explain 90% of variation in their total vehicle-km/hour production: road network density (lane*km per km^2), betweenness centrality, intersection density, and bus production density (bus*km/h/km^2). In their findings, networks with high capacity (in terms of producing vehicle*km) are associated with high lane density, low betweenness centrality, low intersection density, and low bus production density.

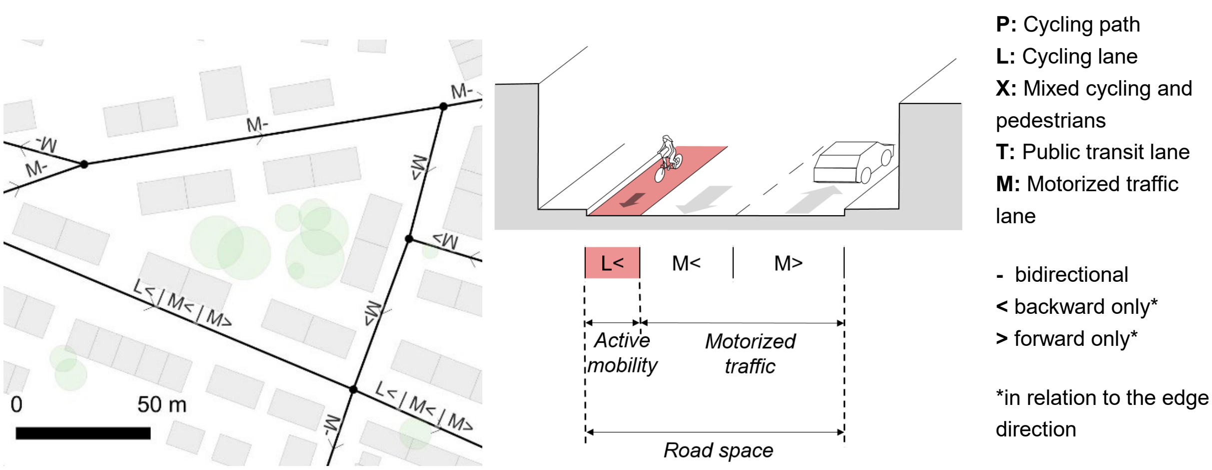
The benefits of cycling infrastructure, as opposed to mixed traffic, are commonly studied using route choice models. [31] have recently estimated a path size logit model from 4'432 cycling trajectories in Zurich. Expressing the parameters in a *Value of Distance* (VoD) space shows the users' perception of individual route attributes in units of distance. The authors report median VoD indicators for average users 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. However, it is likely due to forced choices created by the spatial constellation of Zurich's network.

The findings in [31] are in a similar range as in studies from other cities. [32] reports mean VoD indicators of -0.249 for bicycle paths/lanes in peak hours in Copenhagen. Another study in Copenhagen [33] shows VoD indicators of -0.044 for roads with bicycle lanes and -0.231 for roads with bicycle paths. [34] has found "distance values" of -10.8% to -26% in Portland. [35] reports average "marginal rates of substitution" of 0.49 (bike lanes) to 0.92 (bike routes) in San Francisco.

3. METHODS

3.1 Graph modeling

We define a data structure *street centerline graph* (SCG), a directed graph representing each street as one edge and each intersection as one node. It is based on the data model in `osmnx`. Information about the allocation of road space on each edge is stored as a list of lanes with type, width, and direction, similar to GMNS [24]. The direction of each edge is generally from the lower to the higher node ID and the lanes (both order and direction) must be reversed if the edge direction is changed. Within the "road space", we consider only lanes for motorized traffic, cycling, and public transit. For simplicity, pedestrian-only infrastructure is not considered. This data structure enables a robust evaluation and editing of road space allocation. By exporting the list of lanes as a text attribute, the data can also be manually reviewed and edited in a standard GIS tool. Multiple scenarios of road space allocation can be stored in the same SCG, e.g., the "status quo" and a "rebuilt" state. Figure 1 shows an illustration of the SCG data model.



Street centerlines with lanes — Exemplary street section — Legend

Figure 1: Data model of the street centerline graph

While the SCG allows an efficient storage of street network data with easy editing and no redundancies, it has the disadvantage of not being routable using standard graph tools in `networkx`. To overcome this shortcoming, we add a secondary representation – a *lane graph*. By representing each lane as a separate directed edge, it is routable, while considering the mode-specific generalized cost of every lane type. This secondary data structure allows us to calculate a vast number of graph measures, and facilitate the process of reallocating lanes between different modes of transport.

The following sections explain the workflow. Figure 2 shows a graphical overview.

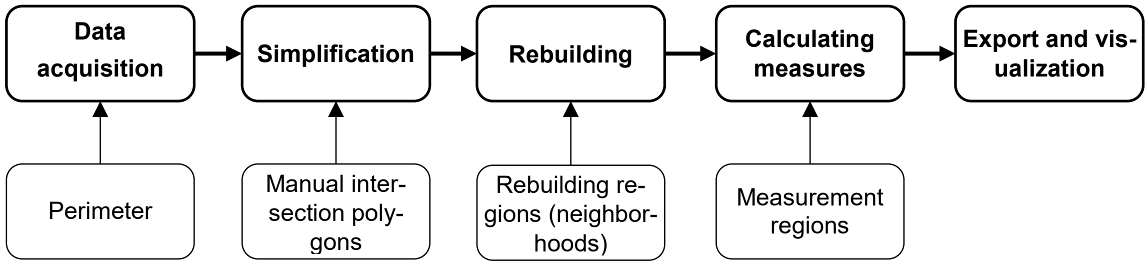


Figure 2: General workflow

3.2 Data acquisition

The network data is requested from OSM using the `osmnx` library and a perimeter polygon. We only request publicly accessible edges that are usable by motorized traffic, public transit, or cycling. Pedestrian-only infrastructure, as well as private links, are excluded. This is essential for limiting the complexity of the network. The following OSM tags are saved into the street graph: `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`. The output (street graph) is a directed graph that represents "nodes" and "ways" (OSM terminology) as nodes and edges. In our case study, the requested data covers the city of Zurich plus a buffer of 5 km. The descriptive statistics of the dataset are shown in Table 1, under "raw network".

3.3 Reconstruction of lanes

After loading the network data, the available OSM tags of each edge are translated into a unified representation of lanes, similar to GMNS. This process relies on the following tags:

- `highway`, `lanes`, `oneway`, `psv`, and `maxspeed` for information about the standard lanes for motorized traffic and their directions
- `vehicle:lanes:forward`, `vehicle:lanes:backward`, `bus:lanes:forward`, and `bus:lanes:backward` for the exact arrangement of designated bus lanes
- `bicycle`, `cycleway:left`, `cycleway:both`, and `cycleway:right` for cycling infrastructure

This process for reconstructing lanes from the tags has been tested in different cities in Switzerland. Because of slight differences in the tagging conventions, as well as local infrastructure designs, it may need further development before being usable in other regions. As OSM typically does not provide any information about the width of individual lanes or entire roads, there is a need to make assumptions. In general, we assume a width of 3.0 meters for general motorized traffic lanes and 1.5 meters for cycling lanes. Bidirectional lanes for motorized traffic are assumed to have a width of 4.5 meters. See Table 2 for an overview of the assumptions and their sources.

3.4 Simplification

At this stage, most intersections are represented by multiple nodes, and many streets are represented by multiple edges. The largest intersections in Zurich contain up to ~100 nodes and many streets have 2-5 parallel edges. To create an SCG, where the entire road space allocation on each street is concentrated into a single edge, the network must undergo a heavy simplification such that each intersection is represented by exactly one node and each street by exactly one edge.

At first, we detect the spatial boundaries of intersections. All nodes with a degree ≥ 3 are grouped using unions of 10-meter buffers. Similar buffer sizes are common in literature [26], [29]. The results are manually verified and in cases where intersections are consolidated incorrectly, the automatically imposed boundaries are overridden by manual polygons.

Second, we split edges passing through the intersection polygons. This step is important for properly consolidating wider streets with multiple parallel edges. Side streets that don't attach to all of the parallel edges (e.g., one-sided junctions) would otherwise prevent a full simplification of such streets into single centerline edges.

Third, we group nodes within each intersection polygon using weakly connected components. This step allows the separation of disconnected parts of intersections, e.g., due to being on different physical levels. However, to include the 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 don't permit motorized traffic are treated separately from those that do. This allows to preserve the information about parts of streets being accessible for different modes. OSM tags, as well as the list of lanes, are copied from the longest edge in each chain, discarding more detailed information about shorter segments (e.g., a short narrow section of a longer street).

The final step merges all sets of parallel edges, i.e., sharing the same pair of start node *u* and end node *v*, as well as the same `layer` tag. The OSM tags are copied in a way that maintains the highest road hierarchy and highest speed while discarding the information about parallel paths that might have lower speeds or hierarchy levels. This step also discards any physical separations (medians, trees) and treats the sum of all available road space as one entity.

The above steps are repeated multiple times until all possible simplifications have been made. Finally, the geometries of all resulting edges are simplified to eliminate any sharp turns produced by attaching the merged edges to the consolidated intersections. Reviewing the simplified network has shown that the quality of the OSM data in Zurich is very high. Only a few instances of incorrect `layer` tags have been fixed in the public OSM database to prevent substantial errors in the resulting network. Other minor errors have been ignored.

Table 1 shows the descriptive statistics for both, the entire raw and simplified graph. The simplification reduces the number of nodes by 59% and the number of edges by 58%. Figure 3 shows an exemplary comparison of the raw and simplified street network at Zurich Hardplatz. The 'Hardbrücke' Bridge, represented by four edges in the raw OSM data has been simplified to a single edge. The complex intersection on two different levels has been consolidated from 47 to 9 nodes, while regular intersections are simplified to exactly one node.

Table 1: Descriptive statistics of the network before and after simplification

	Raw street graph	Simplified street centerline graph	Difference
area	383 km2	383 km2	-
N nodes	49'398	20'180	-59%
N edges	61'250	25'660	-58%

Figure 3: OSM map preview (left), raw street graph (middle), and simplified street centerline graph (right) at Zurich-Hardbrücke

3.5 Enrichment

The SCG maintains all relevant information provided by OSM, such as road hierarchies, and maximum speeds. However, further information is still needed that can only be acquired from other sources. Using spatial joins, we add elevation data from the Swiss digital elevation model DHM25 provided by Swisstopo[1], as well as the up-to-date public transit network data provided as a shape file by Zürcher Verkehrsverbund[2].

3.6 Rebuilding

The enriched SCG enables the generation of alternative arrangements of lanes within the existing road space. However, the set of possible alternative arrangements is limited by network-level requirements, such as the reachability of nodes. As a minimum, the resulting lanes for motorized traffic must ensure that every node is still reachable by motorized traffic and that vehicles don’t get caught in loops of one-way streets. In mathematical terms, the graph of motorized traffic lanes must be strongly connected. More closely, we formulate the following requirements:

(1) Every existing intersection must be reachable for motorized traffic

(2) Every main street (`highway=tertiary` or higher) must allow access for motorized traffic

[1] https://www.swisstopo.admin.ch/de/geodata/height/dhm25.html

[2] https://geolion.zh.ch/geodatensatz/show?gdsid=108

(3) All public transit services (except neighborhood busses and night busses) must be able to operate along the same routes as today

(4) The network must maintain a hierarchy, where main streets allow vehicles to travel between intersections with other main streets without diverting through neighborhoods

While respecting the above requirements, we aim for a network that allocates the maximum possible road space for dedicated cycling infrastructure. Please note that the requirements are formulated in terms of topology only while ignoring the capacity (as we are interested in the maximum possible reallocation). The rest of this section describes the process of finding such a network.

In the SCG, we remove all lanes except those for motorized traffic and split them into three categories: (1) Mandatory lanes with their direction to be defined, (2) mandatory lanes with a fixed direction, and (3) optional lanes. The first category is used on main streets, where at least one lane must remain accessible for motorized traffic. The second category allows to guarantee the lanes that are necessary for public transit. The last category includes all other lanes. Then, we split the SCG into a set of subgraphs, using "rebuilding regions" shown in Figure 4. This allows to create the required hierarchies, as well as reduce the computational complexity. The first subgraph (defined by the red region) includes only the main streets in the city, while the other subgraphs (black regions) include both the main streets and the local streets in every neighborhood. These regions are defined manually, typically as areas created by the mesh of main streets. Neighboring black regions have slight overlaps to ensure that each one of them includes all adjacent main streets. Each subgraph of the SCG is then converted into a lane graph (see section 3.1). Every lane with an undefined direction is represented by a pair of two opposite edges and every mandatory lane with a fixed direction is marked as "fixed".

Next, in each rebuilding region, we find the minimum set of motorized traffic lanes by generating a modified version of MEG (see section 2.2): Instead of finding a graph with the minimum edge count, we iteratively remove unfixed edges that have the lowest betweenness centrality. After each edge is removed, if the resulting graph violates the four requirements above, the edge is added back to the graph and marked as fixed. The process is finished once all remaining edges in the graph are fixed.

The resulting subgraphs are used to rearrange lanes in the SCG. Those lanes that have been removed, are replaced by cycling infrastructure with a width that fills out the available space. For simplicity, all cycling infrastructure is considered equal, i.e. without distinguishing between cycling paths and cycling lanes. Since we have already guaranteed the reachability of every node by motorized vehicles, it is implicitly guaranteed for cyclists as well. However, there is no guarantee that they can reach every place using cycling infrastructure only.

The subgraphs are extracted, rebuilt, and written back into the main SCG one by one so that each one builds on the information resulting from rebuilding the previous subgraphs. The regions are defined such that each street is rebuilt only once. The main streets are rebuilt first. Afterward, parts of the main street network are used in each neighborhood subgraph but they are automatically considered as fixed, in order not to alter them anymore.

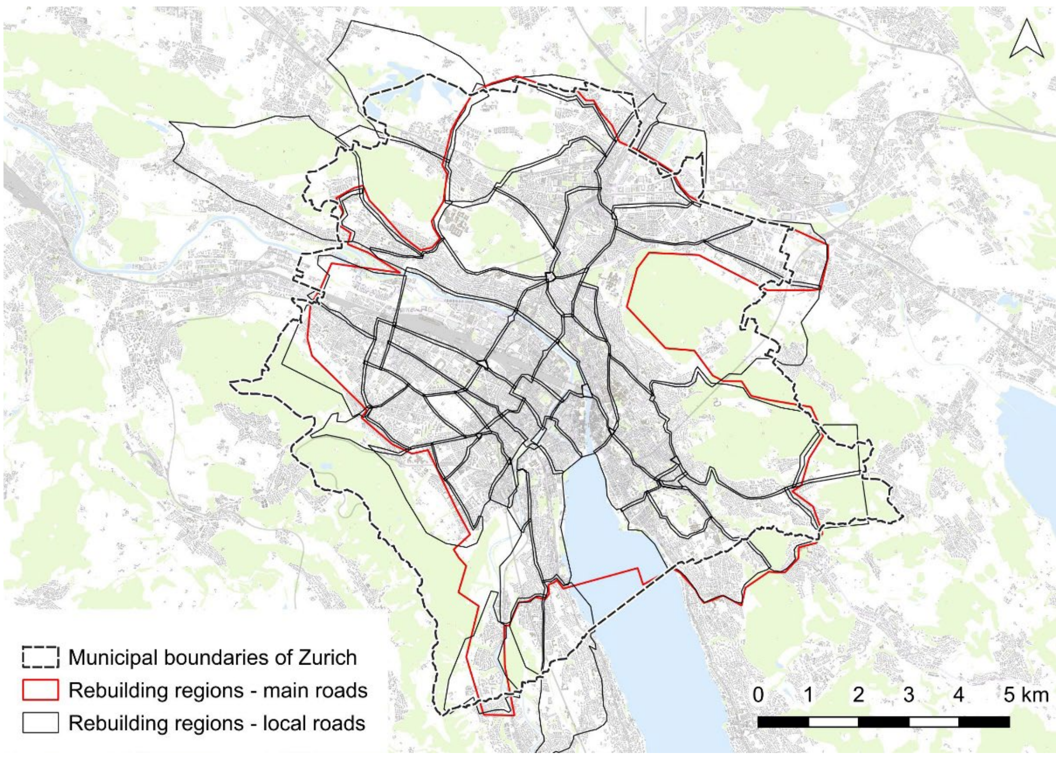


Figure 4: Segmentation of the street graph for rebuilding

3.7 Visualization and calculation of network indicators

A set of metrics is calculated to compare the functional characteristics of the street network before and after rebuilding. These include the estimated area of road surface dedicated to each mode, as well as graph-theory metrics that illustrate the differences in detours and redundancy. For general reference, we also include descriptive metrics showing the number of nodes and edges accessible for each mode. The resulting road space allocation before and after rebuilding is visualized using the open-source software QGIS.

The estimated area of road surface relies on assumptions about lane widths, as the OSM data does not contain this information explicitly (see section 3.3). Differences in detours are shown using the average shortest path (ASP) between nodes. Changes in network redundancy are illustrated using normalized average edge betweenness centrality. To reflect the behavioral reaction of cyclists, we use the VoD indicators from [31] to calculate the perceived length of every link, considering the provision of cycling infrastructure. For simplicity, all cycling infrastructure is treated equally, with a VoD indicator of -0.51 (see Table 2), which is the mean of the values for cycling lanes and cycling paths, reported by [31]. The impact of slopes is not included since they are not subject to change (except for minor effects due to changes in route choice). Although the capacity for motorized traffic is not explicitly studied in this analysis, rough estimates are possible using the model in [30] (see section 2.5).

The network contains a buffer around the city of Zurich. To obtain the metrics only for the municipal area, we clip the SCG to Zurich's administrative borders ("measurement region") and discard the rest. This graph is then converted into six separate lane graphs, representing combinations of two scenarios (before and after rebuilding) and three modes (motorized traffic, cycling, and public transit). For each mode, we create a version of the lane graph where only the accessible edges are included, i.e., the edges that can be legally used by that mode. For example, the lane graph for cyclists includes all cycling lanes/paths, as well as the lanes for motorized traffic, while the lane graph for private cars includes only the latter. To limit the impact of interregional infrastructure, we have excluded all lanes coming from highways (OSM tag highway=`motorway` and `motorway_link`) from this analysis. The geographical clipping may leave parts of the graph inaccessible (i.e. if the connecting edges lay outside of the area). However, since some graph measures require a strongly connected graph, we isolate only the largest strongly connected component.

Table 2: Assumptions and inputs

Name	Value	Comments
tolerance buffer for consolidating intersections	10 m	see [26], [29]
lane width single direction	3.0 m	typical width for single-direction lanes in Zurich
lane width bidirectional	4.5 m	typical width for bidirectional lanes in Zurich
default cycling lane width (on the initial conversion of OSM tags to lanes)	1.5 m	typical (minimum) width of cycling lanes in Zurich
VoD indicator cycling lane or path	-0.51	mean VoD indicators for cycling lanes and paths in [31]

4. RESULTS AND DISCUSSION

Figure 5 shows a preview of the network before and after rebuilding in the Zurich downtown area[3]. While presently, cycling lanes and paths are limited to very few (main) roads, the rebuilt network offers cycling infrastructure nearly on every street. However, on some streets, no cycling infrastructure is possible under the given constraints, e.g., due to the necessity to provide bidirectional travel for public transit (see the street at the bottom right). The computation time for the given Zurich perimeter is roughly 5 hours (one hour for simplification, four hours for rebuilding) on a standard business laptop.

Table 3 shows the relative allocation of road space before and after rebuilding. The rebuilt network allocates 36.4% of road space to cyclists which is an increase by a factor 3.1 in comparison to the present state. In the rebuilt state, 16.9% of road space is allocated to cyclists on primary, secondary, tertiary roads, and service roads, 11.9% is on residential roads, and the rest is divided between living streets, footways (shared with pedestrians), independent paths, dedicated "cycleways", and other road types.

A complete set of descriptive metrics is shown in Table 4. They are shown for motorized traffic, cycling, and public transit, before and after rebuilding. Please note that these metrics are calculated for a lane graph covering the Zurich municipal area, which is different than the entire street (centerline) graph described in Table 1. The number of accessible nodes and edges (lanes) is higher for cyclists than for motorized traffic because every edge that is usable by motorized traffic is also usable by cyclists but not vice versa. The same effect applies to public transit and motorized traffic.

[3] The entire network in PDF is available under https://polybox.ethz.ch/index.php/s/Yj4fxYeBRmcD0rz

Small differences in the number of accessible nodes before and after rebuilding are due to changes in the largest connected components with different allocations of road space (depending on the road space allocation, parts of the network are accessible only using roads that are outside of the "measurement region").

The total length and surface of lanes usable by motorized traffic has decreased by 27.1%. In exchange, the total length of lanes dedicated to cycling has increased by a factor of 2.9. The total road surface dedicated to cycling grew by a factor of 3.1, indicating that the cycling infrastructure has become not only longer but also wider. The network for motorized traffic has become less redundant, with average normalized betweenness centrality growing by 100%. Although a similar effect is shown for public transit, the design criteria guarantee that it has no impact on the existing (major) routes. The ASP for motorized traffic grew by 36%, while the perceived ASP for cyclists decreased by 20%. A slight increase in the ASP for cyclists can be explained by a small increase in the graph size due to differences in the largest connected component. The increase of ASP for public transit refers to all lanes that can be theoretically used by busses but has little practical relevance since the effectively used remain unaffected (see design rules in section 3.6).

Table 3: Proportion of road space before and after rebuilding

Street type (OSM high-way tag)	**Before %**	**After %**
primary	1.39	4.22
secondary	1.51	3.15
tertiary	2.44	6.41
service	0.11	3.19
residential	0.81	11.92
living_street	0.02	0.87
cycleway	0.12	0.19
footway	1.54	1.50
path	1.61	1.68
unclassified	0.07	0.89
(other)	2.04	2.36
Sum	11.67	36.38

Figure 5: Preview of the network before (top) and after (bottom) rebuilding

Table 4: Descriptive network metrics (Zurich municipal area)

	Motorized Traffic		Cycling		Public Transit	
	Before	After	Before	After	Before	After
accessible nodes [-]	6’881	6’776	7’420	7’462	6’904	6’803
accessible edges [-]	12’241	9’074	16’331	18’266	13’365	10’212
usable lanes [km]	1’256	916	1’523	1’820	1’364	1’026
usable lanes [km2]	4.545	3.158	4.964	5.044	4.87	3.49
lanes as primary mode [km]	1’256	916	324	945	107	107
lanes as primary mode [km2]	4.545	3.158	0.646	2.062	0.32	0.32
avg normalized betweenness centrality [-]	0.00398	0.00798	0.00298	0.0029	0.00366	0.00593
avg shortest path (ASP) [km]	5.566	7.584	5.386	5.397	5.48	6.262
perceived ASP VoD [km]	-	-	3.946	3.151	-	-

The analysis shows a substantial unrealized potential to shift the transport system performance in favor of sustainable modes. The space dedicated to cyclists can be more than tripled while maintaining motorized access to all network nodes, as well as keeping the present public transit network. Providing such infrastructure would reduce the average distances perceived by cyclists by 20% while increasing the ASP for motorized traffic by 36%. Traffic management measures may ensure that the travel times of busses and trams don’t increase, despite sharing parts of the reduced capacity with general motorized traffic. These will, however, further reduce the capacity for private motorized traffic.

On the other hand, it may be questioned to which extent there is a justification for increasing the ASPs for drivers by a larger value than decreasing the perceived distances for cyclists. Also, a substantial part of the potential cycling infrastructure is on residential streets where it may not be needed if their traffic volumes are low. Therefore, further refinements in the network design goals may be tested, attempting more satisfactory detours for both modes, as well as a stronger prioritization of main roads for cycling infrastructure. A refined calculation of metrics may increase the accuracy of the ASPs by integrating demand matrices and weighting the paths accordingly.

The presented results build on the assumption of preserving motorized access to every node of the present network, guaranteeing the availability of lanes for present major public transit routes, as well as maintaining street hierarchies. Further, we have only considered the lanes for moving traffic so far, assuming standard widths. Future extensions of the process may consider adding new zones without motorized traffic, changing the routes of transit services, removing on-street parking, or narrowing existing lanes. Adding these factors will likely increase the proportion of road space that can be allocated to cycling infrastructure. Therefore, the potentials presented in this paper are to be considered a lower boundary.

Future work may utilize the method in this paper to create a wide range of mobility futures, e.g., with a focus on transit or autonomous vehicles, serving as an input for simulating different mobility futures, like those called for in [8] in real cities. Further development should add more details, like intersection designs, public transit timetables, or identifying potentials for removing parts of the road space in favor of more attractive pedestrian spaces and greenery. Most importantly, future studies are needed to assess the effective performance of the resulting networks including travel times, mode choice, route choice, accessibility, and equity analysis.

5. CONCLUSION

This work is part of an effort to envision and test the E-Bike City as a tangible vision for overcoming the dilemmas of transport policy. After the first thoughts in [3] and [8], and a more specific description in [13], this paper presents a process for designing the E-Bike City in real settings. The next step toward testing it is to show designs for specific streets and conduct a robust impact assessment. We would like to give an impression of the look and feel of the E-Bike City, as well as use an agent-based simulation to make the expected impacts tangible. Aggregate (emissions, congestion, travel times, mode choice, etc.), as well as disaggregated metrics, should show how will it impact the environment as well as the lives of individual groups of people.

An implementation of the method presented in this paper is available as open-source software under https://github.com/lukasballo/snman/. As a side product but a necessary prerequisite for this work, we have also developed a comprehensive simplification algorithm for OSM data, allowing other researchers to analyze the allocation of road space in cities around the world with a few lines of code.

The climate crisis and rapid urbanization create the need to think about a wide range of futures for urban mobility. The process presented in this paper provides a tool for facilitating such discussions with tangible designs, as well as data from models and simulations.

AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: Conceptualization: L. Ballo; Draft manuscript preparation: L. Ballo; Manuscript review: L. Ballo, K. W. Axhausen. All authors have reviewed the results and approved the final version of the manuscript.

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