Is "small" infrastructure the next factory for accessibility?

Evaluating the regional accessibility effects of a cycling-centric transport policy in Zurich

Working Paper

Author(s):
Ballo, Lukas; Sallard, Aurore; Meyer de Freitas, Lucas; Axhausen, Kay W.

Publication date:
2024-08

Permanent link:
https://doi.org/10.3929/ethz-b-000688987

Originally published in:
Arbeitsberichte Verkehrs- und Raumplanung 1888

TRB Annual Meeting

Is “Small” Infrastructure the Next Factory for Accessibility? Evaluating the Regional Accessibility Effects of a Cycling-Centric Transport Policy in Zurich.

--Manuscript Draft--

Full Title:	Is “Small” Infrastructure the Next Factory for Accessibility? Evaluating the Regional Accessibility Effects of a Cycling-Centric Transport Policy in Zurich.
Abstract:	Decades of investments into “large” transport infrastructure, such as highways and heavy rail have created immense welfare gains through increased accessibility. Today, however, further accessibility improvements in dense urban regions are only possible at rapidly growing costs. Also, the high volumes of car traffic resulting from large highway infrastructure programs conflict with the need for rapid decarbonization. In this paper, we evaluate whether shifting the policy focus toward “small” infrastructure focused on micromobility modes is a viable option for decarbonizing the transport system and creating further accessibility gains. This work analyses a road space reallocation scheme termed “E-Bike City” for Zurich, Switzerland, presented at this conference in 2023. First, we use MATSim to simulate its effects on road traffic. Second, we calculate a logsum accessibility measure for a population sample, before and after the transformation. Value-of-distance indicators from a route choice model are used to quantify the effects of cycling infrastructure, as opposed to mixed traffic. And finally, we report the changes for different population groups and reflect on the impacts. Our first findings indicate that such a policy could strongly reduce the car traffic volumes in some areas, while slightly improving the median accessibility levels across the entire metropolitan region. However, various methodological challenges remain. Given the urgency of the underlying motivation, we want to spur a discussion about the future transport investment focus, as well as an appropriate methodological framework to evaluate the possible paths to be taken.
Additional Information:	
Question	**Response**
The total word count limit is 7500 words including tables. Each table equals 250 words and must be included in your count. Papers exceeding the word limit may be rejected. My word count is:	5949
Manuscript Classifications:	Pedestrians, Bicycles, Human Factors; Bicycle Transportation ACH20; Cycling Research General; Cycling Level of Service; Cycling Planning and Policy; Planning and Analysis; Transportation Planning Analysis and Application AEP15; Accessibility Planning; Nonmotorized Travel; Public Involvement or Visioning; Transportation Planning Policy and Processes AEP10; Long-Range Plan; Metropolitan Planning; Multimodal planning; Sustainability and Resilience; Transportation and Sustainability; Transportation Energy AMS30; Climate Change Policy; Transportation Network Modeling and Simulation
Manuscript Number:	
Article Type:	Presentation
Order of Authors:	Lukas Ballo
	Aurore Sallard, Dr.
	Lucas Meyer de Freitas
	Kay W Axhausen, Prof. Dr.

Is "Small" Infrastructure the Next Factory for Accessibility? Evaluating the Regional Accessibility Effects of a Cycling-Centric Transport Policy in Zurich.

Manuscript for presentation at TRBAM 2025.

Lukas Ballo (corresponding author)
Institute for Transport Planning and Systems, ETH Zurich
CH-8093 Zurich
ORCID: 0000-0002-0843-0553
Email: lballo@ethz.ch

Aurore Sallard
Institute for Transport Planning and Systems, ETH Zurich
CH-8093 Zurich
ORCID: 0000-0001-6465-858X
Email: asallard@ethz.ch

Lucas Meyer de Freitas
Institute for Transport Planning and Systems, ETH Zurich
CH-8093 Zurich
ORCID: 0000-0002-0280-8914
Email: mlucas@ethz.ch

Kay W. Axhausen
Institute for Transport Planning and Systems, ETH Zurich
CH-8093 Zurich
ORCID: 0000-0003-3331-1318
Email: axhausen@ethz.ch

Word count: 4'699 words + 5 Tables = 5'949 words

Submitted: July 27, 2024

ABSTRACT

Decades of investments into "large" transport infrastructure, such as highways and heavy rail have created immense welfare gains through increased accessibility. Today, however, further accessibility improvements in dense urban regions are only possible at rapidly growing costs. Also, the high volumes of car traffic resulting from large highway infrastructure programs conflict with the need for rapid decarbonization. In this paper, we evaluate whether shifting the policy focus toward "small" infrastructure focused on micromobility modes is a viable option for decarbonizing the transport system and creating further accessibility gains. This work analyses a road space reallocation scheme termed "E-Bike City" for Zurich, Switzerland, presented at this conference in 2023. First, we use MATSim to simulate its effects on road traffic. Second, we calculate a logsum accessibility measure for a population sample, before and after the transformation. Value-of-distance indicators from a route choice model are used to quantify the effects of cycling infrastructure, as opposed to mixed traffic. And finally, we report the changes for different population groups and reflect on the impacts.

Our first findings indicate that such a policy could strongly reduce the car traffic volumes in some areas, while slightly improving the median accessibility levels across the entire metropolitan region. However, various methodological challenges remain. Given the urgency of the underlying motivation, we want to spur a discussion about the future transport investment focus, as well as an appropriate methodological framework to evaluate the possible paths to be taken.

KEYWORDS

Transport Infrastructure Investments; Accessibility; MATSim; Value of Distance; Cycling

1 INTRODUCTION

Decades of transport infrastructure investments in Switzerland have delivered massive improvements in accessibility [1]. Increasing speeds and decreasing real travel costs have created economic benefits in consumer choice, specialization, and residential options. More travel has allowed us to reach more destinations and develop settlements with lower density. However, further large infrastructure such as highways or heavy rail in today's complex built environments can only be built at a rapidly increasing cost, with a high proportion of bridges and tunnels [2]. Moreover, it remains unclear how the resulting growth in travel distances and traffic volumes can be reconciled with the need to decarbonize [3] the transport sector within the next decades [4]. Commonly discussed technical developments such as battery-electric vehicles (BEV) may not be sufficient and adopted fast enough [5], [6], [7] to reduce the carbon emissions of motorized traffic. Other approaches like mobility pricing, or massive transit investments are either politically infeasible [8] or will take too long to implement. And even despite high transit and rail investments in Switzerland, the national mode share of transit is stagnating at around only 20% [9].

Recently, we have proposed to discuss a focus shift in metropolitan transport planning, from the current heavily car-based accessibility production towards policies focused on small micromobility vehicles [10]. Building on top of recent urban livability discussions like 15-minute cities [11] or Superblocks [12], [13], our core hypothesis was that such approaches can lower transport-related CO_2 emissions while maintaining or even increasing the accessibility levels. We proposed to test reallocating approximately 50% of road space to dedicated micromobility infrastructure while ensuring prioritization of public transit, as well as access for essential car trips.

An algorithm for generating and rudimentarily evaluating such transportation schemes was presented in [14]. However, it remains unclear, so far, how such a transformation would affect the accessibility levels. In this paper, we use a logsum accessibility measure [15] to represent the changes experienced by people with different residential locations and demographic attributes. We use MATSim [16], in combination with one-to-many routing in R5 [17] and NetworkX [18] to simulate the traffic flows and travel behavior in the present and changed network, and report the resulting accessibility changes for a variety of spatial and social groups. This paper is structured as follows: Section 2 reports the current mobility choices in Zurich. Section 3 gives an overview of previous work. Section 4 explains the methods used and section 5 shows the results. Sections 6 and 7 close the paper with a discussion and conclusions.

2 MOBILITY IN ZURICH

As of 2024, the municipality 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 larger metropolitan region [19]. Table 1 gives an overview of travel in Zurich, based on the trips reported in the Swiss national travel diary [9].

Table 1: Mobility in Zurich based on trips in the Swiss national travel diary

			Other (Motor-cycle)	E-bike	Cars	Public Transport	Bicycle	Walking	All modes	All modes excl. walking
	average occupancy	-	1	1	1.5	20	1			
	emissions CO_2 eq.[1]	g/pkm	163.6	11.3	186.4[2]	25.4	5.6			
	sample scaling[3]	-	164	164	164	164	164	164		
Within the City of Zurich	person km traveled (sample)	pkm	202	793	13'030	14'360	6'886	10'549		
	person km traveled	pkm	33'044	129'721	2'131'484	2'349'049	1'126'431	1'725'635	7'495'365	5'769'730
	vehicle km traveled	vkm	33'044	129'721	1'420'989	117'452	1'126'431			2'827'638
	person km share	%	0.4%	1.7%	28.4%	31.3%	15.0%	23.0%	100.0%	77.0%
	vehicle km share	%	1.2%	4.6%	50.3%	4.2%	39.8%			
	emissions CO_2 eq.	t	5.4	1.5	397.3	59.7	6.3			470
	share of emissions	%	1.1%	0.3%	84.5%	12.7%	1.3%			100.0%
Cross-Border	person km traveled (sample)	pkm	1'189	416	113'723	137'841	2'488	631		
	person km traveled	pkm	194'527	67'975	18'603'186	22'548'356	406'980	103'273	41'924'296	41'821'023
	vehicle km traveled	vkm	194'527	67'975	12'402'124	1'127'418	406'980			14'199'023
	person km share	%	0.5%	0.2%	44.4%	53.8%	1.0%	0.2%	100.0%	99.8%
	vehicle km share	%	31.8	0.8	3'467.6	572.7	2.3			4'075
	emissions CO_2 eq.	t	0.8%	0.0%	85.1%	14.1%	0.1%			100.0%
Cross-Border (part within the city)	person km traveled (sample)	pkm	238	83	10'865	14'658	712	316		
	person km traveled	pkm	38'933	13'577	1'777'327	2'397'797	116'471	51'692	4'395'798	4'344'106
	vehicle km traveled	vkm	38'933	13'577	1'184'885	119'890	116'471			1'473'756
	person km share	%	0.9%	0.3%	40.4%	54.5%	2.6%	1.2%	100.0%	98.8%
	vehicle km share	%	6.4	0.2	331.3	60.9	0.7			399
	emissions CO_2 eq.	t	1.6%	0.0%	83.0%	15.2%	0.2%			100.0%
Total within the city	person km traveled (sample)	pkm	440	876	23'895	29'018	7'598	10'865	72'692	61'827
	person km traveled	pkm	71'976	143'299	3'908'812	4'746'846	1'242'902	1'777'327	11'891'163	10'113'835
	person km share	%	0.6%	1.2%	32.9%	39.9%	10.5%	14.9%	100.0%	85.1%
	cross-border trips share in person km	%	54.1%	9.5%	45.5%	50.5%	9.4%	2.9%	37.0%	43.0%
	vehicle km	vkm	71'976	143'299	2'605'874	237'342	1'242'902			4'301'394
	vehicle km share	%	1.7%	3.3%	60.6%	5.5%	28.9%			100.0%
	cross-border trips share in vehicle km	%	54.1%	9.5%	45.5%	50.5%	9.4%			34.3%
	emissions CO_2 eq.	t	11.8	1.6	728.6	120.6	7.0			870
	share of emissions	%	1.4%	0.2%	83.8%	13.9%	0.8%			100.0%

[1] Mobitool Swiss emission factors: https://www.mobitool.ch/de/tools/mobitool-faktoren-v3-0-25.html?tag=18, Fleet averages in 2024, including all propulsion types
[2] 89.8 g CO_2 eq./pkm for average battery-electric vehicles
[3] Swiss Population 9'000'000 / Sample size 55’018

Trips within the municipal borders are done largely using public transport, walking, and cycling — only 28.4% of person-kilometers (pkm) are traveled by car. The remaining distance traveled relies on public transport (31.3%), walking (23%), and cycling (15%). For cross-border trips (only considering their part within the city), cars account for a mode share of 40.4%. However, despite these moderate shares, they are responsible for 60.6% of vehicle kilometers (vkm) and 83.8% of all traffic-related CO_2 emissions within the city borders. Even if the cross-border trips, accounting for 45.5% of vkm within the city are excluded, the local car trips account for almost 50% of Zurich's transport CO_2 emissions. Replacing the entire car fleet with battery-electric vehicles will theoretically reduce the emissions of car traffic by roughly 50% compared to the fleet in 2024, to 89.8 g CO_2/pkm, cutting Zurich's transport emissions by about 40%. But even in that case, car traffic will still account for 74.2% of transport emissions in Zurich. Lower cost of operating electric vehicles, and potentially the adoption of autonomous driving may induce more car traffic and eliminate some of these benefits. Thus, redesigning the transport system in favor of other modes has a large potential for reducing emissions, while potentially generating negative effects only for a moderate proportion of trips.

3 PREVIOUS WORK

3.1 Accessibility

Many different definitions of accessibility exist to represent the performance of transport systems. [20] criticize that the measures often used are insufficient and propose a systematic framework of different accessibility types. The possibilities of different people to interact with others are commonly expressed using Hansen [21] accessibility. To represent the utilities of different modes, considering each person's capabilities, [15] propose to combine the original formulation with a discrete mode choice model. The resulting measure is a sum of opportunities for every person, discounted by the costs of reaching them, given their residential location, as well as their characteristics, such as age. The generalized cost of reaching an opportunity is the average of all mode-specific generalized costs, weighted by the choice probability of each mode. The resulting accessibility measure captures the combination of place-based opportunities and personal capabilities, following the capability approach [22]. To calculate the underlying travel time matrices efficiently, [17] introduced a Java-based software R5 (Rapid Realistic Routing on Real-world and Reimagined Networks) for rapid calculation of one-to-many connections in multimodal transportation systems. It can account for varying travel times across different public transport connections [23], as well as fare structures [24].

3.2 Representing cycling comfort in models

The effects of cycling infrastructure include not only travel time changes but also safety and comfort gains. Discrete route choice studies such as [25], [26], [27], and [28] have developed robust estimates of these effects on perceived utility. [29] present such estimates specifically based on a recent GPS-tracking study in Zurich. Converting their model parameters to Value of Distance (VoD) indicators allows representing these effects as added or reduced distance, which can be converted into travel time. This approach allows for representing the benefits of cycling infrastructure while using parts of the modeling methodology that rely purely on travel time.

3.3 Mode choice modeling

The behavioral mode choice component of accessibility [15] introduced above requires a discrete choice model to provide the choice probability of each mode. [30] present such a model for Switzerland, originally developed for a study on the usage of future autonomous vehicles. However, high uncertainty remains about secondary effects, such as those of shifting transport cultures [31].

4 METHODS

4.1 Perimeter

The perimeter for analyzing the outcomes covers the larger Zurich area (1'343 km^2). We define it as all municipalities with at least 15% of their population commuting to the City of Zurich. For generating travel demand in the MATSim model (see section 4.4), the synthetic population is provided for the same area plus a 5 km buffer. Traffic generated by trips beyond that buffer is represented by trip portions cut out of the available nationwide model. The transportation network includes an additional buffer of 5 km, with small extensions for adjacent highway interchanges to avoid long disconnected highway sections. Figure 1 shows a map of the perimeter geometries.

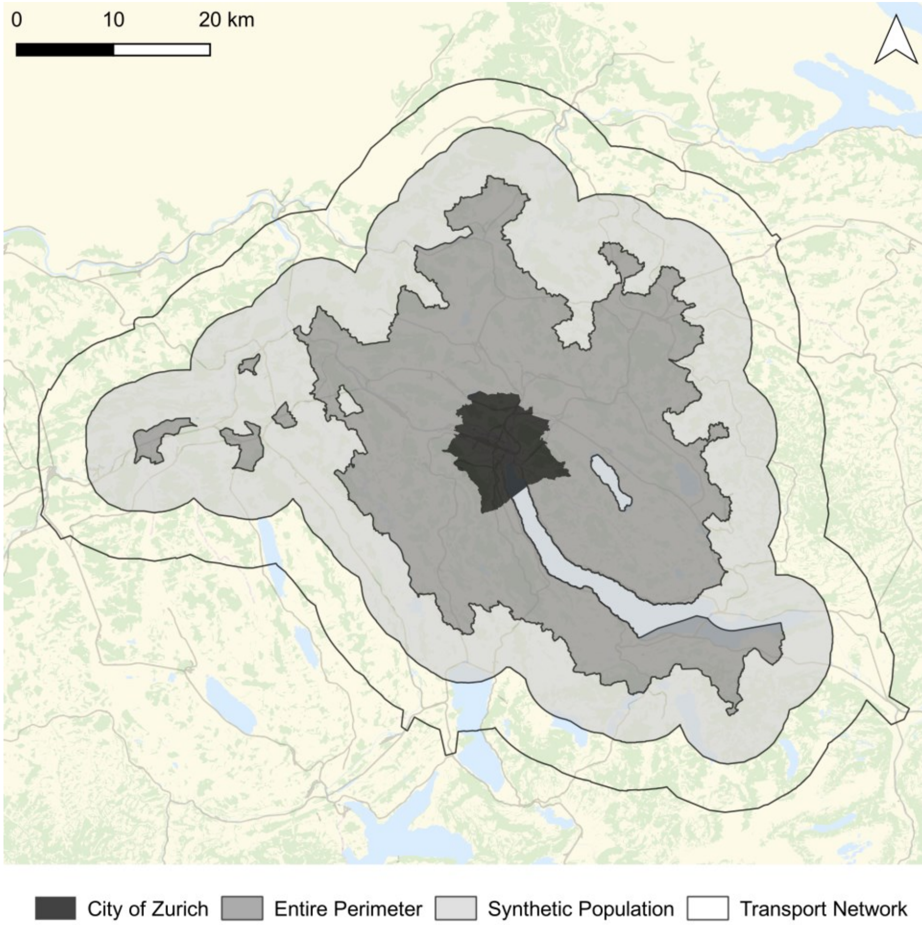


Figure 1: Perimeter geometries

4.2 Datasets on population and destinations

The population data is provided by the 2017 STATPOP dataset of Switzerland[4], representing the home location of each permanent resident, with attributes such as age, sex, and residence permit, but no data on income. The residential locations in this dataset show slight spatial disparities, with a higher-than-average proportion of foreigners, younger residents, as well as males at central locations. The destinations are based on the aggregated STATENT dataset[5], containing economic information, such as the number of jobs, aggregated to cells of 100x100 meters.

[4] https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken.assetdetail.27965868.html
[5]https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/geostat/geodaten-bundesstatistik/arbeitsstaetten-beschaeftigung/statistik-unternehmensstruktur-statent-ab-2011.html

4.3 Network data

The transportation network data is acquired from OpenStreetMap (OSM) and enriched with an on-street-parking dataset of the City of Zurich[6] and public transit routes[7]. Out of this data, we generate a status quo network, as well as one that has been transformed to represent the proposed policies[8]. The latter allocates a large proportion of the existing road space within the city to separated cycling paths and reorganizes the remaining travel lanes to provide access for essential car trips. It creates a high-quality infrastructure for cycling and other micromobility vehicles while maintaining the total road width on every street — unlike other approaches for generating cycling infrastructure which ignore the road space trade-offs, e.g., [32] and [33]. The transformation is limited to an area that roughly corresponds to the municipal boundary. No changes are made to the transportation systems beyond this area. The generation process was introduced in [14] and the network used in this paper is a newer version, presented in [34].

The effects of infrastructure and grades on the generalized cost of cycling trips are included by adjusting the cycling length $l_{uvk,\text{cycling}}$ of each link *uvk* (*u*: node from, *v*: node to, *k*: key for distinguishing multiple parallel links) with VoD indicators from [29]:

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

For $\text{VoD}_{\text{infra}}$, we assume -0.5 if dedicated cycling infrastructure is present and 0 otherwise. For the effects of elevation differences, $\text{VoD}_{\text{grade}}$ is 0.55 for $2\% < \text{grade} \leq 6\%$, 3.11 for $6\% < \text{grade} \leq 10\%$ and 4.33 for $\text{grade} > 10\%$.

Table 2 shows descriptive statistics of the current, as well as of the reallocated transportation network, adapted from [34]. The transformation increases the proportion of road space allocated to cycling infrastructure from 12.1% to 54.3%, while the space for motorized traffic lanes decreases from 66.6% to 35.1%. As a result of many one-way streets and detours in the car network, the average shortest path for car trips increases by 35.7%. On the other hand, the higher number of streets with cycling infrastructure reduces the generalized cost for cycling trips at a level that is equivalent to reducing their average shortest path by 24.1%. The total road space changes slightly due to limitations of the algorithm that cannot guarantee the road space constraint under some circumstances.

[6] https://data.stadt-zuerich.ch/dataset/geo_oeffentlich_zugaengliche_strassenparkplaetze_ogd
[7] https://data.stadt-zuerich.ch/dataset/ktzh_linien_des_oeffentlichen_verkehrs__ogd_
[8] A complete map of the network before and after transformation can be found here: https://polybox.ethz.ch/index.php/s/msguyrD6M9zd0qk

Table 2: Descriptive statistics of the network from [34]

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 dedicated public transport 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%

4.4 MATSim simulation

The distances, after they were adjusted using the VoD indicators can be transformed directly to travel time, using assumptions about average speeds. However, in the case of car traffic, they would not account for differences due to congestion. Therefore, we use the agent-based traffic simulation toolkit MATSim to obtain the car travel times on each link. These are then used as inputs for the successive accessibility calculations. We use the travel times for the morning peak time, at 7:00-7:30.

The MATSim [16] simulation is built using the eqasim pipeline [35] and its implementation for Switzerland [36]. [37] describes the process of cutting the national scenario to the perimeter in Figure 1, with a resulting synthetic population of roughly 2.6 million. We create two separate simulations, one with the network before space reallocation and one after. Both simulations are run for 60 iterations with MATSim 13.0 and the eqasim 1.3.1 discrete mode choice models extension [35]. At the beginning of each iteration, 5% of the agents are replanning their schedule: given the travel times and conditions they experienced previously, they reevaluate their mode (see section 4.5) and route choice. No changes in destination choice or departure time are considered. The remaining 95% keep their previously selected plan. Six transport modes are modeled: “bike”, “car”, “car passenger”, “truck”, “walk”, and “public transport”. Only tours that contain trips by car, bike, public transport, and walking are allowed to change modes during the replanning stage. All motorized individual modes (“car”, “car passenger”, and “truck”), as well as “bike” are routed on the network, which allows for modeling the effects of congestion. For bicycles, we use a seepage [38] link dynamics on links shared with motorized traffic – they are affected by congestion but can seep through the queues. Walking and public transport are modeled as teleported modes. Any effects of additional congestion on the punctuality of public transport are neglected, which is reasonable given that all dedicated bus lanes, as well as the effective priority at signalized intersections, remain unchanged. Any systematic congestion-related delays occurring in the status quo, however, are included in the official scheduled travel times which are different for the peak hours than for the rest of the day.

The key metrics of the two simulations are presented in Table 3. We distinguish between the entire study area and the trips that start and/or end in the city of Zurich. Over the entire area, the volume of cycling grows the most (+14.78% in pkm, +11.29% in pkm-based mode share), followed by public transport (+6.78% in pkm, +3.65% in pkm-based mode share). However, the total volume of car travel increases as well (+0.44% in pkm, -2.52% in pkm-based mode share).

Table 3: Comparison between the two simulations

Metric			Before reallocation		After reallocation		Relative difference (%)	
			All trips	Start/End within City of Zurich	All trips	Start/End within City of Zurich	All trips	Start/End within City of Zurich
Mode share (trip-based)	Car	%	31.56	21.62	30.03	16.12	-4.85	-25.44
	Public transport	%	17.90	34.42	18.54	36.62	+3.58	+6.39
	Bike	%	9.38	9.95	10.27	13.34	+9.49	+34.07
Mode share (pkm-based)	Car	%	48.82	37.67	47.59	34.03	-2.52	-9.66
	Public transport	%	24.94	41.35	25.85	43.03	+3.65	+4.06
	Bike	%	4.43	4.96	4.93	6.70	+11.29	+35.08
Person-km	Car	$x10^6$	37.35	7.62	37.51	7.40	+0.44	-2.86
	Public transport	$x10^6$	19.08	8.37	20.37	9.36	+6.78	+11.92
	Bike	$x10^6$	3.39	1.00	3.89	1.46	+14.78	+45.42
Person-hours	Car	$x10^4$	124..68	27.78	126.92	36.89	+1.79	+32.79
	Public transport	$x10^4$	118.29	51.56	124.46	56.15	+5.22	+8.90
	Bike	$x10^4$	27.43	8.7	41.36	20.87	+50.79	+139.86

These effects are visible to a greater extent in trips that start or end in the city: The trip-based mode shares decreases for cars by 25.44% and increases for cycling by 34.07%. However, the pkm-based mode shares change by -9.66% and +35.08%. This suggests that either predominantly short car trips were replaced, or existing trips became longer due to detours.

The total number of pkm increases for all modes, including cars (despite a slight decrease in the pkm-based mode share), indicating that the new network leads to longer trips. An analysis of the temporal distribution of departures and arrivals reveals that the maximum car traffic flows (and levels of congestion) observed during peak hours decrease, but they take more time to dissolve in the network. This suggests that car drivers travel longer distances and spend more time driving until they reach their destinations during peak hours.

4.5 Mode choice model

The mode choice model used in the MATSim simulation, as well as in the logsum accessibility measure is adapted from [30] and represents the choice probabilities for cars, public transport (PT), cycling, and walking. It considers the attributes of each trip, as well as the age of the person. The model parameters used are shown in Table 4.

$$
\begin{aligned}
U_{\text{car}}(x) = \alpha_{\text{car}} \\
&+ \beta_{\text{TT,car}}\, x_{\text{IVT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\
&+ \beta_{\text{TT,walk}}\, x_{\text{AET}} \\
&+ \beta_{\text{cost}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distCost}}} x_{\text{cost}} \left(\frac{x_{\text{hhIncome}}}{\mu_{\text{hhIncome}}}\right)^{x_{\text{hhIncome}}} \\
&+ \beta_{\text{work,car}}\, x_{\text{work}} \\
&+ \beta_{\text{cityCenter,car}}\, x_{\text{cityCenter}}
\end{aligned}
$$

$$
\begin{aligned}
U_{\text{PT}}(x) = \alpha_{\text{PT}} \\
&+ \left(\beta_{\text{railTT}}\, x_{\text{railTT}} + \beta_{\text{busTT}} x_{\text{busTT}}\right) \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\
&+ \beta_{\text{AET}}\, x_{\text{AET}} \\
&+ \beta_{\text{wait}}\, x_{\text{waitingTime}} \\
&+ \beta_{\text{lineSwitch}}\, x_{\text{numberOfConnections}} \\
&+ \beta_{\text{cost}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distCost}}} x_{\text{cost}} \left(\frac{x_{\text{hhIncome}}}{\mu_{\text{hhIncome}}}\right)^{x_{\text{hhIncome}}} \\
&+ \beta_{\text{headway}}\, x_{\text{headway}} \\
&+ \beta_{\text{OVGK}}
\end{aligned}
$$

$$
\begin{aligned}
U_{\text{bike}}(x) = \alpha_{\text{bike}} \\
&+ \beta_{\text{TT,bike}}\, x_{\text{bikeTT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\
&+ \beta_{\text{age} \geq 60\text{,bike}}\, x_{\text{age} \geq 60}
\end{aligned}
$$

$$U_{\text{walk}}(x) = \alpha_{\text{walk}} + \beta_{\text{TT,walk}}\, x_{\text{walkTT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} + \left(1 - 100^{\frac{x_{\text{walkTT}}}{\theta_{\text{thresholdWalkTT}}}}\right)$$

The choice probability for mode *i* is calculated as follows:

$$P_i = \frac{e^{U_i}}{\sum_j e^{U_j}}$$

Variables used in the model:

x_{IVT}	Car in-vehicle time (min)
x_{dist}	Euclidean distance (km)
x_{AET}	Acees-egress time (min)
x_{IVT}	Cost of the trip (CHF)
x_{hhIncome}	Monthly household income (CHF)
x_{work}	1 if the origin or destination purpose is work, otherwise 0 (-)
$x_{\text{cityCenter}}$	1 if the origin or the destination of the trip lies within the boundaries of the City of Zurich, otherwise 0 (-)
x_{railTT}	Travel time in rail vehicles (min)
x_{busTT}	Travel time in busses (min)
$x_{\text{waitingTime}}$	Waiting time (min)
$x_{\text{numberOfConnections}}$	Number of trip legs (-)
x_{headway}	PT connection headway (min)
x_{bikeTT}	Bicycle travel time (min)
$x_{\text{age}\geq 60}$	1 if the person is at least 60 years old, otherwise 0 (-)
x_{walkTT}	Travel time walking (min)

The cost variables are being calculated as follows:

$x_{\text{costCar}} = 0.26\ \text{CHF/km} * x_{\text{dist}}$	Car trip cost (CHF)
$x_{\text{costPT}} = \max(2.7\ \text{CHF}, 0.6\ \text{CHF/km} * x_{\text{dist}})$	PT trip costs, at least 2.70 (CHF)

The mode choice model relies on a set of trip and personal attributes, in addition to travel time. Some of them are not available in the STATPOP dataset or cannot be calculated by R5 and NetworkX without a heavy computational overhead. We replace these missing attributes with the following assumptions:

$x_{\text{hhIncome}} = 10'000\ \text{CHF}$	
$x_{\text{work}} = 0.5$	50% of trips for work
$x_{\text{cityCenter}} = 0.2$	20% of trips start or end in the city
$x_{\text{railTT}} = 0.8\ x_{\text{TT,PT}}$	80% travel time in rail vehicles
$x_{\text{busTT}} = 0.2\ x_{\text{TT,PT}}$	20% travel time in busses
$x_{\text{AET,PT}} = 0$	Access and egress are already included in the travel times from R5, therefore 0
$x_{\text{numberOfConnections}} = x_{\text{TT,PT}}\ /\ 20\ \text{min}$	Transfers on average every 20 minutes
$x_{\text{headway}} = 10\ \text{min}$	
$x_{\text{waitingTime}} = 5\ \text{min}$	

Table 4: Mode choice model parameters adapted from [30]

General	$\mu_{hhIncome}$	CHF	12'260	Reference monthly household income
	μ_{dist}	km	39	Reference distance
	λ_{distTT}	-	0.1147	Elasticity of travel time w.r.t. distance
	β_{cost}	-	-0.088	
	$\lambda_{distCost}$	-	-0.2209	Elasticity of travel cost w.r.t. distance
	$\lambda_{hhIncome}$		-0.8169	Elasticity of cost w.r.t. monthly household income
Car	α_{car}	CHF	-0.8	Alternative-specific constant
	$\beta_{TT,car}$	CHF/min	-0.0192	
	$\beta_{work, car}$	CHF	-1.1606	
	$\beta_{cityCenter, car}$	CHF	-0.4590	
Public Transport	α_{pt}	CHF	0.0	Alternative-specific constant
	β_{railTT}	CHF/min	-0.0072	
	β_{busTT}	CHF/min	-0.0124	
	β_{AET_PT}	CHF/min	-0.0142	
	β_{wait}	CHF/min	-0.0124	
	$\beta_{lineSwitch}$	CHF	-0.17	
	$\beta_{headway}$	CHF/min	-0.0301	
	β_{OVGK}	-	-0.8	PT quality level at the trip origin
Bike	α_{bike}	CHF	-0.1522	Alternative-specific constant
	$\beta_{travelTime,bike}$	CHF/min	-0.1258	
	$\beta_{age\geq 60,bike}$	CHF	-0.0496	
Walking	α_{walk}	CHF	0.5903	Alternative-specific constant
	$\beta_{TT,walk}$	CHF/min	-0.0457	
	$\Theta_{thresholdWalkTT}$	min	120	

4.6 Accessibility calculation

We calculate the accessibility for every person, with their residential location as a starting point and all employment opportunities as destinations. The modes considered are car, bicycle, public transport, and walking with their respective choice probabilities according to the mode choice model in section 4.5. The cost c_{ij} of reaching each destination j from an origin i is a weighted average of the costs of the available modes m, using the choice probability P_{ijm} as the weight:

$$c_{ij} = \sum_m P_{ijm} * c_{ijm} \quad \text{with the cost from the mode choice utility function:} \quad c_{ijm} = -U_{ijm}$$

The utility of each destination is equal to the number of full-time job equivalents. The accessibility a_i of an origin i is the sum of all destination utilities u_j within a given distance, each discounted by the travel cost of reaching it c_{ij}, by applying a cost function:

$a_i = \sum_j f(c_{ij}) * u_j$ with the cost function: $a_i\, f(c_{ij}) = c_{ij}{}^{-0.7}$

The shortest paths by public transport are calculated on the Swiss 2023 GTFS dataset[9], using the travel time matrix calculator in r5py[10] [39], a Python wrapper for R5 [17]. For walking, cycling, and car trips, we use the one-to-many Dijkstra algorithm implementation in NetworkX[11] [18], which, unlike R5, enables the use of pre-calculated edge weights without further adjustments. In R5, we have provided the coordinates of the origin and destination. In NetworkX, the shortest path is found between a pair of nodes in the street network. These are chosen as the closest points to the origin/destination, accessible by the respective mode. The crowfly distance between the origin/destination points and those nodes is considered the access/egress walking distance and it is multiplied by a detour factor of 1.5. To reduce the computational workload, we calculate the accessibility for a reduced sample: 50% origin cells, 5% of the population within each cell, and 10% of all destinations within 70 km – resulting in a sample size of 43'783 persons, each with ~3'000 destinations. Given the option of four modes, in total, ~530 Million paths need to be considered. The calculation was carried out on the ETH Euler cluster, running on 60 CPUs in parallel.

5 RESULTS

The results are documented in a set of maps, showing the traffic flows in the downtown area of Zurich (Figure 2), the region-wide accessibility changes for car and cycling trips (Figure 3), as well as a table showing the aggregate median accessibility changes for different population groups (Table 5).

Figure 2 shows a decrease in car speeds and car traffic volumes in parts of the inner city. Residents living in these areas experience the highest reductions in their car-based accessibility. The region-wide accessibility maps in Figure 3 show, however, no substantial car accessibility changes outside of the city. In the western part, around the city of Aarau, car-based accessibility even slightly improves. On the other hand, the cycling-based accessibility increases substantially across the entire city and roughly 10km beyond the area where the road space reallocation was applied. Table 5 shows that car-based accessibility in the city decreases in the median by ~2%. Focusing only on the Seefeld area, on the eastern side of the lake in Figure 2, the median decrease is 7-8%. Outside of the city, the car-based accessibility levels decrease only slightly, by 0.5% in the median. Cycling-

9 https://opendata.swiss/en/dataset/timetable-2023-gtfs2020
10 https://github.com/r5py/r5py
11 https://github.com/networkx/networkx

based accessibility grows in the median by up to ~19% within the city and by 3-4% in the rest of the region. Since no changes were made to public transit, its accessibility remains unchanged. Across the entire perimeter, car-based accessibility decreases by 1%, and cycling-based accessibility grows by 4.5%.

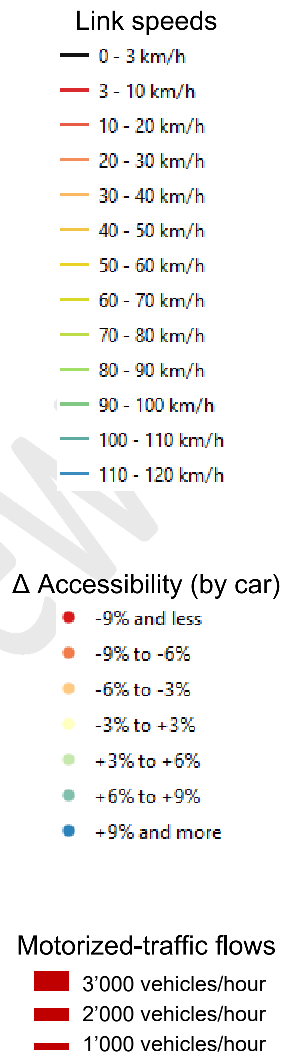
The spatial disparities in the residential locations of the different groups have no substantial impact on their accessibility changes. However, residents over 60 receive substantially lower cycling accessibility gains in comparison to the rest of the population, with only 5.3% within the city, compared to ~19% for the other age groups. This effect is even stronger in the Seefeld area, with cycling accessibility improvements of 32.7% for other age groups but only 6.5% for people above 60. This is due to the formulation of the mode choice model that penalizes cycling trips of residents above 60. As a result, the logsum accessibility of this group living within the city decreases slightly by 1.1% (and -3% in the Seefeld area) while for all other age groups, it grows by ~5.5%. Outside of the city, the logsum accessibility for the elderly remains unchanged and increases for all other age groups by no more than 0.5%. Over the entire area, the logsum accessibility remains almost constant, with +0.7% in the median.

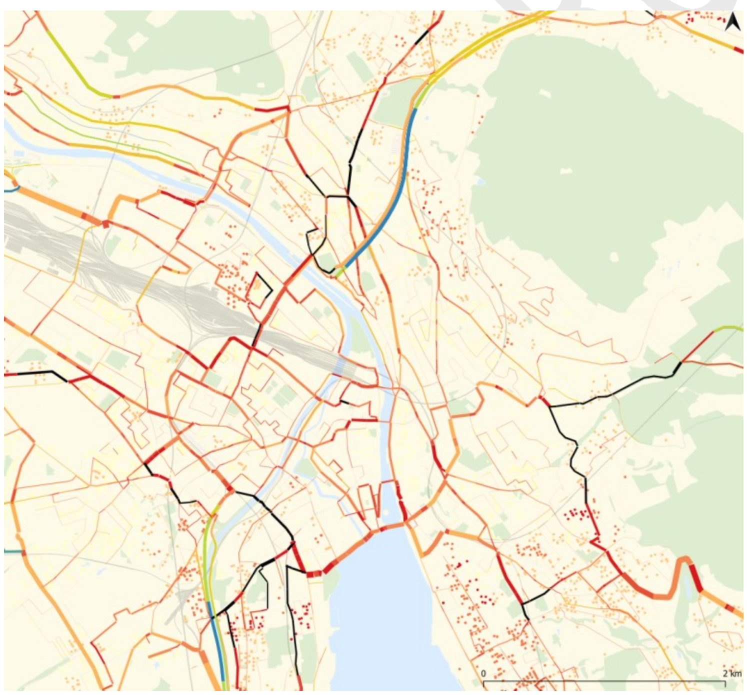
Table 5: Median accessibility and changes during the peak time 7:00-7:30

Sce-nario	Mode	Entire Region excl. City of Zurich							City of Zurich							All
		age: other	age <=25	age >=60	nat: other	nat: swiss	sex: female	sex: male	age: other	age <=25	age >=60	nat: other	nat: swiss	sex: female	sex: male	
(Count)	All	14'769	8'120	6'870	7'883	21'876	14'849	14'910	6'062	2'745	2'024	3'511	7'320	5'358	5'473	41'030
Before	Cars	67'099	67'103	67'000	67'439	66'949	67'030	67'119	71'462	71'259	71'203	71'475	71'272	71'349	71'386	68'254
	PT	59'459	59'367	59'325	60'250	59'168	59'390	59'404	70'378	69'791	69'605	70'325	69'982	70'046	70'149	61'507
	Cycling	43'231	43'051	29'956	43'371	38'926	39'697	40'596	73'542	71'479	36'712	71'630	68'584	69'110	70'046	43'168
	Foot	1'902	1'894	1'808	2'204	1'789	1'866	1'880	12'040	11'135	10'834	11'717	11'481	11'471	11'652	2'939
After	Cars	66'524	66'484	66'401	66'864	66'355	66'446	66'524	69'546	69'333	69'302	69'626	69'388	69'440	69'462	67'356
	PT	59'459	59'367	59'325	60'250	59'168	59'390	59'404	70'378	69'791	69'605	70'325	69'982	70'046	70'149	61'507
	Cycling	45'001	44'750	30'758	45'170	40'158	41'017	41'980	88'951	86'463	38'682	86'410	81'585	82'456	84'256	44'908
	Foot	1'903	1'895	1'810	2'206	1'790	1'868	1'882	12'161	11'253	10'920	11'864	11'628	11'568	11'766	2'945
Diff	Cars	-0.5%	-0.5%	-0.5%	-0.4%	-0.5%	-0.5%	-0.5%	-2.1%	-2.2%	-2.1%	-2.1%	-2.1%	-2.1%	-2.1%	-1.0%
	PT	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Cycling	3.9%	3.8%	2.6%	4.0%	3.2%	3.4%	3.5%	19.2%	19.0%	5.3%	17.9%	16.9%	17.2%	17.4%	4.5%
	Foot	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.0%
Before	All	67'322	67'251	66'841	67'759	66'944	67'086	67'224	78'956	78'020	70'769	78'326	76'692	76'922	77'517	68'459
After	All	67'466	67'392	66'783	67'927	67'016	67'154	67'263	83'713	82'573	69'685	83'057	80'940	81'365	81'998	68'451
Diff	All	0.5%	0.4%	0.0%	0.5%	0.3%	0.3%	0.3%	5.6%	5.5%	-1.1%	5.3%	4.9%	5.0%	5.1%	0.7%

Sce-nario	Mode	Seefeld						
		age: other	age <=25	age >=60	nat: other	nat: swiss	sex: female	sex: male
(Count)	All	191	71	73	113	222	180	155
Before	Cars	71'866	71'866	71'775	71'887	71'761	71'866	71'775
	PT	72'052	72'052	71'980	72'485	71'991	72'052	72'047
	Cycling	74'068	74'068	37'093	74'068	69'682	72'391	72'391
	Foot	13'773	15'049	14'191	14'470	14'005	13'796	14'470
After	Cars	66'540	66'761	66'698	66'630	66'630	66'638	66'559
	PT	72'052	72'052	71'980	72'485	71'991	72'052	72'047
	Cycling	98'471	97'802	39'526	96'908	94'998	96'246	95'363
	Foot	14'243	15'161	14'576	14'576	14'367	14'367	14'367
Diff	Cars	-8.0%	-6.7%	-6.8%	-8.2%	-7.0%	-7.0%	-7.8%
	PT	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Cycling	32.7%	32.7%	6.5%	31.6%	30.4%	31.6%	29.2%
	Foot	0.2%	-0.1%	1.0%	0.2%	0.2%	0.1%	1.0%
Before	All	80'221	80'275	73'126	80'275	78'535	79'117	78'759
After	All	85'808	85'344	70'943	85'808	84'368	84'889	84'743
Diff	All	7.0%	7.2%	-3.0%	6.4%	6.0%	6.2%	6.0%

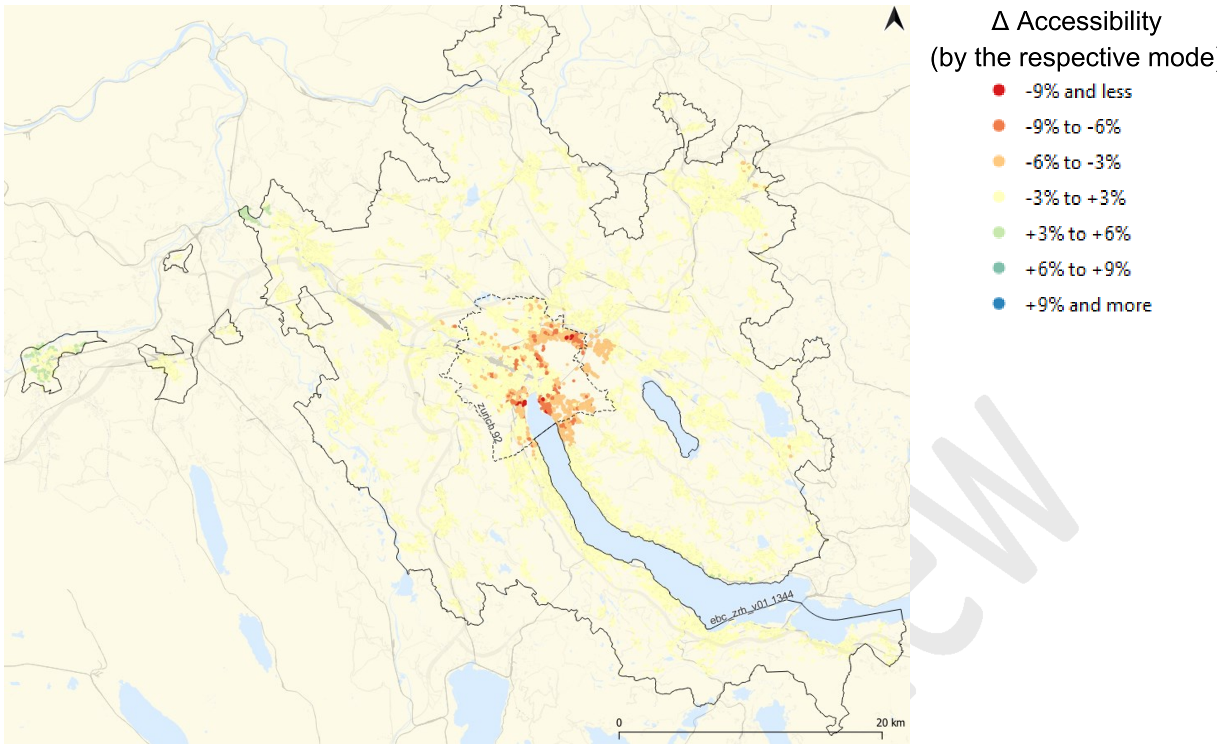
Motorized traffic flows before the reallocation (link widths) and
accessibility changes for car trips (dots)



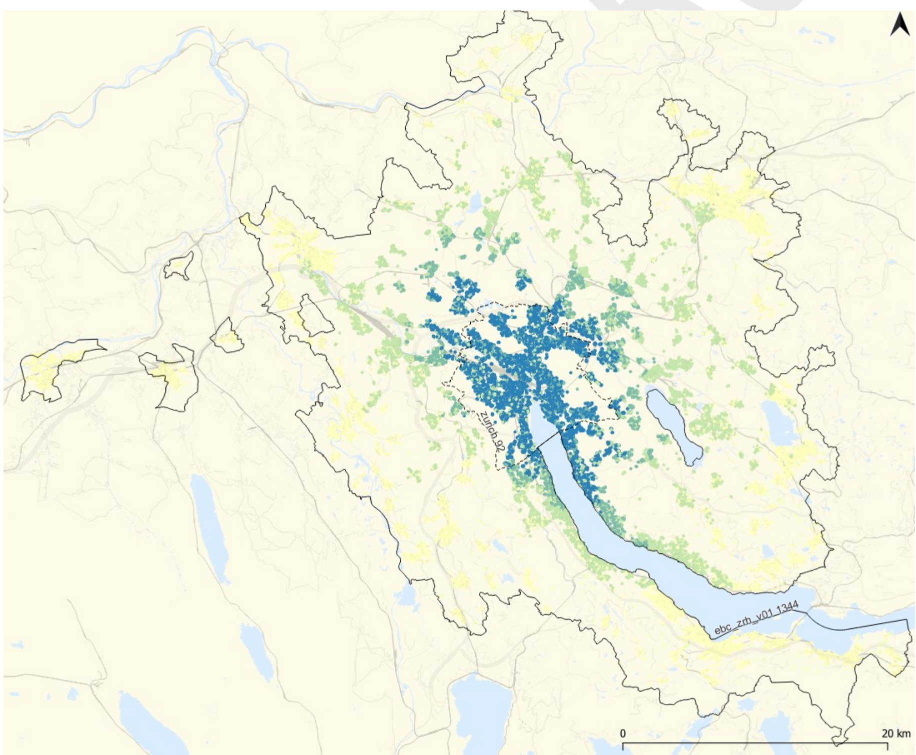


Motorized traffic flows after the reallocation (link widths) and
accessibility changes for car trips (dots)

Figure 2: Traffic flows and car accessibility changes in Zurich's downtown, 7:00-7:30



Accessibility changes for car trips



Accessibility changes for cycling trips

Figure 3: Accessibility changes for cars and cyclists, 7:00-7:30

6 DISCUSSION

Our results indicate that reallocating 42.2% of road space within the city to cycling infrastructure would increase the overall accessibility values for all population groups, except the elderly living in the city assuming unchanged behavior. Within the city, notable accessibility gains of up to ~7% can be achieved, while the rest of the region also experiences very small gains. This is contrary to the original assumptions conceptualized in [10], suggesting that the accessibility of urban residents will grow at the expense of those living outside of the city. Although they feel slight accessibility losses for car trips, these are compensated by the improved cycling accessibility. Creating such benefits by merely repainting existing roads within the city would be a promising approach for producing accessibility in the future, potentially with a return on investment that is superior to the present paradigm. On the other hand, however, despite reduced traffic flows in the peak hour, the overall volume of car traffic does not decrease, as any benefits of mode shifts are consumed by detours and growing trip lengths.

Nevertheless, the results are subject to multiple methodological limitations. First, the mode choice model used includes only age as a personal characteristic affecting the choice probabilities, neglecting any special needs, individual skill levels, culturally imposed behaviors, or the present mode choice. Second, the route choice model used to account for cycling comfort only distinguishes whether cycling infrastructure is present and does not provide a reliable distinction between different cycling infrastructure types: Converting narrow cycling lanes without protection to fully separated cycling paths with larger widths currently does not generate any accessibility changes, thus vastly underestimating the cycling accessibility improvements. Third, the micromobility modes were represented by bicycles only. Higher comfort and speed of newer vehicle types such as e-bikes, electric scooters, or vehicles for the elderly have not been included yet. Considering these advances would further increase the cycling accessibility gains. Fourth, the opportunities considered do not include any personal needs for specific destinations that cannot be easily replaced and the origin-centric perspective does not reflect the impacts on destinations, such as businesses. Fifth, the accessibility measure used is strictly trip-based, thus neglecting any constraints that emerge from previous trips (although this aspect is considered in the MATSim simulation). Finally, the accessibility analysis was done only for the morning peak time, while the results may be different for other times of the day.

7 CONCLUSIONS AND FURTHER WORK

In this paper, we have presented the first steps toward assessing a hypothetical car-reduced transport planning paradigm in the Zurich metropolitan region. The first results suggest that reallocating large parts of the road space within the city to micromobility modes has a high potential to increase cycling activity, reduce car traffic in some areas, and generate slight accessibility gains. However, in its current form, the scheme does not succeed in reducing the overall number of person kilometers traveled by car.

To strengthen the evidence, future work should focus on two areas: Improving the assessment methodology, and evolving the design. In the case of cycling, a more precise representation of the attributes affecting behavior is needed. The models should distinguish different cycling infrastructure types, traffic volumes, and vehicle types. Including further personal characteristics of people beyond age, such as level of education, household size, employment status and home responsibilities, gender, and cultural background, is crucial for a better, finer-grained understanding of the equity effects. The micromobility modes should be extended with the advantages of newer, electric vehicles that offer higher speeds and comfort. Further work may also focus on including each person's present mode choice and destination preferences, as well as using activity-based accessibility measures [40], [41] to include the effects of trip chaining. Also, exploring destination-based accessibility changes would help to understand the impacts on a variety of stakeholders, including business owners. Finally, a better understanding of the traffic patterns and accessibility changes during other times of the day would be beneficial.

On the design front, the outcomes are heavily determined by assumptions made when generating the reallocated network. Experimenting with different design strategies that address the detours issue may produce scenarios with better performance. Moreover, the mere road space reallocation may be combined with further adjustments and policy measures such as restricting through traffic in some areas, imposing mobility pricing, parking restrictions, or changes in the public transport supply. A quick automated generation of the scenarios enables to test a large number of different approaches, without introducing possible sources of bias through manual preparation of the designs. Advancing the field of automated transport network design approaches, e.g., [32], [33], [42], [43], together with interactive tools, e.g., [44] to focus on "small" infrastructure may spur a new generation of transport planning approaches that leverage rapid experimentation, rather than the implementation of few large capital projects.

AUTHOR CONTRIBUTIONS

Lukas Ballo: Conceptualization, Accessibility Calculations, Investigation, Writing – Original Draft,
Aurore Sallard: MATSim Simulations, Writing – Original Draft
Lucas Meyer de Freitas: Data on Mobility in Zurich, Writing – Review & Editing
Kay Axhausen: Conceptualization, Writing – Review & Editing

ACKNOWLEDGEMENTS

Thanks to Miriam Sonnak for preparing the initial MATSim setup and answering questions about the process used, to Milos Balac and Sebastian Hörl for advice on the mode choice model, and to Catherine Elliot for coordinating the E-Bike City project team.
Thanks to Anson Stewart for providing access to the Conveyal platform and clarifying the concepts behind R5.
Thanks to the anonymous reviewers at TRB for reviewing this manuscript.

FUNDING

Internal funds of Prof. Kay W. Axhausen;
Lighthouse Project funding of ETH D-BAUG;
Swiss Federal Office of Energy

CONFLICTS OF INTEREST

None.

NOTES

The code used in this paper is published open-source as part of the Python project `snman`: https://github.com/lukasballo/snman. To access the version used to produce the presented results, refer to the "accessibility_paper" branch.

The maps are created using data from OpenStreetMap contributors.

REFERENCE LIST

[1] K. W. Axhausen, P. Froelich, and M. Tschopp, "Changes in Swiss accessibility since 1850," *Research in Transportation Economics*, vol. 31, no. 1, pp. 72–80, Jan. 2011, doi: 10.1016/j.retrec.2010.11.010.

[2] S. Wampfler and D. Ottinger, "Kostenentwicklung im Autobahnbau," Bachelor Thesis, ETH Zurich, Zurich, 2013.

[3] IPCC, "Climate change 2022, mitigation of climate change, summary for policymakers," Intergovernmental Panel on Climate Change, Geneva, 2022.

[4] K. W. Axhausen, "The dilemma of transport policy making and the COVID-19 accelerator," in *Transport and Sustainability, Transport and Pandemic Experiences, Volume 17*, M. Attard and C. Mulley, Eds., Bingley: Emerald Publishing Limited, 2022, pp. 39–51. doi: 10.1108/S2044-994120220000017003.

[5] I. de Blas, M. Mediavilla, I. Capellán-Pérez, and C. Duce, "The limits of transport decarbonization under the current growth paradigm," *Energy Strategy Reviews*, vol. 32, p. 100543, Nov. 2020, doi: 10.1016/j.esr.2020.100543.

[6] M. Gebler, J. F. Cerdas, S. Thiede, and C. Herrmann, "Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production – A case study," *Journal of Cleaner Production*, vol. 270, p. 122330, Oct. 2020, doi: 10.1016/j.jclepro.2020.122330.

[7] B. Cox, C. L. Mutel, C. Bauer, A. Mendoza Beltran, and D. P. van Vuuren, "Uncertain environmental footprint of current and future battery electric vehicles," *Environ. Sci. Technol.*, vol. 52, no. 8, pp. 4989–4995, Apr. 2018, doi: 10.1021/acs.est.8b00261.

[8] F. Lichtin, E. K. Smith, K. W. Axhausen, and T. Bernauer, "How to design publicly acceptable road pricing? Experimental insights from Switzerland," *Ecological Economics*, vol. 218, p. 108102, Apr. 2024, doi: 10.1016/j.ecolecon.2023.108102.

[9] BFS and ARE, "Mobilitätsverhalten der Bevölkerung: Ergebnisse des Mikrozensus Mobilität und Verkehr 2021," Bundesamt für Statistik, Bundesamt für Raumentwicklung, Neuchâtel, 2023.

[10] L. Ballo, L. Meyer de Freitas, A. Meister, and K. W. Axhausen, "The E-Bike City as a radical shift toward zero-emission transport: Sustainable? Equitable? Desirable?," *Journal of Transport Geography*, vol. 111, p. 103663, 2023.

[11] C. Moreno, Z. Allam, D. Chabaud, C. Gall, and F. Pratlong, "Introducing the '15-minute city': Sustainability, resilience and place identity in future post-pandemic cities," *Smart Cities*, vol. 4, no. 1, pp. 93–111, Jan. 2021, doi: 10.3390/smartcities4010006.

[12] S. Rueda, "Superblocks for the design of new cities and renovation of existing ones: Barcelona's case," in *Integrating Human Health into Urban and Transport Planning*, M. Nieuwenhuijsen and H. Khreis, Eds., Cham: Springer International Publishing, 2019, pp. 135–153. doi: 10.1007/978-3-319-74983-9_8.

[13] S. Eggimann, "The potential of implementing superblocks for multifunctional street use in cities," *Nature Sustainability*, vol. 5, pp. 406–414, 2022.

[14] L. Ballo and K. W. Axhausen, "Modeling sustainable mobility futures using an automated process of road space reallocation in urban street networks: A case study in Zurich," presented at the 103rd Annual Meeting of the Transportation Research Board, Washington DC, Jan. 2024.

[15] M. Ben-Akiva and S. R. Lerman, “Disaggregate travel and mobility-choice models and measures of accessibility,” in *Behavioural Travel Modelling*, 1st ed., D. A. Hensher and P. R. Stopher, Eds., London: Routledge, 1979, pp. 654–679. doi: 10.4324/9781003156055-39.

[16] A. Horni, K. Nagel, and K. W. Axhausen, *The Multi-Agent Transport Simulation MATSim*. London: Ubiquity Press, 2016. doi: 10.5334/baw.

[17] M. W. Conway, A. Byrd, and M. Van Der Linden, “Evidence-based transit and land use sketch planning using interactive accessibility methods on combined schedule and headway-based networks,” *Transportation Research Record*, vol. 2653, no. 1, pp. 45–53, Jan. 2017, doi: 10.3141/2653-06.

[18] A. A. Hagberg, D. A. Schult, and P. J. Swart, “Exploring network structure, dynamics, and function using NetworkX,” in *Proceedings of the 7th Python in Science Conference*, Pasadena, 2008.

[19] City of Zurich, “Zürich in Zahlen - Stadt Zürich.” Accessed: Apr. 24, 2024. [Online]. Available: https://www.stadt-zuerich.ch/portal/de/index/portraet_der_stadt_zuerich/zuerich_in_zahlen.html

[20] K. T. Geurs and B. van Wee, “Accessibility evaluation of land-use and transport strategies: review and research directions,” *Journal of Transport Geography*, vol. 12, no. 2, pp. 127–140, Jun. 2004, doi: 10.1016/j.jtrangeo.2003.10.005.

[21] W. G. Hansen, “How accessibility shapes land use,” *Journal of the American Institute of Planners*, vol. 25, no. 2, pp. 73–76, May 1959, doi: 10.1080/01944365908978307.

[22] A. Sen, *The Idea of Justice*. Cambridge: Belknap Press of Harvard University Press, 2009.

[23] M. W. Conway, A. Byrd, and M. Van Eggermond, “Accounting for uncertainty and variation in accessibility metrics for public transport sketch planning,” *JTLU*, vol. 11, no. 1, pp. 541–558, Jul. 2018, doi: 10.5198/jtlu.2018.1074.

[24] M. W. Conway and A. F. Stewart, “Getting Charlie off the MTA: a multiobjective optimization method to account for cost constraints in public transit accessibility metrics,” *International Journal of Geographical Information Science*, vol. 33, no. 9, pp. 1759–1787, Sep. 2019, doi: 10.1080/13658816.2019.1605075.

[25] D. M. Scott, W. Lu, and M. J. Brown, “Route choice of bike share users: Leveraging GPS data to derive choice sets,” *Journal of Transport Geography*, vol. 90, p. 102903, Jan. 2021, doi: 10.1016/j.jtrangeo.2020.102903.

[26] A. F. Jensen, “Using crowd source data in bicycle route choice modeling,” in *Proceedings from the Annual Transport Conference at Aalborg University*, Aalborg, Jul. 2019.

[27] J. Hood, E. Sall, and B. Charlton, “A GPS-based bicycle route choice model for San Francisco, California,” *Transportation Letters*, vol. 3, no. 1, pp. 63–75, Jan. 2011, doi: 10.3328/TL.2011.03.01.63-75.

[28] J. Broach, J. Dill, and J. Gliebe, “Where do cyclists ride? A route choice model developed with revealed preference GPS data,” *Transportation Research Part A: Policy and Practice*, vol. 46, no. 10, pp. 1730–1740, Dec. 2012, doi: 10.1016/j.tra.2012.07.005.

[29] A. Meister, M. Felder, B. Schmid, and K. W. Axhausen, “Route choice modeling for cyclists on urban networks,” *Transportation Research Part A: Policy and Practice*, vol. 173, p. 103723, Jul. 2023, doi: 10.1016/j.tra.2023.103723.

[30] S. Hörl, F. Becker, and K. W. Axhausen, “Simulation of price, customer behaviour and system impact for a cost-covering automated taxi system in Zurich,” *Transportation Research Part C: Emerging Technologies*, vol. 123, p. 102974, Feb. 2021, doi: 10.1016/j.trc.2021.102974.

[31] M. te Brömmelstroet, W. Boterman, and G. Kuipers, “How culture shapes - and is shaped by - mobility: Cycling transitions in The Netherlands,” in *Handbook of Sustainable Transport*, C. Curtis, Ed., Cheltenham: Edward Elgar Publishing, 2020, pp. 109–118.
[32] M. Szell, S. Mimar, T. Perlman, G. Ghoshal, and R. Sinatra, “Growing urban bicycle networks,” *Sci Rep*, vol. 12, no. 1, p. 6765, Apr. 2022, doi: 10.1038/s41598-022-10783-y.
[33] C. Steinacker, D.-M. Storch, M. Timme, and M. Schröder, “Demand-driven design of bicycle infrastructure networks for improved urban bikeability,” *Nat Comput Sci*, Oct. 2022, doi: https://doi.org/10.1038/s43588-022-00318-w.
[34] L. Ballo, K. W. Axhausen, and M. Raubal, “Designing an E-Bike City: An automated process for network-wide multimodal road space reallocation,” *Arbeitsberichte Verkehrs- und Raumplanung*, Jun. 2024, Accessed: Jun. 25, 2024. [Online]. Available: https://www.research-collection.ethz.ch/handle/20.500.11850/679713
[35] S. Hörl and M. Balac, “Introducing the eqasim pipeline: From raw data to agent-based transport simulation,” *Procedia Computer Science*, vol. 184, pp. 712–719, 2021, doi: 10.1016/j.procs.2021.03.089.
[36] C. Tchervenkov, G. O. Kagho, A. Sallard, S. Hörl, M. Balać, and K. W. Axhausen, “The Switzerland agent-based scenario,” *Arbeitsberichte Verkehrs- und Raumplanung*, vol. 1802, Dec. 2022, Accessed: Jul. 24, 2024. [Application/pdf]. Available: http://hdl.handle.net/20.500.11850/592622
[37] M. Sonnak, “Evaluation of E-Bike-City road networks,” Master Thesis, ETH Zurich, Zurich, 2024.
[38] A. Agarwal and G. Lämmel, “Modeling seepage behavior of smaller vehicles in mixed traffic conditions using an agent based simulation,” *Transp. in Dev. Econ.*, vol. 2, no. 2, p. 8, Apr. 2016, doi: 10.1007/s40890-016-0014-9.
[39] C. Fink, W. Klumpenhouwer, M. Saraiva, R. Pereira, and H. Tenkanen, “r5py: Rapid Realistic Routing with R5 in Python,” Sep. 2022, doi: 10.5281/zenodo.7060438.
[40] C. Chen, W. Recker, and M. G. McNally, “An activity-based approach to accessibility,” University of California, Irvine, 1997.
[41] X. Dong, M. E. Ben-Akiva, J. L. Bowman, and J. L. Walker, “Moving from trip-based to activity-based measures of accessibility,” *Transportation Research Part A: Policy and Practice*, vol. 40, no. 2, pp. 163–180, Feb. 2006, doi: 10.1016/j.tra.2005.05.002.
[42] N. Wiedemann, C. Nöbel, H. Martin, L. Ballo, and M. Raubal, “Bike network planning in limited urban space,” May 02, 2024, *arXiv*: arXiv:2405.01770. Accessed: May 18, 2024. [Online]. Available: http://arxiv.org/abs/2405.01770
[43] M. Paulsen and J. Rich, “Societally optimal expansion of bicycle networks,” *Transportation Research Part B: Methodological*, vol. 174, p. 102778, Aug. 2023, doi: 10.1016/j.trb.2023.06.002.
[44] A. Stewart and P. C. Zegras, “Interactive mapping for public transit planning: Comparing accessibility and travel-time framings,” *JTLU*, vol. 15, no. 1, pp. 635–650, Oct. 2022, doi: 10.5198/jtlu.2022.1760.