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Procedia Computer Science 238 (2024) 749–756

Procedia Computer Science

www.elsevier.com/locate/procedia

The 13th International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTrans 2024)
April 23-25, 2024, Hasselt, Belgium

Agent-based modeling of residential parking zones in Leipzig

Gregor Rybczak[a,*], Simon Meinhardt[a], Tilmann Schlenther[a], Christian Rakow[a], Dominik Ziemke[b], Kai Nagel[a]

[a]*Transport Systems Planning and Transport Telematics, Technische Universität Berlin, Kaiserin-Augusta-Allee 104, 10553 Berlin, Germany*
[b]*Chair of Mobility System Planning, Technische Universsät Dresden, Hettnerstr. 1, 01069 Dresden, Germany*

Abstract

This study introduces a methodology to model parking cost and residential parking zones within the agent-based simulation framework MATSim. An overview of related research and a description of the implementation are given. The results suggest that parking pricing has a larger impact on the share of motorized transport than longer access and egress walks to the activity. Raising parking costs could prove to be an effective tool to reduce motorized transport.

Keywords: MATSim; parking; multi-agent transport simulation; residential parking zones

1. Introduction

Parking availability is known to influence travel behavior. For example, people may shift their departure time in order to still catch a parking space, or they may switch to an alternative mode if they expect limited or no parking to be available at the destination [15]. Also, they may select a different destination where parking their car is (more easily) possible [17]. In consequence, parking pricing or parking restrictions are generally an effective travel demand management tool [20]. In Germany, tolls – i.e. fees for *moving* traffic – for passenger cars are not in use. In contrast, fees for parking have been used for decades. This mostly concerns visitor parking, for example in inner cities. Also, there is a lot of experience with residential parking zones, which are increasingly used in inner-city areas and more densely populated neighborhoods. In 2020, federal legislation for residential parking in Germany was changed, removing a previously existing price cap of 30.70 EUR per year, so that it can be expected that various parking charges will be used even more than in the past to influence travel behavior [1, 9].

* Corresponding author. Tel.: +49 30 314-78793; fax: +0-000-000-0000.
E-mail address: rybczak@vsp.tu-berlin.de

10.1016/j.procs.2024.06.087

The project *Sustainable mobility and urban qualities through automation in traffic* ("Nachhaltige Mobilität und städtebauliche Qualitäten durch Automatisierung im Verkehr", NaMAV) investigates opportunities and risks of automated vehicles (AV) for urban transport systems using the example of Leipzig, Germany. It analyzes how transport planning should prepare for scenarios of automation in mobility today and actively shape them [23]. The conceptualization process is supported and driven by transport simulations, in particular by MATSim [12], which helps to understand and quantify impacts. The NaMAV project is accompanied by a scouting process which identifies policy interventions that should be considered together with or as alternatives to automation. One of these interventions are car-free zones.

As is standard in transport planning, the impacts of the interventions are determined by comparing the intervention cases with a base case. In consequence, first, a base case model needs to be developed. Since car-free zones interact with parking, the modeling of parking behavior needs to be represented in a sufficiently detailed way already in the base case. The city of Leipzig – as many other German cities – uses residential parking zones (in Leipzig defined as zones where only residents are allowed to park but have to pay an annual fee) as a travel demand management tool. In consequence, residential parking zones need to be explicitly modeled in the base case model for Leipzig, as they are part of the city's current parking price scheme.

The remainder of this text is structured in four parts: Section 2 describes existing research, Section 3 describes the simulation setup and the integration of residential parking zones and parking cost in it, in Section 4 we present the results of this study, and in Section 5 the results will be discussed and a conclusion will be drawn.

2. Related Research

2.1. Person-centric modeling of travel behavior

In order to better take into account complex individual behavior, 'microscopic' or 'agent-based' or 'person-centric' transport planning models are used. They populate the region of interest with synthetic persons, which execute daily plans. This is arguably furthest developed in the area of activity-based demand generation (ABDG, [10, 18, 4]) Recognizing a need for more person-centric behavioral variation also on the 'traffic assignment' level (route choice, departure time choice, mode choice; [3, 24]), there is now an increasing number of person-centric assignment models (e.g. [12, 24, 2]). These typically consist of at least the following elements:

1. **A simulation of traffic flow behavior**, which executes the plans of all synthetic persons simultaneously, simulating the movements of all persons with all modes, including walk, through the transport system.
2. **An iterative procedure** that keeps adapting the plans of the synthetic persons along the available choice dimensions (route, mode, time, etc.) and re-submitting them to repeated runs of the traffic flow simulation.

Many choices are possible for the objective function of the iterative procedure. In MATSim [12], each synthetic person tries to maximize its individual scoring (or utility) function – if this is successful, the system reaches a generalized Nash equilibrium. The scoring function of MATSim consists of rewards for performing activities, and penalties for traveling from one activity to the next, based on the concept of time use [8, 13]. MATSim's scoring function is quite flexible; important contributions are

- a marginal utility of time spent traveling (separate for each mode),
- a mode-specific constant for each stage ("leg") of a trip,
- a monetary distance rates for such modes where monetary expenditures are relevant (e.g. car). For public transport, an approximate fare model is used (cf. 6),
- a mode-specific *daily* constant modelling fixed costs, dividing annual fixed costs by the same 'representative number of days' as used for the annual vehicle costs, here 250.

In MATSim, the transport infrastructure is represented by a directed graph with unidirectional links connecting nodes [12]. The nodes are geo-referenced, i.e. directly attached to a coordinate. While links are not directly geo-referenced, each instance connects one *fromNode* with one *toNode*. Each link holds information on flow and storage capacities, number of lanes, allowed modes of transport, free speed as well as an unlimited number of user-defined attributes.

2.2. Modeling parking in agent-based transport simulations

The arguably earliest agent-based approaches to parking model individual drivers while approaching their destination. They need to decide (a) if to pick an available parking spot already before the destination, or (b) if this fails they need to search for parking afterwards. In this vein, Benenson et al. [5] present a framework named PARKAGENT to explicitly model parking choice of agents, including strategies that were derived from behavioral surveys for Basel and Tel Aviv. Spitaels et al. [21] present SUSTAPARK, which allows to model parking behavior with respect to destination activity types. The model is based on cellular automata and neither accounts for mode choice nor access/egress walks. Bischoff and Nagel [7] use the existing 'taxi' implementation of MATSim to demonstrate its applicability to model explicit parking search [12]. They use the method to investigate multiple parking strategies for autonomous vehicles (AV) [6]. Ewert and Nagel [11] present another application to the use case of parking bus coaches in Berlin. Here, buses need to search appropriate parking between dropping off passengers at sights and picking them up later. Vuurstaek et al. [25] present SimPark, which is primarily designed as a plug-in to the FEATHERS ABDG model [4]. Tchervenkov [22] uses the approach by Bischoff and Nagel [7] to integrate it into the iterative MATSim loop. First, he imputes which synthetic persons have parking available at home or at work. Second, he considers those who do make a choice between on-street parking or garage parking. Third, those who choose on-street parking search for an available slot using the approach of [7]. Fourth, the properties of the search such as its duration are fed back into the choice in step two.

Bischoff and Nagel [7] note that modeling explicit parking search for all vehicles in a city-wide MATSim simulation is computationally too expensive to be used within normal MATSim transport simulations. In order to overcome this issue, Tchervenkov [22] scales his simulations down to a 0.1% sample of the Zurich traffic.

Waraich [26] moves one step away from the actual process. At vehicle arrival, they consider all available parking spots and select the one that is "best" as defined by a parking utility that takes into account parking prices and access/egress walk effort. The car is then "teleported" to the parking location, while the agent is left at the arrival location and starts its activity. At the end of the activity, the car is teleported back to the arrival (now: departure) location, where the agent enters it, etc. To reflect the disutility of the parking operation, a penalty is added to the agent's score. This penalty is user-defined, but typically includes elements such as parking price, walk effort, and possibly the cost of additionally driven distance. The authors note that in principle the routes would need to be adjusted, reflecting the new departure and arrival links, but the the corresponding code implementation ('parking contrib') does not reflect this.

In contrast to explicit simulation, the disutility imposed by parking search can be parameterized, possibly by accounting for spatial and temporal components. Schlenther et al. [19] model parking pressure with generalized costs representing monetary and time efforts in the city of Hamburg. These costs are input to the model and thus static, i.e. not sensitive to the occupation of parking capacity in the model, and monetary and time components cannot be distinguished in the analysis.

Overall, three different approaches to agent-based simulations of parking can be distinguished:

1. **Explicit simulation of parking search behavior**: a synthetic person in a car, while approaching its final destination, needs to decide (a) if to pick an available parking spot already before the destination [25, 5, 11], or (b) if this fails how to search for parking afterwards, possibly automated [6].
2. **A global view to parking behavior**: the simulation logic has a global overview of parking availability, and the vehicle uses an available parking space which might possibly be somewhat away from the final destination. This behavior can either also be "physically" modeled by directing the car to the parking location and then have the synthetic person walk to its final destination, or it is parameterized.
3. **A parameterization of parking pressure**: the simulation logic "parks" the car near the destination no matter how many cars are already parked there and imposes some penalty for parking in areas where parking is scarce. This penalty can be computed in many different ways, e.g. by considering solely the link or by averaging over an area [19], and there can be different temporal averages.

An explicit simulation of parking behavior (approach 1) is computationally too expensive for our Leipzig scenario, as was already discussed above with respect to the similarly sized Zurich scenario. Approach 3 does not address the issue that for our Leipzig scenario the parking *location* may have to be differentiated by the destination activity type: while for a home activity one can park regularly but needs to pay a flat fee, for all other activity types one either needs to pay commercial parking fees, or park outside the area. In consequence, a variant of approach 2 was implemented. In contrast to [26], our approach decides based on activity type, not based on parking space availability – for the latter, our model additionally would need information on parking capacity. Also, other than [26], our approach effects that the vehicles is parked at a different location, and makes the agent walk between parking location and final destination.

3. Methodology

Base case model. The creation of a MATSim model implementation for the region of Leipzig is explained in supplementary material, see Sec. 6. That model implementation is hereafter referred to as Base Case (for this paper). It does not contain a detailed model of residential parking zones.

Parking – parking fees. We implement a parking fee handler in MATSim as follows: First, one tags all links for which parking fees should be charged with one or more link attributes. These should contain, for each link separately, information about that link's pricing scheme and its parameters. Next, one adds a so-called 'MATSim events handler', which records when a vehicle starts parking on such a link, and upon vehicle departure computes the parking fee and adds it, as a 'PersonMoneyEvent', into the simulation events stream. MATSim will automatically include any PersonMoneyEvent into the 'scoring' (i.e. the utility-based evaluation of the daily activity-travel plan) of the corresponding synthetic person. For Leipzig, the parking fee is 3 EUR per hour for all parking zones except one, where 1 EUR per hour is charged, as depicted in Figure 1.

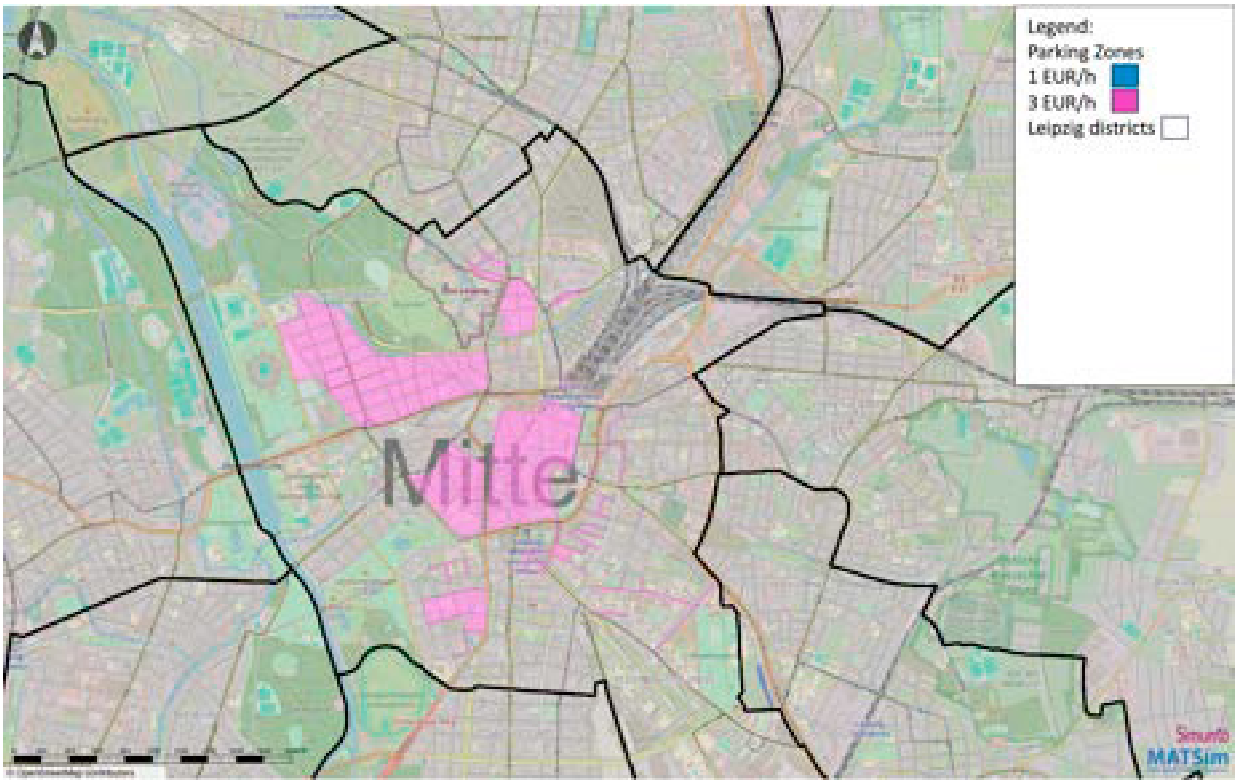

Fig. 1: Location and extent of parking zones in Leipzig (Source: Own illustration based on direct communication with the administration of the City of Leipzig, background: OpenStreetMap).

For residential parking, the annual fee is converted into a daily fee by dividing it by the same 'representative number of days' (250) as we do for the annual vehicle costs (see Sec. 6). For Leipzig, this translates the annual fee of 30.70 EUR to 12.28 ct per day. Evidently, one needs to make sure that this is charged only once per day, i.e. not if a vehicle returns to its home link and then leaves again. In consequence, all other things being equal, a resident of a 'residential parking zone' will have a lower utility for car than a resident outside such a zone, because of the additional residential parking cost.

Parking – parking link selection. A challenge for the Leipzig implementation was that in Leipzig non-residents are not allowed to park at all on public streets in such zones. In consequence, the standard MATSim approach – where all car users visiting the same destination park on the same link but may have to pay different penalties – no longer works: while residents can park on the link of their residence, non-residents can only park outside the zone and then need to walk to their final destination. Thus, the destination link for the car routing now depends on the activity type at the destination. This cannot be resolved by using different sub-networks, since non-residents are still allowed to drive through the restricted zones. Instead, this is addressed by using a conditional link selection logic in the router:

1. If the destination activity is 'home' or 'shopping', the standard MATSim link selection logic is used. 'Shopping' is included as it is assumed that (most) shopping facilities provide private parking lots.
2. If the destination activity is something else, the link selection logic searches for a destination link in a (sub-) network that does not contain the residential parking links.

4. Results

All runs are performed with a 10% sample of all travelers. To make numbers comparable across studies with different sample sizes, all results are scaled up to 100%. In consequence, in the following all 'numbers of trips' are multiples of ten.

We first analyze **trips to or from a *home* activity in one of the residential parking zones**. The results are displayed in Table 1. In total, there are 32,800 such trips, performed by 14,590 synthetic persons. Recall that for these persons, the price of using a car will increase by 12.28 ct per day. Correspondingly, the number of trips done by car decreases and the number of trips by other modes of transport increases. The number of trips is more than twice the number of synthetic persons, as the synthetic persons can have more than one home activity in their daily plan.

Table 1: Number of trips with a home activity in the residential parking zone

Case	car	bike	pt	ride	walk	sum of trips
Base Case	7,160	6,990	5,270	2,580	10,800	32,800
Residential Parking Cost 0.123 EUR	6,800	7,210	5,370	2,770	10,650	32,800
Residential Parking Cost 1.23 EUR	6,510	7,020	5,460	2,860	10,950	32,800
Residential Parking Cost 12.3 EUR	3,950	7,520	6,290	3,570	11,470	32,800

The average travel time increases from 1,452 seconds to 1,460 seconds per trip. The reason presumably is that some synthetic persons switch to slower modes in order to save money. In total, all agents together pay 448.95 EUR per day for residential parking.

To test the **sensitivity** of the model, the prices for residential parking are multiplied by a factor of 10, increasing the price to 1.23 EUR per day, which corresponds to 307 EUR per year. As a result, the number of home-based car trips falls to 6,510. These synthetic persons together pay a total of 4329.60 EUR per day for residential parking. If the residential parking cost is increased by another factor of 10, to 12.28 EUR per day (corresponding to 3,070 EUR per year), the number of home-based car trips decreases to 3,950 per day. The synthetic persons together now pay a total of 27,306 EUR per day. Even with such a high daily fee, many synthetic persons keep using their car. Presumably, they have destinations that are difficult to reach by any other mode. Agents who keep using their car perform on average more trips. Thus, the increased cost is divided by more trips. The average income of the agents performing these trips is very close to the average income of the whole synthetic population. Increasing the residential parking cost even further results in even larger reductions of car usage (results not shown), meaning that there is no mechanical barrier in the model, and instead even parking costs of 12.28 EUR per day are "cheaper" for some synthetic persons than any alternative allowed by the model.

Next, we analyze **trips to or from a *shopping* activity in one of the residential parking zones**; this includes trips between shopping activities in those zones. These add up 31,170 trips. The results are displayed in Table 2. Recall that car trips of this type require a parking payment of 3 (in some places 1) EUR per hour. As a result, the number of car trips falls by 29%. In contrast, the number of trips made by walking, by car as passenger (‘ride’) and by bicycle increases. The largest increase in trips (12%) can be observed in public transport.

The average travel time of all trips of this type increases by 32 seconds from 1,356 seconds to 1,388 seconds per trip. The agents have to pay a total of 15,760 EUR per day in parking costs.

Table 2: Number of trips with a shopping activity inside a residential parking zone

Case	car	bike	pt	ride	walk	sum of trips
Base Case	7,570	2,540	8,810	2,140	10,110	31,170
Normal Parking Cost at a shopping activity	5,060	2,830	9,910	2,780	10,590	31,170
Parking Cost at a shopping activity increased by a factor of 10	1,600	3,110	11,040	4,180	11,240	31,170
Parking Cost at a shopping activity increased by a factor of 100	940	3,520	11,190	4,390	11,130	31,170

To again test the **sensitivity** of the model, parking costs for shopping are increased by a factor of 10 and 100, respectively. This causes total parking costs to rise to 31,500 EUR and 207,000 EUR, respectively, while the numbers of car trips reduce from 7’570 to 1’600 and to 940, respectively. Similar to the very high residential parking costs, the agents who still perform trips by car, have on average more trips then the rest of the population. The average income of those agents is again also slightly higher.

Finally, all **trips to or from *any other activity* in one of the residential parking zones** are analyzed; again, this includes trips between those zones. The total number of these trips is 236,420. The number of car trips decreases from 67,990 to 65,140 (by 4%); results for other modes are given in Table 3. Recall that here no parking fee is levied, but car travelers need to park outside the parking zone and walk to their final destination. At this stage, no parking space scarcity is modeled.

Table 3: Number of trips with any other activity inside a residential parking zone

Case	car	bike	pt	ride	walk	sum of trips
Base Case	67,990	23,730	63,770	17,970	62,960	236,420
Park outside zone	65,140	23,850	64,930	18,710	63,790	236,420

5. Summary and Discussion

The present paper investigates the introduction of residential parking zones into a transport model for the city and region of Leipzig. In principle, modeling the underlying parking scheme could be done in a straightforward way by dividing the annual fee into a daily fee for residents, and charging hourly fees for everybody else. However, in Leipzig the parking scheme is more complicated in that non-residents, with the exception of shoppers, cannot park in these zones at all, but need to park outside these zones and reach their actual destination by walking. This is somewhat similar to the (more involved) study by Tchervenkov [22]. Different to that study, we need to be able to run the model with much larger sample sizes, principally with a full population representation (‘100% scenario’). As a compromise, no parking scarcity was modeled for the time being, and car drivers simply park on the nearest link outside the zone.

We find that residential parking fees of several tens of Euros per year (approx. 10 ct per day) have little influence on the number of car trips, while several hundreds of Euros per year (approx. 1 EUR per day) could reduce their number by about 10%. Comparatively, parking fees for non-residents of 3 EUR per hour reduce the number of car trips by about 30%. Making people park outside the parking zones and have them walk to their final destination reduces the number of car trips only by 4%. Other studies have shown larger effects [14] – but have used larger zone sizes and in consequence longer access/egress walking times and distances. In addition, driving through these zones by car was not permitted, in contrast to this study.

Parking price elasticities in the literature range from 0 to −3, with typical values between −0.1 and −0.3 [16, 15]. Litman [16] also points out that these values depend on the overall trip cost – if the trip already costs 10 EUR, then an additional parking fee of 1 EUR has less of a relative effect than if the trip by itself only costs 1 EUR. Given a daily car cost of about 15 EUR per day (fixed plus variable cost) in our Leipzig scenario, it is clear that parking costs below 1 EUR will have relatively little influence on car mode choice. Accordingly, assuming an overall vehicle cost elasticity of 1 ([16] p. 26), a parking price increase from 0 to 1.5 EUR leads a a vehicle cost increase of 10%, and should thus reduce car usage by about 10%. These are indeed approximately the reactions that our model displays. The current parking implementation for Leipzig does not take into account behavioral alternatives beyond mode choice – neither can shoppers park outside the zones and thus avoid the monetary fee, nor can non-shoppers park inside the zones and pay for parking to avoid the access/egress walk. Also, scarcity of parking, which can, in particular, be expected in the areas adjacent to the residential parking zones, is not modeled. Future research should focus on the integration of the existing approaches and try to find a generalized approach to better represent the phenomenon of parking in MATSim.

6. Supplementary material

Supplementary material can be found under: 10.14279/depositonce-19841.

Acknowledgements

This work was funded in part by the German Federal Ministry of Education and Research (grant 01UV2081B). We thank Benjamin Wagner, City of Leipzig, for providing information on Leipzig's current parking schemes.

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