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Conference Paper

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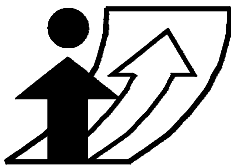
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July 2012

Abstract

This paper reports on the development of an agent-based cruising-for-parking simulation using the cellular automaton approach. The software is ready for application in a real-world scenario and for calibration with empirical data currently surveyed at the authors' institute.

Keywords

Parking Search Microsimulation, cellular automaton

Preferred citation style

1 Introduction

Parking search induced traffic—although difficult to quantify (Kipke, 1993, Arnott and Inci, 2005)—is regarded as substantial (Shoup, 2005) and consequently an ample body of parking literature (for a review see e.g., Young *et al.* (1991)) exists, spanning a huge number of empirical studies and estimated models [1] but also numerous simulations [2] .

This report is structured as follows. In Section 2 its research goal is presented. The agent-based cellular automaton approach is detailed in Section 3 and preliminary results for a small-scale scenario are shown in Section 4.

Terminology:
To the authors' knowledge a certain ambiguity exists in parking terminology. In this paper, only two terms are used. *Parking space* refers to a place for one car. A *parking lot* on the other hand consists of 1..*n* parking spaces. In the simulation agents choose among parking lots.

2 Research Goal

The context of this research is that cruising for parking is seen as a significant part of traffic in city centers and thus one of the reasons for congestion. To predict effects of parking policies (see e.g., Marsden, 2006, Topp, 1991, Feeney, 1989) parking models are needed. This report describes a stand-alone agent-based cellular automaton cruising-for-parking simulation combining microsimulation and parking choice models in one framework.

This report's goal is to generate by simulation an aggregate model specifying parking search time dependent on parking supply as similarly estimated with empirical data in Axhausen *et al.* (e.g., 1994, p.309). In general, such models, specifying parking choice key values, can be applied in aggregate contexts and might complement or at least validate (e.g. spatially transfer) estimated functions.

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[1] a sample of papers investigating parking itself but also its interaction with other travel choices (such as destination choice) is van der Waerden *et al.* (2009, 2006), Marsden (2006), Widmer and Vrtic (2004), Anderson and de Palma (2004), Golias *et al.* (2002), Hensher and King (2001), Gerrard *et al.* (2001), Baier *et al.* (2000), Albrecht *et al.* (1998), van der Waerden *et al.* (1998), Axhausen *et al.* (1994), van der Waerden *et al.* (1993), Glazer and Niskanen (1992), Topp (1991), Axhausen and Polak (1991), Arnott *et al.* (1991), Feeney (1989), Miller and Everett (1982), Gillen (1978, 1977).

[2] such as Benenson *et al.* (2008), Gallo *et al.* (2011), Thompson and Richardson (1998), Dieussaert *et al.* (2009), van der Waerden *et al.* (2002), Young (1986), Young and Thompson (1987)

As mentioned earlier, multiple parking simulations exist already. Why is yet another parking search simulation needed? As far as we know, only the proposed parking search model by Kaplan and Bekhor (2011) combines the components, considered relevant by us, in one framework, however, this conceptual paper is *not* yet implemented. These components are: disaggregate traffic assignment (using a CA), agent-based approach (including a memory for every agent) and inclusion of transit traffic passing the study area without parking.

The model will in the future be integrated in the agent-based transport simulation MATSim (MATSim-T, 2011) following a hybrid aggregate-disaggregate approach as described in Section 5. Instead of using existing code, an own implementation is expected to be practically beneficial for this integration and intense calibration.

The simulation is also expected to be a useful testbed during parking model estimation based on GPS and SP surveys currently running at the authors' institute (Montini *et al.,* 2012, Rieser-Schüssler *et al.,* 2011, Weis *et al.,* 2011). As an example, investigation of latent variables such as parking search starting point (for more details see Section 3.2.2) might be supported by a well-calibrated parking search simulation.

3 Method

Cornerstones of our model are traffic assignment with a cellular automaton based microsimulation (Section 3.1) and parking choice modeling (Section 3.2). The model incorporates a limited short-term agent memory, whereas long-term learning mechanisms will only be captured as exogenously given scenario demand. In our case, the demand can be generated using MATSim.

Probabilistic decision making leads to stochastic simulation potentially making variability analysis necessary (e.g., Horni *et al.,* 2011a), which will be performed together with thorough future model calibration.

3.1 Cellular Automaton

The implemented cellular automaton (class CA, see Figure 4) is based on Nagel and Schreckenberg (1992), which is able to predict urban flow patterns (Wu and Brilon, 1997, p.1). In terms of resolution this model lies between aggregate assignment methods or queue-based models (such as Charypar *et al.* (2007)) and detailed car following models (see also (Wu and Brilon, 1997) for a CA extended by more detailed car-following rules).

The update process is performed as described in Nagel and Schreckenberg (1992, p.2222).

Cell size is defined as in Wu and Brilon (1997, p.3), where reciprocal jam density is used (133 *vehicles/km*). No unacceptable discretization errors are reported for this value. An approach adapting cell size according to actual minimum speed on the link might drastically improve performance. I.e., if there is no jam on a link, cell size should be increased. This would speed up the simulation as less checks have to be performed if traveled cells are free.

At the moment, only one agent is allowed to cross an intersection per time step. These rough intersection dynamics or capacities need to be enhanced, e.g., by signaled and multi-lane intersections handling. Similarly, capacity definition of links needs future consideration as roads, clearly, not only have different speed-limits but also different capacities.

Parking lots are attached to cells, where attaching them to relatively short links—as usually the case for navigation networks—should be tested for performance reasons.

3.1.1 Implementation Details

Instead of naively iterating over nodes, links and cells in every time step, the procedure is essentially reduced to iteration *over agents*. This is achieved with auxiliary data structures (members of `CAServer` class) which dynamically manage agents' positions with waiting queues (class `Queue`). Queues are chosen randomly, such that, for example, links do not have fixed priorities.

Activity-based models such as MATSim implement a complete day activity plan. Here, for implementation simplicity, in the first instance, a maximum of two activities and one parking search is realized by an agent. To model further trips of the same person, a new agent is generated in pre-processing scenario creation (see (a) in Figure 1).

For parking agents, the route from their intermediate destination to the final home activity is approximated. To circumvent implementation of a router, instead of departing from the chosen parking lot the precomputed route from the intermediate location to the home location is used (see (b) in Figure 1).

3.2 Cruising-For-Parking

For modeling purposes, the cruising-for-parking process and possibly succeeding choices can be split into 3 parts (see also Kaplan and Bekhor (2011)):

(i) Parking type choice (e.g., private or public parking, on-street or off-street parking),
 (ii) choice of search route and search starting point, usually determined by a person-specific search tactic (Polak and Axhausen, 1990), and
(iii) actual parking lot choice.

Here, only en-route choices are handled endogenously, i.e., parking choices made before departure, usually also related to other choice dimensions such as destination choice, are neglected. In the first instance, the model only considers travel and search time costs, whereas further choice determinants, such as monetary costs are not yet taken into account.

3.2.1 Parking Type Choice

Parking type choice differentiates for the Zurich scenario between private and public parking. However, these choices are not modeled but specified exogenously as follows. The share of private parking lots in the study area is measured. Private and public parking supply shares are weighted with daily capacity $f_{capacity}$ and are used to specify respective demand. In other words, demand is derived from the supply situation, assuming that supply corresponds more or less with demand. In Switzerland $f_{capacity}$ is often called *"spezifisches Verkehrspotential (SVP)"* (see e.g., (Axhausen, 2007, slide 4)), it specifies the number of trips to a parking lot per day, which is the same as the number of parked cars per day. Typically, $f_{capacity}$ for private parking is much smaller than for public parking. As a starting point the values $f_{capacity,private} = 1.0$ and $f_{capacity,public} = 5.0$ are chosen.

Private parkers do not have to do parking search; in the simulation they are routed directly to their destination and then removed from simulation. In the future, this exogenous choice together with other parking type choices, such as on- or off-street parking, will be endogenously modeled.

3.2.2 Choice of Parking Search Tactic

Contrary to first expectations, parking search *starting point* cannot be specified sharply let alone operationalized easily. One can reasonably assume that drivers observe unconsciously the parking situation while driving towards their destination. Therefore, without actively searching, it can happen that a driver observes unexpectedly few free parkings, that may start *active* search earlier than actually planned. In this perspective, search starting point becomes fuzzy even for specification and, obviously, operationalization in surveys is difficult. For non-interview surveys (e.g., pure GPS surveys) parking search starting point is even more latent.

Based on a GPS and Stated Preference survey at the authors' institute (Rieser-Schüssler *et al.,* 2011*,* Weis *et al.,* 2011) simple observable criteria/proxies (e.g., arrival in destination area defined by a certain radius around destination etc.) will be tested and finally used to calibrate this simulation.

Having said that, we here define the starting point dependent on the linear distance to the destination. Starting points for agents are randomly, uniformly sampled from the distance range specified in the configuration file and randomly assigned to agents.

The search starting point defines if a person first drives to the destination and then starts searching, or if a person accepts a parking space while initially driving toward the destination and thereby is willing to take the risk of missing a closer parking space. Clearly, the first tactic is usually associated with higher search times but shorter distances to the destination, while for the second tactic the opposite is true.

The *search route* is generated on the fly on the basis of a weighted/biased random walk (see class `WeightedRandomRouteChoice` and also Kaplan and Bekhor (2011, p.4/5), Frejinger *et al.* (2009)) combined with a simple short-term agent memory. Usage of short-term memory (in other words, agent's mental map of the area) further exploits the agent-based approach, and has to the knowledge of the authors not yet been applied in a large-scale scenario.

In more detail, when leaving an intersection, the agent choses the next link as follows. Either the agent has not yet started searching and just follows the prespecified route or the agent is searching and choses the next link randomly but weighted according to the following criteria, being considered simultaneously:

- **Destination approaching efficiency**: This measure depends on the angle to the destination and on link length. The link length is used to reduce the probability that agents chose very long links taking them far away from the destination, such as express highways or for example *Hardbrücke* in Zurich. Note, that turns are not possible on simulation links.
- **Memorized free parking spaces**: Additional weight is given to the direction pointing to the parking lot in the agent's memory with most free spaces. In the future, this favorite parking lot should be evaluated under consideration of distance to destination or actual position. At the moment, this is roughly approximated by only considering the closest 5 parking lots. Memory currently has a size of 10 parking lots.
  Instead of total number of parking lots, the ratio r of free spaces divided by size of the lot could be tested. Presumably, an S-curve weighting with parking size needs to be applied. Parking lots with e.g., $r = 0.8$ of medium size are optimal, whereas very small lots harbor the risk of being filled fast and very large lots are difficult to evaluate while driving by.

For all evaluations Euclidian distances and not network route distances are used. Weights are specified according to rough plausibility tests but will be calibrated thoroughly based on the IVT-GPS survey mentioned earlier. At the moment, weights are chosen such that the direction to the destination dominates the other measures.

Class `RandomRouteChoice` is provided for comparisons with behaviorally more plausible weighted random walk.

3.2.3 Parking Lot Choice

Parking lot choice, implemented with classes `AcceptanceRadiusLinear`, `ParkingDecisionLinear`, and `ParkingDecision`, is modeled as a probabilistic choice, dependent on elapsed search time, t_{search} and distance to destination, $d_{destination}$ as shown in Figure 2. Up to distance $d_{acceptance}$ (see also Birkner (1995)) a free parking space is taken with a very high probability (here set to 1.0), where afterward probability decreases linearly or quadratically (configurable) with distance. $d_{acceptance}$ specifies the radius of a circular area around the destination and increases linearly or quadratically (configurable) with elapsed search time. In other words, agents behave according to dynamic preferences.

Choice of this function with decreasing acceptance probability for higher distances to destination is natural. Its calibration, however, is not simple. On the one hand, the decreasing slope should be moderate, such that, *in case all parking lots with distance smaller than $d_{acceptance}$ are taken*, also parking lots with distance only slightly greater than $d_{acceptance}$ are accepted with very high probability. A counterexample is shown in Figure 3 (a). On the other hand, rather obviously, the slope must nevertheless decrease significantly, such that an agent does not choose a very distant parking lot just because it is the first one he encounters after search has started (agents would do that in Figure 3 (b)).

Plausibility investigations showed that $d_{acceptance}$ and *parking search starting point* (described above) must be modeled independently, although, at first sight, a direct relation seems plausible. Argumentation here is that acceptance probability differs significantly for *initially* driving toward destination as compared to the subsequent searching behavior with the knowledge that no parking space is available close to the destination. This behavior can only be modeled with two independent variables.

In general, it seems necessary to enhance the decision models to be *directly* dependent on parking supply and load, and not indirectly through proxy 'elapsed search time' (see also Section 3.2.4). More specific, $d_{acceptance}$ should change dependent on agent's observed parking situation (see the next section).

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3.2.4 Conclusion

Parking search, clearly, is a highly complex process with many determinants. Fitting its outcomes with a few-variables model of course is principally associated with a large approximation error ϵ_a. Recognizing the moment during calibration where ϵ_a is achieved and where further calibration only means moving this irreducible error around in the model is not easy.

Development and calibration revealed that, as a next step, the procedure proposed in Benenson *et al.* (2008, p.434) should be integrated as it captures look-ahead search behavior—in other words, behavior directly influenced by actual parking situation— presumably central to modeling urban parking search. In this procedure, agents—in general terms following Baysian learning—adapt the expectation for finding a free parking lot close to the destination, based on continuous observation of the parking situation while driving.

3.3 Software Design

MATLAB is designed for procedural matrices computations but also supports an object-oriented (oo) approach (although suffering from a few performance issues). Object-oriented programming paradigm is chosen here for following reasons. First, agents nicely translate to objects, which makes code elegant and easy to understand. Second, according to the authors' opinion, oo-approach with intrinsically good modularization perfectly fits team software projects and makes adaptation of functionality (encapsulated in software modules) straight forward. Third, authors are developers of the oo-software MATSim. General simulation concepts (such as usage of a controller class) and design patterns easily translate from MATSim to the new simulation. Additionally, later migration to and integration in MATSim are more efficient with an oo-standalone model.

Figure 4 presents an UML-inspired simulation components overview showing the main components' relations.

4 Results and Discussion

For efficient development, testing and basic illustration purposes three toy scenarios are created, named *chessboard* (Figure 5), *square* (Figure 6) and *miniNetwork* (Figure 7). The real-world Zurich scenario (Figure 8) is ready but not yet calibrated.

In general (and somehow fuzzy) terms the developed software fulfills the global research

goals formulated in Section 2. Software seems appropriate for later migration and application in MATSim, and it has already now inspired research for the current IVT-GPS survey and is, thus, expected to be a great testbed for subsequent choice model estimations.

More practically, preliminary results for the chessboard scenario indicate that specification or validation of aggregate models for key parking search measures (such as average parking search time, see e.g., Axhausen *et al.* (1994, p.309, Figure 4) and Figure 9) can be done with our simulation. These functions, after thorough calibration on real world scenarios can be used in aggregate contexts to model, for example, parking search times.

The chessboard scenario is simulated with 100 agents having different trip start times and a desired activity duration of 30 minutes. Private parkers and transit agents are not included in this scenario. 30 minutes are simulated, meaning that in this setting no agent leaves the parking lot during simulation period. This is similar to overnight parking.

Figure 10 shows the median search time dependent on number of parking spaces in the study area. Median, instead of average, is used here, for appropriate handling of outliers, such as persons not yet having found a parking space after simulation has finished.

A non-linear relation between median search time and parking supply is observed. Clearly, parking density in a limited area around destination should be used instead of number of parking lots in the study area. Nevertheless, simulation results—assuming that varying demand and supply is isomorphic—corresponds with estimated results of Axhausen *et al.* (1994, p.308), where a non-linear relation between average search time and parking demand (approximated by parking lots' occupancy) is reported. However, current work validating this estiamtions with GPS data indicates that for high occupancy levels a correction factor may be necessary. Testing this hypothesis might be supported by using our simulation as a testbed.

The non-linear trend, empirically observed and here simulated, should be related to the work of Benenson *et al.* (2008, p.438), who confirm by simulation the empirical finding of Shoup (2005) that *"[...] average search time and [...] hardly react to changes in parking supply as long as the demand/supply ratio is around one [...]"*.

5 Future Work and Integration Into MATSim

Besides the numerous future tasks described at the appropriate locations following future work will be performed.

First and foremost, speed needs even more consideration. Technical issues to be solved

include substantial overhead in internal functions reported by MATLAB profiler (possibly due to object handling) and parallelization using built in tools such as `parfor` to begin with.

Decision models need calibration and enhancement by further choice determinants and mechanisms. An example is the look-ahead procedure mentioned earlier and described in Benenson *et al.* (2008, p.434).

The real-world Zurich scenario is set up and will be calibrated and simulated when first GPS survey results are available. Scenario covers the inner-city of Zurich defined here as an area with 1km radius around Bellevue. A high-resolution navigation network (TomTom MultiNet, 2011) is chosen as supposedly parking effects are local in nature. Demand is derived from the MATSim Zurich scenario (Horni *et al.*, 2011b). For performance reasons not a complete day is simulated but only the evening hours 16-19 o'clock, where only the last hour is analyzed. For future validation a GPS and SP survey as well as road count data is available. Boundary effects for agents with destination very close to the study area limits need further consideration in future work.

Travel speed is usually reduced during searching, although in situations with high traffic volumes this effect is probably smaller or diminishing due to consideration of other drivers. However, this effect should be considered for implementation in a future version.

The stand-alone MATLAB model is planned to be migrated to JAVA and integrated into MATSim, where, due to huge computation times for high-resolution large-scale scenarios, a hybrid approach will be implemented: In areas with high competition for parking lots (e.g., in city centers) parking search is microsimulated based on the cellular automaton approach; in regions with low competition (e.g., residential areas) average search times are derived from aggregate functions specifying search times. The hybrid approach is expected to increase model accuracy and at the same time maintain feasible computation times for large-scale scenarios.

The final MATSim model will be used to investigate effects of parking on shopping destination choice. This is particularly important as simulation of the MATSim Saturday scenario, with usually higher shopping activities share, will be developed soon.

work

route_to
(pre-computed)

(b)

P

search start   destination

work

route_away
(pre-computed)

home
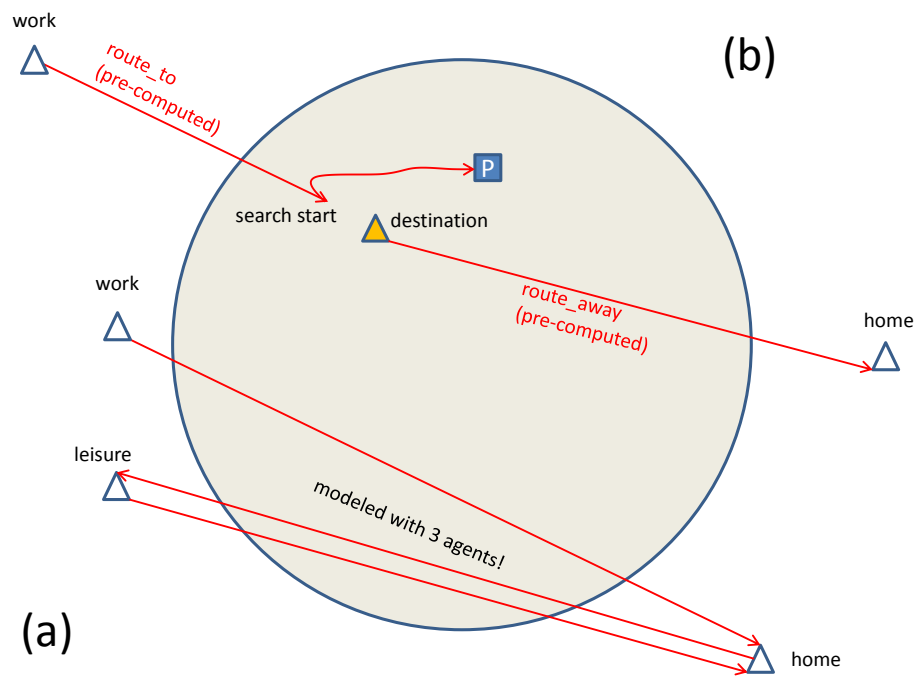
leisure

modeled with 3 agents!
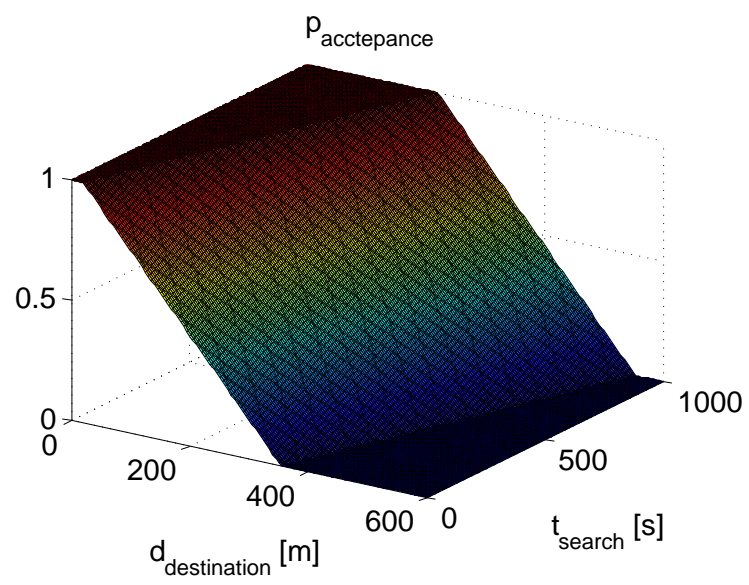
(a)

home

Figure 1: Conversion of MATSim Demand

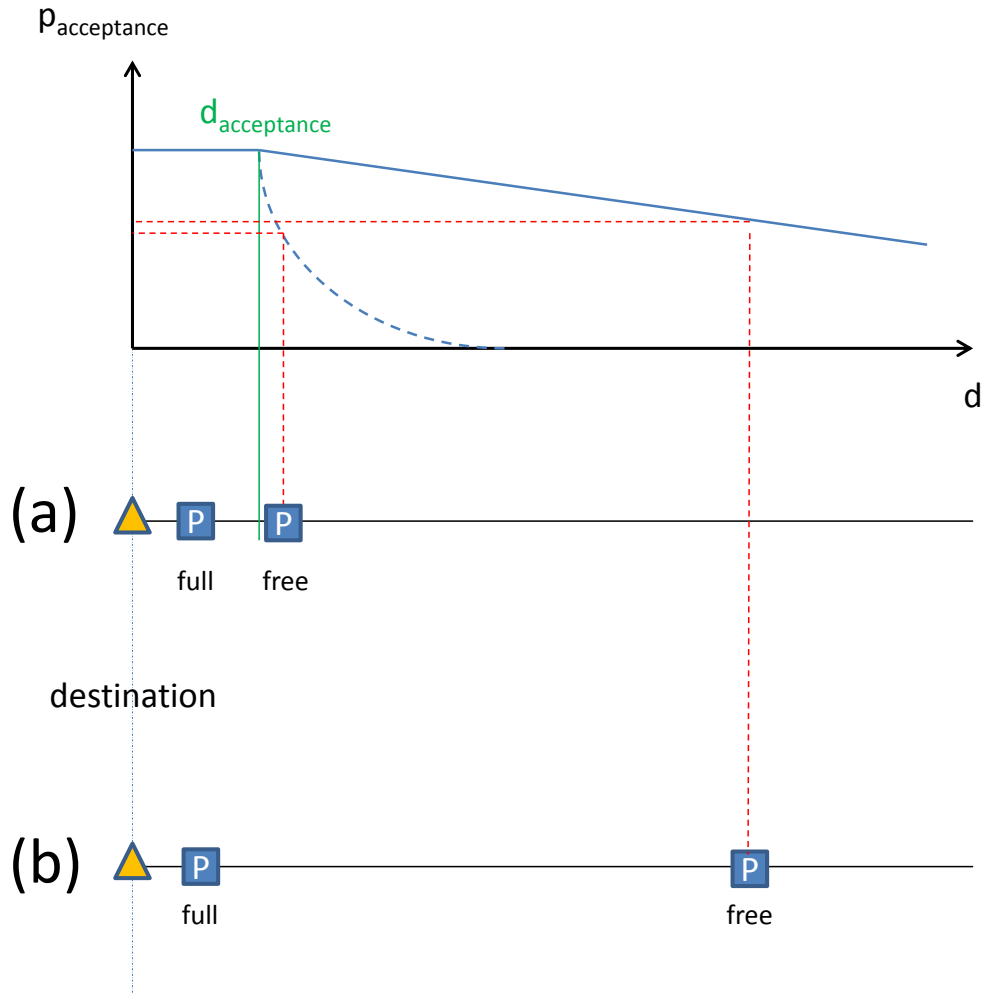Figure 2: Specification of Acceptance Probability (Example Configuration)
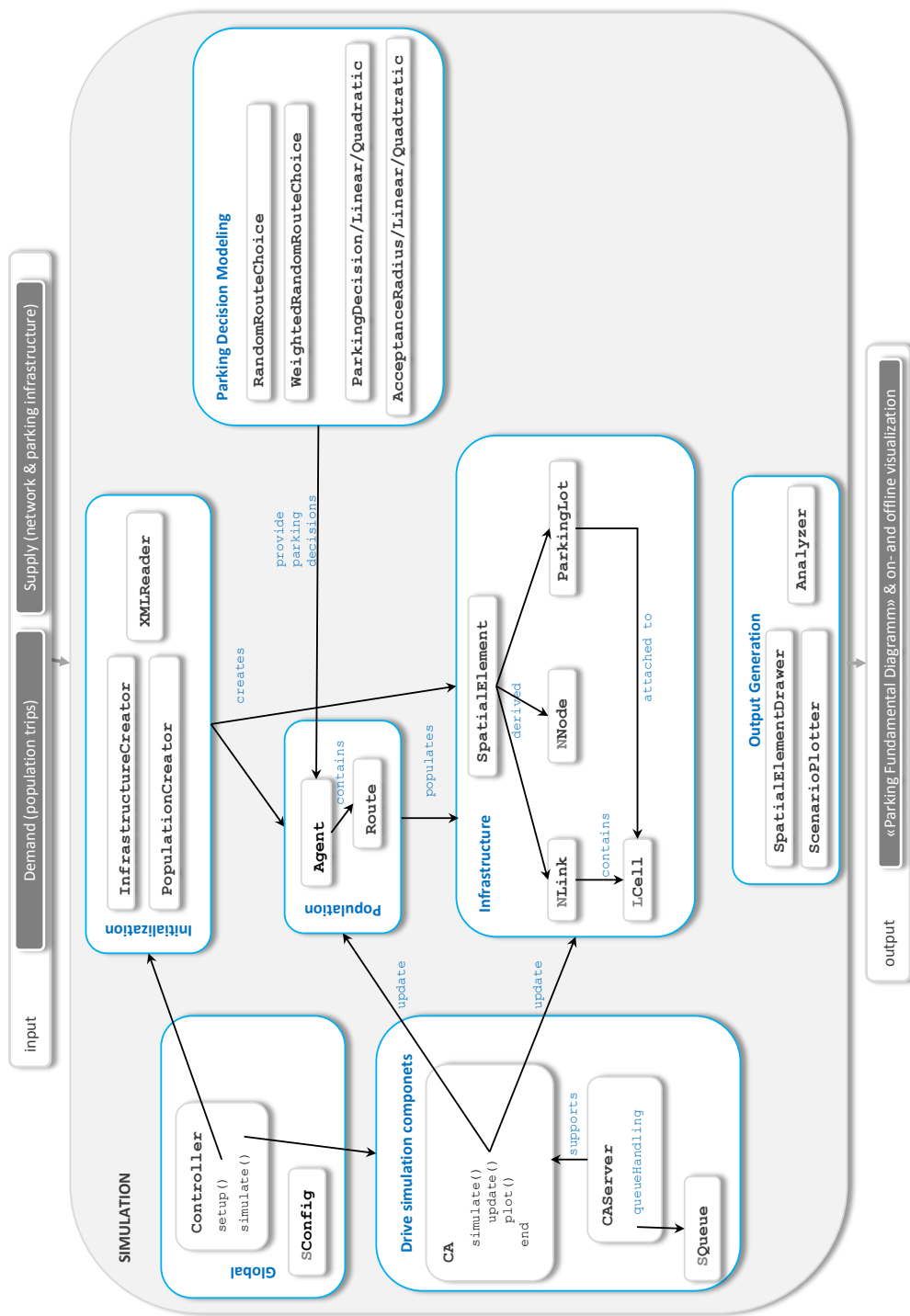
Figure 3: Specification of Acceptance Probability

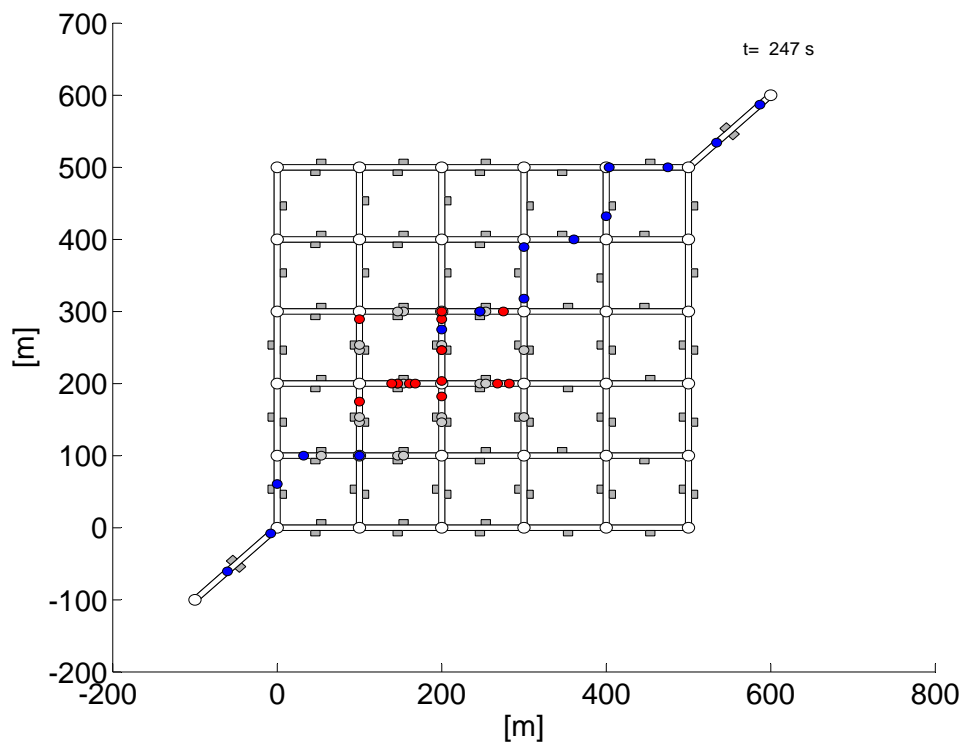Figure 4: Simulation Components

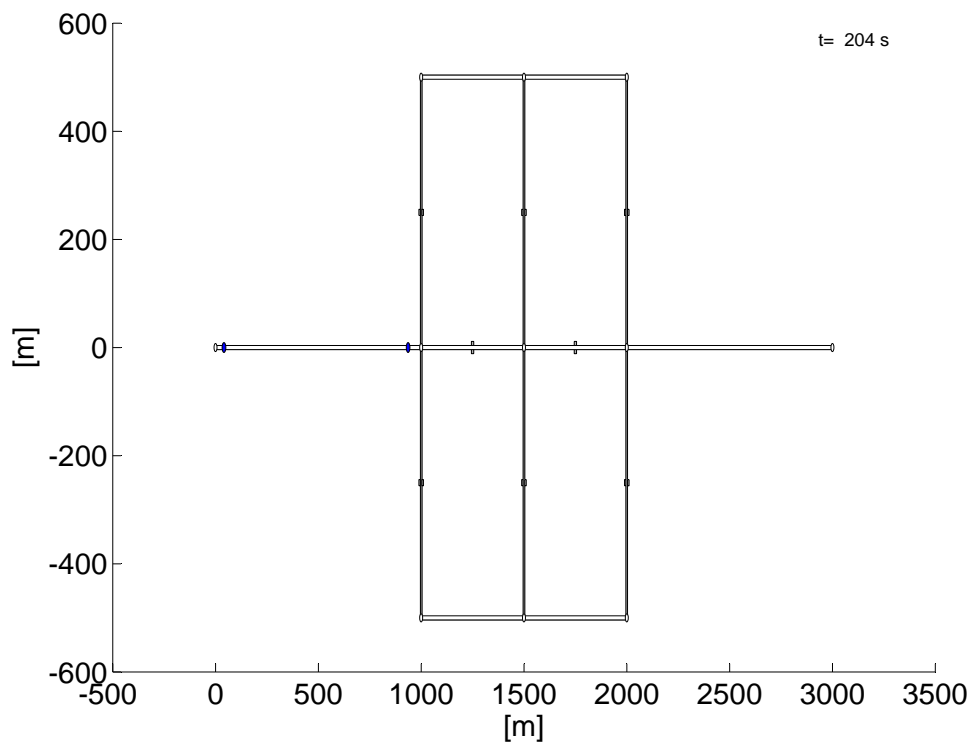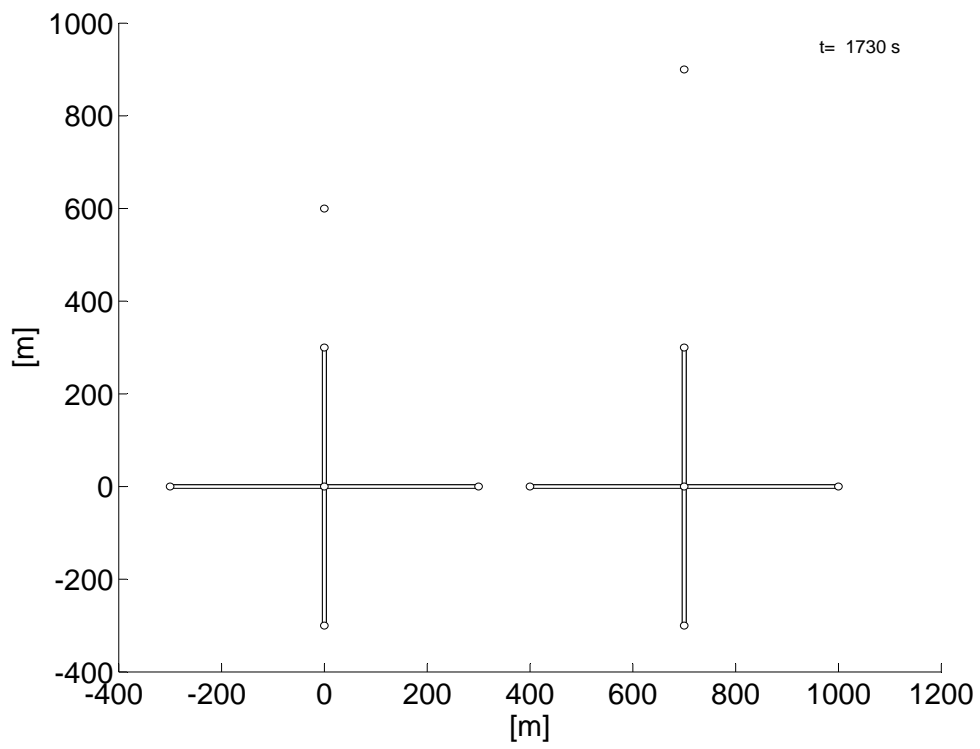Figure 5: Chessboard Scenario

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Figure 6: Square Scenario
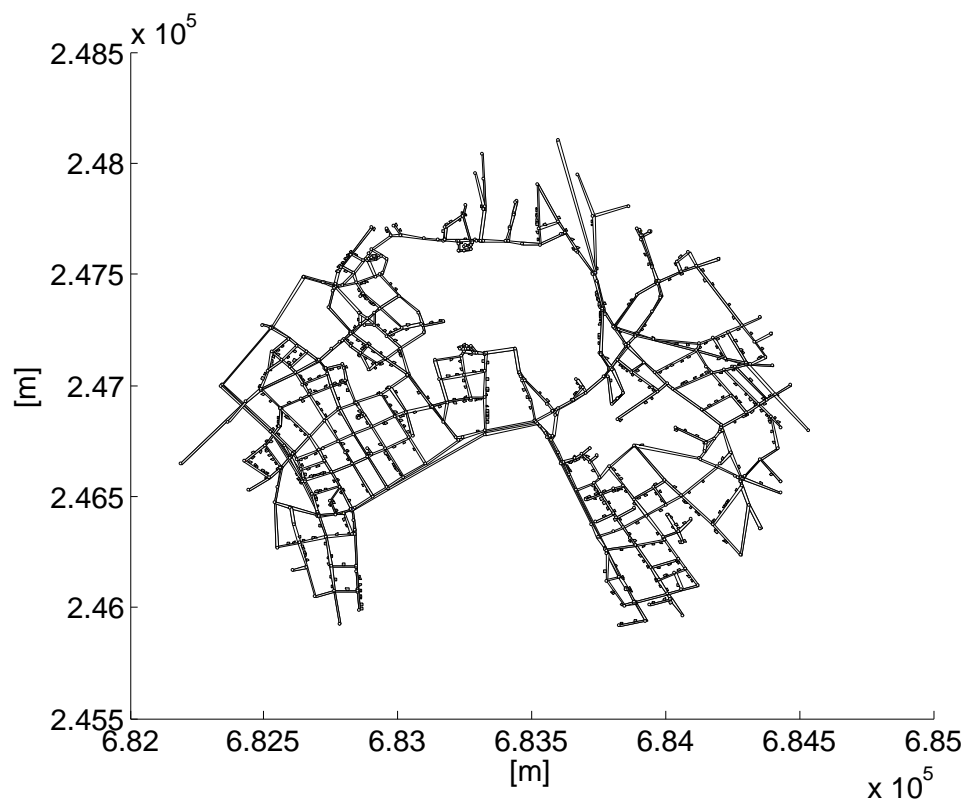
16

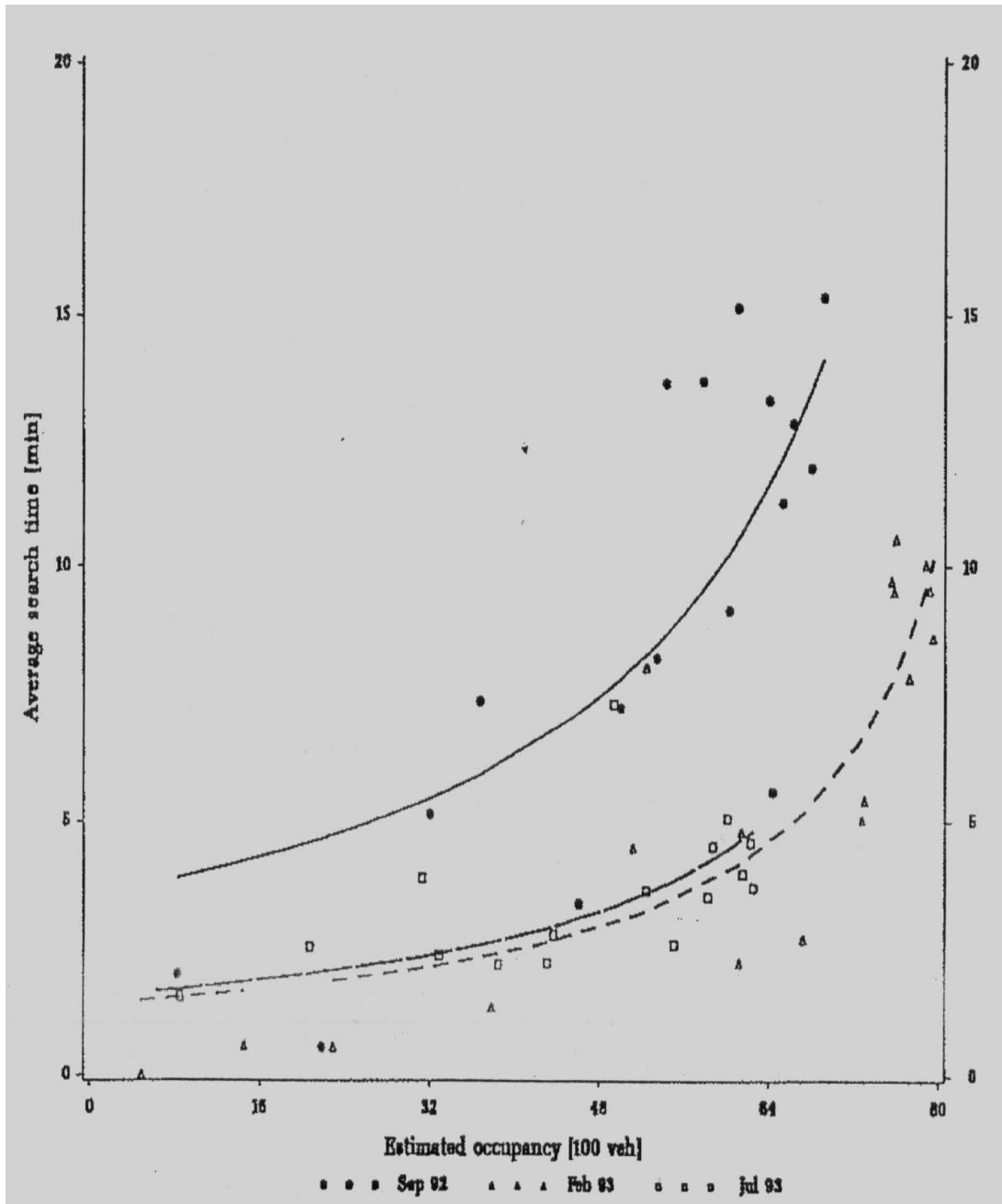Figure 7: Mininetwork Scenario

Figure 8: Zurich Scenario

Figure 9: Aggregate Search Time Model of Axhausen *et al.* (1994) (scanned)
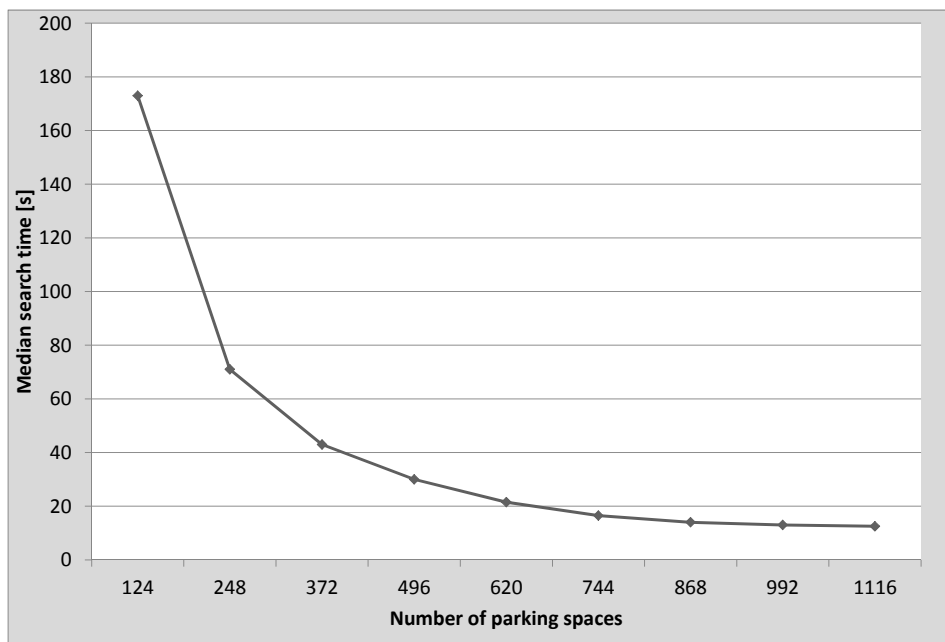
19

Figure 10: Aggregate Search Time Model Chessboard Scenario

References

Albrecht, B., T. Lütolf and T. Waltert (1998) Verkehrskennwerte von Einkaufszentren: Verkehrsaufkommen, Parkfelder und Verkehrsflächen, *Research Report*, **VSS 7/95**, Schweizerischer Verband der Strassen- und Verkehrsfachleute (VSS), Albrecht & Partner AG, Lucerne.

Anderson, S. P. and A. de Palma (2004) The economics of pricing parking, *Journal of Urban Economics*, **55**, 1–20.

Arnott, R., A. de Palma and R. Lindsey (1991) A temporal and spatial equilibrium analysis of commuter parking, *Journal of Public Economics*, **45**, 301–335.

Arnott, R. and E. Inci (2005) An Integrated Model of Downtown Parking and Traffic Congestion, *Working Paper*, **11118**, National Bureau of Economic Research, Cambridge, February 2005.

Axhausen, K. W. (2007) Fahrtenmodelle und andere Ansätze der Nachfragesteuerung, presentation, Vorlesung Verkehrstechnische Aspekte des Städtebaus, ETH ZurichZurich, December.

Axhausen, K. W. and J. W. Polak (1991) Choice of parking: Stated preference approach, *Transportation*, **18** (1) 59–81.

Axhausen, K. W., J. W. Polak, M. Boltze and J. Puzicha (1994) Effectiveness of the parking guidance information system in frankfurt am main, *Traffic Engineering and Control*, **35** (5) 304–309.

Baier, R., C. Hebel, C. Peter and K. H. Schäfer (2000) Gesamtwirkungsanalyse zur Parkraumbewirtschaftung, *Research Report*, Bundesamt für Strassenwesen (BAST), Büro für Stadt- und Verkehrsplanung Dr.Ing. Reinhold Baier GmbH, Aachen.

Benenson, I., K. Martens and S. Birfir (2008) PARKAGENT: an agent-based model of parking in the city, *Computers, Environment and Urban Systems*, **32** (6) 431–439.

Birkner, T. (1995) Innerstädtischer Parksuchverkehr: Eine unbekannte Grösse?, *Straßenverkehrstechnik*, **95** (7) 323–327.

Charypar, D., K. W. Axhausen and K. Nagel (2007) Event-driven queue-based traffic flow microsimulation, *Transportation Research Record*, **2003**, 35–40.

Dieussaert, K., K. Aerts, T. Steenberghen, S. Maerivoet and K. Spitaels (2009) SUSTAPARK: an agent-based model for simulating parking search, paper presented at the *AGILE International Conference on Geographic Information Science*, Hannover.

Feeney, B. P. (1989) A review of the impact of parking policy measures on travel demand, *Transportation Planning and Technology*, **13** (4) 229–234.

Frejinger, E., M. Bierlaire and M. E. Ben-Akiva (2009) Sampling of alternatives for route choice modeling, *Transportation Research Part B: Methodological*, **43** (10) 984–994.

Gallo, M., L. D'Acierno and B. Montella (2011) A multilayer model to simulate cruising for parking in urban areas, *Transport Policy*, **18** (5) 735–744.

Gerrard, B., B. Still and A. Jopson (2001) The impact of road pricing and workplace parking levies on the urban economy: results from a survey of business attitudes, *Environment and Planning A*, **33**, 1985–2002.

Gillen, D. W. (1977) Estimation and specification of the effects of parking costs on urban transport mode choice, *Journal of Urban Economics*, **4** (2) 186–199.

Gillen, D. W. (1978) Parking policy, parking location decisions and the distribution of congestion, *Transportation*, **7** (1) 69–85.

Glazer, A. and E. Niskanen (1992) Parking fees and congestion, *Regional Science and Urban Economics*, **22** (1) 123–132.

Golias, J., G. Yannis and M. Harvatis (2002) Off-street parking choice sensitivity, *Transportation Planning and Technology*, **25** (4) 333–348.

Hensher, D. A. and J. King (2001) Parking demand and responsiveness to supply, pricing and location in the Sidney central business district, *Transportation Research Part A: Policy and Practice*, **35** (3) 177–196.

Horni, A., D. Charypar and K. W. Axhausen (2011a) Variability in transport microsimulations investigated with the multi-agent transport simulation matsim, *Working Paper*, **692**, IVT, ETH Zurich, Zurich.

Horni, A., B. J. Vitins and K. W. Axhausen (2011b) The Zurich scenario: A technical overview, *Working Paper*, **687**, IVT, ETH Zurich, Zurich.

Kaplan, S. and S. Bekhor (2011) Exploring en-route parking type and parking-search route choice: Decision making framework and survey design, paper presented at the *2nd International Choice Modelling Conference*, Leeds, July 2011.

Kipke, H. (1993) Theoretische Überlegungen zum Parksuchverkehr, *Straßenverkehrstechnik*, **93** (4) 246–249.

Marsden, G. (2006) The evidence base for parking policies - a review, *Transport Policy*, **13** (6) 447–457.

MATSim-T (2011) Multi Agent Transportation Simulation Toolkit, webpage, `http://www.matsim.org`.

Miller, G. K. and C. T. Everett (1982) Raising commuter parking prices - An empirical study, *Transportation*, **11** (2) 105–129.

Montini, L., A. Horni, N. Rieser-Schüssler and K. W. Axhausen (2012) Searching for parking in GPS data, paper presented at the *13th International Conference on Travel Behaviour Research (IATBR)*, Toronto, July 2012.

Nagel, K. and M. Schreckenberg (1992) A cellular automaton for freeway traffic, *Journal de Physique I*, **2** (1992) 2221–2229.

Polak, J. W. and K. W. Axhausen (1990) Parking search behaviour: A review of current research and future prospects, *Working Paper*, **540**, Transport Studies Unit, University of Oxford, Oxford.

Rieser-Schüssler, N., L. Montini and C. Dobler (2011) Improving automatic post-processing routines for GPS observations using prompted-recall data, paper presented at the *9th International Conference on Survey Methods in Transport*, Termas de Puyehue, November 2011.

Shoup, D. (2005) *The High Cost of Free Parking*, Planners Press, Chicago.

Thompson, R. G. and A. J. Richardson (1998) A parking search model, *Transportation Research Part A: Policy and Practice*, **32** (3) 159–170.

TomTom MultiNet (2011) MultiNet: The most powerful map database ever built, webpage, `http://licensing.tomtom.com/OurProducts/MapData/Multinet/index.htm`. Accessed 25/05/2011.

Topp, H. H. (1991) Parking policies in large cities in Germany, *Transportation*, **18** (1) 3–21.

van der Waerden, P., A. W. J. Borgers and H. J. P. Timmermans (1998) The impact of the parking situation in shopping centres on store choice behaviour, *GeoJournal*, **45** (4) 309–315.

van der Waerden, P., A. W. J. Borgers and H. J. P. Timmermans (2006) Attitudes and behavioral responses to parking measures, *European Journal of Transport and Infrastructure Research*, **6** (4) 301–312.

van der Waerden, P., A. W. J. Borgers and H. J. P. Timmermans (2009) Consumer response to the introduction of paid parking in a regional shopping center, paper presented at the *88th Annual Meeting of the Transportation Research Board*, Washington, D.C., January 2009.

van der Waerden, P., H. Oppewal and H. J. P. Timmermans (1993) Adaptive choice behaviour of motorists in congested shopping centre parking lots, *Transportation*, **20**, 395–408.

van der Waerden, P., H. J. P. Timmermans and A. W. J. Borgers (2002) PAMELA: Parking analysis model for predicting effects in local areas, *Transportation Research Record*, **1781**, 10–18.

Weis, C., M. Vrtic, J.-P. Widmer and K. W. Axhausen (2011) Influence of parking on location and mode choice: A stated choice survey, *Working Paper*, **684**, IVT, ETH Zurich, Zurich.

Widmer, J.-P. and M. Vrtic (2004) Einfluss von Änderungen des Parkierungsangebots auf das Verkehrsverhalten, *Research Report*, **VSS 1997/46**, Schweizerischer Verband der Strassen- und Verkehrsfachleute (VSS), Büro Widmer, Frauenfeld.

Wu, N. and W. Brilon (1997) Cellular automata for highway traffic flow simulation, paper presented at the *14th International Symposium on Transportation and Traffic Theory (ISTTT)*, Jerusalem, July 1997.

Young, W. (1986) PARKSIM/1: a simulation model of driver behaviour in parking lots, *Traffic Engineering and Control*, **27** (12) 606–613.

Young, W. and R. G. Thompson (1987) PARKSIM/1: a computer graphics approach for parking lot layouts, *Traffic Engineering and Control*, **28** (3) 120–123.

Young, W., R. G. Thompson and M. A. P. Taylor (1991) A review of urban car parking models, *Transport Reviews*, **11** (1) 63–84.