Coupling Transport and Land-Use: Investigating accessibility indicators for feedback from a travel to a land use model

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Abstract

Urban land-use and transportation are influencing each other in a dynamic and complex manner; this needs an integrated view of the interactions between land-use and transport. In this paper, we summarize the steps integrating UrbanSim[1] with MATSim[2] directly at a microscopic person centric level. The standard feedback from external travel models to UrbanSim is on an aggregated zone level. In this paper we investigate how an utility-based accessibility measure like the so-called logsum term can be used for this purpose at the example of work place accessibility. This study will address issues such as (i) different resolutions, (ii) different generalized costs of travel such as free speed car-, congested car-, bicycle- and walk travel times and (iii) sensitivity to a modification in the transport network.

Keywords: MATSim, UrbanSim, land-use, transportation, integrated agent-based modeling, econometric accessibility

1 Introduction

UrbanSim [1, 2, 3] is an extensible, microscopic, agent-based urban simulation model. It aims at simulating interactions between land use, transportation, economy and the environment at large-scale metropolitan areas and over a long time period. UrbanSim consists of several models reflecting the decisions of households, businesses, developers, governments (as policy inputs), and their interactions in the real estate market.

Similar to other urban simulation models like DELTA, CUFM, MUSSA, POLIS or RURBAN, UrbanSim does not model transport itself [4]. Instead, it relies on an interaction with external transport models to update the traffic conditions resulting from the current land-use.

[1]see urbansim.org/
[2]see matsim.org/

In the past, some efforts towards integrating UrbanSim with external travel models like EMME [5] or VISUM [6, 7] have been made. However, both EMME and VISUM are traditional assignment models using origin-destination matrices (OD-matrices) as inputs [8, 9]. Thus, they do not make use of the disaggregated nature of UrbanSim. In this situation it seems quite natural to link UrbanSim with an agent-based travel model.

MATSim (Multi-Agent Transport Simulation) [10, 11, 12] is a disaggregated, agent-based transport model that is capable of simulating several million travellers (agents) individually for large real-world transport scenarios. Furthermore, MATSim provides additional advantages such as simulating time-dependent congestion, time-dependent mode choice, or speeding up computation times by running small samples of a scenario.

As part of the SustainCity[3] project, MATSim is coupled with UrbanSim. The coupling is referred to as MATSim4UrbanSim [13, 14, 15]. MATSim takes the synthetic UrbanSim population directly at the agent level, simulates their joint travel behaviour and updates the traffic conditions in UrbanSim. For more detailed information, please refer to Appendix A.

from_zone_id	to_zone_id	am_single_vehicle_to_work_travel_time
601	601	1.2
602	601	10.5120915
603	601	10.84997029
604	601	47.72225589
605	601	54.58448668
606	601	33.78333333
607	601	60.57128651
608	601	10.78460873
609	601	88.72431786
610	601	35.32687035
611	601	10.71284562
612	601	11.51725003
613	601	13.42148847
614	601	48.76746873

Figure 1: Excerpt of the zone-to-zone impedance matrix including travel time in minutes from any origin zone "from_zone_id" to any destination zone "to_zone_id".

UrbanSim Models	**Short Description**
Real Estate Price Model (REPM)	Simulates the prices of each building
Expected Sales Price Model (ESPM)	Predicts the expected unit price for each proposed development project based on the same specification and estimation parameters as used in the REPM
Household Location Choice Model (HLCM)	Selects a location for households that have no current residence location
Employment Location Choice Model (ELCM)	Selects a location for jobs that have no current location

Table 1: UrbanSim models that make use of the results from the travel model are the Real Estate Price Model, the Expected Sales Price Model, the Household Location Choice Model and the Employment Location Choice model.

The standard feedback from external travel models to UrbanSim is a zone-to-zone impedance matrix, see Fig. 1, including generalized costs of travel between any given pair of zones. This is an $n \times n$ matrix, where n is the number of zones. UrbanSim uses this matrix as input for location choice decisions of residents, firms, and developers, which are listed and briefly described in Tab. 1. Such matrices are growing quadratically with the number of zones and thus quickly become very large: For instance, a typical number of

[3] see sustaincity.org

10'000 zones leads to $10'000^2 = 100'000'000$ entries for one attribute, e.g. congested car travel times. If each entry is represented as an 8Byte floating point number, this results in 800 MB of memory. Although this may still be possible, it does not leave much room for additional attributes such as generalized costs of travel for different times-of-a-day or by different mode of transport. Another drawback is the spatial resolution that is on an aggregate, zone level. Therefore, it makes sense to search for an alternative, improved measures as feedback from a travel model.

The present paper looks at utility-based accessibility measures that are computed in the travel model and then fed back to UrbanSim. This investigation is performed using the example of work place accessibility.

The paper is organized as follows. Sec. 2 explains the concept of accessibility and describes the accessibility measure that is used in this paper. The implementation approach is given in Sec. 3. Details on the data, configuration settings and simulation approach are presented in Sec. 4. In Sec. 5 the results of the accessibility investigation are illustrated. The paper is concluded by a discussion and a conclusion. Appendix A describes the simulation approach in MATSim and UrbanSim and how both frameworks are integrated.

2 Accessibility

There is some agreement that access to certain activity locations such as work, shopping or leisure have an influence on location choice decisions of residents, firms, and developers. Hansen [16] shows that areas which have more access to such locations have a greater growth potential in residential development. Moeckel [17] asserts that the principal idea of Hansen's approach is also true for businesses. In other words: Locations with easier access are more attractive compared with otherwise similar locations with less access.

The terms “accessibility” and “access” are often used synonymously. In this paper accessibility is used for a single-point-value that is assigned to one location itself, where two-point-values, i.e. OD-pairs, are referred to as access or impedance.

In the following, a brief overview of some accessibility measures are presented. A comprehensive review of these accessibility measures can be found in [18, 19]. Accessibility measures can be broadly classified into three categories [18]:

1. The **infrastructure-based** approach is based on the performance of the transport system.

2. The **activity-based** measure deals with the distribution of activities in space and time.

3. A **utility-based** measure of accessibility reflects the (economic) benefits, as the maximum expected utility, that someone gains from access to spatially distributed opportunities [18, 20].

In addition, accessibility can be seen as the result of the following four independent components [18, 19]:

1. A **land-use** component that deals with the number and spatial distribution of opportunities.

2. A **transport** component, which describes the effort to travel from a given origin to a given destination.

3. A **temporal** component, which considers the availability of activities at different times-of-a-day, e.g. in the morning peak hours.
4. An **individual** component that addresses the different needs and opportunities of different socio-economic groups, e.g. different income groups.

For the present study, the utility-based measure from Ben-Akiva and Lerman [21] is selected, which is also known as the logsum. It is defined as

$$A_i := \frac{1}{\beta_{scale}} \ln \sum_k e^{-\beta_{scale}\, c_{ik}} \ , \tag{1}$$

where c_{ik} are generalized costs of travel in order to get from location i to location k, and β_{scale} is the logit model scale parameter. The logsum term includes both, a land-use component that considers the number and distribution of opportunities, and a transport component that determines the effort to get there.

The logsum term is a weighted sum over possible destinations for a given origin, but it can also be interpreted as an expected maximum utility. If one traces the expected maximum utility derivation (e.g.[21]), one finds that $-c_{ik}$ should actually be replaced by $V_{typ} - c_{ik}$, where V_{typ} is the typical systematic utility at the destination. If it is assumed that this is the same for every person at every opportunity, then this can be factored out, and in the end just becomes a constant addend to the accessibility. That is, A_i does *not* include the intrinsic systematic utility of the activity at the destination. It *does*, however, include the averaged effect of the ϵ_k that describe the fluctuations around the systematic utility.

When multiple opportunities can be aggregated into the same location, then Eq. 1 can be re-written as

$$A_i := \frac{1}{\beta_{scale}} \ln \sum_j D_j e^{-\beta_{scale}\, c_{ij}} \ , \tag{2}$$

where D_j gives the number of opportunities at location j.

The following section describes in detail how this accessibility measure is implemented.

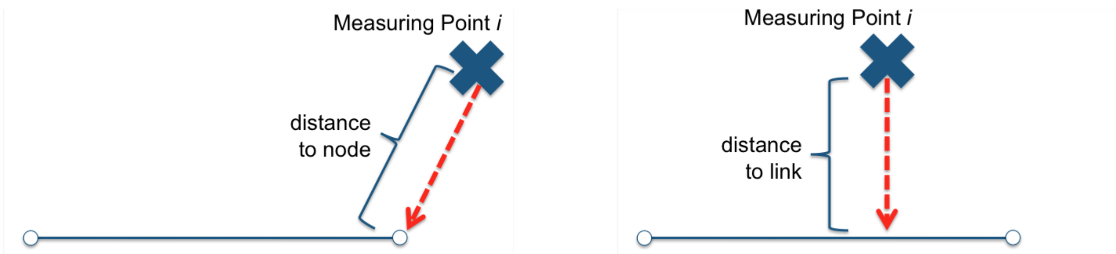
3 Methodology: High Resolution Accessibility

This section looks at the implementation of the econometric accessibility measure that is given by Equation 2. This task is performed in MATSim. In this section it is assumed that MATSim completed the traffic flow simulation based on the land-use pattern provided by UrbanSim. As a result MATSim possesses a congested road network on which it then calculates the accessibility indicators as feedback for UrbanSim. A comprehensive description of the simulation and integration approach of MATSim and UrbanSim is given in the Appendix A.

In order to calculate the accessibility A_i, origin locations i and opportunity locations j are assigned to the MATSim road network. For every given origin i a so-called "least cost path tree" runs through the network and determines the best route to each opportunity location j by using the Dijkstra shortest path algorithm [22]. The best route from i to j depends on the given cost type such as link travel times or distances. Once the least cost path tree has explored all nodes, MATSim queries the resulting travel costs c_{ij} for all opportunities and calculates the accessibility as stated in Equation 2.

When looking at high-resolution accessibility calculations, there are, in fact, two resolutions to consider: One that defines for how many origins i the accessibility is to be computed. And a second one that defines to what level the opportunities j are to be resolved.

3.1 Spatial resolution of the origin



(a) Euclidean distance measure between the origin location i in accessibility calculation and the nearest network node.

(b) Orthogonal distance measure between the origin i in accessibility calculation and the nearest network link.

Figure 2: The calculation of c_{ij} includes the costs of travel to overcome the gap between a measuring point (blue cross) and the network, which is based on the shortest distance. This is either given by the euclidean distance to the nearest node or the orthogonal distance to the nearest link on the network.

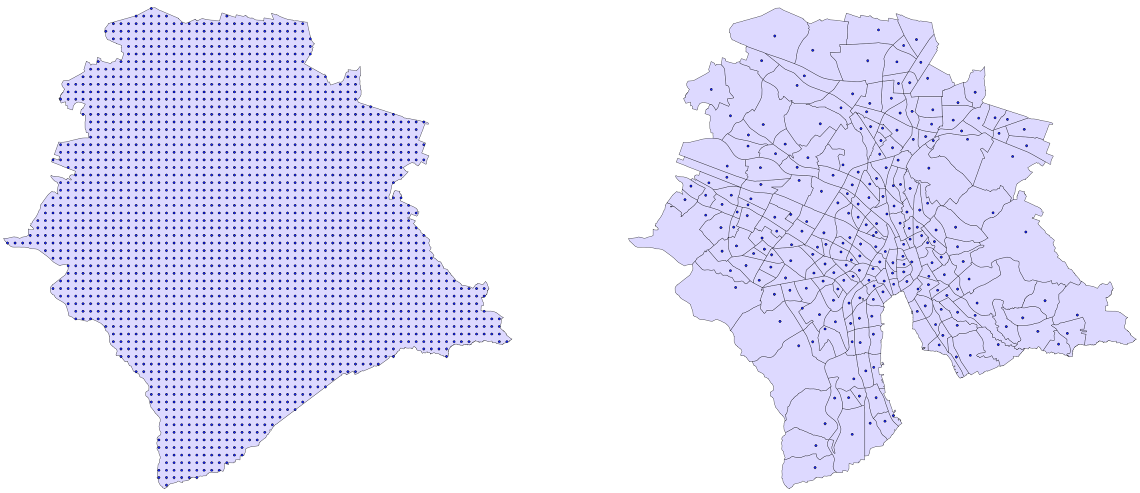
The Dijkstra algorithm calculates the best route, and thus the lowest travel costs c_{ij}, starting from the network node that is next to the origin location, or measuring point, i to all opportunities. However, location i does not necessarily lie on the network; see also Fig. 2. Thus, the calculation of c_{ij} includes in addition the costs of travel to overcome the gap between the origin location i and the road network. The gap is determined by taking the shortest distance to the network, which is either given by the Euclidean distance to the nearest node or the orthogonal distance to the nearest link on the network. It is assumed that this distance is covered on foot with a constant speed of 5km/h. If the mapping of location i is on a link, as in case of the orthogonal projection (Fig. 2(b)), c_{ij} further includes the travel costs to overcome the distance to the nearest node. The travel costs are calculated by dividing the distance to the node by the travel speed of the according transport mode, e.g. car (free speed or congested car travel times at a given time-of-a-day), bicycle (15km/h) or walk (5km/h).

The origin side can be calculated for two spatial units, cells or zones. Their spatial resolutions determine the number of points for which the accessibility will be computed:

- **Cell-based Approach**: In this approach the study area is subdivided into square cells, where the resulting cell centroids serve as measuring points (origins) for the accessibility calculation; see Fig. 3a. The spatial resolution depends on the selected cell size, which is configurable.

- **Zone-based Approach**: This approach uses the zone centroids as measuring points, as shown in Fig. 3b. The centroid coordinates can be obtained from a variety of definitions. In this paper, they are determined by averaging all parcel coordinates that belong to a zone. This corresponds to weighting each parcel equally; this may not be justified when, say, the number of residents or households varies strongly between parcels.[4] The number of measuring points is defined by the number of zones.

Since the latter approach is on an aggregate zone level, the following paragraphs concentrate on the cell-based approach that is qualified for high resolution accessibility calculations. Nevertheless, the calculation procedure of the logsum term is the same for both approaches.



(a) Cell-based approach using a $200m \times 200m$ side length

(b) Zone-based approach

Figure 3: The figures visualize the cell- and zone-based approach in accessibility calculation at the example of the city of Zurich (blue area). The measuring points (origins) for accessibility calculation are determined as follows: The cell-based approach subdivides the study area in square cells of configurable size; here a side length of 200m is used for visibility reasons. The cell centroids (blue dots) serve as origins. The zone-based approach is using zone centroids instead, which are determined by averaging all parcel coordinates that belong to a zone. The number of measuring points is given by the number of zones.

3.2 Spatial resolution of the destinations (= opportunities)

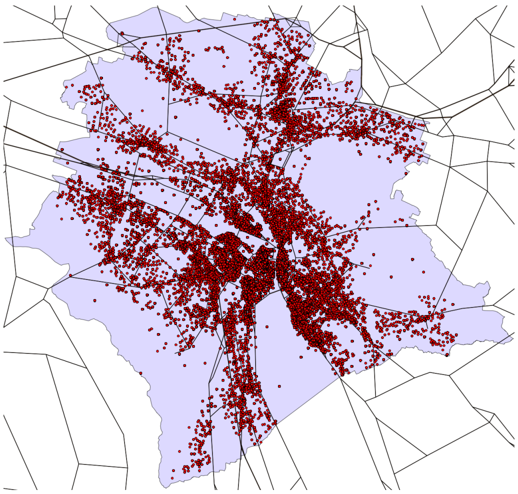
As stated earlier (Eq. (1), the computation of the accessibility for a given origin location i contains a summation of the term $e^{\beta_{scale} c_{ik}}$ for all opportunity locations k. The determination of the generalized cost of travel, c_{ik}, consists of the following contributions:

1. The generalized cost of reaching the transport network from origin i. This is described in Sec. 3.1. It is assumed that opportunities can only be reached via the transport network.

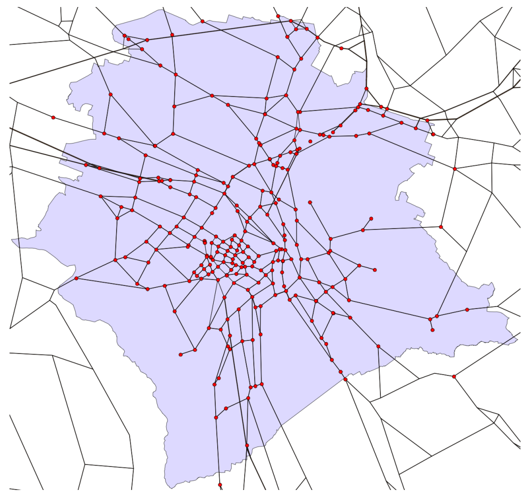
2. The generalized cost *on* the transport network towards k.

3. The generalized cost of reaching the opportunity k from the transport network.

[4]This is another example of an assumption that does not have to be made for the high resolution accessibility computation.



(a) Opportunities with parcel coordinates given by the land-use model



(b) Opportunities, aggregated on the nearest node on the road network

Figure 4: Opportunity locations (red dots) are provided from the land-use model on a disaggregated parcel level. The spatial resolution inside MATSim depends on the resolution of the road network, i.e. on the number of nodes and link lengths. Thus, opportunities are directly aggregated to their nearest node on the given road network.

Unlike origins, for the present paper the locations of the opportunities are directly aggregated to the nearest nodes on the road network as depicted in Fig. 4. The number of aggregated opportunities are included as a weight D_j in the accessibility calculation. This implies that the generalized cost from the node (i.e. the network) to the opportunity is approximated as zero.[5] We believe that this approximation can be made because of the following reasons:

- In the present study, the opportunities are work locations. One could argue that, at least for the Zurich region, work locations are normally quite well connected to the transport network.
- One could expect that the effect "averages out": A node will typically be an average over several opportunities, some of them in reality close to the node and others not. Yet for the accessibility, only an average over these matters. In consequence, the effect of the approximation will, in leading order, just a (small) increase of the overall accessibility everywhere, corresponding to the neglected average generalized cost to reach opportunities from the network.

[5]This assumption could be removed as follows: Assume the generalized cost from the node j to the opportunity k is c_{jk}. Then $c_{ik} = c_{ij} + c_{jk}$ and therefore $e^{\beta_{scale} c_{ik}} = e^{\beta_{scale} c_{jk}} e^{\beta_{scale} c_{ij}}$. That is, if the D_j were replaced by $\sum_{k \in j} e^{\beta_{scale} c_{jk}}$, where the sum goes over all opportunities attached to j, then the generalized cost from the node to the opportunity would be included. The remaining problem would be that, in reality and according to the MATSim design, opportunities are not attached to the nodes but to the links. That is, for some approaches it may, in fact, be a detour to first go to the node n. The issue could be resolved by attaching the aggregated opportunities to links, not nodes. This could be implemented at very little additional computational cost.

3.3 Generalized cost of travel

The generalized costs are composed as follows:

$$\begin{array}{rcrcr} c_{ij,tt_{free}} & := & \beta_{tt_{wlk}} \cdot tt_{wlk,gap} & + & \beta_{tt_{free}} \cdot tt_{free} \\ c_{ij,tt_{car}} & := & \beta_{tt_{wlk}} \cdot tt_{wlk,gap} & + & \beta_{tt_{car}} \cdot tt_{car} \\ c_{ij,tt_{bic}} & := & \beta_{tt_{wlk}} \cdot tt_{wlk,gap} & + & \beta_{tt_{bic}} \cdot tt_{bic} \\ c_{ij,tt_{wlk}} & := & \beta_{tt_{wlk}} \cdot tt_{wlk,gap} & + & \beta_{tt_{wlk}} \cdot tt_{wlk} \end{array} \tag{3}$$

where

- tt_{free} is the free speed car travel time [in hours]
- tt_{car} is the congested car travel time [in hours]
- tt_{bic} is travel time by bicycle [in hours], using a constant speed of 15km/h
- tt_{wlk} is travel time on foot [in hours], using a constant speed of 5km/h
- $tt_{wlk,gap}$ is travel time on foot to overcome the gap between the origin location i and the road network [in hours], using a constant speed of 5km/h
- $\beta_{tt_{free}}$, $\beta_{tt_{car}}$, $\beta_{tt_{bic}}$ and $\beta_{tt_{wlk}}$ are marginal utilities [in utils/hour] that convert travel times into utils. By default all marginal utilites are set to -12 utils/hour. In MATSim terms, this is the sum of the marginal opportunity cost of time (typically -6 utils/hour) and the marginal additional disutility of travel (typically another -6 utils/hour). In calibrated applications, a util is often worth roughly one Euro or one Dollar.

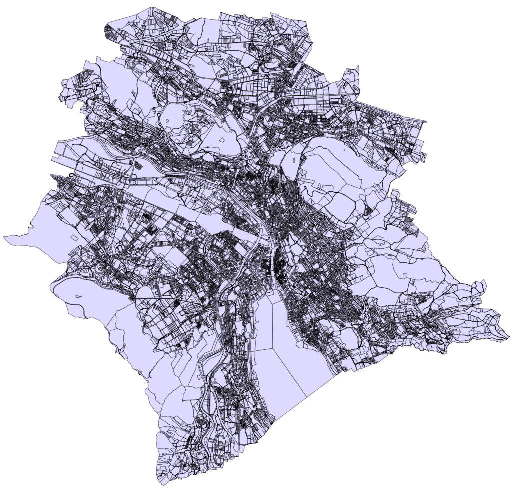
4 Scenario: Zurich, Switzerland

The present study is applied to a real-world scenario. This is the city of Zurich, a parcel-based UrbanSim application that will be briefly discussed here. A full description is given in [23, 24].

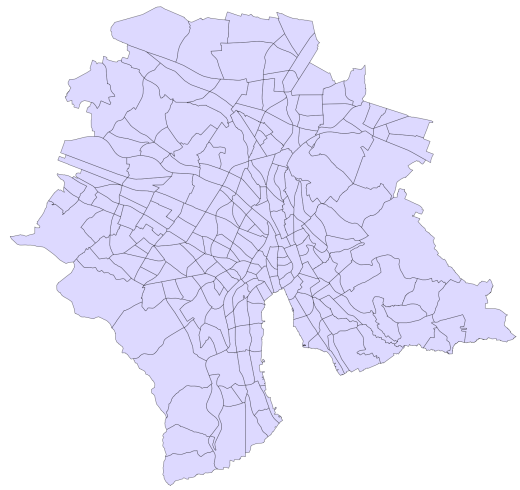
The Zurich case study uses the the year 2000 as the UrbanSim base year. It stores the initial state of the study area. The data that is needed to create the base year such as a population census, mobility census, enterprise census, etc., comes from several sources that can be divided into two main categories: governmental and private data. The sources for governmental data includes various Swiss federal, cantonal,[6] and municipal offices. The acquisition of private data includes private institutions, web-sites, and self created data. For more details on the base year data and data processing methods see [23, 24].

The Zurich application consists of 40 407 parcels and 234 zones; see Fig. 5. The synthetic population of Zurich counts 336 291 inhabitants. 316 703 jobs are provided in the study area. In this paper the UrbanSim base year is used to create the input for the MATSim runs. After that, UrbanSim is no longer needed for the present study.

[6] A Swiss Canton corresponds to a federal state



(a) UrbanSim Parcels



(b) UrbanSim Zones

Figure 5: UrbansinSim provides different geographic units of analysis such as parcels (a) and zones (b) [3]. The blue area indicates the city of Zurich.

4.1 Population and Travel Demand

In order to speed up computation times, MATSim considers a 10% random sample of the synthetic UrbanSim population, consisting of 33 629 agents. All MATSim agents have complete day plans with “home-to-work-to-home” activity chains. Work activities can be started between 7 and 9 o’clock with a typical duration of 8 hours. The home activity has a typical duration of 12 hours and no temporal restriction.

4.2 Network and Adjustments

A revised Swiss regional planning network [25] is used that includes major European transit corridors; see Fig. 6. The network consists of 24 180 nodes and 60 492 links, where each link is defined by an origin and a destination node, a length, a free speed car travel time, a flow capacity and a number of lanes. In addition each link obtains congested car travel times once the traffic flow simulation in MATSim is completed; see Appendix A.

The following summarizes modifications to improve link capacities especially at the urban scale; a detailed description is given in [26] and [27]. All links within a radius of 4 kilometers around the Zurich city center were modified as follows:

- Links that correspond to so-called primary[7] roads in OpenStreetMap[8] (OSM) get a capacity of at least 2000 vehicles per hour. Links with higher capacities remain unchanged.
- Links that correspond to secondary roads in OSM keep their initial capacity (usually between 1000 and 2000 vehicles per hour).

[7] an open street map road classification is given at `http://wiki.openstreetmap.org/wiki/Highway_tag_usage`

[8] see `http://www.openstreetmap.org`

- The remaining links get a capacity with a maximum of 600 vehicles per hour. If the original capacity is lower, it is not changed.
- Finally, a few individual links are adjusted manually based on local knowledge.

The flow- and storage capacity of the road network are automatically adjusted based on the given population sampling rate used for the MATSim runs. This is done in order to preserve congestion effects when running MATSim at small samples. The flow capacity gives the maximum number of vehicles per time unit that can pass a link [28]. It is adjusted by a flow capacity factor, which is set to the same value as the given *Population Sampling Rate*. The storage capacity defines the maximum number of vehicles that can be on a link [28]. The corresponding storage capacity factor is defined by $\frac{Population\ Sampling\ Rate}{Heuristic\ Factor}$, where the $Heuristic\ Factor = \sqrt[4]{Population\ Sampling\ Rate}$. The $Heuristic\ Factor$ is a fit function based on engineer heuristics. It aims to raise the storage capacity especially at low sampling rates to avoid network breakdowns caused by strong but spurious backlogs. This effect is explained in [29].

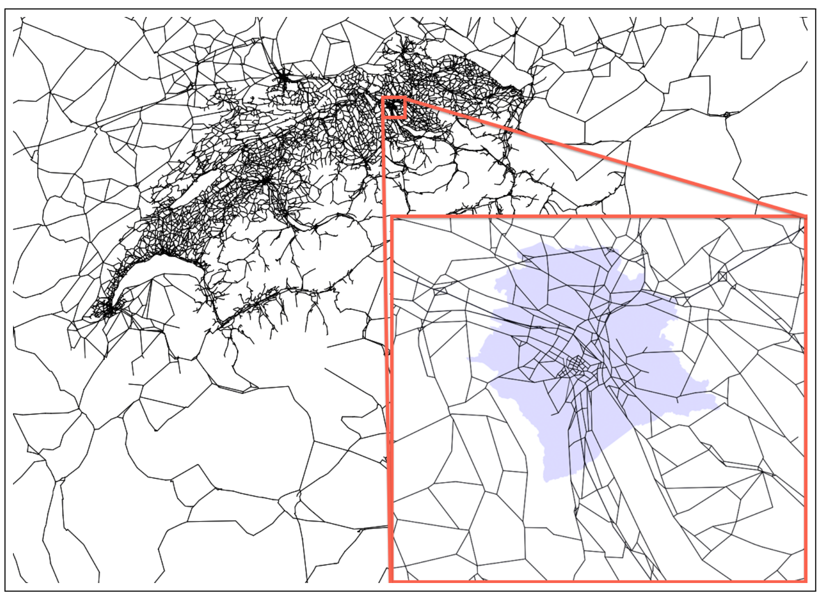


Figure 6: The Zurich case study network, area of Zurich (in blue) enlarged.

4.3 Simulation Run

First, a preparatory MATSim run is performed by running the simulation for 1000 iterations. During the first 800 iterations 10% of the agents perform “time adaptation”, which changes the departure times of an agent, and 10% adapt their routes. The remaining agents switch between their plans. During the last 200 iterations time and route adaptations are switched off. Thus, agents only switch between existing plans. The output of this run is referred to as the **base case**.

4.4 Accessibility Setup

The present study looks at the proposed econometric accessibility measure using the example of work place accessibility. By aggregating the work places on the network nodes the number of opportunities is significantly reduced from 316 703 to 272 as described in Sec. 3.

	Reference Setting	**Setting 1** ("resolution")	**Setting 2** ("mode")
Spatial Units (SU)	cell	cell zone	cell
Resolution	100m	50m 100m 200m 400m 800m 1600m	100m
Mode	congested car	congested car	free speed car congested car bicycle walk
Generalized Cost of Travel	travel times [minutes]	travel times [minutes]	travel times [minutes]
Scale Parameter	$\beta_{scale} = 2$	$\beta_{scale} = 2$	$\beta_{scale} = 2$
Beta Parameter	$\beta_{tt_{car}}$=−12utils/hour	$\beta_{tt_{car}}$=−12utils/hour	$\beta_{tt_{free}}$=−12utils/hour $\beta_{tt_{car}}$=−12utils/hour $\beta_{tt_{bic}}$=−12utils/hour $\beta_{tt_{wlk}}$=−12utils/hour

Table 2: Accessibility parameter settings.

All accessibility measures are applied to the **base case** based on the road network for the morning peak hour at 8am, when most travellers are commuting to work.

In order to analyse and evaluate the measure, four settings are created. A so-called "reference" setting, and three alternative settings, where each alternative only differs in one parameter setting compared with the reference. An overview can be found in Tab. 2:

1. **Reference Setting:** This can be seen as a default setting for the present accessibility study. It is used to evaluate the impact of the following, alternative parameter settings. This setting uses the cell-based approach with a resolution of $100m \times 100m$ and congested car travel time as generalized cost. The scale parameter (β_{scale}) is set to 2, which is the MATSim default setting. The marginal utility for car ($\beta_{tt_{car}}$) is set to −12utils/hour.

2. **Spatial Resolution (Setting 1)**: This is performed at two spatial units (SU), cells and zones. For the cell-based approach the following resolutions are compared in terms of "information-gain" and computing time: $50m \times 50m$, $100m \times 100m$, $200m \times 200m$ and $400m \times 400m$. In addition the results of the zone-based approach are presented and compared with the outcome of the reference setting.

3. **Mode (Setting 2):** This setting compares three travel modes in accessibility computation, which are car, bicycle and walk. For car, free speed and congested travel times are used. The travel times for traveling by bicycle or on foot are computed by taking the travel distance with a constant velocity of 15km/h (bicycle) or 5km/h (walk).

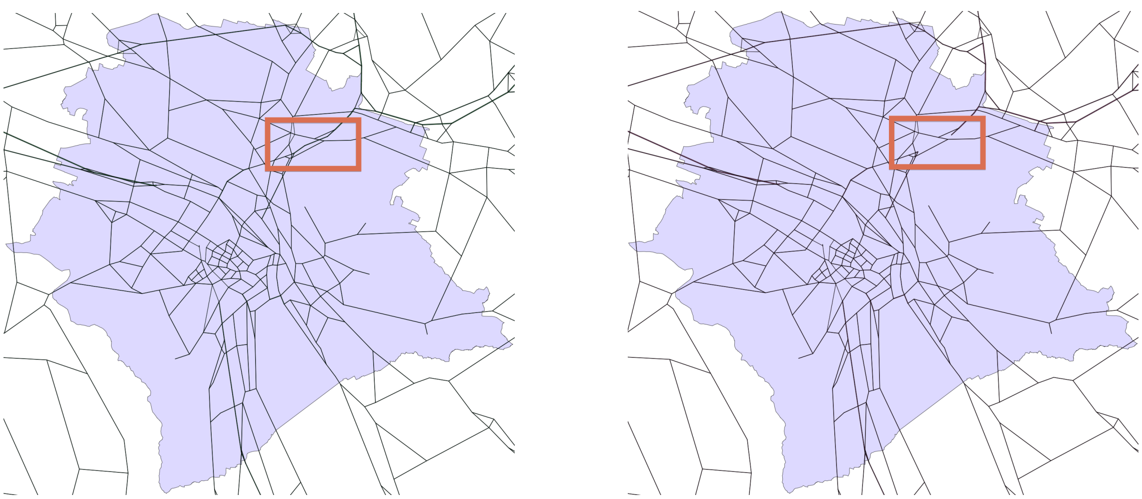
4.5 Sensitivity to a modification in the transport system

In addition a sensitivity test is performed to investigate the impact from changes on the road network on the accessibility outcome. For this purpose two scenarios are created, which only differ in the network set-up:

1. **Base Scenario**: The base scenario leaves the road network as it is.

2. **Schöneichtunnel**: In this scenario the "Schöneichtunnel", an important intersection-free artery connection in the western part of Zurich is closed; see Fig. 7. It connects the north-easterly suburbs and the central business district with a capacity of 5 740 vehicles per h in each direction. In Fig. 8 it can be seen that there are no alternative roads that can compensate such a closure. The idea for this scenario is loosely based on a real closure of the Schöneichtunnel due to maintenance works in the year 2001 [30].

Both scenarios are using the **base case** as input and run for another 1000 iterations with the same time and route adaptation settings as described above.



(a) Network used in the Base Scenario

(b) Network used in the Schöneichtunnel Scenario

Figure 7: In order to investigate the impact of changes in the transport system, the "Schöneichtunnel" is closed by removing links from the road network as illustrated in Figure (b). Figure (a) shows the default, unchanged network.

5 Results

5.1 Reference setting

Fig. 9 depicts the accessibility measure with the reference settings that are explained in Sec. 4.4. To improve the interpretability, the road network is overlayed. The color bar on the right hand side indicates the accessibility level, where a good work place accessibility is indicated by green areas and poor accessibility is indicated by dark blue or black areas. As might be expected, the plot exhibits a very good work place accessibility in areas

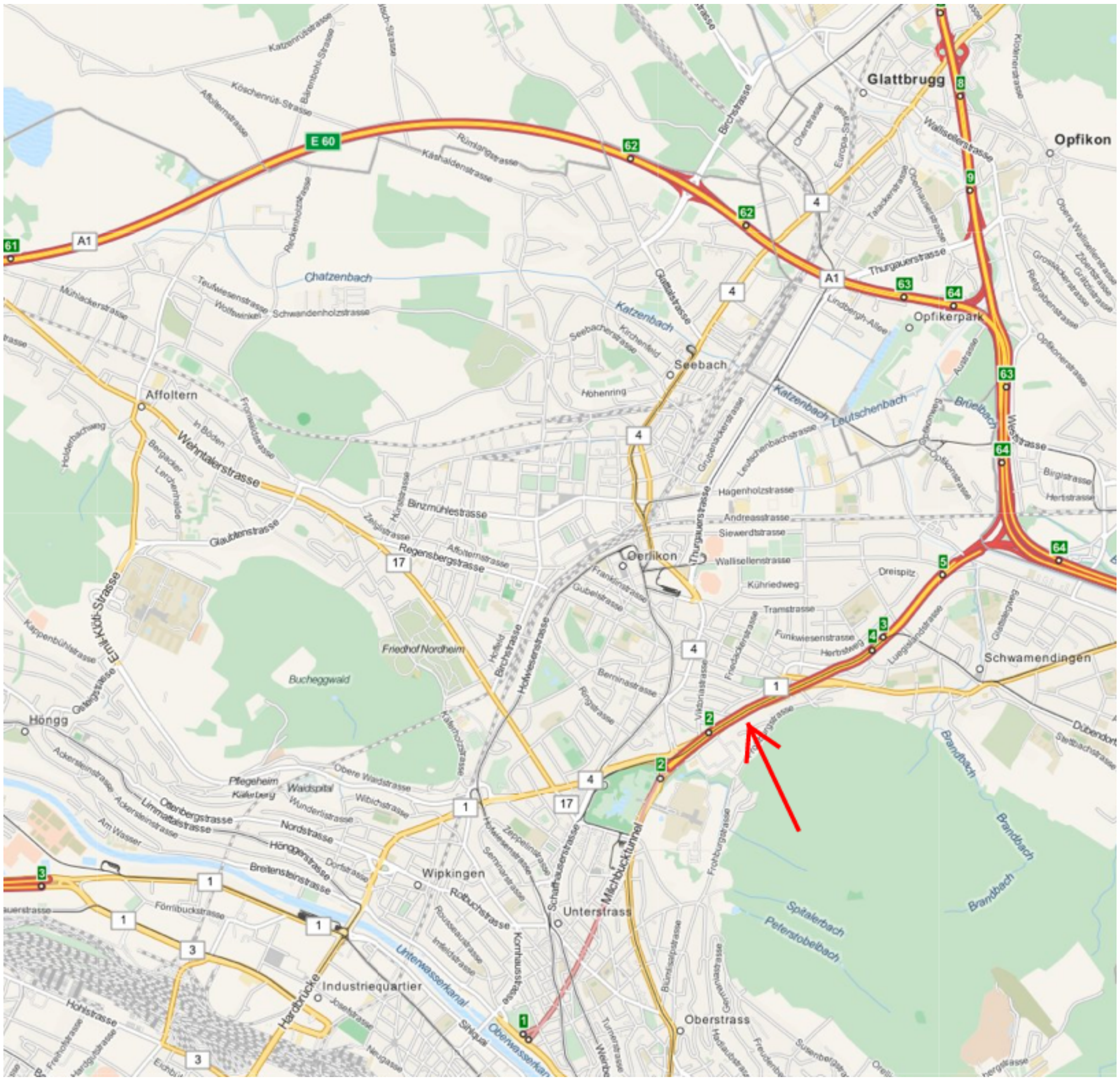


Figure 8: Network from `www.openstreetmap.org`. The arrow points to the links that are removed. The downtown area is to the bottom left of the picture.

that provide a high density of opportunities and a well developed road network. These characteristics apply for the inner city, where the highest utility values are measured, and the areas along the major access roads from and to Zurich, visible as green or yellow lines. In contrast, less accessible areas with a low work place density have a color gradient from red to dark blue or black. This for instance applies for the "Zürichberg" and the "Uetliberg", which are two undeveloped wooden hills located in east and the south west part of Zurich. The several "islands of low accessibility" in the center of Zurich are due to localized congestion on those links: If there is strong congestion at the origin, then *all* opportunities k incur a large c_{ik} and thus make only a small contribution to the sum.

5.2 Spatial Resolution

The results of different resolutions in the cell-based accessibility computation (**Setting 1**) are depicted in Fig. 10. The lowest resolution ($400m \times 400m$) provides a quite undif-

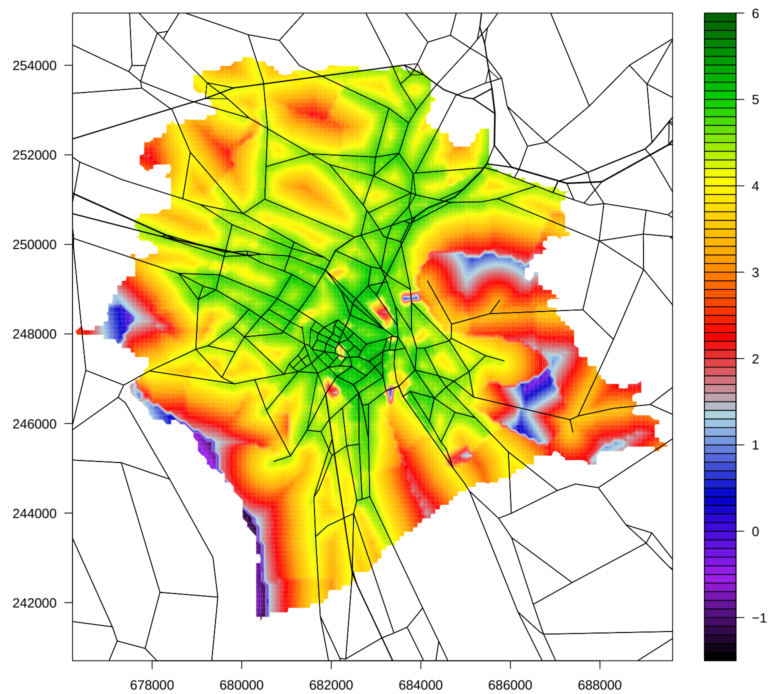
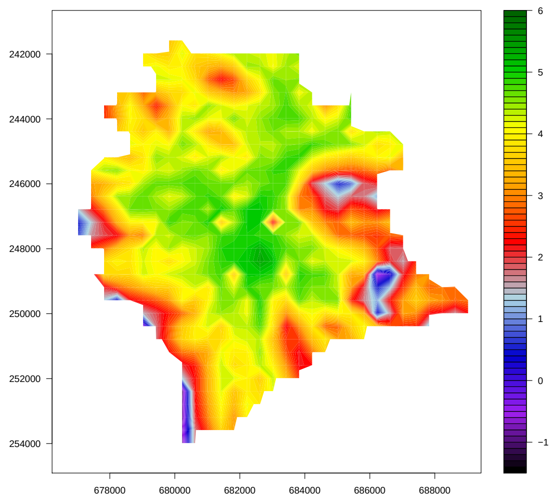


Figure 9: This shows the accessibility measure with the reference settings and the underlying road network.

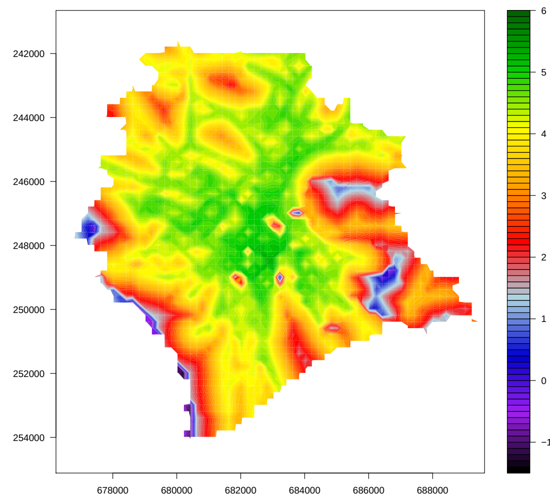
ferentiated picture. Higher resolutions lead to more detailed accessibility measures. For instance, at a resolution of $50m \times 50m$ even fine road structures in the city center can be clearly recognized. However, a significant increase in the level of detail can be observed until the $100m \times 100m$ resolution. Beyond that point the plot just looks smoother and sharper, but offers only little more detail.

Resolution Cell-Based Approach	**Measuring Points**	**Aggregated Opportunities**	**Computing Time [minutes]**
$50m \times 50m$	36 748	272	213
$100m \times 100m$	9195	272	54
$200m \times 200m$	2292	272	13
$400m \times 400m$	577	272	3
$800m \times 800m$	142	272	< 1
$1600m \times 1600m$	36	272	< 1
Number of Zones Zone-Based Approach	**Measuring Points**	**Aggregated Opportunities**	**Computing Time [minutes]**
234	234	272	≈ 1

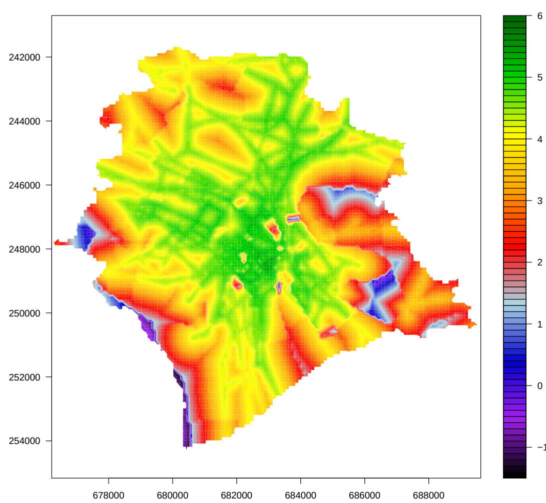
Table 3: This table summarizes the consumed computing times to measure accessibility at different resolutions and different spatial units, i.e. zones and cells. All measures are performed on a Mac Book Pro with an Intel Core 2 Duo 2.5GHz processor and 4 GB of memory, where 1 CPU core is used to execute the accessibility measures.



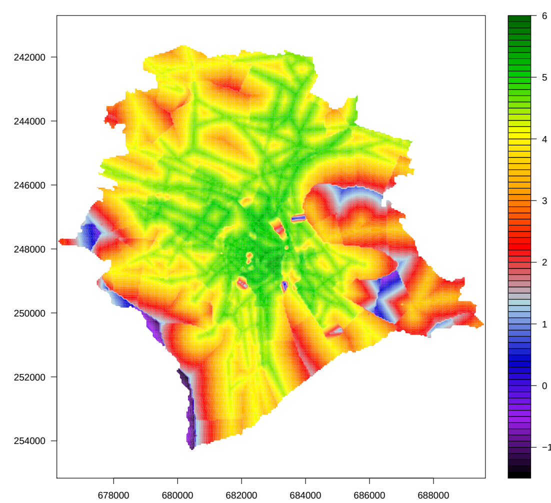
(a) Resolution $400m \times 400m$



(b) Resolution $200m \times 200m$



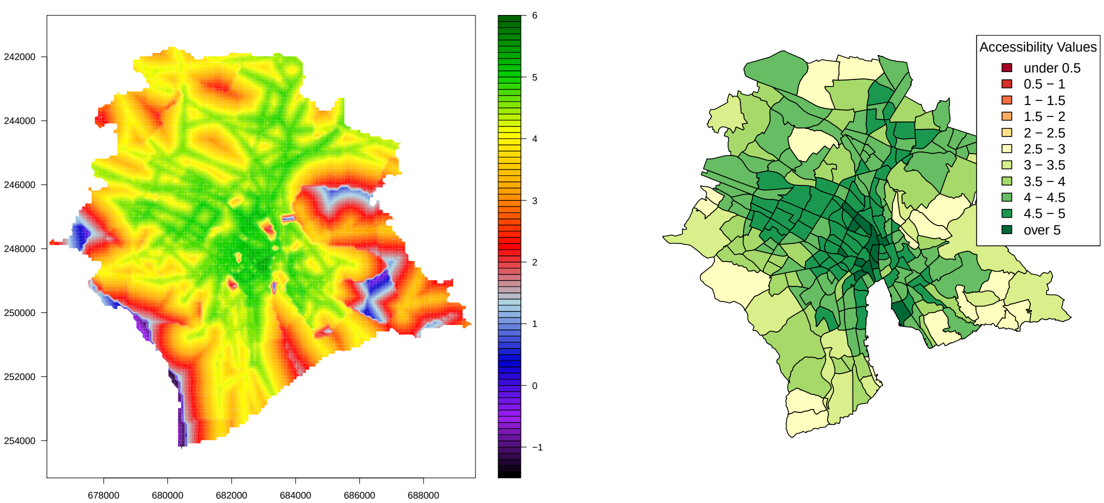
(c) Resolution $100m \times 100m$ (reference setting)



(d) Resolution $50m \times 50m$

Figure 10: This depicts the results using different resolutions in the cell-based accessibility measure in ascending order from the top left to the bottom with the side lengths of $400m \times 400m$, $200m \times 200m$, $100m \times 100m$ and $50m \times 50m$ (accessibility measures at the resolutions of $800m \times 800m$ and $1600m \times 1600m$ are performed but not shown here). The color bar on the right hand side of each plot indicates the accessibility to work places, where green indicates a good accessibility and blue or black areas stand for poor accessibility.

In this set-up the resolution of two successive plots is doubled by halving the site lengths of cells. In consequence the number of measuring points are quadrupled, which is also reflected by the measured computation times listed in Tab. 3.



(a) Parcel representation with $100m \times 100m$ resolution (reference setting)

(b) Zone representation

Figure 11: Comparing the cell- vs. the zone-based approach using congested car travel times in accessibility computation.

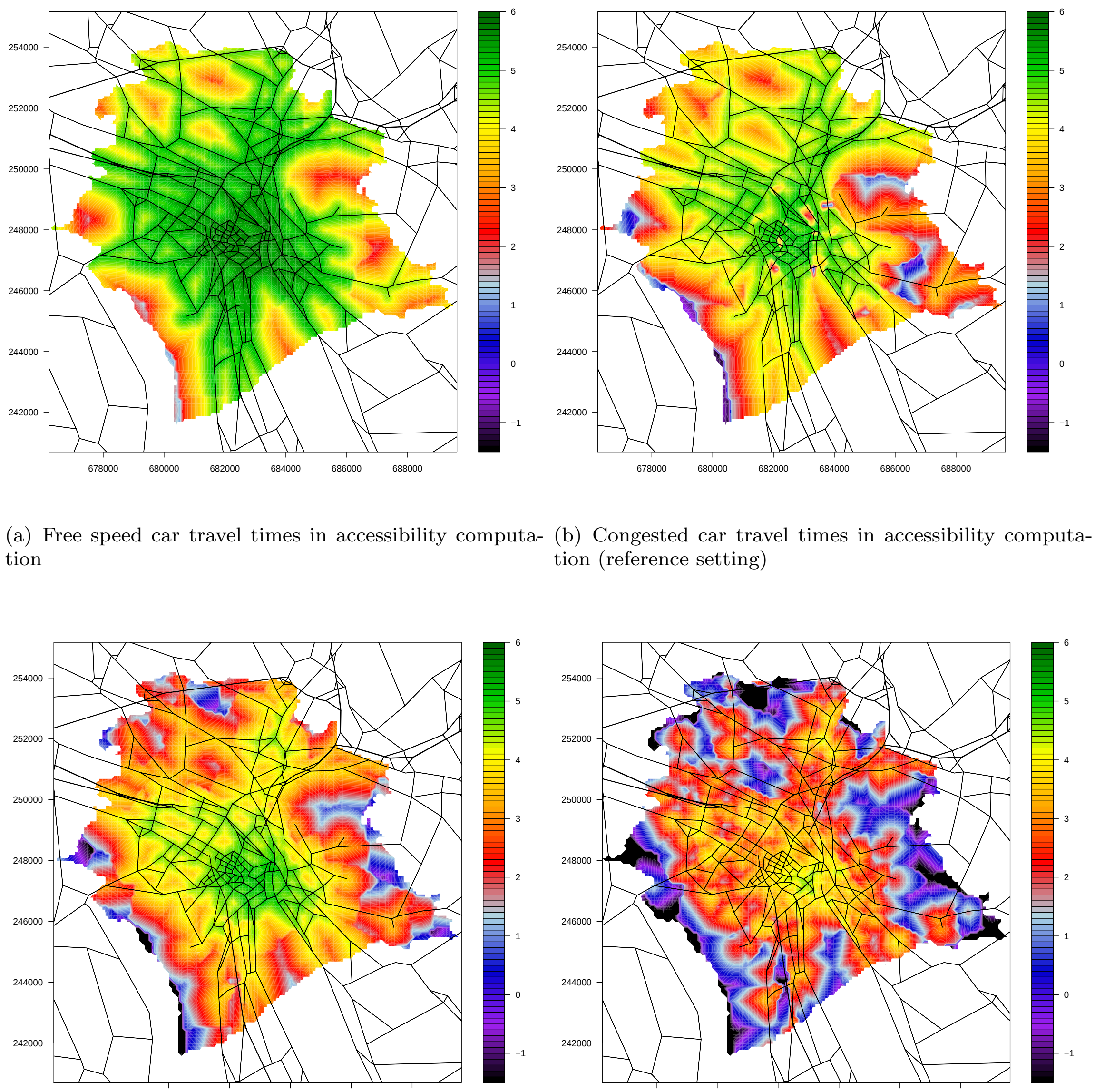
The accessibility measures for the zone-based approach are performed for each zone centroid, which represents the accessibility of an entire zone. Although this limits the number of measuring points, see Tab. 3, the result correlates with the reference plot; see Fig. 11. Zones covering the city center and major access roads have a good accessibility. Zones at the border areas with a low density of opportunities and a less developed road infrastructure have a poor accessibility. Nevertheless, the zonal approach has a tendency to give the same accessibility values to areas which accessibility is clearly not uniform. Also, the accessibility value of locations close to zone boundaries depend on the exact drawing of that boundary, which does not seem realistic.

Overall, the following conclusions can be drawn at this point:

- The computation of a cell-based (rather than a zone-based) accessibility measure is computationally feasible.
- For the given Zurich scenario, including the given network, a resolution better than $100m \times 100m$ does not deliver noticeable additional gains.
- The computing time for $100m \times 100m$ is currently about one hour. Given that these are independent calculations, they can be divided by the number of available CPU cores.
- The computational complexity of the accessibility computation for *one* cell is roughly linear in the number of links. That is, using a high resolution network with, say, ten

times as many links will take ten times as much computation time. This is, however, the same increase one will face in the MATSim routing computation in general, which means that the increase in the accessibility computation time will be similar to the overall increase in computation time that comes with a higher resolution network. The *relative* computational burden will remain approximately the same.

5.3 Mode



(a) Free speed car travel times in accessibility computation

(b) Congested car travel times in accessibility computation (reference setting)

(c) Bicycle travel times in accessibility computation

(d) Walk travel times in accessibility computation

Figure 12: These plots visualize the influence of different transport modes on the accessibility computation.

The results of **Setting 2** are shown in Fig. 12. The first two plots are illustrating how congestion significantly reduces accessibility.

The third and fourth plot illustrate accessibility by bicycle and by walking, repsectively. Congestion has no effect on these modes. Both plots show that spatial proximity to opportunities has a strong influence on the results. Locations away from the city center and the commercial areas in the northeast and western part of Zurich have a rapidly decreasing accessibility. As seems plausible, near the city center the bicycle provides similar accessibility as the car under congested conditions. Farther away from the center, the car gains ground, even under congested conditions.

Overall, one might speculate that Fig. 12(a) is what people who plan to use a car expect but Fig. 12(b) is what they actually get. And what they actually get is not much different from what one gets by using a bicycle (Fig. 12(c)). In contrast, walk is truly much worse (Fig. 12(d)).

5.4 Sensitivity to a modification in the transport system

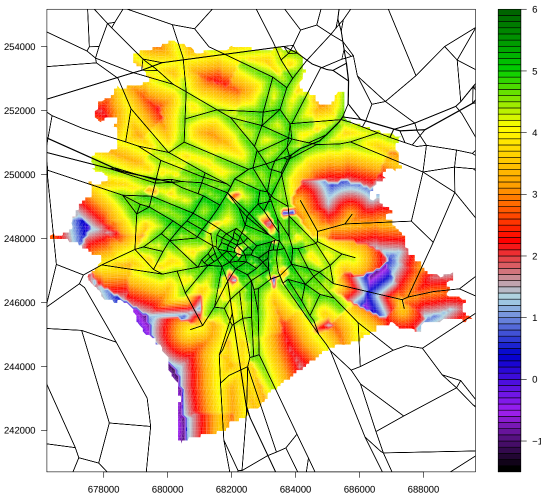
In this section, the accessibility consequences of a tunnel closure, as described in Sec. 4.5, are considered. Fig. 13(a) shows, as described in Sec. 4.5, the reference case, but after another 1000 iterations.

For Fig. 13(b) the following was done: (i) The tunnel was closed. (ii) For all routes that used the tunnel, an alternative route was computed, based on the free speed travel times , but minus the tunnel. (iii) A traffic flow simulation was run based on these routes. The result (Fig. 13(b)) is significantly reduced accessibility in the north-eastern sector of the city. Strong congestion upstream and parallel to where the tunnel was significantly hinders car traffic.

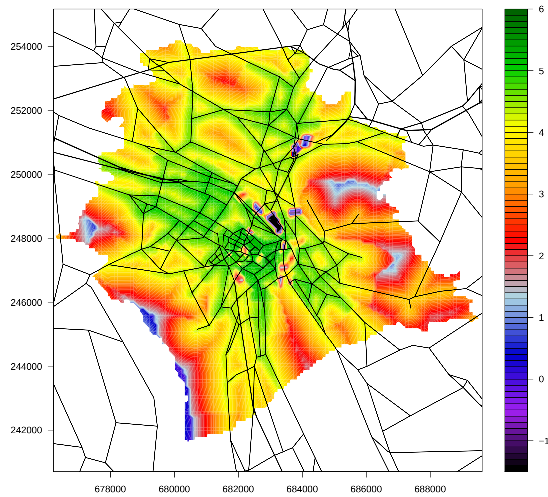
Fig. 13(c) then shows accessibility after the system had a chance to adjust to the closed tunnel. Surprisingly, there seem to be *no* accessibility consequences. Seemingly, the system re-equilibrates in a way that the status quo ante in terms of accessibility is recovered. The simulation results are, however, distinctly different, since the average trip distances in the simulation area drop from $9800m$ to $9350m$. Thus, the long-term effect of the tunnel closure seems to be a reduction in average trips distances, while the average travel times remain the same. This may seem a bit counter-intuitive. We have, however, seen similar results in previous studies [31, 32]. Presumably, a local change in a networked transport system can lead to a re-arrangment of the traffic patterns in such a way that it redistributes the effects of the change throughout the system; the overall effect is then a small but globally felt accessibility change. In the present situation, there does not even seem to be that globally felt accessibility change; it may therefore be a real-world example of the Braess paradox [33]. Such results, however, do not hold in all situations; Ref. [34] describes a modification where the gains and losses (albeit differently measured) show a clear spatial picture.

6 Discussion and Outlook

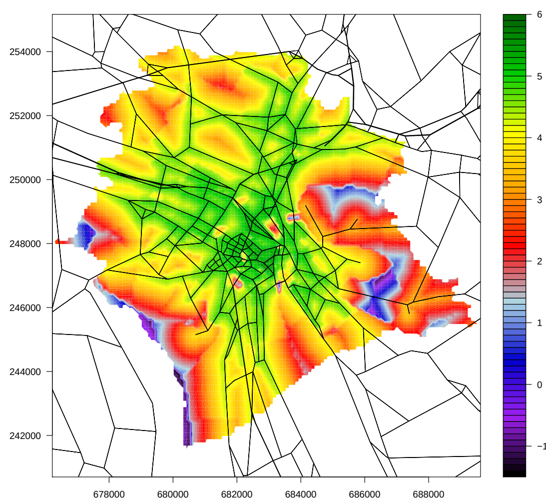
The accessibility outcome shows no significant improvements with a resolution finer than $100m \times 100m$. The reason for this is the spatial resolution inside MATSim, which is determined by the road network. It is given by the (i) number of nodes that incorporate the opportunities and (ii) the broad range of different link lengths, which are in this configuration at least 200 meters long for the inner city of Zurich. Thus, there is no additional



(a) Base Scenario after 1000 iterations



(b) Schöneichtunnel closure after 1 iteration



(c) Schöneichtunnel closure after 1000 iterations

Figure 13: The sensitivity test illustrates the impact from a change in the transport system, simulated by a tunnel closure, on the accessibility measure.

resolution beyond the network. The present network is created for Swiss-wide planning purposes and thus has a limited resolution. In consequence, the present study should be repeated with a higher resolution network. Our own investigations with higher resolution networks ([35] and unpublished) indicate that additional gains beyond a resolution $100m$ are small in general. This seems intuitively plausible: A typical person will not consider accessibility consequences of a locational difference of 100 meters. Other small scale effects, such as noise, will play a larger role here.

A closer look on the cell-based accessibility computation method shows the following: The number of measurement points, even at the highest resolution (36 748), is still lower than if the number of UrbanSim parcels (40 407) would be calculated separately. Furthermore, the cell-based computation method measures the accessibility for the entire study area. Parcels only cover parts of the study area; see also Fig. 5a. Presumably, one could consider adaptive mesh sizes as is common in finite difference schemes. Such an adaptive scheme would have fewer grid cells in areas where the uniform geometry is not disturbed by network links.

The present study uses an algorithmic set-up that first computes, for each origin, the least cost tree, and then goes over all aggregated opportunities, extracts the generalized cost to get there, and sums up the exponential of this. This is still a fairly inefficient approach: The generalized cost to get to any node of the network needs to be stored, and the relevant stored node needs to be found from the node of the aggregated opportunities via a relatively slow HashMap lookup. It would, however, be possible to perform the summing up directly inside the least cost tree computation; this would obviate both the need for storing the generalized cost at every node and the need to look up these costs via a relatively slow data structure. The advantages of such an approach may not be very large for the present study where the opportunities could be aggregated into less than 300 locations. It would, however, make a crucial difference for high resolution networks where many more links carry smaller numbers of opportunities.

7 Conclusion

Accessibility measures are, for a given origin, a weighted sum over possible destinations. In this paper, the econometric logsum term is used as an example. It measures accessibility as a benefit that someone at a specific location derives from access to spatially distributed opportunities. It includes, as usual, a land-use component by considering the distribution of opportunities and a transport component by determining the effort to get there.

This paper presents an implementation approach that allows to calculate the logsum term at high resolutions. The present paper applies this approach to a real-world scenario, the city of Zurich (Switzerland), with the example of measuring work place accessibilities. The measure is tested with different spatial resolutions and for different transport modes such as car, bicycle and traveling on foot.

In addition a sensitivity test was carried out, where the Schöneichtunnel, an important access road, is closed.

Acknowledgments

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A Appendix

The following paragraphs explain (i) the simulation approach in MATSim and UrbanSim and (ii) provide an insight into the effort of integrating both frameworks. The underlying software design issues and decisions of this integration are explained in [13].

UrbanSim: UrbanSim (e.g. [1, 2, 3]) is an extensible, microscopic urban simulation model. It aims at simulating interactions between land use, transportation, economy and the environment at large-scale metropolitan areas and over a long time period. UrbanSim mainly consists of six models reflecting the decisions of households, businesses, developers and governments (as policy inputs). This are the Econometric and Demographic Transition Models, the Household and Employment Mobility Models, the Household and Employment Location Models, the Real Estate Development Model, and the Real Estate Price Model. The processing sequence of the main models are shown in Fig. 14, where Household and Employment models are independent and only illustrated jointly in for simplicity. The bold arrows illustrate the sequence of events without necessarily indicating an interaction between contiguous models.

The input to the UrbanSim models includes the base year data, the access indicators from the external travel model, and control totals derived from external macro-economic forecast models. The base year data store contains the initial state of a scenario. Typically the database includes geographic information, initial household and job information, ect., for a given base year. The primary source of the base year data usually comes from surveys or census. The UrbanSim models, listed above, maintain the data store and simulate its evolution from one year to the next.

MATSim4UrbanSim: The interaction between MATSim and UrbanSim is a bi-directional relationship consisting of three steps; see Fig. 15: (i) When UrbanSim moves forward in time from year to year, it calls MATSim in regular intervals. It passes the traffic network together with the UrbanSim population including the residence and work location of each individual person. (ii) Based in this information MATSim generates the traffic assignment and returns the resulting access and accessibility indicators. Then MATSim terminates. (iii) Finally, UrbanSim uses the indicators as input to its location choice models, listed in Tab. 1, for the next iteration.

MATSim computes several access- and accessibility indicators as feedback for UrbanSim such as (i) zone-to-zone skims, (ii) individual agent-based performances as well as (iii) accessibilities for UrbanSim zone and parcel applications:

- **Zone-to-zone Impedances**: The zone-to-zone matrix is an origin-destination-matrix (OD-matrix) comprising congested car and walk travel times, generalized travel costs and vehicle trips for each pair of zones. To calculate these indicators zones are assigned to the road network by connecting the zone centroid to the closest node in the network. The coordinates of the zone centroids are either directly given in the MATSim input tables, as in case of UrbanSim zone models, or are determined by averaging over all parcel coordinates that belong to a zone like in UrbanSim parcel models. The car travel times are based on link travel times from the congested

MATSim road network for the morning peak hours at 8a.m.. The generalized travel costs at this point consist of car travel time and toll (as time equivalent). Walk travel times are based on the shortest path on the road network with a constant speed of 5km/h. The vehicle trips are giving the number of trips for any pair of zones.

- **Agent-Based Performance**: This feedback contains the individual travel performance for each MATSim agent including congested car travel times and travel distances for both directions, commuting from home to work and back.

- **Accessibility Computation**: The accessibility measure is based on the so-called logsum term from Ben-Akiva and Lerman. It is an utility-based measure of accessibility reflecting the (economic) benefits, as the maximum expected utility, someone gains from access to spatially distributed opportunities. This measure is applied for zones and cells. A comprehensive description on this is given in Sec. 2 and 3. For UrbanSim zone applications MATSim calculates accessibilities using the zone-based approach, which determines and returns accssibilities on the zone level. For UrbanSim parcel applications the cell-based approach is used. Once the calculation for each cell is completed MATSim interpolates accessibility value from the grid-cell for each UrbanSim parcel. By default a bi-linear interpolation method is used. Two other methods, a bi-cubic and an inverse distance weighting interpolation, are available.

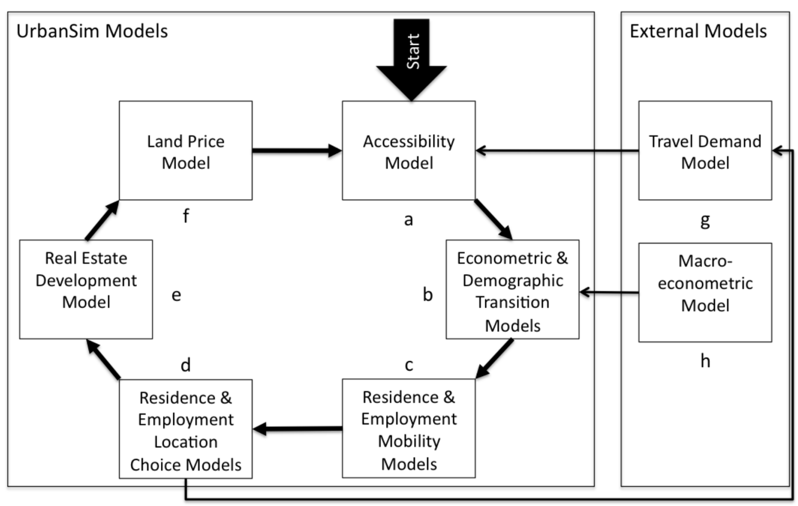

Figure 14: The sequence of UrbanSim main models after [1].

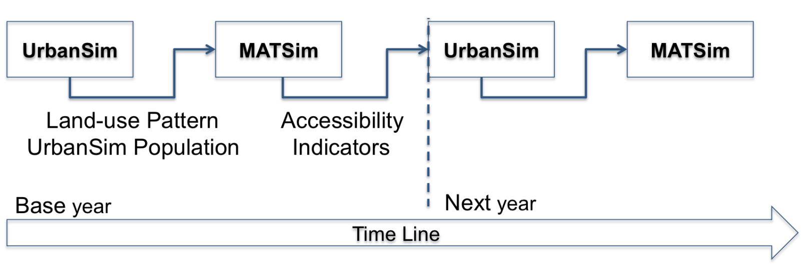

Figure 15: Interaction sequence between UrbanSim and MATSim.

MATSim: The following briefly describes the MATSim simulation structure, for more details see [10]. MATSim simulates each traveler individually. The simulation approach consist of an iterative loop with four important steps:

- **Initial demand generation**: For each UrbanSim person MATSim generates an independent plan that encodes a "home-to-work-to-home" activity chain based on the persons residence and job location.
- **Execution**: The mobility simulation executes all agent plans simultaneously on the road network.
- **Scoring**: All executed plans are scored by a utility function.
- **Re-planning**: Some of the agents obtain new plans for the next iteration by modifying existing plans with respect to two choice dimensions: route and departure time choice.

The repetition of the iteration cycle coupled with the agent memory, the capability to remember more than one plan per agent, enables the agents to improve their plans over several iterations [10]. At the end of this iteration cycle MATSim obtains a congested road network. Based on this it computes the access- and accessibility indicators as feedback for UrbanSim.

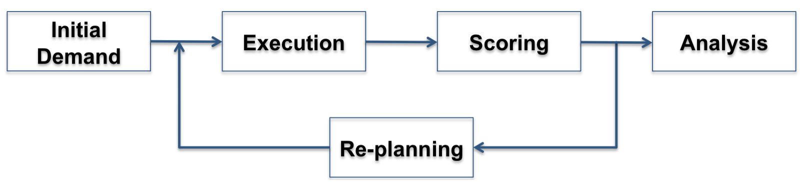

Figure 16: The simulation inside MATSim consists of an iterative loop with the following important steps: the initial demand generation, the execution of agent plans, a utility scoring function, the re-planning, were agents obtain new plans, and the calculation of access- and accessibility indicators as feedback from MATSim to UrbanSim.

References

[1] Waddell, P., Journal of American planning Association **68** (2002) 297 .

[2] Miller, E., Nagel, K., Ševčíková, H., Socha, D., and Waddell, P., OPUS: An open platform for urban simulation, in *9th Conference on Computers in Urban planning and urban management (CUPUM)*, University College London, UK, 2005, See www.cupum.org.

[3] OPUS User Guide, *The Open Platform for Urban Simulation and UrbanSim Version 4.3*, University of California Berkley and University of Washington, 2011.

[4] Wegener, M., Overview of land-use transport models, in *Transport Geography and Spatial Systems*, edited by Hensher, D.A.; Button, K., number 5 in Handbook in Transport, pages 127–146, Pergamon/Elsevier Science, 2004.

[5] Babin, A., Florian, M., James-Lefebvre, L., and Spiess, H., Transportation Research Record **866** (1982) 1.

[6] PTV AG, *VISUM 11.0 Grundlagen*, 76131 Karlsruhe, 2009.

[7] PTV AG, *VISUM 11.0 Benutzerhandbuch*, 76131 Karlsruhe, 2009.

[8] Ortúzar, J. d. D. and Willumsen, L., *Modelling transport*, John Wiley Sons Ltd, Chichester, 3. edition, 2001.

[9] Balmer, M., Rieser, M., Vogel, A., Axhausen, K., and Nagel, K., Generating day plans using hourly origin-destination matrices, in *Jahrbuch 2004/05 Schweizerische Verkehrswirtschaft*, edited by Bieger, T., Laesser, C., and Maggi, R., pages 5–36, Schweizer Verkehrswissenschaftliche Gesellschaft, 2005.

[10] Balmer, M., Raney, B., and Nagel, K., Adjustment of activity timing and duration in an agent-based traffic flow simulation, in *Progress in activity-based analysis*, edited by Timmermans, H., pages 91–114, Elsevier, Oxford, UK, 2005.

[11] Raney, B. and Nagel, K., An improved framework for large-scale multi-agent simulations of travel behaviour, in *Towards better performing European Transportation Systems*, edited by Rietveld, P., Jourquin, B., and Westin, K., pages 305–347, Routledge, London, 2006.

[12] Balmer, M. et al., MATSim-T: Architecture and simulation times, in *Multi-Agent Systems for Traffic and Transportation*, edited by Bazzan, A. and Klügl, F., pages 57–78, IGI Global, 2009.

[13] Nicolai, T. and Nagel, K., Coupling MATSim and UrbanSim: Software design issues, VSP Working Paper 10-13, TU Berlin, Transport Systems Planning and Transport Telematics, 2010, see www.vsp.tu-berlin.de/publications.

[14] Nicolai, T. W., Wang, L., Nagel, K., and Waddell, P., Coupling an urban simulation model with a travel model – A first sensitivity test, in *Computers in Urban Planning and Urban Management (CUPUM)*, Lake Louise, Canada, 2011, also VSP WP 11-07, see www.vsp.tu-berlin.de/publications.

[15] Nicolai, T., *MATSim4UrbanSim – Guide on UrbanSim usage of the travel model plug-in*, acessed 2012, see matsim.org/extensions/matsim4urbansim.

[16] Hansen, W., Journal of the American Planning Association **25** (1959) 73 .

[17] Moeckel, R., *Business Location Decisions and Urban Sprawl A Microsimulation of Business Relocation and Firmography*, PhD thesis, University of Dortmund, 2006.

[18] Geurs, K. and Ritsema van Eck, J., Accessibility measures: review and applications, Technical report, National Institut of Public Health and the Environment, RIVM, P.O. Box 1, 3720 BA Bilthoven, 2001.

[19] Geurs, K. T. and van Wee, B., Journal of Transport Geography **12** (2004) 127 .

[20] de Jong, G., Daly, A., Pieters, M., and van der Hoorn, T., Transportation Research Part A: Policy and Practice **41** (2007) 874.

[21] Ben-Akiva, M. and Lerman, S. R., *Discrete choice analysis*, The MIT Press, Cambridge, MA, 1985.

[22] Dijkstra, E., Numerische Mathematik **1** (1959) 269.

[23] Schirmer, P., Zöllig, C., Bodenmann, B. R., and Axhausen, K. W., The Zurich case study of UrbanSim, in *European Regional Science Association Conference*, 2011.

[24] Schirmer, P., Options and constraints of a parcel based approach in 'UrbanSimE', in *Proceedings of the 10th Swiss Transport Research Conference (STRC)*, 2010, see www.strc.ch.

[25] Vrtic, M., Fröhlich, P., and Axhausen, K., Schweizerische Netzmodelle für Strassen- und Schienenverkehr, in *Jahrbuch 2002/03 Schweizerische Verkehrswirtschaft*, edited by Bieger, T., Lässer, C., and Maggi, R., pages 119–140, Schweizer Verkehrswissenschaftliche Gesellschaft, St. Gallen, 2003.

[26] Grether, D., Chen, Y., Rieser, M., Beuck, U., and Nagel, K., Emergent effects in multi-agent simulations of road pricing, in *Proceedings of the Annual Meeting of the European Regional Science Association (ERSA)*, 2008.

[27] Chen, Y., Rieser, M., Grether, D., and Nagel, K., Improving a large-scale agent-based simulation scenario, VSP Working Paper 08-15, TU Berlin, Transport Systems Planning and Transport Telematics, 2008, see www.vsp.tu-berlin.de/publications.

[28] Nagel, K., *Multi-agent transport simulation (draft-in-progress)*, 2007, Draft-in-progress for a book.

[29] Rieser, M. and Nagel, K., European Journal of Physics **63** (2008) 321.

[30] Rederlechner, N., Änderung der Luftbelastung in Zürich Nord während der Sanierung des Schöneichtunnels im Sommerhalbjahr 2001, Bericht 2002070, Stadt Zürich, 2001.

[31] Nagel, K., Towards simulation-based sketch planning: Some results concerning the Alaskan Way viaduct in Seattle WA, VSP Working Paper 08-22, TU Berlin, Transport Systems Planning and Transport Telematics, 2008, see www.vsp.tu-berlin.de/publications.

[32] Balmer, M. et al., Wirkungen der Westumfahrung Zürich: Eine Analyse mit einer agentenbasierten Mikrosimulation, IVT Working paper 550, Institute for Transport Planning and Systems, ETH Zurich, Zurich, Switzerland, 2009.

[33] Braess, D., Unternehmensforschung **12** (1968) 258.

[34] Nagel, K., Towards simulation-based sketch planning, part II: Some results concerning a freeway extension in Berlin, VSP Working Paper 11-18, TU Berlin, Transport Systems Planning and Transport Telematics, 2011, see www.vsp.tu-berlin.de/publications.

[35] Nicolai, T. W. and Nagel, K., Investigating accessibility indicators for feedback from a travel to a land use model, in *European Regional Science Association Conference*, Barcelona, Spain, 2011, also VSP WP 11-09, see www.vsp.tu-berlin.de/publications.