Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Computer Science 19 (2013) 821 – 828

Procedia Computer Science

The 2nd International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS'13)

Agent-based Modelling and Simulation of Air Transport Technology

D. Grether, S. Fürbas, K. Nagel

Transport Systems Planning and Transport Telematics, Berlin Institute of Technology, Salzufer 17-19, D-10587 Berlin, Germany, Tel: +49-30-314 21383, Fax: +49-30-314 26269, E-mail: grether@vsp.tu-berlin.de,

Abstract

Declining travel time differences of mid-distance transport modes motivate use of multi-agent simulation models to analyze and forecast behaviour of actors in the transport system. This paper focuses on air-transport technology. A simulation model is proposed, that represents details of air traffic microscopically but is fast enough to enable an iterative simulation-based passenger-trip assignment. Aircraft are modelled in detail in respect to departure time and seat availability. Modelling of airports and routes of aircraft focuses on the available capacity of runways. Several simulation runs illustrate how the model can be calibrated using available parameters. The model can be used for an agent-based traffic assignment. Overall, the approach appears to be suited to analyze and forecast mid-distance transport.

Selection and peer-review under responsibility of Elhadi M. Shakshuki

Keywords:
air transport planning, queueing model, agent-based simulation

1. Introduction

Considering state-of-practice high-speed railway services mid-distance traffic modes no longer differ that much in terms of travel time. This technological change raises new requirements on time-dependent forecasting of mid-distance air, rail and road traffic. Each mode possesses specific characteristics, while choice of mode is not considered trivial due to heterogeneous user preferences. Thus, a mode-specific, high resolution, agent-based simulation model can help in mid-distance traffic analysis and forecasting, e.g. for the assessment of (dis-)utility arising from a new runway or a change of opening hours of train stations or airports.

This paper proposes a simulation model for air-transport technology capturing relevant details on a microscopic level. It is shown that a simulation, originally built and successfully used for ground transportation [e.g. 1] can be used to model time-dependent, capacity restricted air transport technology. Due to the agent based nature of the model, specialities of air transportation, e.g. , see [2], can be captured easily by the model. Recent prototypes show that same holds for rail transport. The simulation can be used for an agent-based, iterative passenger-trip assignment that is presented in an accompanying paper [3].

Selection and peer-review under responsibility of Elhadi M. Shakshuki
doi:10.1016/j.procs.2013.06.109

The paper is organized as follows. The next section highlights some related work in the field. Sec. 3 introduces relevant details of simulation and points to further references. Modelling of airports, network and aircrafts is presented in Sec. 4. Results of illustrative simulation runs for a scenario covering the European airspace are shown in Sec. 5. The paper ends with a discussion and conclusion.

2. Related Work

Many commercial simulation tools for air traffic are available, e.g. SIMMOD (www.airporttools.com, last access 22.10.2012), CAST (www.airport-consultants.com, last access 22.10.2012), AirTOp (www.airtopsoft.com, last access 22.10.2012), RAMSrams plus (www.ramsplus.com, last access 22.10.2012) or Total Airspace and Airport Modeler (TAAM) (www.jeppesen.com/taam, last access 22.10.2012). All of them provide high level of detail modelling of airports and airspace; some of them use multi-agent architectures for different actors of the scene, e.g. for airport controllers, air traffic manangement, etc. Also in research, simulation toolkits of a high level of detail are available, [e.g. see 4, 5, 6]. All of them aim at detailed simulations of air traffic in order to improve air traffic management concepts. Neither commercial nor scientific simulation frameworks support agent-based modelling of individual passengers on all stages of a flight.

Queueing theory and queueing models are widely used to model the technology of air transportation systems. For example, [7] use queueing theory to model the propagation of delay through the network. Effects of new airspace management technologies are studied by [8]. The models for traffic flow on roads are usually more complex, e.g. “cell transmission models” [9, 10], which model traffic based on discretized partial differential equations, “car following models” [11, 12], which model traffic by following each car individually, typically using discretized time but continuous space, “cellular automata models” [13], which are similar to car following models but also discretize space. Yet, all these models are computationally rather expensive. For that reason, also queue models are in use, which are computationally much faster [14, 15, 16, 17]. This paper uses a queue model. The model provides several parameters for an explicitly modelled segment of transport systems: The maximum flow that can pass a segment, the maximum amount of vehicles on the segment and a maximum velocity per segment or vehicle. Several segments can be connected via nodes, building a transport network, on which individual vehicles can be simulated. Segments are modelled as FIFO (first-in first-out) queues, nodes can be interpreted as servers. Thus, the modelling of the road network is quite similar to queueing theory approaches in air transport [e.g. 7]. However, the proposed model is not solved analytically but by simulation. While analytical solveable models may conserve computational resources, a computational fast simulation model enables an agent-based modelling of every individual throughout the complete simulation lifecycle in complex scenarios.

3. Multi-Agent Transport Simulation

The simulation approach used in this paper is based on the software tool MATSim (Multi-Agent Transport Simulation, see www.matsim.org.). The next paragraphs provide an overview of the simulation approach and highlight the most important details used in this work. For more detailed information on technical aspects, please see [18] or [19]. For a detailed discussion of methodology, see, e.g., [20]. Regarding economic concepts used in the simulation approach, see, e.g. [21, 22].

Simulation Overview. In MATSim, each traveler of the real system is modeled as an individual virtual person. The approach consists of an iterative loop that has the following important steps:

1. **Plans generation**: All virtual persons independently generate daily *plans* that encode, among other things, their desired activities during a typical day as well as the transportation mode. Virtual persons typically have more than one plan (“plan database”).
2. **Traffic flow simulation**: All selected plans are simultaneously executed in a simulation of the physical system (often called “network loading”).

3. **Scoring**: All executed plans are scored by an *utility function* which can be personalized for every individual.
4. **Learning**: At the beginning of every iteration, some virtual persons obtain new plans by modifying copies of existing plans. This is done by several *modules* that correspond to the choice dimensions available, e.g. time choice, route choice, and mode choice. In this paper, time and route choice will be used. Virtual persons choose between their plans according to a Random Utility Model (RUM).

The repetition of the iteration cycle coupled with the plan database enables the virtual persons to improve (learn) their plans over many iterations. This is why it is also called **learning mechanism** which is described in more detail by [19]. The iteration cycle continues until the system has reached a relaxed state. At this point, there is no quantitative measure of when the system is "relaxed"; we just allow the cycle to continue until the outcome is stable.

Microsimulation. The microsimulation consists of a model of the physical environment, several agent-representations and a model for traffic flow. The physical environment comprises at least a model of the transportation network. Agent-representations exist for virtual persons, public transit vehicle drivers, traffic lights, etc. The traffic flow model is a queue model, that moves vehicles through the transportation network. Queue models for traffic flow disregard most of the details of vehicle movements on a road. Traffic networks are modelled as graphs. Each vertex models a crossing. Vertexes are connected by *links*, a directed edge that describes a road segment. Each link of a road network is described by the following attributes: maximum flow (capacity) c_{flow}, length l, and the amount of vehicles that fit on the link $c_{storage}$ if cars stand bumper to bumper.

Vehicles entering a link have to stay on that link at least as long as they would travel at their desired velocity or as fast as the speed limit on the link permits. During this time no computation needs to be done, the vehicles are stored in a priority queue. Afterwards the vehicle is placed into another FIFO-queue. In each simulated timestep $floor(c_{flow})$ vehicles may leave the FIFO-queue plus one additional vehicle when the accumulation over the last timesteps of fractional part of c_{flow} is equal or greater than 1. If there is space available on the downstream link, i.e. the number of vehicles is less than $c_{storage}$, a vehicle is moved to the downstream link. This makes the model capable to model spill-back.

Modelling of Public Transit. The public transit module of MATSim aims at modelling microscopic public transit simulation with a focus on several types of ground transportation, e.g. buses, streetcars or para transit [23]. In a *TransitSchedule* transit stop facilities, lines and routes are specified. Passengers can access and leave vehicles at transit stop facilities. Each transit line contains one or more transit routes. Transit routes specify the order in which stops are lined up to a route and the departure time of a vehicle at the beginning of the route. Furthermore each route specifies which links in the network are used to connect stop facilites. Traffic flow is modelled by the queue model.

Characteristics of transit vehicles are specified using the default configuration of the MATSim framework (`http://matsim.org/files/dtd/vehicleDefinitions_v1.0.xsd`). Several *vehicle type*s can be defined that contain information as length, width, passenger capacity, maximum velocity and energy consumption. How fast passengers can access and leave a vehicle is also specified via the vehicle type. In addition to the different vehicle types a set of particular vehicles can be defined. Each vehicle has exactly one type assigned and inherits all its attributes.

4. Modelling Air Transport Technology

This sections shows how the techonology of air transport networks, i.e. airports, network and aircraft, can be modelled using a queue model based network representation and a simulation approach for urban transport systems.

Data Sources. The air traffic technology model takes advantage of data provided by OAG Aviation (`www.oagaviation.com`, last access 08.08.2012). An OAG snapshot of worldwide direct flights in September 2009 is available for schedule generation. All flights with IATA airport codes, flight times, flight numbers and designators, aircraft types, available seats and distance between airport are gathered from the database and processed. Codeshares, multi-stop flights, buses and trains with flight numbers and cargo flights are filtered out of the schedule during the generation process.

Relevent data for schedule and network generation is excerpted from the OAG data using all flights departing on a Tuesday, taking each specific flight number into account only once. This may not always result in complete flight cycles, e.g. when the outbound and inbound flight operate on different days of the week. Compared to using all flights of an entire week, the network may be incomplete, as certain destinations are only served on specific days.

Since the OAG data does not include any airport coordinates, two alternative sources are consulted. OpenNav (`www.opennav.com`, last access 09.08.2012) is an online database of aeronautical navigation information featuring airport coordinates that may be retrieved with a web query based on the IATA airport code. Coordinates for those airports not available on openNav are prompted in the same manner from the Great Circle Mapper (`www.gcmap.com`, last access 09.08.2012), which also includes a searchable database of airports. Worldwide, a total of 2683 airports with IATA code is retrieved from these data sources. The scenario used in this paper contains all Europe to worldwide, non-stop flights. For this scenario 73 airports are missing in our database (bus and train stations with IATA code are counted as missing airports when no coordinates are found) while for the majority of 808 airports coordinates are available. Airports for which no coordinates were available were removed for the present study.

Airport capacity data is available from many sources. However, no machine-readable source was found. Thus, the 50 busiest European airports in terms of total passengers per year were taken from wikipedia (`en.wikipedia.org/wiki/List_of_the_busiest_airports_in_Europe`, last access 05.08.2012), and data for those airports was researched manually. A list of airport capacity information is given in the Appendix of [**?**], together with the source for each information item. The list provides separate capacities for departures and arrivals. All remaining airports are modelled with arrival and departure capacities of 60 planes per hour each. This is considerably more than what these airports have.

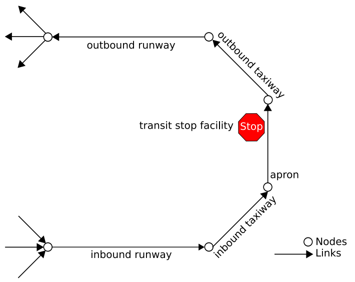
Modelling. Based on the presented data an air network, a flight schedule and aircraft are generated as a precondition to run an air traffic simulation.

The air network consists of airports, each showing an identical layout, and point-to-point connections in between. Every runway is solely used either for inbound or outbound flights with taxiways connecting the runways to the apron. The latter accommodates a transit stop where flight movements originate and terminate (see Fig. 1a).

The two runways of each airport possess a restriction of flow capacity (c_{flow}) that is varied in the subsequent simulation runs. Furthermore not more than one aircraft can be simultaneously on a runway. This is modelled by setting the $c_{storage}$ parameter of the model accordingly. If the flow capacity restriction should have any influence on the model the storage capacity restriction should be at least as equal to $length/v_{fs} \cdot c_{flow}$, i.e. the time needed to traverse the runway in free flow conditions times the maximal permitted flow on the runway. If the storage capacity restriction is smaller, flow constraints would have any effect. As both values flow and storage capacity shall be set, freespeed velocity is varied according to the choosen value for flow capacity. E.g. an outbound runway of an airport with an outbound flow capacity of 60 veh/h on a 1500 m runway with a storage capacity constraint of 1 vehicle the speed restriction is set to $\frac{1500\text{m} \cdot 60\text{veh/h}}{1\text{veh}} = \ldots = 90\text{km/h}$.

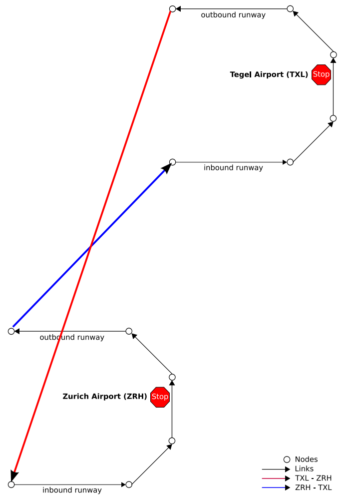
Each airport pair is directly connected by airway links, one for each flight and direction of travel (see Fig. 1b). The maximum speed on any of these links is calculated based on the distance and flight duration provided by OAG. Times for taxi, take-off and landing are also taken into account, i.e. the flight duration is reduced by the time needed from push-back to airborne before the maximum speed for an airway link is calculated.

ATS (Air Traffic Services) routes are not implemented, in order to simplify matters and because of data not being available in a desirable format. Note however, that each flight has an individual link that could be



Linktype	Count	Length [m]	Speed [km/h]
Runway	2	1500	$length \cdot c_{flow}$
Taxiway	2	500	20
Apron	1	500	20

(a) Airport layout and characteristics



(b) Network layout

Fig. 1: Air Network

Area pair	Airports	Airports missing	O-D Pairs	Flights	Flights missing
Worldwide	2333	81	27496	56376	2644
Europe to worldwide	808	16	14156	21425	577
Germany to worldwide	269	3	2814	4394	189

Table 1: Some numbers for different geospatial extends of the model.

interpreted as route, each possessing individual characteristics. Fig. 2 shows the network used for European air traffic.

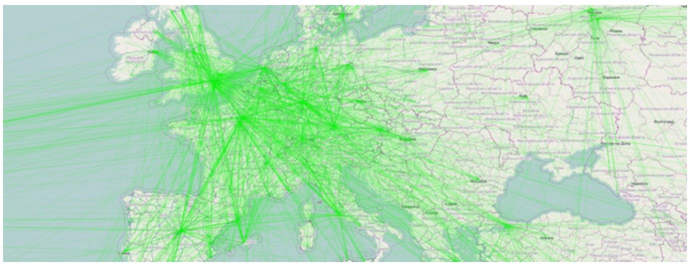
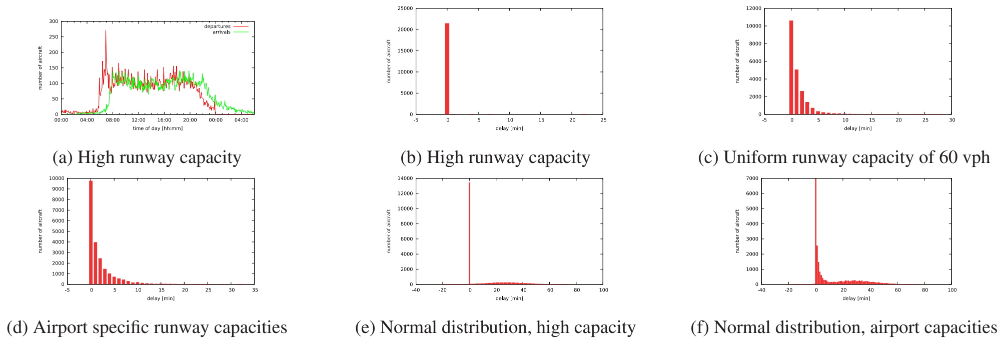


Fig. 2: Part of European air network with EU country boarders in the background (country boarders © `openstreetmap.org`)

The flight schedule is taken from the OAG data and translated to a MATSim *TransitSchedule* containing information about each line, route and departure. For each airline that offers a connection between two airports a transit line is generated. A transit route, which represents the route on the air traffic network, is created for each flight offered by this airline. The route contains the links belonging to the airport representation plus the specific link for this flight connecting the airports' out- and inbound runway. Mutual interferences of aircrafts en-route are not included in the model. Tab. 1 lists the number of (not included) airports, direct O-D connections and flight movements for three different area pairs.

For matters of consistency all local times are converted into Universal Time Coordinated (UTC). This ensures aircraft taking off and landing at the scheduled times throughout all time zones and also enables the



(a) High runway capacity (b) High runway capacity (c) Uniform runway capacity of 60 vph

(d) Airport specific runway capacities (e) Normal distribution, high capacity (f) Normal distribution, airport capacities

Fig. 3: Results for distinct delay models. (a) Arrivals and departures over time of day. (b-f) Number of delayed aircraft over minutes.

model to reflect incoming and outgoing waves at hub airports worldwide at the appropriate times.

Vehicles are created on the basis of OAG data to represent individual aircraft in the simulation. IATA aircraft codes, operating airlines and seating capacities are reflected in the respective aircraft representation for every flight. Information about boarding times, i.e. passenger flow per door over time, is not available but could be set for each aircraft type. One aircraft per flight is generated, thus delays resulting from a delayed incoming aircraft are not modelled. Accordingly, no aircraft rotations and vehicle trip chains are implemented for the time being. The maximum velocity is set to twofold sonic speed, since speed limitations are set for each airway link of the network.

5. Simulation Results

Results of a simulation for flights to, from, and within Europe are presented in the following. Several versions of the model have been simulated allowing a comparison of a model without capacity constraints, a model with runway capacity constraints, and a model including some delay. The simulation is run for one iteration, which starts at midnight and continues until after 40 h the last flight has arrived at its destination.

Delay resulting from changes of runway capacity is studied in three simulation runs. Scheduled flight times from the OAG data are compared to the simulated time each flight needs from its departure transit stop facility to its arrival transit stop facility. The resulting three arrival delay distributions are shown in Fig. 3.

First, the simulation is run with unrealistically high runway capacities. As expected, resulted in all flights being on time. Fig. 3a shows the simulated number of departures and arrivals over time of day. Clearly, one can observe the morning departure peak between 05:00 am and 07:00 am UTC. The resulting delay distribution is depicted in Fig. 3b.

Second, in order to test sensitivity, all runway capacities are set to 60 vehicles per hour (vph), i.e. on each runway one take-off or landing per minute is possible. This is effectively *larger* than in reality for most airports, except for CDG and AMS, where it is less. The impact on the system is more profound than one might expect: The delay distribution shown in Fig. 3c. 10589 flights, i.e. 49,2 % of the simulated 21425 flights, arrive at their scheduled time; 99,6 % of the flights possess less than 16 min delay. The most delayed flight arrives 28 minutes after scheduled arrival.

In the third simulation run regarding delays, airport specific data is used for capacity of runways (see Sec. 4). Each modelled airport's arrival runway is set to the arrival capacity from the table, and each departure runway is set to the departure capacity from the table. As explained earlier, if no data is available, then each runway's capacity is set to 60 vph as in the previous experiment; since these are fairly large capacities, this implies that the model will generate few if any delays at those airports. Fig. 3d shows that the resulting overall delay distribution is similar to the run which was based on homogeneous runway capacities (Fig. 3c). 45,5 % of all flights arrive at the scheduled minute, while 99,2 % have a delay less than 16 min. The latest arrival is 32 min beyond schedule.

The delay runs show that limited runway capacities are a source of delay [24]. By themselves, however, they can only explain a small part of delays. For 2011, the Central Office for Delay Analysis (CODA) reports that 37.1 % of all flights were delayed on departure [25], with an average delay of 27.6 min. Those CODA values for 2011 are used for a rough approximation of randomly occuring delay in the simulation, as follows. In a preprocessing, a 37.1 % sample of all simulated flights is drawn, using a uniform distribution. The length of delay is then drawn from a normal distribution with a mean of 27.6 min and a standard derivation of 13.8 min, and added to the scheduled departure time. In order to get a clear picture of the effects of this method, the simulation is first run without capacity constraints. The resulting overall delays are shown in Fig. 3e; delayed flights show the expected shape of a normal distribution around 27.6 min. For the next and last simulation run, the model with more realistic runway flow capacities is used. About 39 % of all flights are now delayed more than five minutes, average delay is 27,90 min. The resulting overall delay distribution (Fig. 3f) still posesses the shape of the normal distribution, but effects of flow capacity restrictions are observable as well.

6. Interpretation & Discussion

The results show that the the proposed approach can be used to model some important charactaristics of air traffic technology. In particular, runway capacity restrictions can be added to the model.

The current model uses two separate links for the runways of an airport, one for arrival and another for departure. In reality, it might happen that both runways are used for the same purpose for periods of time. The model thus could possibly be improved by modelling both runways as one link. When doing this, however, more elements of air traffic control would need to be included, such as priorization between incoming and outgoing aircraft. Furthermore, values for capacity and speed of the runway have to be adjusted.

Also, the model of the air network is not capturing delays resulting from en-route capacity constraints that may occur in the real ATS route network. Due to differences in air traffic flow and capacity management strategies, the present model may be more appropriate to model US airspace than EU airspace [26]. This could be addressed by employing the time-variant network feature of the simulation [27] that can vary a link's flow capacity, or set speed limits for certain time periods. Finally, the ATS route network itself could be included in the modelling process if exact data and routes are provided.

Reactive delays due to delayed incoming aircraft are not reproduced as aircraft rotations are currently not included in the model. The multi-agent approach is, in general, particularly suitable to to model reactive delays. For this, one would either need detailed trip-planning and scheduling data from private companies, or appropriate approximation algorithms for these elements.

7. Conclusion & Outlook

This paper proposes a microscopic modelling approach for air transport technology. A multi-agent simulation approach from urban transport planning is used. Aircraft are represented microscopically featuring attributes as speed, available seats and boarding constraints. The air traffic network as well as flight performance is modelled at a low level of detail as the model is not intended for air traffic management. Despite the lack of detail, some relevant aspects of congestion and delays can be captured by the use of a queuing model for traffic flow. The queuing model is computationally relatively cheap so large scenarios can be simulated. As proof of example results for an Europe to world air transport supply are presented.

Acknowledgements

For the model and simulation approach proposed in this paper several prototype studies have been conducted [28, 29, 30]. These prototypes have been target to further improvement and development, the paper describes the overall result. Further acknowledgements to all providers of data used in this study. Without accessible data suited for machine processing this work would not have been possible.

References

[1] A. Neumann, M. Balmer, Micro meets macro: A combined approach for a large-scale, agent-based, multi-modal and dynamic transport model for Berlin, VSP Working Paper 11-14, TU Berlin, Transport Systems Planning and Transport Telematics, see www.vsp.tu-berlin.de/publications (2011).

[2] J. Kim, An agent-based model for airline evolution, competition, and airport congestion, Ph.D. thesis, Virginia Tech (05 2005).

[3] D. Grether, S. Furbas, K. Nagel, Agent-based modelling and simulation of air transport passenger demand, in: The 2nd International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications, 2013.

[4] K. Bilimoria, B. Sridhar, G. Chatterji, K. Sheth, S. Grabbe, FACET: Future ATM Concepts Evaluation Tool, 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli, Italy (06 2000).

[5] D. Sweet, V. Manikonda, J. Aronson, K. Roth, M. Blake, Fast-Time Simulation System for Analysis of Advanced Air Transportation Concepts, in: AIAA Modeling and Simulation Technologies Conference and Exhibit, no. AIAA-2002-4593, Monterey, CA, 2002.

[6] S. Alam, H. Abbass, M. Barlow, Atoms: Air traffic operations and management simulator, Intelligent Transportation Systems, IEEE Transactions on 9 (2) (2008) 209–225. doi:10.1109/TITS.2008.922877.

[7] N. Pyrgiotis, K. M. Malone, A. Odoni, Modelling Delay Propagation within an Airport Network, Transportation Research Part C: Emerging Technologies (0). doi:10.1016/j.trc.2011.05.017.

[8] T. Nikoleris, M. Hansen, Queueing models for trajectory-based aircraft operations, Transportation Sciencedoi:10.1287/trsc.1120.0411.

[9] C. Daganzo, The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory, Transportation Research B 28B (4) (1994) 269–287.

[10] C. Daganzo, The cell transmission model, part II: Network traffic, Transportation Research B 29B (2) (1995) 79–93.

[11] R. Wiedemann, Simulation des Strassenverkehrsflusses, Schriftenreihe Heft 8, Institute for Transportation Science, University of Karlsruhe, Germany (1974).

[12] P. G. Gipps, A behavioural car-following model for computer simulation, Transportation Research B 15 (1981) 105–111.

[13] K. Nagel, M. Schreckenberg, A cellular automaton model for freeway traffic, Journal de Physique I France 2 (1992) 2221–2229.

[14] C. Gawron, Simulation-based traffic assignment, Ph.D. thesis, University of Cologne, Cologne, Germany (1998).

[15] N. Cetin, A. Burri, K. Nagel, A large-scale agent-based traffic microsimulation based on queue model, in: Proceedings of the Swiss Transport Research Conference (STRC), Monte Verita, CH, 2003.

[16] N. Cetin, Large-scale parallel graph-based simulations, Ph.D. thesis, Swiss Federal Institute of Technology (ETH) Zürich, Switzerland (2005).

[17] M. Cremer, M. Landenfeld, A mesoscopic model for saturated urban road networks, in: M. Schreckenberg, D. Wolf (Eds.), Traffic and Granular Flow '97, Springer, Singapore, 1998, pp. 169 –180.

[18] B. Raney, K. Nagel, An improved framework for large-scale multi-agent simulations of travel behaviour, in: P. Rietveld, B. Jourquin, K. Westin (Eds.), Towards better performing European Transportation Systems, Routledge, London, 2006, pp. 305–347.

[19] M. Balmer, B. Raney, K. Nagel, Adjustment of activity timing and duration in an agent-based traffic flow simulation, in: H. Timmermans (Ed.), Progress in activity-based analysis, Elsevier, Oxford, UK, 2005, pp. 91–114.

[20] K. Nagel, G. Flötteröd, Agent-based traffic assignment: Going from trips to behavioural travelers, in: R. Pendyala, C. Bhat (Eds.), Travel Behaviour Research in an Evolving World – Selected papers from the 12th international conference on travel behaviour research, International Association for Travel Behaviour Research, 2012, Ch. 12, pp. 261–294.

[21] K. Nagel, D. Grether, U. Beuck, Y. Chen, M. Rieser, K. Axhausen, Multi-agent transport simulations and economic evaluation, Journal of Economics and Statistics (Jahrbücher für Nationalökonomie und Statistik) 228 (2+3) (2008) 173–194.

[22] B. Kickhöfer, D. Grether, K. Nagel, Income-contingent user preferences in policy evaluation: application and discussion based on multi-agent transport simulations, Transportation 38 (2011) 849–870. doi:10.1007/s11116-011-9357-6.

[23] M. Rieser, Adding transit to an agent-based transportation simulation concepts and implementation, Ph.D. thesis, TU Berlin, also VSP WP 10-05, see www.vsp.tu-berlin.de/publications (2010).

[24] B. Bubalo, J. Daduna, Airport capacity and demand calculations by simulation–the case of Berlin-Brandenburg International Airport, NETNOMICS (2012) 1–21doi:10.1007/s11066-011-9065-6.

[25] Central Office for Delay Analysis, CODA Digest – Delays to Air Transport in Europe Annual 2011, Tech. rep., Eurocontrol (03 2012).

[26] G. Lulli, A. Odoni, The European Air Traffic Flow Management Problem, Transportation Science 41 (4) (2007) 431–443. doi:10.1287/trsc.1070.0214.

[27] G. Lämmel, D. Grether, K. Nagel, The representation and implementation of time-dependent inundation in large-scale microscopic evacuation simulations, Transportation Research Part C: Emerging Technologies 18 (1) (2010) 84–98. doi:DOI:10.1016/j.trc.2009.04.020.

[28] S. Fürbas, Modellierung und Simulation des europäischen Linien–Luftverkehrs, Bachelor's thesis, TU Berlin, Institute for Land and Sea Transport Systems, Berlin, Germany (03 2011).

[29] T. Böhme, Analyse und Simulation von Verspätungen im europäischen Linien-Luftverkehr, Bachelor's thesis, TU Berlin, Institute for Land and Sea Transport Systems, Berlin, Germany (10 2011).

[30] P. Krüger, Verspätungen im Flugverkehr: Modellerweiterung für die Simulation des europäischen Linien-Luftverkehrs, Studienarbeit, TU Berlin, Institute for Land and Sea Transport Systems, Berlin, Germany (07 2012).