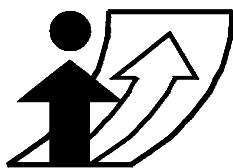

An Agent-Based Cellular Automaton Cruising- For-Parking Simulation

**Andreas Horni
Lara Montini
Rashid A. Waraich
Kay W. Axhausen**



**Travel Behaviour Research: Current Foundations,
Future Prospects**

13th International Conference on Travel Behaviour Research
Toronto 15-20, July 2012

An Agent-Based Cellular Automaton Cruising-For-Parking Simulation

Andreas Horni
IVT
ETH Zürich
CH-8093 Zürich
phone: +41-44-633 31 51
fax: +41-44-633 10 57
horni@ivt.baug.ethz.ch

Lara Montini
IVT
ETH Zürich
CH-8093 Zürich
phone: +41-44-633 30 88
fax: +41-44-633 10 57
montini@ivt.baug.ethz.ch

Rashid A. Waraich
IVT
ETH Zürich
CH-8093 Zürich
phone: +41-44-633 32 79
fax: +41-44-633 10 57
waraich@ivt.baug.ethz.ch

Kay W. Axhausen
IVT
ETH Zürich
CH-8093 Zürich
phone: +41-44-633 39 43
fax: +41-44-633 10 57
axhausen@ivt.baug.ethz.ch

July 2012

Abstract

This paper reports on the development of an agent-based cruising-for-parking simulation using the cellular automaton (CA) approach. The software was tested on small-scale scenarios, and a first verification step was performed for a real-world scenario for the town center of Zürich. Approaches to integrating the simulation into MATSim, a multi-agent transport simulation program, are discussed. The software is open source and can be downloaded from a free software repository. Empirical data which may be valuable for future model calibration is currently being surveyed in a GPS study at the authors' institute.

Keywords

Parking Search Microsimulation, cellular automaton

Preferred citation style

Horni, A., Montini, L., Waraich, R. A. and Axhausen, K. W. (2012) An Agent-Based Cellular Automaton Cruising-For-Parking Simulation, paper presented at the *13th International Conference on Travel Behaviour Research*, Toronto, July 2012.

1 Introduction and Research Goal

Parking search 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 models¹. This report describes a stand-alone, agent-based, cellular automaton (CA) cruising-for-parking simulation that combines microsimulation and parking choice models in one framework. A few similar simulations exist combining the components we consider relevant, namely: disaggregate traffic assignment (using a CA); the agent-based approach (including a memory for every agent); and the inclusion of transit traffic passing through the study area without parking. The closest approach to our model is perhaps PAMELA (van der Waerden *et al.*, 2002), who linked a parking search model with ALBATROSS (Arentze and Timmermans, 2000) and used a cellular automaton for the parking search. Another related approach was proposed by Kaplan and Bekhor (2011), who based their model calibration on GPS data, as we intend to do for our model in our future research. An interesting potential future extension to our model was implemented by Benenson *et al.* (2008), namely, the driver’s on-the-fly estimation of free parking lots on the way to a destination. In a future version of our model we intend to integrate parking strategies as described by Dieussaert *et al.* (2009). Another intriguing potential improvement was given by Gallo *et al.* (2011), who explicitly included a walking network layer to account for egress trips. Earlier parking search models were described by Thompson and Richardson (1998), Young (1986), Young and Thompson (1987), Arnott and Rowse (1999).

Why yet another parking search simulation? This model will later be integrated into MATSim, an agent-based transport simulation program (MATSim-T, 2011), according to the hybrid aggregate-disaggregate approach described in section 4. Instead of using existing code, we have created our own unique implementation that is expected to be more practical (for example, in terms of adaptability and extendability) for integration into MATSim and intense calibration with our GPS data. Nevertheless, considering the relatively large number of existing simulations, a consolidating and unifying focus might be constructive in a future project.

This simulation is also expected to be a useful testing ground for the 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). For example, the investigation of latent variables such as the starting point of the parking search (for more details see Section 2.2.2) could be supported by a well-calibrated parking search

¹Some papers that investigate parking in conjunction with other travel choices (such as destination choice) are: 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), Bonsall and Palmer (2004).

simulation.

This report is structured as follows: In section 2, the agent-based cellular automaton approach and the parking search model are described in detail, including some notes on software design. Results for a small-scale chessboard scenario and a first verification step for the Zürich town center scenario are shown in section 3. Section 4 contains conclusions and ideas for future work, in particular for the integration of the model into MATSim.

Terminology:

To the authors' knowledge, there is a certain ambiguity in parking terminology. In this paper, only two terms are used: *Parking space* refers to a place for one car and a *parking lot* consists of at least one parking space. In the simulation, the agents choose among parking lots.

2 Methodology

The cornerstones of our model are traffic and parking assignment via a cellular automaton-based microsimulation (section 2.1) and parking choice modeling (section 2.2). The model incorporates a limited short-term agent memory. Demand can be generated by adapting existing MATSim scenarios.

Probabilistic decision making leads to stochastic simulations that may necessitate variability analyses (e.g., Horni *et al.*, 2011a), which will be performed together with thorough future model calibrations.

2.1 Cellular Automaton

The cellular automaton that we implemented (class *CA*, see figure 4) is based on Nagel and Schreckenberg (1992). Their model 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 Wu and Brilon (1997) for a cellular automaton extended by more detailed car-following rules).

2.1.1 Infrastructure

The cellular representation of the infrastructure consists of one cell per node, several cells per link, and parking lots added to cells. Multi-lane networks are modeled with multiple parallel links.

The cell size for links is defined as in Wu and Brilon (1997, p.3), where reciprocal jam density was used (133 vehicles per km). No unacceptable discretization errors were reported for this value. Adapting the cell size to the actual minimum speed on the link might improve performance, i.e., if there is no jam on a link, the cell size should be increased. This would speed up the simulation, as fewer checks would need to be performed when cells are free.

Parking lots are attached to the nearest cell. If two possible cells are found, the parking lots are split and attached to both cells. Alternatively, attaching parking lots to relatively short links—as is usually the case for navigation networks—should be tested for performance.

2.1.2 Agents

To simplify implementation, we only distinguish between three types of agents in our model: parking agents who drive to an activity, search for a parking space and later leave the activity; private parking agents who do the same, except that they do not have to search for a parking space; and transit agents who just drive through the study area. Transport demand scenarios can be derived from activity-based models such as MATSim. However, these often provide complete plans per person and day. Adapting the mapping of these day plans to our three types of agents, who only have one activity each, is performed by duplicating agents in a pre-processing step (see (a) in Figure 1).

For parking agents, the route from intermediate destination to the final home activity is approximated. To circumvent having to use a router, a pre-computed route from the intermediate location to the home location is used instead of departures from the chosen parking lot (see (b) in figure 1).

2.1.3 Implementing Dynamics

The update process is performed as described by Nagel and Schreckenberg (1992, p.2222). Instead of simply iterating over nodes, links and cells in every time step, the procedure is essentially reduced to iteration *over agents*. This is achieved by using auxiliary data structures (members of the `CAServer` class), which dynamically manage

agents' positions by means of waiting queues (class `Queue`). Queues are randomly chosen for processing, which prevents links from having fixed priorities.

So far, 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 handling signalled and multi-lane intersections.

2.2 Cruising For Parking

For modeling purposes, the cruising-for-parking process and the choices it may entail can be divided into three categories (see also Kaplan and Bekhor (2011)):

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

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

2.2.1 The Parking Type Choice

The parking type choice differentiates between private and public parking. Private parkers do not have to search for parking; they are routed directly to their destinations and then removed from the simulation. The share of private parkers is defined in the configuration file. Each agent is randomly assigned to private or public parking, according to this share.

In the future, this exogenous choice and other parking-type choices such as on- or off-street parking could be endogenously modeled, e.g., by taking the trip purpose into account.

2.2.2 The Choice of a Search Starting Point and Search Route

The starting point of the parking search cannot be sharply specified, let alone easily operationalized. One can reasonably assume that drivers unconsciously observe the parking situation while driving toward their destination. For instance, a driver may observe that there seem to be extraordinarily few free parking spaces before actively searching, and this may initiate an active search earlier than actually planned. In this case, the starting point becomes fuzzy even for specification, and it illustrates why operationalization in surveys is difficult.

In our model we *define* the agents' starting points as dependent on the linear distance to the destination. In other words, as soon as an agent in the simulation comes within a given distance to the destination, he or she starts searching. To represent different search tactics, the agents' starting points are uniformly sampled from a distance range specified in the configuration file.

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

To describe the process in more detail, when an agent leaves an intersection, he or she then chooses the next link. Either the agent has not yet started searching and simply follows a pre-specified route, or the agent is actively searching, in which case the set of possible links is adapted so that any links leading back to the previous node are removed with a high probability (currently 90%). The next link is then randomly chosen from the adapted set, but weighted according to the following criteria, which are simultaneously considered:

- **Destination-approaching efficiency:** This measure depends on the angle to the destination and on the link length. The link length is used to reduce the probability that agents choose very long links, such as express highways or long bridges, which would take them far away from their destination. (Please 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 with the most free spaces in the agent's memory. Of course, a remembered empty parking lot loses its attractiveness with increasing distance to the agent's actual position (she does not want to drive a long way back). In view of this, the agent's memory is currently limited to 10 parking lots. In the future, instead of the total number of spaces, the ratio of free spaces divided by the size of the lot could be tested, whereby an S-curve weighting with parking size would presumably bring good results. Medium-size lots may be optimal,

since very small lots harbor the risk of being filled fast, and very large lots are difficult to evaluate while driving by.

Euclidian distances rather than network route distances are used for all of the evaluations. Weights are specified according to rough plausibility tests.

2.2.3 The Parking Lot Choice

Parking lot choice is modeled as a probabilistic choice, dependent on the elapsed search time t_{search} and the distance to the destination $d_{destination}$, as shown in figure 2 (for the implementation, see `AcceptanceRadiusLinear`, `ParkingDecisionLinear` and `ParkingDecision`). Up to the acceptance distance ($d_{acceptance}$ see also Birkner (1995)), a free parking space is taken with a very high probability (set in our model to 1.0), whereby probability decreases with distance according to a configurable function. $d_{acceptance}$ increases linearly according to the elapsed search time.

Using a function of decreasing acceptance probability for higher distances to the destination is natural; its calibration, however, is not simple. On the one hand, the decreasing slope should be moderate, so that if all parking lots at a distance smaller than $d_{acceptance}$ are already taken, parking lots at a distance only slightly greater than $d_{acceptance}$ are also accepted with a very high probability. A counterexample is given in figure 3 (a). On the other hand, and rather obviously, the slope must still decrease significantly so that an agent does not choose a very distant parking lot just because it happens to be the first one he or she encounters once the search has started (agents would do that in figure 3 (b)).

Plausibility investigations show that $d_{acceptance}$ and the *starting point of the parking search* (described above) must be modeled independently, although a direct relation seems plausible at first glance. We argue that acceptance probability differs significantly for *initially* driving toward a destination as opposed to 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.

The implementation allows us to set different parking-lot choice models in the configuration file and specify for each model the share of agents who should adopt each model.

2.2.4 Conclusion

Parking search, clearly, is a highly complex process with many determinants. When the outcomes of a model are determined by only a few variables, one runs the risk of a large approximation error. It is not easy to recognize the moment during calibration when the

error is actually irreducible and thus further calibration only means moving the error around in the model.

In general, it seems necessary to expand the decision models to be *directly* dependent on the given parking supply and on the load of the infrastructure and roads, rather than indirectly dependent on these through proxy 'elapsed search times' (see also section 2.2.4). More specifically, $d_{acceptance}$ should change in relation to an agent's observed parking situation. To this end, the procedure proposed by Benenson *et al.* (2008, p.434) could be integrated. In that procedure—in general terms, following Bayesian learning theory—agents adapt their expectation of finding a free parking lot close to their destination based on their continuous observation of the parking situation while driving. Therefore, this procedure captures look-ahead search behavior.

2.3 Software Design

We chose MATLAB to implement this model, as the idea originated in a MATLAB course. MATLAB was designed for procedural matrices computations, but also supports an object-oriented (oo) approach (although it suffers from a few performance issues). The object-oriented programming paradigm was chosen here for various reasons. First, agents nicely translate to objects, which makes code elegant and easy to understand. Second, in the authors' opinion, the oo-approach with its intrinsically good modularization perfectly suits team software projects and makes the adaptation of functionality (encapsulated in software modules) straightforward. Third, the authors are developers of MATSim oo-software. General simulation concepts (such as using a controller class) and design patterns easily translate from MATSim to the new simulation. Additionally, later integration into MATSim is more efficient with an oo-model.

Figure 4 depicts an overview of UML-inspired simulation components, showing the main components' relationships.

The software is open source and can be downloaded (LaHowara & Commander Spock, 2013).

3 Results and Discussion

In this section, several small-scale scenarios and one real-world scenario that were tested are described.

3.1 Small-Scale Toy Scenarios

For efficient development, testing and basic illustration purposes, three toy scenarios were created, named *chessboard* (figure 5), *square* (figure 6) and *mini-network* (figure 7).

The chessboard scenario was simulated with 100 agents with different trip starting times and a desired activity duration of 30 minutes. Private parkers and transit agents were not included in this scenario. Thirty minutes were simulated, which means that no agent left the parking lot during the simulation period. This is similar to overnight parking.

Figure 10 shows the median search time ² dependent on the number of parking spaces in the study area. A non-linear relationship between the median search time and parking supply was observed. Clearly, the parking density in a limited area around the destination should be used in a next version rather than the number of parking lots in the study area. Nevertheless, the simulation results—assuming that variations of either demand or supply are isomorphic—corresponds with the results in Axhausen *et al.* (1994, p.308) (see also figure 9). They report a non-linear relationship between the average search time and parking demand (approximated by the parking lots' occupancy). However, current work validating this estimation with GPS data indicates that a correction factor may be necessary for high occupancy levels.

The non-linear trend, empirically observed and simulated here, should in a future analysis be contrasted with the work of Benenson *et al.* (2008, p.438), whose simulation confirmed the empirical finding by Shoup (2005) that average search times and "(...) *hardly react to changes in parking supply as long as the demand/supply ratio is around one.*"

3.2 A Real-World Scenario: The Town Center of Zürich

A very first verification step was undertaken for a real-world scenario in the town center of Zürich, defined here as the area within a 1.5 km radius around Bellevue.

As the parking supply was expected to be local in nature, a detailed navigation network (see figure 8(a)) comprising 1'218 nodes and 4'750 links composed of 43'881 cellular automaton cells was used (derived from (TomTom MultiNet, 2011)). Multi-lane streets were modeled with multiple parallel links. Parking supply data data were gathered from various sources, and 1'355 parking lots with a variable number of spaces were created. A MATSim planning network (Vrtic *et al.*, 2003) with 78 nodes and 325 links built by 19'000 cellular automaton cells was also available (see figure 8(b)).

²Here the median was used instead of the average in order to account for outliers such as persons who had not yet found a parking space by the end of the simulation.

Demand was derived from a MATSim Zürich scenario (Horni *et al.*, 2011b) in which a total of 190'000 agents were generated for the whole day. For performance reasons, not a complete day was simulated but only the morning hours from 8-10 o'clock, whereby only the second hour was evaluated due to boundary or warm-up effects. Approximately 20 hours of runtime were required for a 100% run. Approximately half of the population was in transit and the other half was looking for a parking space in the study region. A share of 25% private parkers who did not have to search for a public parking space was assumed.

As a first step, two 10% runs were performed. To reduce the complexity of the implementation, parking capacity was scaled, but not road capacity. The first run was performed with the actual parking supply available in Zürich (but scaled), and the second with doubled scaled supply. The search-time histogram looks similar to the one observed for road travel times (see figure 11). Average values decreased from 3.9 minutes to 3.6 minutes when the supply was doubled, which is a smaller decrease than expected.

Similarly, 100% runs have been conducted. These clearly revealed two major issues to be solved: First and foremost, the network shows serious deadlocks, resulting in unrealistic results. The link and node (i.e., street and cross-section) capacities need to be investigated. In MATSim queue simulations, the storage capacity, i.e., how many cars fit onto a link, has always been a crucial issue. The same probably holds true here. Furthermore, the runtime is very high. A migration to Java, which is usually associated with good parallelization capabilities, would probably be beneficial.

4 Future Research and Integration into MATSim

The larger aim of this work is to improve MATSim destination interactions modeling. We plan to migrate the stand-alone MATLAB model to Java and integrate it into MATSim by taking advantage of parking modeling approaches tested for MATSim. In Waraich and Axhausen (2012a,b), a first MATSim parking choice approach which took different parking types into account was implemented and applied in the Zürich scenario. The parking search process was intentionally left out, and the utility function was not yet based on estimation. Waraich *et al.* (2013, 2012b), which was loosely based on Waraich *et al.* (2012a), presented an improved MATSim parking model that was based on a utility function estimated on a Swiss survey. Continuous, i.e., on-the-fly parking searches were not modeled; instead, a smart-phone-guided scenario was implemented. Agents optimized their searches by means of a smart phone that communicated all decision-relevant factors. Interactions in the parking lot were not taken into account. Dobler and Lämmel (2012) simulated driving, but not searching, in the parking lot of a single shopping center. Interactions with other modes (e.g., driving and walking) were not considered.

The integration of a high-resolution parking search process into MATSim poses two main problems. First, MATSim is an equilibrium model, which means that agents maximize utility, given the constraints imposed by competition with other agents. It is unclear whether the inclusion of a very detailed on-the-fly search process ever leads to a stable equilibrium. Second, as MATSim is intended for large-scale applications, a high-resolution parking search model may be prohibitively expensive for practical use.

For the second problem, a hybrid approach would probably be the best solution. In areas with high competition for parking lots (e.g., in city centers), the parking search can be microsimulated based on the cellular automaton approach. In regions with low competition (e.g., residential areas), either average search times can be derived from aggregate functions, or an existing MATSim parking model approach as described above can be applied. Obviously, the hybrid approach increases model accuracy and at the same time maintains feasible computation times for large-scale scenarios. The final MATSim model will be used to investigate the effects of parking on shopping destination choice. This is particularly relevant because a simulation of the MATSim Saturday scenario, with a higher share of shopping activities, is under development.

In addition to the tasks described above, future work should also be performed in the following areas:

Calibration and validation are the next important tasks, for which the following data sources are available: GPS and SP surveys (Montini *et al.*, 2012, Rieser-Schüssler *et al.*, 2011, Weis *et al.*, 2011), road count data (e.g., ASTRA, 2006), and several municipal surveys (Planungsbüro Jud, 2010, 1990, DemoSCOPE und Planungsbüro Jud, 2007). Decision models need calibration and enhancement by further choice determinants and mechanisms. An example is the look-ahead procedure mentioned earlier and described by Benenson *et al.* (2008, p.434).

Travel speed is usually reduced during searching. Although this effect is probably small or diminishing in situations with high traffic volumes, it should be implemented in a future version.

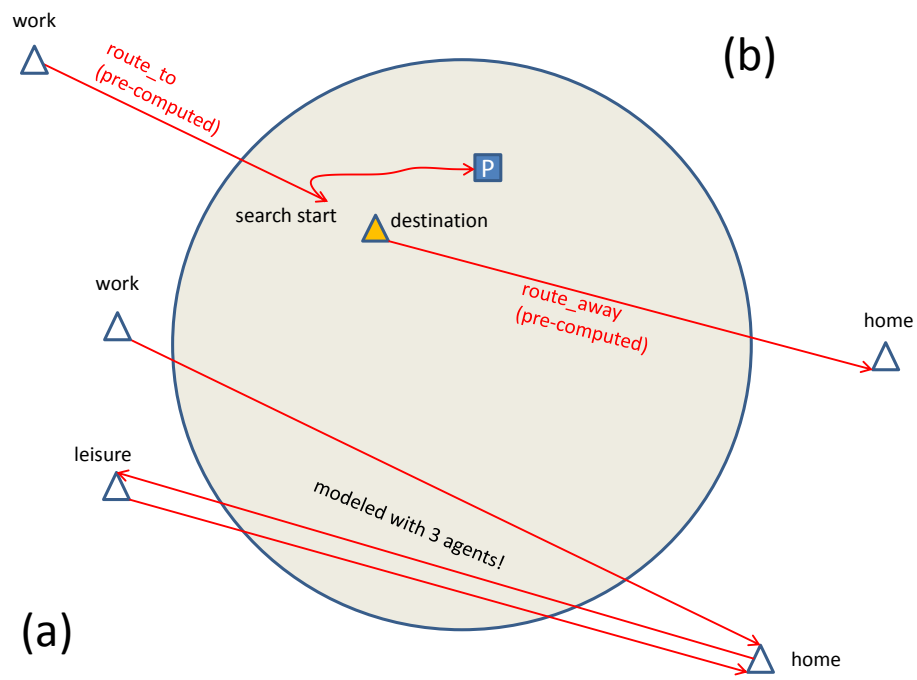


Figure 1: Conversion of MATSim demand

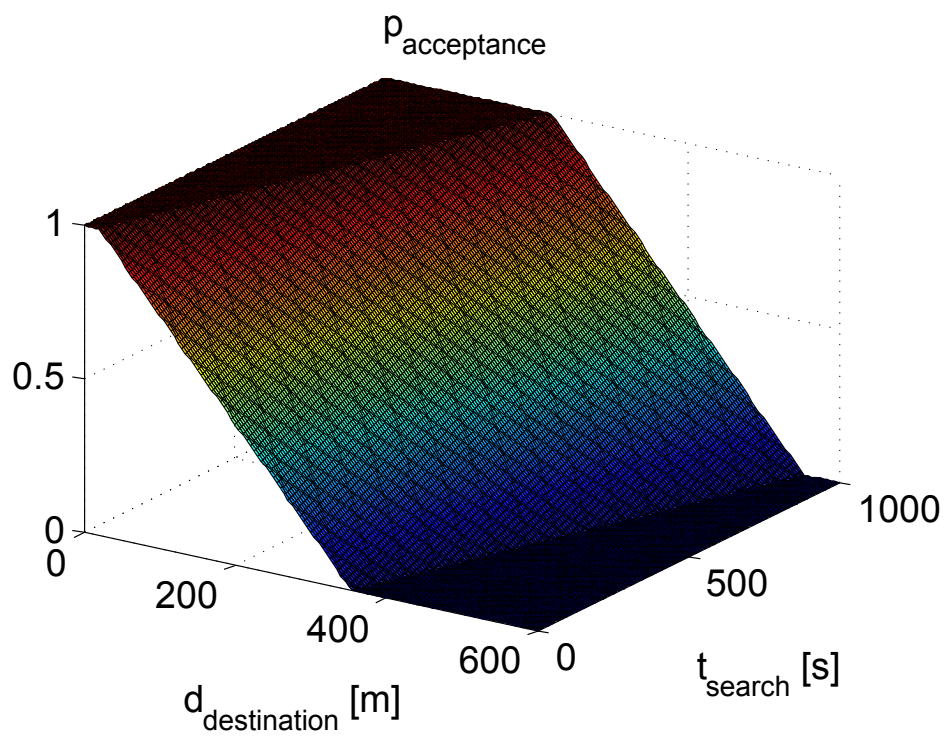


Figure 2: Specification of acceptance probability (configuration example)

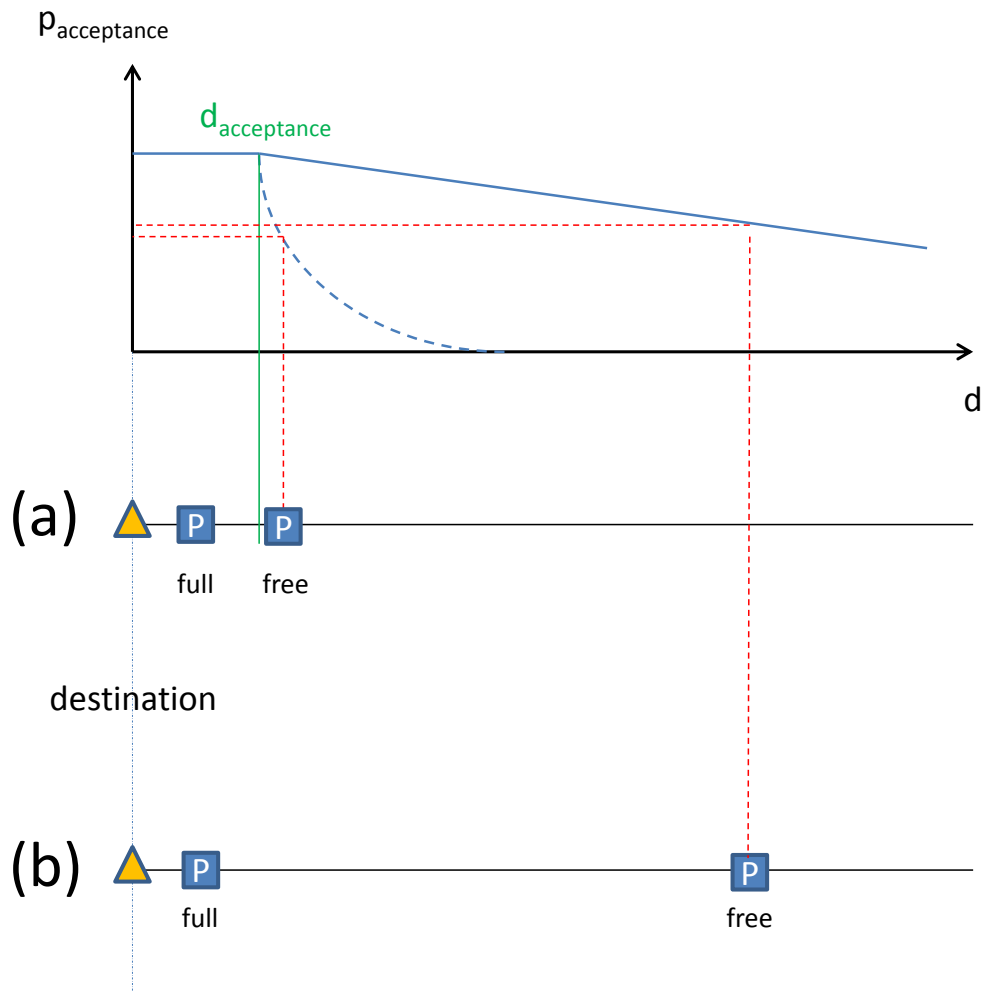


Figure 3: Specification of acceptance probability: Acceptance probability is very high up to a distance of $d_{\text{acceptance}}$ and then decreases either linearly or quadratically (configurable).

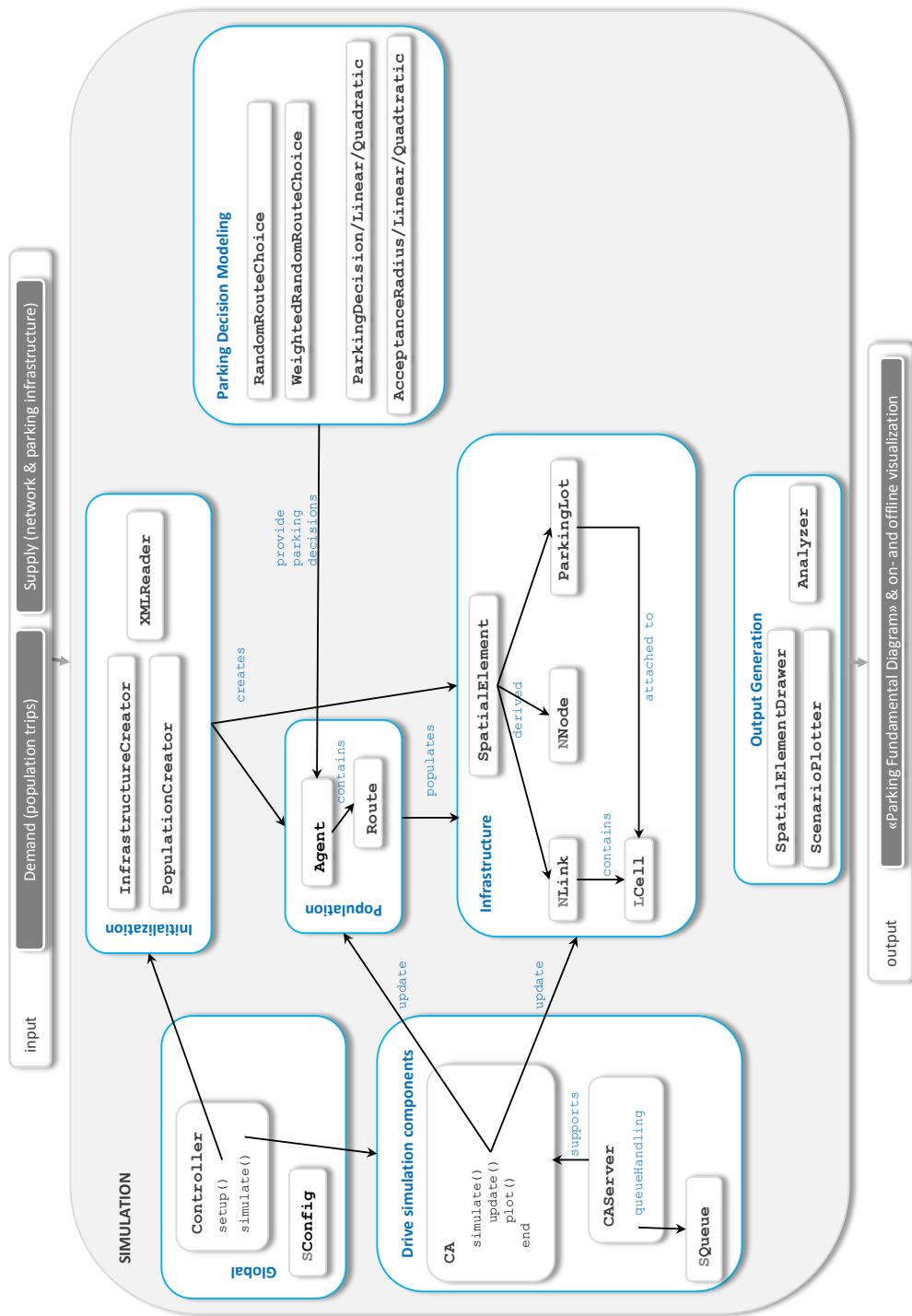


Figure 4: Simulation components: This figure is intended to facilitate reading the computer code.

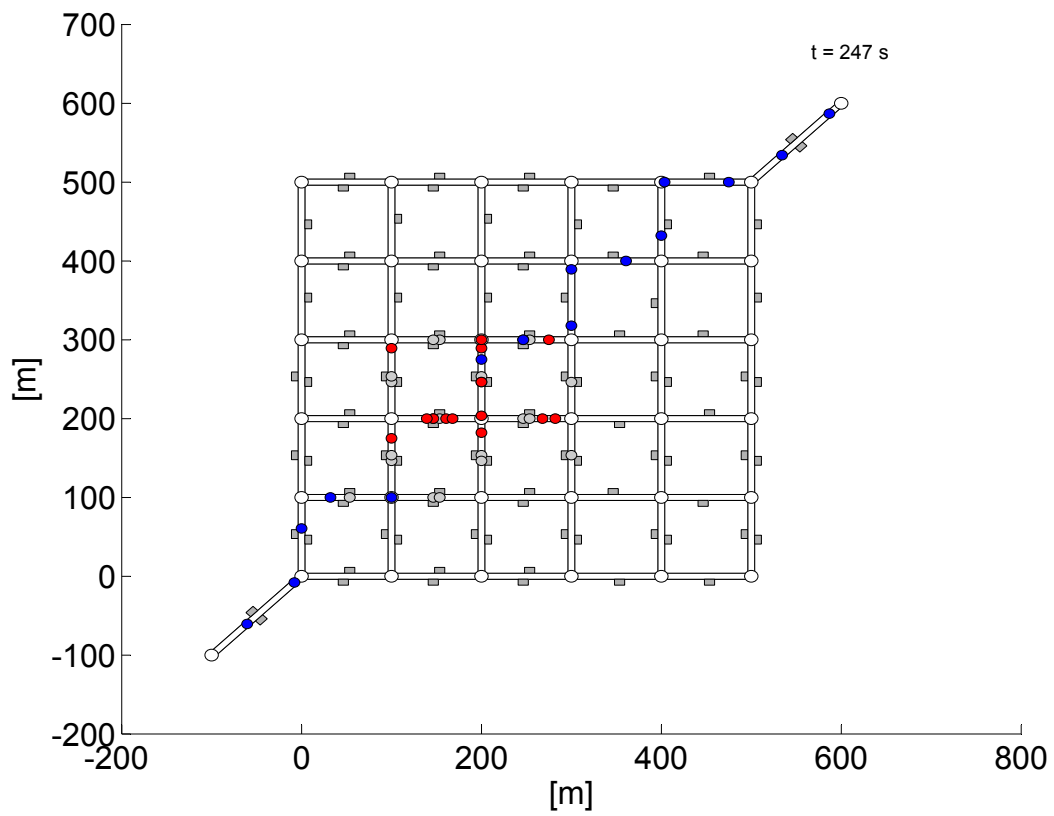


Figure 5: Chessboard scenario

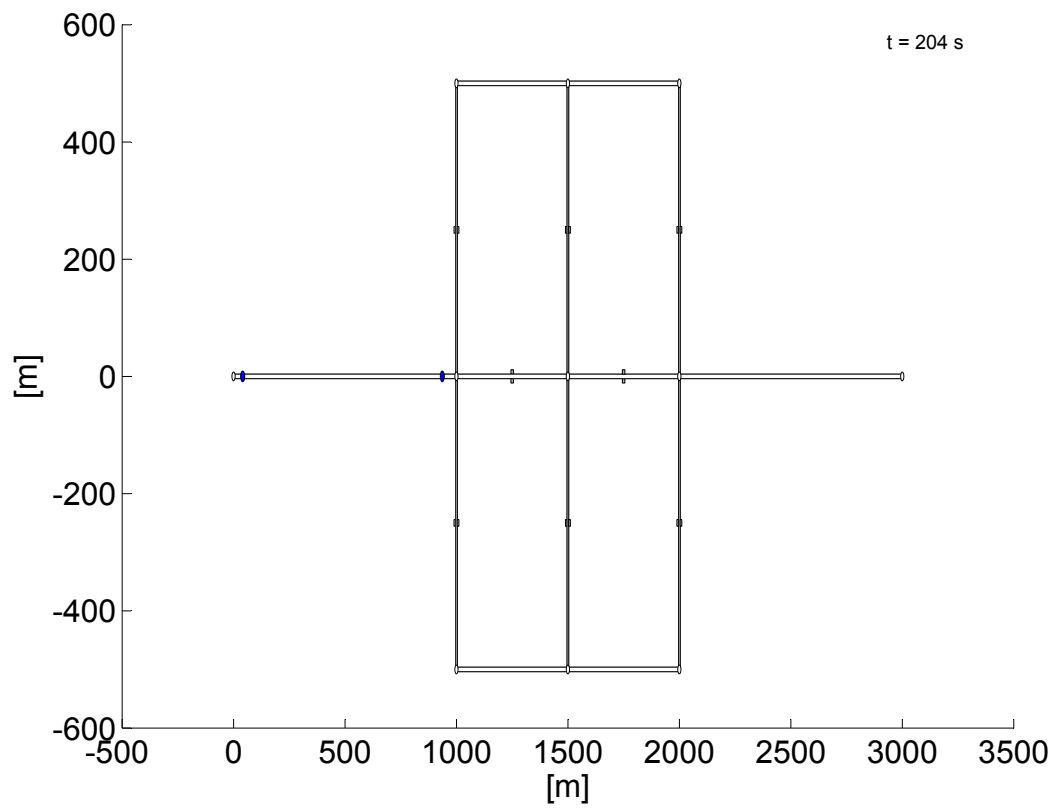


Figure 6: Square scenario

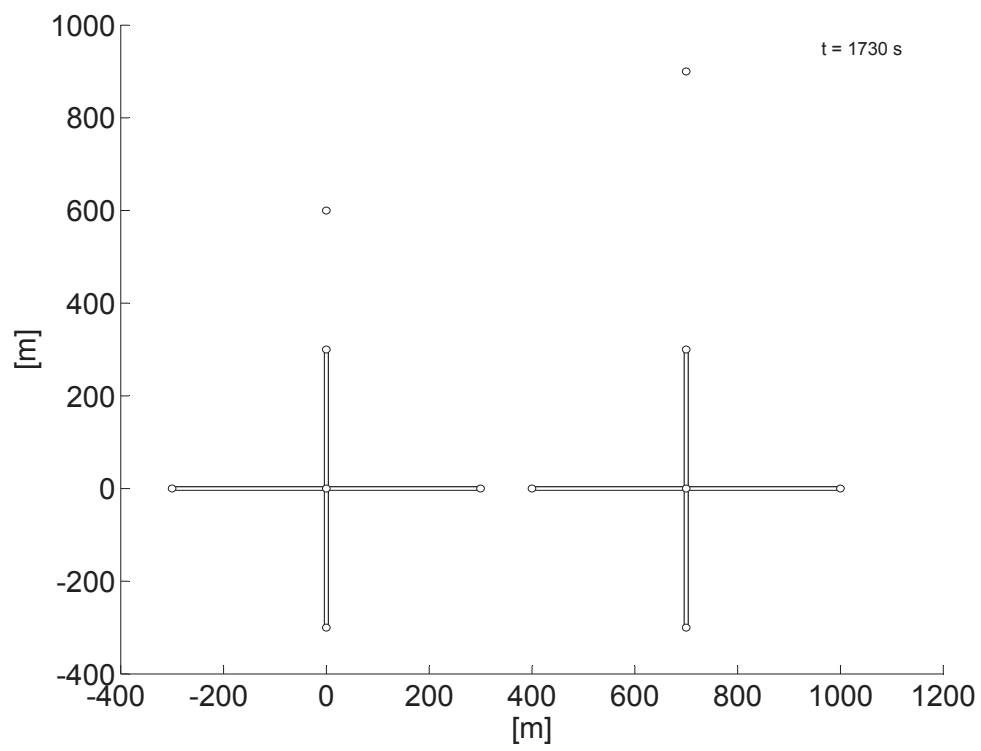
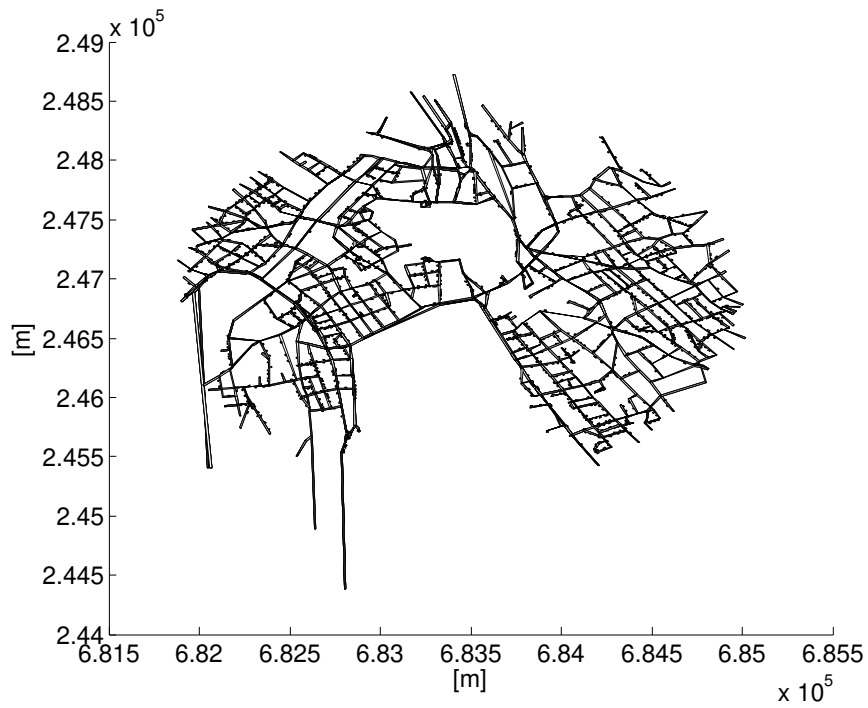
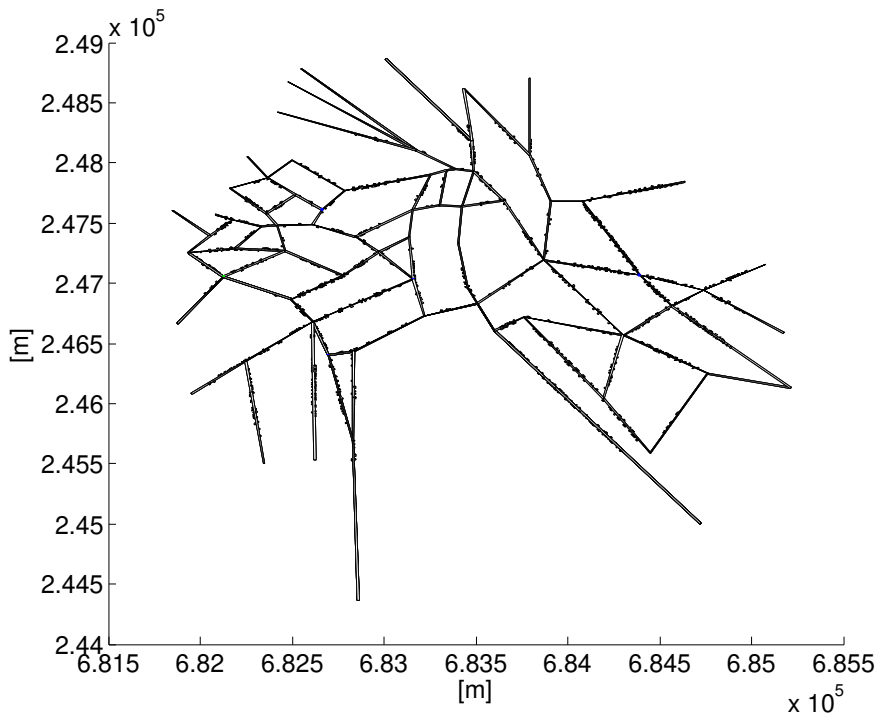


Figure 7: Mini-network scenario



(a) Navigation network



(b) Planning network

Figure 8: Zürich scenario

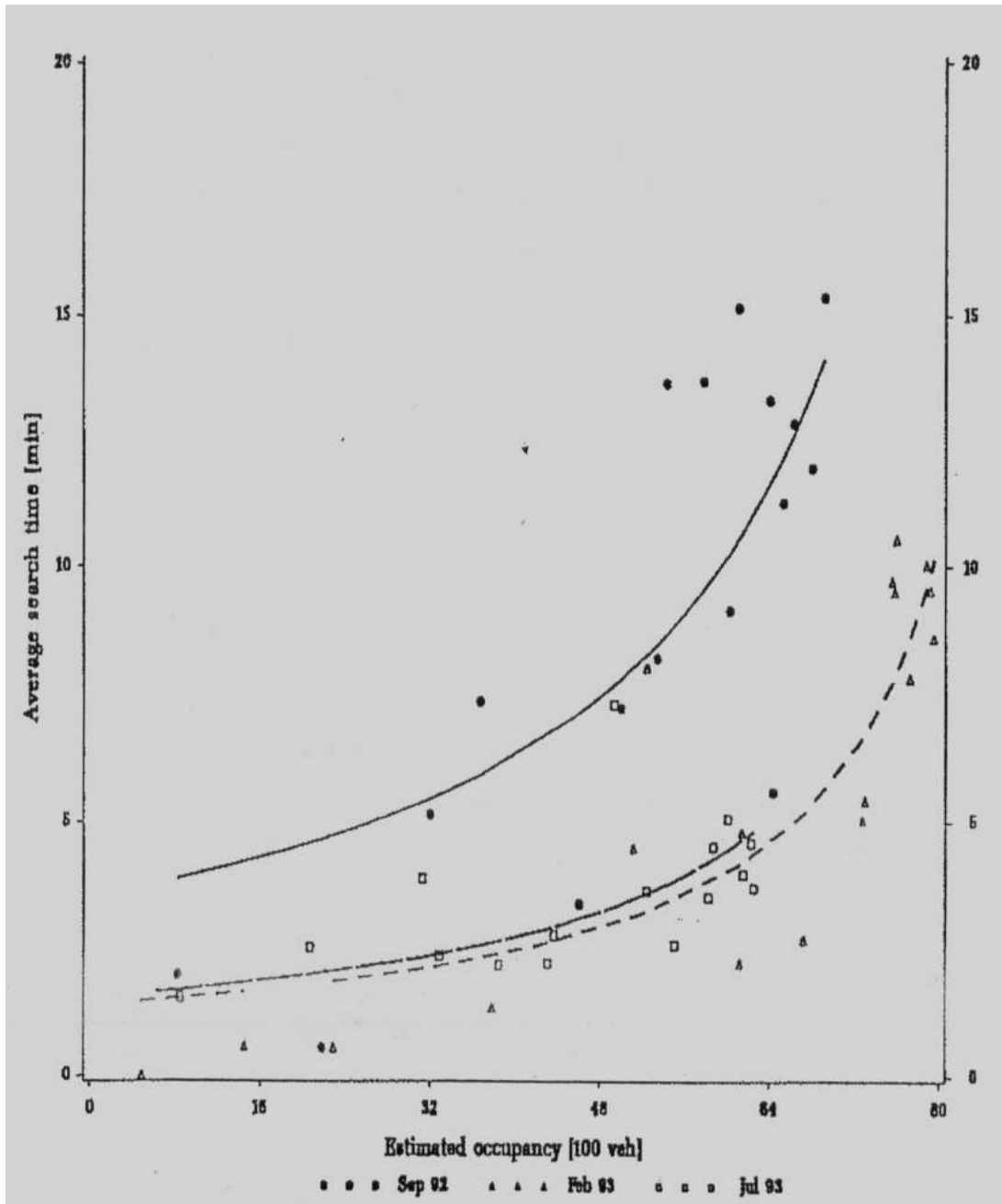


Figure 9: Aggregate search time model by Axhausen *et al.* (1994) (scanned)

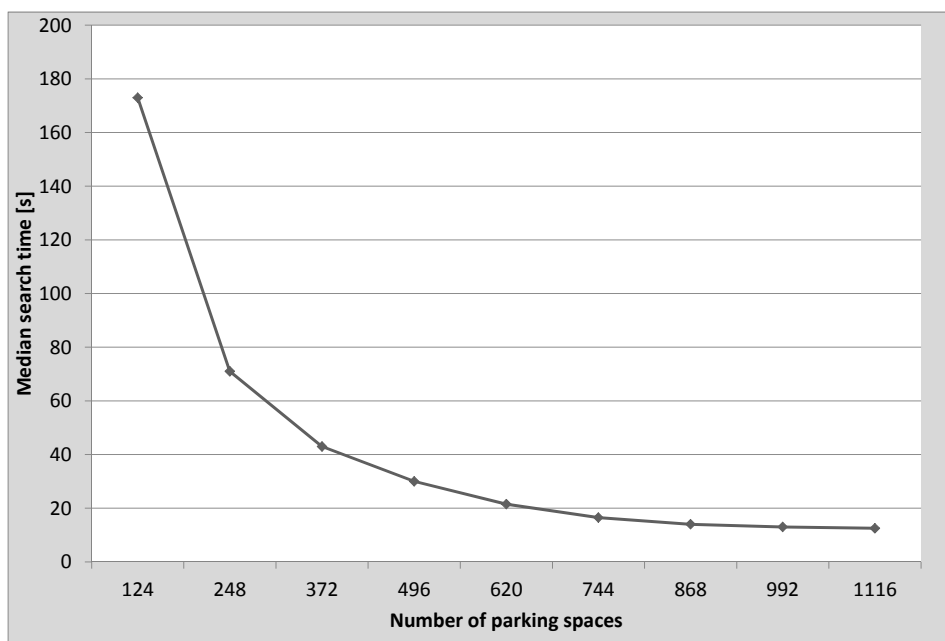


Figure 10: Aggregate search time model, chessboard scenario

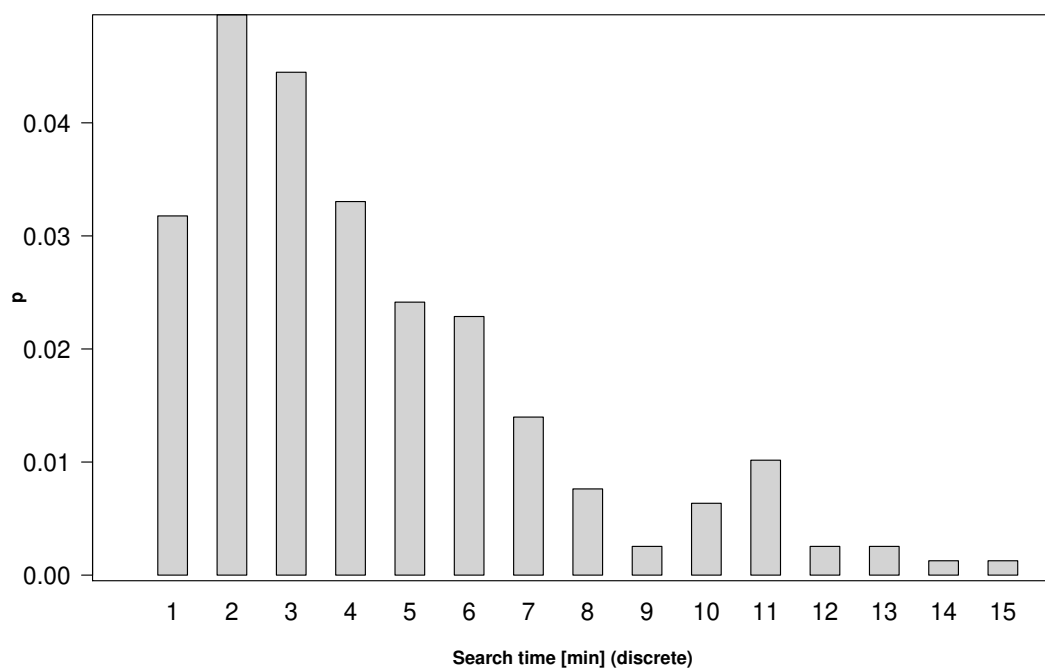


Figure 11: Search time distribution

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.
- Arentze, T. A. and H. J. P. Timmermans (2000) *ALBATROSS: A Learning-Based Transportation Oriented Simulation*, EIRASS, Eindhoven.
- 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.
- Arnott, R. and J. Rowse (1999) Modeling parking, *Journal of Urban Economics*, **45** (1) 97–124.
- ASTRA (2006) Swiss Federal Roads Authority, webpage, <http://www.astra.admin.ch/>.
- 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.
- Bonsall, P. W. and I. A. Palmer (2004) Modelling drivers' car parking behaviour using data from a travel choice simulator, *Transportation Research Part C: Emerging Technologies*, **12** (5) 321–347.

- Charypar, D., K. W. Axhausen and K. Nagel (2007) Event-driven queue-based traffic flow microsimulation, *Transportation Research Record*, **2003**, 35–40.
- DemoSCOPE und Planungsbüro Jud (2007) Rennweg mit und ohne Parkplätze: Erhebungen und Befragungen, *Final Report*, Stadt Zürich, DemoSCOPE und Planungsbüro Jud, Zurich.
- 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.
- Dobler, C. and G. Lämmel (2012) Integration of a multi-modal simulation module into a framework for large-scale transport systems simulation, paper presented at the *6th International Conference on Pedestrian and Evacuation Dynamics*, Zurich, June 2012.
- 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.
- LaHowara & Commander Spock (2013) An Agent-Based Cellular Automaton Cruising-For-Parking Simulation published on sourceforge.net, software, <https://sourceforge.net/projects/lahowara/>.
- 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.
- Planungsbüro Jud (1990) Parksuchverkehr Zürich, *Research Report*, Stadtplanungsamt der Stadt Zürich, Planungsbüro Jud.
- Planungsbüro Jud (2010) Belegung und Verkehrsaufkommen von Parkfeldern in der Stadt Zürich, *Research Report*, Tiefbauamt der Stadt Zürich, Planungsbüro Jud.
- 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.
- Vrtic, M., P. Fröhlich and K. W. Axhausen (2003) Schweizerische Netzmodelle für Strassen- und Schienenverkehr, in T. Bieger, C. Lässer and R. Maggi (eds.) *Jahrbuch 2002/2003 Schweizerische Verkehrswirtschaft*, 119–140, Schweizerische Verkehrswissenschaftliche Gesellschaft (SVWG), St. Gallen.
- Waraich, R. A. and K. W. Axhausen (2012a) An agent-based parking choice model, *Transportation Research Record*.
- Waraich, R. A. and K. W. Axhausen (2012b) An agent-based parking choice model, *Arbeitsberichte Verkehrs- und Raumplanung*, **696**, IVT, ETH Zurich, Zurich, August 2012.
- Waraich, R. A., C. Dobler and K. W. Axhausen (2012a) Modelling Parking Search Behaviour with an Agent-Based Approach, presentation, 13th International Conference on Travel Behaviour Research, Toronto, July 2012.
- Waraich, R. A., C. Dobler, C. Weis and K. W. Axhausen (2012b) Optimizing parking prices using an agent based approach, *Arbeitsberichte Verkehrs- und Raumplanung*, **794**, IVT, ETH Zurich, Zurich.
- Waraich, R. A., C. Dobler, C. Weis and K. W. Axhausen (2013) Optimizing Parking Prices Using an Agent Based Approach, poster presentation, 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., January 2013.

- 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.