High resolution accessibility computations

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1 Introduction

Researchers assert that accessibility has a measurable impact in the real world: Hansen (1959) shows that areas which have more access to opportunities have a greater growth potential in residential development. Moeckel (2006) asserts that the principal idea of Hansen's approach is also true for businesses. In other words: Locations with easier access to other locations are more attractive compared to otherwise similar locations with less access.

Many quantitative indicators can be used for accessibility. Some examples are

- distance to next shopping area
- travel time (e.g. Vandenbulcke et al., 2009) or distance (e.g. Borzacchiello et al., 2010) to next railway station
- number of opportunities (e.g. workplaces, places to shop) within, say, 1 kilometer.

Comprehensive reviews of accessibility measurements are provided by Geurs and Ritsema van Eck (2001) and Geurs and van Wee (2004).

Accessibility can be seen as the result of the following four independent components (Geurs and Ritsema van Eck, 2001; Geurs and van Wee, 2004):

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-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.

Accordingly, accessibility measures can concentrate on one or several of these components (Geurs and Ritsema van Eck, 2001):

1. For example, the **infrastructure-based** approach is based on the performance of the transport system. An example would be the average speed by mode at certain locations.
2. The **activity-based** measurement deals with the distribution of possible activity locations in space and time. An example would be the number of shopping locations or workplaces within a certain geodesic distance. Alternatively, one could look at the number of shopping locations or workplaces within a certain travel time, which would combine the infrastructure-based with the activity-based approach.

3. A **utility-based** measurement of accessibility reflects the (economic) benefits, as the maximum expected utility, that someone gains from access to spatially distributed opportunities (Geurs and Ritsema van Eck, 2001; de Jong et al., 2007). The typical example is the logsum term, also discussed below.

Normally, accessibilities are attached to spatial units i. These spatial units are typically relatively large zones, but one could equally well calculate accessibilities for each parcel or building in the region of interest. In many cases, however, the computational effort for this would be rather large. In addition, it may not be necessary: Since accessibility is a spatially averaged quantity, it is plausible to assume that the accessibility of a building between two other buildings might be interpolated from the two neighboring accessibility values.

Taking this argument further, one could as well consider accessibility as a field, i.e. as continuously varying in space, $A(x, y)$, where x and y are the coordinates. As is common in many areas of science, such fields can be visualized by calculating the values on regular grid points, and then using an averaging plotting routine. A similar approach was also used by Borzacchiello et al. (2010). Going beyond that paper, however, we will compute accessibility not based on Euclidean distance, but using the network oriented performance of the transport system.

Sec. 2 describes in detail how this accessibility measurement is implemented. Sec. 3 describes a real-world scenario to which the approach was applied. Sec. 4 presents results of this application, in particular with respect to spatial resolution and computing times. The paper ends with a discussion and a conclusion.

2 Methodology: high resolution accessibility

2.1 Accessibility indicator

This section looks at the implementation to compute accessibilities at high resolutions. For the present study, a utility-based measurement is selected (e.g. Ben-Akiva and Lerman (1985)), which is also known as the logsum. It is defined as

$$A_i := \ln \sum_k e^{V_{ik}} \ , \tag{1}$$

where k goes over all possible destinations, V_{ik} is the disutility of travel in order to get from location i to location k. The logsum term includes a land-use component that considers the number and distribution of opportunities, and a transport component that determines the effort to get there.

It may be useful to recall the origins of Eq. (1). For this, assume that the full utility of location k, seen from i, is $U_{ik} = V_{base} + V_{ik} + \epsilon_{ik}$, where V_{base} is a constant base utility for doing the activity at any location, V_{ik} is the systematic (= observed) disutility to get there, and ϵ_{ik} is a random term which absorbs the randomness of the travel disutility, but more importantly the utility fluctuations of doing the activity around V_{base}. Under the typical assumption that the ϵ_{ik} are independent and identically Gumbel-distributed random variables, the expectation value of U_{ik}, averaged over all possible destinations k, becomes

$$E(U_i) = A_i + Const \ .$$

$Const$ is an integration constant which can, in principle, be computed. It contains both the effect of the base utility, V_{base}, and some constants related to the Gumbel distribtion. Since it is the same for all locations, it is typically dropped. As a result, A_i can become negative.

Eq. (1) sometimes includes a so-called scale parameter. See Sec. 5 for a discussion of this.

Eq. (1) can be seen as a proxy for other accessibility indicators of the form $g(\sum_k f_{ik})$, where f_{ik} is some measure related to the difficulty of getting from i to k, and g is a typically non-linear and monotonic transformation. For example, with

$$f_{ik} = \begin{cases} 1 & \text{if distance } < 1\,km \\ 0 & else \end{cases}$$

and $g(x) = x$ the indicator counts the number of opportunities within $1\,km$.

Accessibilities in the present paper are computed based on a congested road network with time dependent travel times. This task is part of an attempt to couple a land use model, UrbanSim (Waddell, 2002; Miller et al., 2005; OPUS User Guide, 2011), with a transport model, MATSim (Balmer et al., 2005; Raney and Nagel, 2006; Balmer et al., 2009). In this configuration MATSim performs a traffic flow simulation based on the land-use and commuting patterns provided by UrbanSim. A comprehensive description of the simulation and integration approach of MATSim and UrbanSim is given in Nicolai and Nagel (2012) (pp.21).

2.2 Overview of computation

In order to calculate the accessibility A_i, origin locations i and opportunity locations k are assigned to a congested road network with time dependent travel times. For every given origin i a so-called "least cost path tree" computation runs through the network and determines the best route, and thus the least negative travel utility V_{ik}, to each opportunity location k by using the Dijkstra shortest path algorithm (Dijkstra, 1959). The best route from i to k depends on the given cost type such as link travel times or distances. Once the least cost path tree has explored all nodes, the resulting disutilities V_{ik} for all opportunities are queried and the accessibility is calculated as stated in Eq. (1).

2.3 Assignment of locations to the network

Origin and opportunity locations do not necessarily lie on the network. Thus, the calculation of V_{ik} includes the disutility of travel to overcome the gap between locations and the road network.

For origin locations i, the shortest distance to the network is either given by (i) the Euclidean distance to the nearest node or (ii) the orthogonal distance to the nearest link on the network. If the mapping of location i is to a link, as in case (ii), V_{ik} further includes the travel disutility to overcome the distance to the nearest node. The travel costs on the link are calculated by dividing the distance to the node by the travel speed of the considered transport mode, e.g. car (free speed or congested car travel times at a given time-of-day), bicycle, or walk. For opportunity locations k, the Euclidean distance to the nearest node is used to determine the shortest distance to the network.

2.4 Disutility of travel

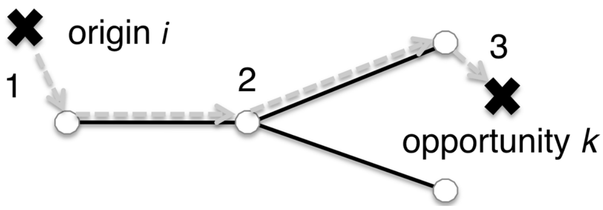


Figure 1: The composition of the travel disutility V_{ik} consists of three parts: (1) the disutility to reach the network from i, (2) the disutility on the network and (3) the disutility to reach opportunity k from the network.

As stated in Eq. (1), the computation of the accessibility for a given origin location i contains a summation of the term $e^{V_{ik}}$ for all opportunity locations k. The determination of the disutility of travel, V_{ik}, consists of the following contributions, as depicted in Fig. 1:

1. The disutility of travel of reaching the transport network from origin i, as described in Sec. 2.3. It is assumed that opportunities can only be reached via the transport network.
2. The disutility of travel *on* the transport network towards k.
3. The disutility of travel of reaching the opportunity k from the transport network, as explained in Sec. 2.3.

As a result the disutility of travel is composed as follows:

$$V_{ik,tt_{mode}} := \beta_{tt_{wlk}} \cdot tt_{wlk,gap,i} + \beta_{tt_{mode}} \cdot tt_{mode} + \beta_{tt_{wlk}} \cdot tt_{wlk,gap,k} \quad (2)$$

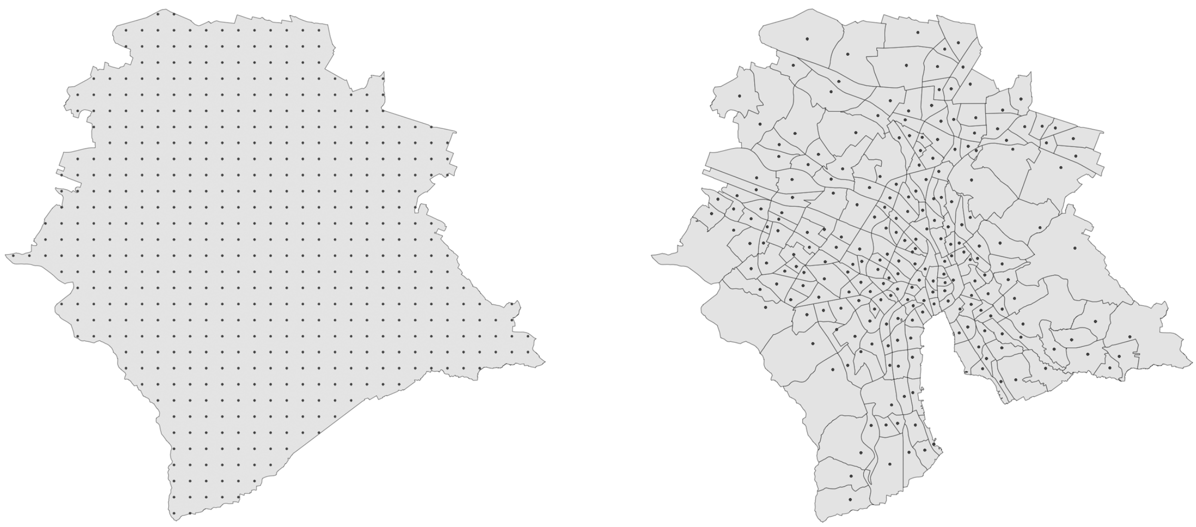
where

- tt_{wlk} is the travel time [in h] on foot.
- tt_{mode} is the travel time [in h] according to the given transport mode. Transport modes are either car (free speed or congested), bicycle or walk.
- $tt_{wlk,gap,i}$ is the travel time [in h] on foot to overcome the gap between the origin location i and the road network.
- $tt_{wlk,gap,k}$ is the travel time [in h] on foot to overcome the gap between the road network and the opportunity location k.
- $\beta_{tt_{mode}}$ and $\beta_{tt_{wlk}}$ are marginal utilities [in utils/h] that convert travel times into utils. By default all marginal utilites are set to -12 utils/h. In MATSim terms, this is the sum of the marginal opportunity cost of time (typically -6 utils/h) and the marginal additional disutility of travel (typically another -6 utils/h).

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).

2.5 Spatial resolution

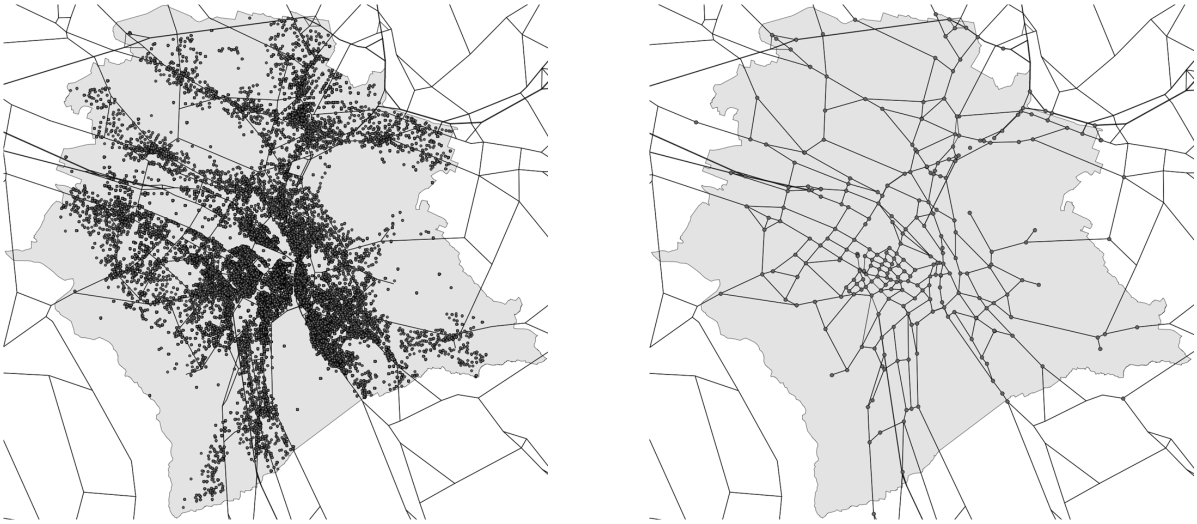
When looking at high-resolution accessibility calculations, there are, in fact, two resolutions to consider: One that defines for how many origins i the accessibility is to be computed. And a second one that defines to what level the opportunities k are to be resolved.



(a) Cell-based approach a the example of $400m \times 400m$ side length

(b) Zone-based approach

Figure 2: The figures visualize the (a) cell- and (b) zone-based approach in accessibility calculation at the example of the city of Zurich (gray area). The origins or measuring points 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 $400m \times 400m$ is used for visibility reasons. The cell centroids (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.



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

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

Figure 3: In (a) opportunity locations (dots) provided by the land-use model are at 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 as depicted in (b).

Spatial resolution of the origin In the present implementation, the origin side can be calculated for two spatial units, cells or zones. Their spatial resolution determines the number of measuring 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 origins or measuring points for the accessibility calculation; see Fig. 2(a). The spatial resolution depends on the selected cell size, which is configurable.

- **Zone-based Approach**: This approach uses zone centroids as measuring points, see Fig. 2(b). 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. This is another example of an assumption that does not have to be made for the high resolution accessibility computation. The number of measuring points is defined by the number of zones.

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.

Spatial resolution of opportunities Opportunity locations such as work places are given by land-use. Unlike origins, for the present paper such locations are directly aggregated to the nearest node on the road network as depicted in Fig. 3.

2.6 Computational procedures

Exploring the entire network by using the "least cost path tree" is a computationally expensive task. In order to accelerate the overall computing speed, the execution time of the "least cost path tree" is reduced by the following elements.

Origins For each origin location i, the nearest node on the road network is identified. Locations that share the same node have the same travel disutilities on the network. In this case the "least cost path tree" is executed only once and the calculated disutilities on the network are reused for all i that are mapped on the same node. Only the calculation of the travel disutility to overcome the gap between location i and the network is done individually.

Opportunities It is, in fact, sufficient to sum over all opportunities k attached to a node j only once. For this, assume that the travel disutility V_{ik} can be decomposed as

$$V_{ik} = V_{ij} + V_{jk} \ \forall k \in j \ ,$$

where the notation $k \in j$ shall refer to all opportunities k attached to node j. Then

$$\sum_{k \in j} e^{V_{ik}} = \sum_{k \in j} e^{(V_{ij}+V_{jk})} = \sum_{k \in j} e^{V_{ij}} e^{V_{jk}}$$
$$= e^{V_{ij}} \sum_{k \in j} e^{V_{jk}} =: e^{V_{ij}} \cdot Opp_j$$

Thus, it is sufficient to compute Opp_j once for every network node j, and from then on compute accessibilities by

$$A_i = ln \sum_k e^{V_{ik}} = ln \sum_j e^{V_{ij}} \cdot Opp_j \ .$$

This is an exact result. The only approximation was already done earlier; it is that all opportunities are matched to only one network node.

3 Scenario: Zurich, Switzerland

The above approach 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 by Schirmer et al. (2011); Schirmer (2010).

The Zurich application consists of 40'407 parcels, 336'291 inhabitants, and 316'703 jobs. In this paper the UrbanSim base year, 2000, is used to create the input for the MATSim runs. After that, UrbanSim is no longer needed for the present study.

3.1 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, and have a typical duration of 8 hours. The home activity has a typical duration of 12 hours and no temporal restriction.

3.2 Network and Adjustments

A revised Swiss regional planning network (Vrtic et al., 2003; Chen et al., 2008) is used that includes major European transit corridors; see Fig. 4. 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 Nicolai and Nagel, 2012).

The flow and storage capacities 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 (Nagel, 2007). 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 (Nagel, 2007). The corresponding storage capacity factor is defined as $Population\ Sampling\ Rate/Heuristic\ Factor$, where the $Heuristic\ Factor = Population\ Sampling\ Rate^{-1/4}$. The *Heuristic Factor* 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 by Rieser and Nagel (2008).

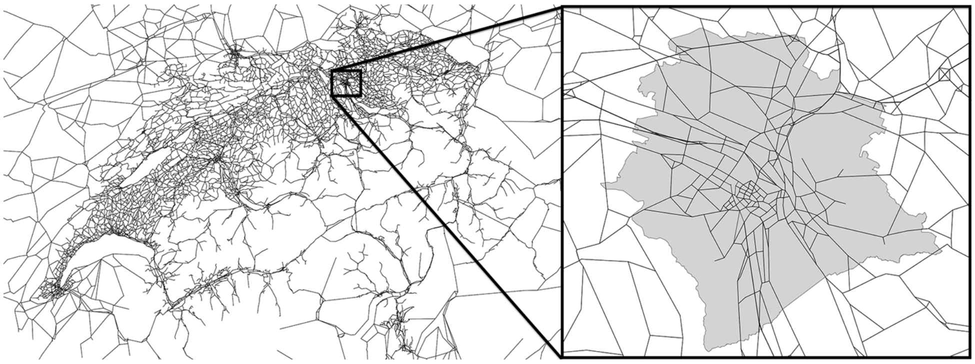


Figure 4: The Zurich case study network, area of Zurich (light gray) enlarged.

3.3 Traffic Simulation

First, a base case 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.

4 Application

This section will specifically look at the proposed high resolution accessibility approach at the example of work place accessibility. In particular the influence of the spatial resolution on the quality of the results and on computational performance are considered. In addition, as one example of a sensitivity test, the congested accessibility field is compared to uncongested accessibility as well as accessibility by bicycle and by walking.

All measurements are applied for the morning peak hour at 8am. At this time most travellers are commuting to work. Table 1 summarizes relevant parameter settings.

Default Setting	
Resolution	$100m \times 100m$
Travel Cost	congested car travel times [minutes]
$\beta_{tt_{car}}$	-12utils/hour
$\beta_{tt_{wlk}}$	-12utils/hour

Table 1: Default settings for the accessibility computation.

4.1 Default setting

Figure 5 depicts the accessibility outcome using the "Default Setting" as stated in Tab. 1. To improve interpretability, the road network is overlayed. The scale bar on the right hand side indicates the accessibility level. Good work place accessibility is indicated by white areas and poor accessibility is indicated by dark gray or black areas.

The plot exhibits very good work place accessibility in areas 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 white or light gray corridors. In contrast, areas with less work-place accessibility have a gradient from dark gray to black. This for instance applies for the "Zürichberg" and the "Uetliberg", which are two undeveloped wooden hills located in the east and 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

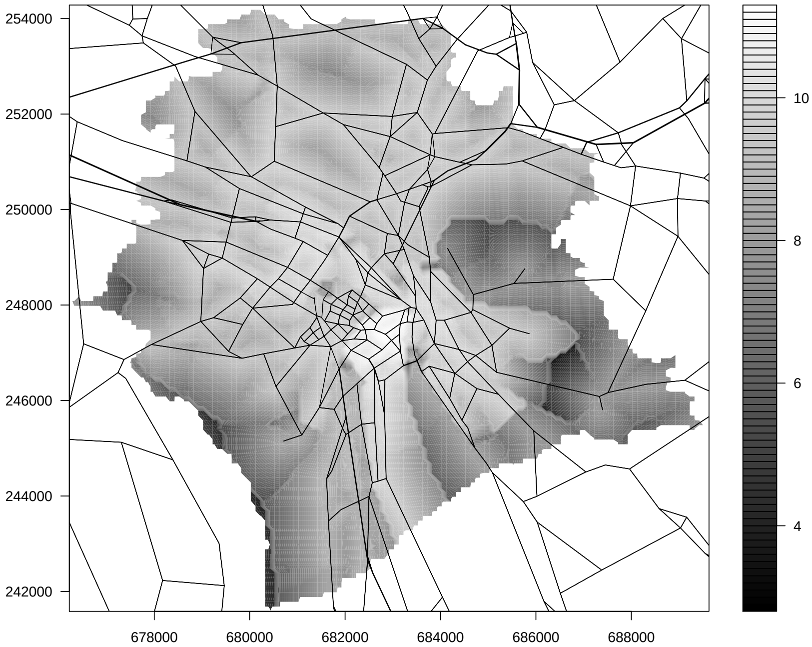
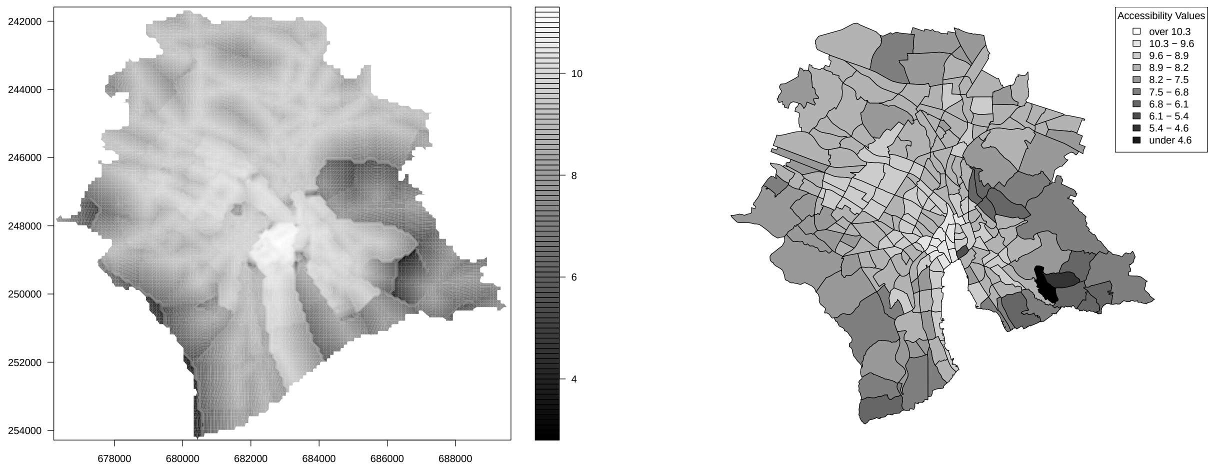


Figure 5: This depicts the outcome of the proposed accessibility measurement using the “Default Settings” as stated in Tab. 1.

all opportunities k incur a strongly negative V_{ik} and thus make only a small contribution to the sum.

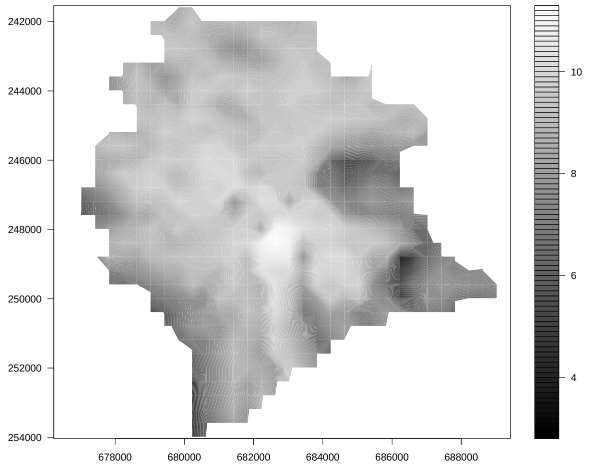


(a) The same as Fig. 5, but without showing the road network. (b) The same congestion data as Fig. 5, but now based on zones as is traditionally done.

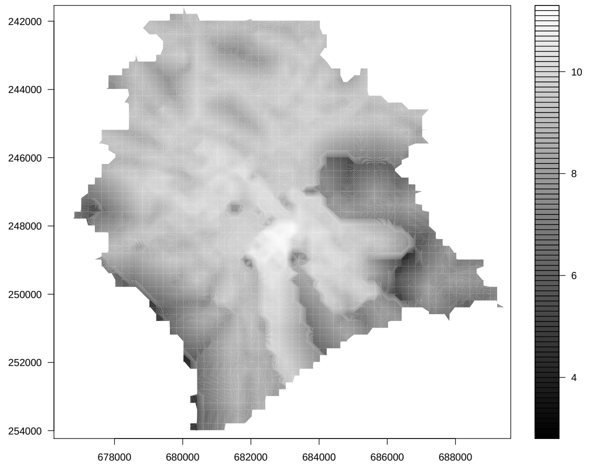
Figure 6: Alternative representations of the same congestion data as Fig. 5.

It should be noted that accessibility is now smooth in space, see Fig. 6. Figure 6(a) is the same as Fig. 5 but without the road network. One clearly sees how highly accessible areas trace the road network. The zone representation of the same data is shown in Fig. 6(b). Clearly, all additional spatial resolution within the zones is now gone. Also, with the zones approach the question in how far the transport network becomes visible in the accessibility plot hinges entirely on the question if the zones reflect the structure of the transport network or not. Such arbitrariness is removed with an approach that does not rely on zones.

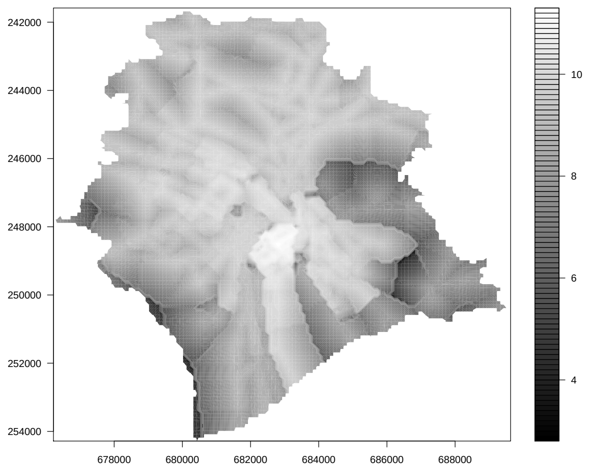
4.2 Spatial resolution



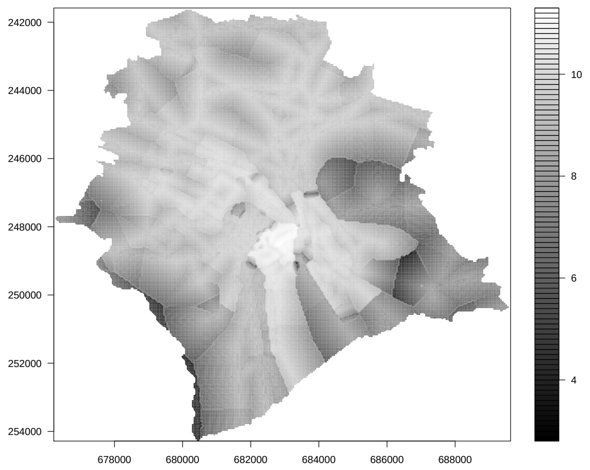
(a) Resolution $400m \times 400m$



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



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



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

Figure 7: Results of different resolutions. In ascending order from the top left to the bottom with the following cell sizes $400m \times 400m$, $200m \times 200m$, $100m \times 100m$ and $50m \times 50m$.

Figure 7 shows the outcome of the accessibility measurement at the following resolutions: $50m \times 50m$, $100m \times 100m$, $200m \times 200m$ and $400m \times 400m$. In terms of information gain it can be stated that the lowest resolution with $400m \times 400m$ provides a rather undifferentiated picture, whereas higher resolutions lead to more detailed measurements. In the $50m \times 50m$ resolution, even fine road structures in the city center are clearly visible. However, a significant increase in the level of detail can be observed up to the resolution of $100m \times 100m$. The higher resolution ($50m \times 50m$) looks smoother and sharper, but does not offer noticeable gains.

4.3 Computing times

In Sec. 4.2, the resolution of two successive plots is doubled. This corresponds to a quadrupling of the measuring points. However, this increase is not reflected in the computing times, see Tab. 2, due to the run time optimizations outlined in Sec. 2.6. Instead, there is no advantage

Cell Resolution	Origins	Aggregated Opportunities	Computing Time [min]
$50m \times 50m$	36 748	272	2-3
$100m \times 100m$	9195	272	2
$200m \times 200m$	2292	272	≈ 2
$400m \times 400m$	577	272	≈ 1
Zone Resolution	**Origins**	**Aggregated Opportunities**	**Computing Time [min]**
Given by zones	234	272	≈ 1

Table 2: This table lists the computation times to measure accessibility at different resolutions and the zone level. All measurements are performed on a Mac Book Pro with an Intel Core 2 Duo 2.5GHz processor and 4 GB of memory. Currently 1 CPU core is used to execute the accessibility computations.

in terms of computing speed for the traditional zone based accessibility measure despite the low resolution.

Computing times could be further improved by using multiple threads: Since the computations for different origins are independent, they could be distributed between all available CPU cores.

4.4 Mode

The results of congested vs. uncongested car and of using bicycle or walk mode are shown in Fig. 8. The first two plots are illustrating how congestion significantly reduces accessibility.

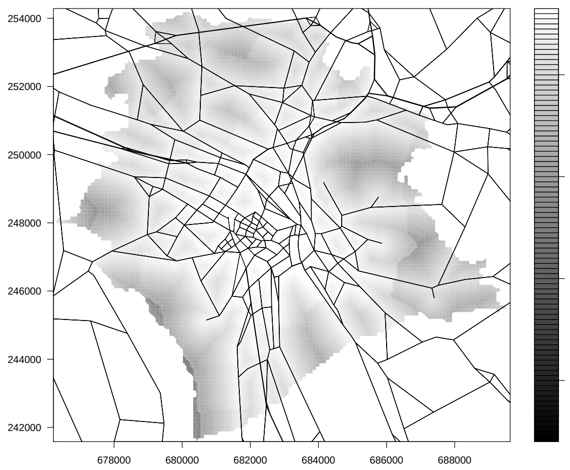
The third and fourth plot illustrate accessibility by bicycle and by walking, respectively. Congestion has no effect on these modes. Both plots show that spatial proximity to opportunities has a strong influence on the results. Locations away from the city center and the commercial areas in the northeast 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.

One might speculate that Fig. 8(a) is what people who plan to use a car expect but Fig. 8(b) is what they actually get. And what they actually get is not much different from what one gets by using a bicycle (Fig. 8(c)). In contrast, walk is truly much worse (Fig. 8(d)).

5 Discussion

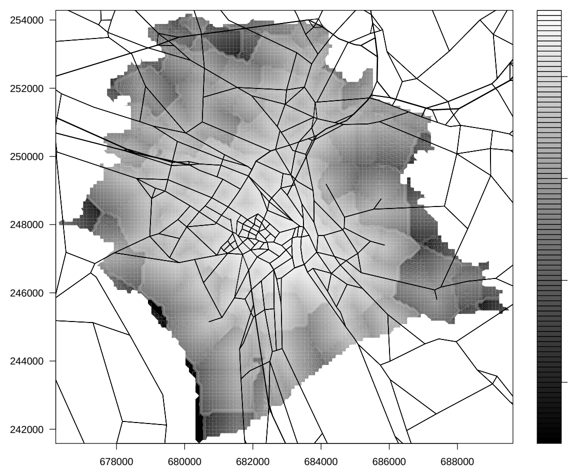
The unit of the accessibility measurement The logsum term, Eq. (1), sometimes contains a scale parameter, i.e. it reads $(1/\mu)\ \ln \sum_k \exp(\mu\, \tilde{V}_{ik})$ (*). When the utility function is estimated, Eq. (1) is the correct form (also see Train, 2003). Clearly, the user can decompose the estimated utility function V_{ik} as $V_{ik} = \mu\, \tilde{V}_{ik}$, in which case Eq. (1) needs to be replaced by Eq. (*) in order to obtain the accessibility in the rescaled units. This may, for example, be useful if the utility function is to be scaled to monetary units, and accessibility is to be expressed in those same monetary units. Since $\mu \tilde{V}_{ik}$ is the same as V_{ik}, such re-scaling does not change the structure of the plots; however, all accessibility values will be multiplied by $1/\mu$.

Spatial resolution Most plots in this paper are based on a grid resolution of $100m \times 100m$, and the road network as shown in some of the figures. As it was argued, higher spatial resolutions with the same road network do not lead to discernible improvements. In contrast, a higher resolution road network would clearly make a difference – the present method assumes that the access from an arbitrary location to the given road network is done by walking while there may be minor roads in reality. Using a higher resolution road network is feasible – the computational cost scales roughly in the number of links since the worst case complexity of the Dijkstra tree computation is roughly linear in the number of links for planar graphs. In the present situation, we decided to stick with the lower resolution network. One reason was that we wanted to investigate how

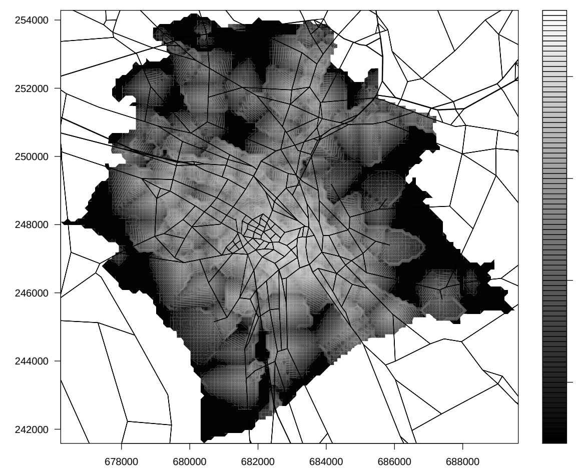


(a) Free speed car travel times in accessibility computation

(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 8: These plots visualize the influence of different transport modes on the accessibility computation.

our approach would perform in such a situation. Another reason was that we had no higher resolution network together with a calibrated scenario available.

6 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 can also be interpreted 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. Important results include:

- The approach is able to provide a spatially differentiated picture. Artefacts such as supposedly homogeneous accessibility within zones are removed.
- The computation of a cell-based accessibility measurement at high resolutions is computationally feasible.
- For the present scenario and network a resolution finer than $100m \times 100m$ does not deliver noticeable additional gains.
- The effect of congestion is very clearly visible. The result also confirms that, in the urban core, accessibility by bicycle is similar to accessibility by car during congested peak hours. Outside the urban core, however, accessibility by bicycle is clearly worse than by car also during peak hours.

  In contrast, accessibility when walking is definitely much worse than either by car of by biclye, and reaches levels comparable to accessibilities by bicycle or by car only in the inner center of the city.

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