Agent-Based Pedestrian Simulation

A Case Study of the Bern Railway Station

Guido Rindsfüser and Franziska Klügl

Abstract: Pedestrian simulation is a challenging and fruitful application area for agent-based modeling and simulation in the traffic and transportation domain: for one, the design and implementation involve interesting issues, while agent-based modeling also allows reproducing pedestrian behavior at a level of detail beyond pure collison-free locomotion. In this paper, we will present a prototypical study: a simulation of pedestrian traffic throughout the entire SBB railway station of the City of Bern, Switzerland during the busiest morning hours. The objectives of this study were twofold: one, assessments and recommendations had to be produced for SBB, and two, we wanted to show that an agent-based simulation with capabilities beyond locomotion is feasible for scenarios in realistic size.

1. Introduction

How many minutes would be needed to evacuate a football stadium or a pop concert arena? Where is the best place for passenger information or a poster wall? How many exit signs should be distributed over the area and where should they be placed? How many minutes does a traveler need to change trains? Are transfer times still realistic when the pedestrians are not familiar with the layout? These questions arise while planning for pedestrians, especially against the background of increasing leisure time and the increasing number of (huge) events with their accompanying pedestrian masses. One way to get a better understanding of human behavior in this area of planning and to enrich the tools for planning is pedestrian microsimulation. In particular, agent-based simulation is an attractive paradigm for modeling and simulating pedestrian decision-making and behavior because as it supports a one-to-one correspondence between the subject of observation and the simulated agent.

The growing number of travelers using the SBB railway station in Bern and the wish to offer better services, shorter connections and higher frequencies have led to the development of the Scenario 2030 for infrastructure and operation. To test the effects of the planned measures, a multi-agent simulation seemed to be a good solution for two reasons: It can be designed in a way that both memory consumption and computation time is feasible; and second, it allows the integration of higher-level decision-making for realistic simulations beyond collision-free smooth locomotion.

The remainder of this paper is structured as follows. After a short overview of microscopic pedestrian simulation, we introduce the practical objectives of this particular project. In section 4, we discuss some general aspects of agent-based pedestrian simulation, followed by details of our model in section 5. Section 6 gives a brief summary of the project results, while Section 7 presents a short conclusion.

2. Pedestrian Simulations

Traditionally, pedestrian simulation has used techniques such as flow-speed-density equations, which aggregate pedestrian movement into flows, average speed or density. This approach, derived from vehicular traffic simulation, may be efficient, but it is not capable of taking the basic behaviors and interactions between the pedestrians into account (Teknomo 2002). Due to improvements in computing power, microscopic models have become feasible for representing low-level behavior of pedestrians, including their interactions during movement as well as higher-level cognitive abilities for flexible routing in detailed environments. In the last decade, there has been remarkable progress in modeling pedestrian behavior on a microscopic level. Basically, three types of microscopic models have been proposed:

Force-based models, such as Helbing and Molnár (1995), are based on the assumption that the direction and speed of a pedestrian can be computed based on the combination of different forces that attract the pedestrian towards his goal, but repels him from moving or static objects. These force-based models are quite brittle, as the weights for the different forces have to be thoroughly balanced in order to produce reasonable behavior.

A second type of microscopic model, cellular automata (e.g., Schadschneider 2002a; Adler, Blue 2000; Burstedde et al. 2001), is based on

Guido Rindsfüser is the Head of the Department for Mobility and Transport and a member of the Executive Committee at Emch+Berger AG Bern, Switzerland.

Dr. Franziska Klügl is a Scientific Associate at the Department for Artificial Intelligence and Applied Computer Science at the University of Würzburg in Germany.

discrete spatial representations. In this model, cells of a particular size can generate static or dynamic potential fields that can represent the local effect of obstacles or of moving pedestrians. Pedestrians move according to this information by integrating some conflict resolution when more than one pedestrian wants to move onto the same cell.

The third model, agent-based simulations, bases the simulated pedestrian on the paradigm of an agent as an entity that acts and interacts autonomously. Although, in principle, it is possible to integrate complex details of higher-level cognitive abilities, most proposals for agent-based pedestrian simulations only deal with collision-free, goal-oriented movement. Examples for the latter are Osaragi (2004), Willis et al. (2000), Teknomo (2002), and Dijkstra et al. (2006). For a detailed overview in relation to public transport facilities, see Daamen (2004). Meanwhile, commercial tools are also available (e.g., SIMWALK by Savannah Simulations).

An interesting model, but presented here without further classification, is the application of econometric modeling to pedestrian movement dynamics. Bierlaire et al. (2003) suggest a statistical model that uses movement directions and speed to model pedestrian dynamics based on automatic video surveillance data.

The usefulness of a particular model also depends not only on geometric layout and pedestrian movement, it also depends on the situation that is to be simulated, for example, an evacuation simulation poses fewer implications for the cognitive abilities of the simulated pedestrians who are all heading towards the emergency exits than a standard transit station or airport where each simulated pedestrian may pursue heterogeneous individual activities and goals.

Scherger (2006) compared three microscopic models in three different situations (evacuation, public transport and shopping center) on the implementation level to evaluate their capabilities for representing higher-level decision-making, efficiency and various technical aspects, such as simulation time and memory consumption. Although the appropriateness of representation should be the decisive element for choosing a particular model type, the technical aspects are also important for the management of real-world scenarios with larger application size, as in our project. The results of our comparison were mainly that cellular automata models are problematic from the technical point of memory consumption, whereas the challenge of continuous force-based models lies in computational efficiency. These results were not surprising and can be improved using techniques ranging from lazy evaluation to hybrid simulation (Gloor et al. 2004).

Another critical point was the brittleness of the force-based models in relation to parameter settings for weighting the reaction to obstacles or goal-orientedness of the simulated pedestrians. In addition, only the agent-based approach seems to allow higher-level decision-making without major modifications of the basic behavioral model.

After introducing the actual questions that had to be addressed by our model, details about the design of agent-based models in general and our particular model are given.

Scenario	**2006 RE**	**2006 PA**	**2030 RA**
Exits	3	5	3
Stairways/Ramps	39	45	40
Tracks	12	12	13
Trains	83	83	77
First train	6:18	6:18	6:18
Last train	8:30	8:30	8:10
Doors of trains	3–26	3–26	3–26
Short-distance trains	54	54	56
Long-distance trains	29	29	18
Overall passengers	42 300	42 300	43 454
Boarding passengers	14 055	14 055	14 955
Alighting passengers	25 745	27 545	26 085
Transfer passengers	2500	2500	2505

Tab. 1: Three scenarios developed for the SBB Railway Station in Bern, Switzerland.

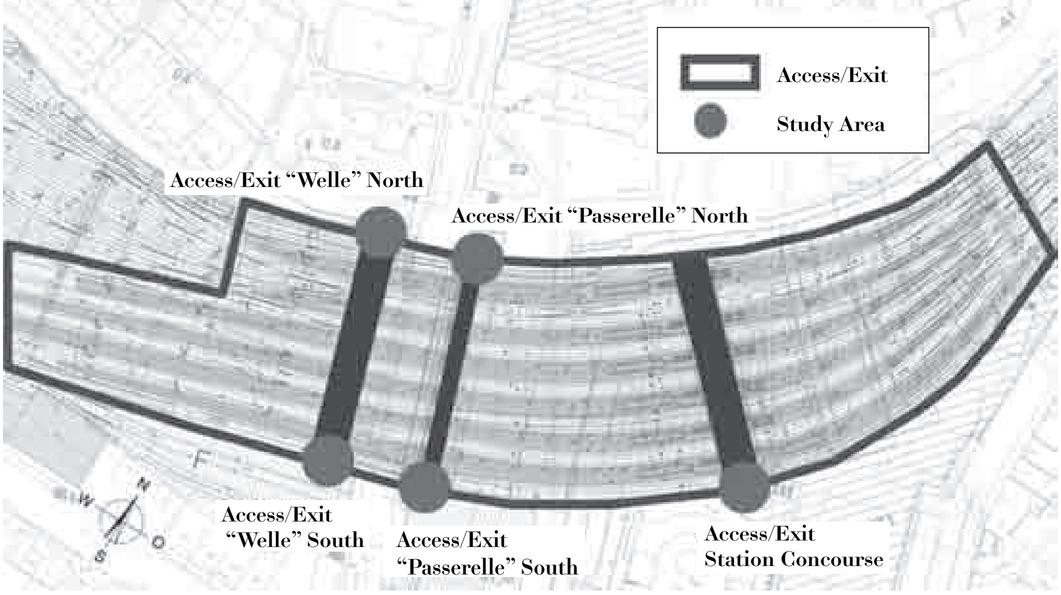

Fig. 1: SBB Railway Station Bern, study area and simulation "world" (schema).

3. SBB Railway Station Bern Scenario 2030

While thinking about infrastructure, facilities and operations for the year 2030, questions concerning the pedestrian flow within the SBB railway station in Bern arose. An assumed 20 to 25% increase in passengers using the station in the future, a higher frequency of train departures and arrivals and the limited spatial possibilities for infrastructural development required in-depth analyses and a search for solutions for the projected problems in pedestrian flow. Because of the high complexity of the whole system and the *per se* dynamic processes, the idea of developing an adequate simulation tool led to the choice of an agent-based simulation.

The task was to set up a model of pedestrian behavior and to simulate the pedestrian flow during the morning peak hours throughout the entire SBB railway station in Bern. One special interest was to get detailed information about expected bottlenecks, pedestrian travel times and the time needed to change trains. In the current approach, infrastructure, timetables, number of passengers and train-changes are specific for each scenario. Pedestrian behavior was not modified between the scenarios. This means that the individual behavior of all behavioral objects is the same in each scenario.

Two different comparisons were requested by SBB, who provided the specific scenarios and the corresponding data. One test was a comparison between the current situation with an additional traverse (alte Passerelle), 2006PA, and without it, 2006RE. The third scenario is Scenario 2030RA, which is based on assumptions of increasing numbers of passengers, an additional track, an additional timetable and some other operational items. Table 1 summarizes the different scenarios.

Figure 1 shows the basic structure of the overall study area for Scenario 2006PA. It contains all train tracks and main pedestrian movement areas. The traverse passage is omitted in Scenario 2006RE, while north of the platforms there is an additional one for Scenario 2030RA, which also differs in train numbers, schedules, etc. All structural data was provided by SBB, including passenger numbers. We simulated all trains in the respective time intervals without assuming initial densities.

4. Agent-Based Simulation of Pedestrian Behavior

An agent-based simulation of pedestrian behavior reproducing every individual pedestrian as an autonomous and (more or less) intelligent actor in a simulated environment is an attractive way of reproducing pedestrian dynamics as it is possible to integrate higher-level cognitive behavior. Modeling the movement level in an agent-based manner is also attractive as it can be done in an efficient way in terms of memory and computational time. Another important advantage is that an agent-based simulation allows pedestrian behavior to be separated from a particular spatial layout. This is due to the concept of a pedestrian as a self-contained, autonomous entity that is presented as such an agent in its environment. Thus, environmental changes, i.e., basically consisting of modifications of the layout or train schedules, can be done without affecting pedestrian model-making. Such adaptations are less expensive in terms of modeling costs.

However, as mentioned above, there are various existing models that can produce collision-free movement that is realistic for individuals as well as for crowd dynamics. Given the size of our project, we had to carefully consider the technical details affecting the feasibility of large-scale pedestrian simulations. Against this background of existing models, the following issues for designing an appropriate agent-based model were considered.

The basic question concerns how much information should be processed by the agents themselves. What data structures should only be accessible locally, for example, agents' mental maps of the railway station, or should be computed globally, for example, the path between possible starting and end points of movement. This dichotomy of complex agent versus complex environment can already be found in the relationship between force-based models (the agent processes all influencing forces itself) and cellular automata (a spatial unit stores information about the movements of other agents, nearby objects, etc.). Obviously, individual behavior and higher-level cognitive abilities require complex agents. However, the question remains if it would be better for basic movement models to rely on elaborate environmental structures, which then leads to the question of how the different levels of behavior can be integrated.

Another, more technical issue refers to the basic spatial representation: discrete or continuous space, three-dimensional space or a multi-layer layout that is basically two-dimensional but has areas/points such as stairways or elevators that connect the different areas without influencing pedestrian dynamics in an unrealistic way. At least for the latter, the solution is quite obvious: a three-dimensional layout makes no sense if the simulated pedestrians can only move in two dimensions and do not incorporate cognitive models of orientation, for example, related to visibility of signs at different heights, etc.

5. The SBBpedes Model

For reproducing the pedestrian dynamics in the SBB railway station Bern during the morning rush hour, we used a time-discrete, agent-based model that combines simple, but flexible individual path planning with collision avoidance in continuous space and a multi-level layout. Details about the model are given in the following.

Environmental Structure

It is quite clear that the most important agents in our scenario are the simulated pedestrians. Before giving details on their decision-making behavior, the environmental model will be discussed because it frames the pedestrian model.

The environmental representation deals with space basically on two levels: areas in which simulated pedestrians can move and a graph structure for representing accessibility and connections between those areas.

In general, space is continuous, consisting of areas that are connected, such as platforms, all stairways and ramps, and the overpass and underpass. Whereas stairways and ramps are directly connected to the platforms, for accessing areas on other levels like the underpass or traverse, so-called transfer areas are introduced that connect these different areas without distortion in pedestrian movement. Thus, 3D representation of the railway station could be avoided. Areas, such as stairways that are not contained in the movement plan of an agent, are treated as obstacles. Densities in the next area are perceivable by the simulated pedestrian directly in the case of two connected areas (Platform-Stairway/Ramp or Transfer Area/Overpass): The perception of densities on the overpass while the simulated pedestrian is still moving on the stairway is only indirectly possible via some tailback effects for the transfer areas. The areas construct some graph structure that an agent uses for path planning and replanning on the area level. This is similar to the model of scene spaces (see Rüetschi and Timpf 2004) in spatial cognition.

Figure 2 shows a screenshot of the simulated layout of Scenario 2006Re. The curved geometry of the railway station was straightened for the simulation, preserving the length as far as possible, although it influences orientation times, especially for simulated pedestrians who are not familiar with the station. The straightening was done due to the restriction of the simulation environment. In the current version of the simulator, we use the correct geometry.

Fig. 2: Screenshot of the simulated layout of the railway station. The overpass and underpass are depicted below the actual tracks and platforms. The small dark areas connect the stairways and the overpass/underpass without distortion in pedestrian behavior. Larger dark areas represent the entrances and exits of the station. Tracks are light gray; platforms are framed by thin black lines.

Some aspects of the environment were also modeled using the agent concept:

- Sensor agents represent data collectors who actively count simulated pedestrians passing some cross-section or recording densities on some sub-area.
- Rail tracks are also represented as agents as they manage the trains assigned to them. This means, a rail track generates the door-agents of a train and closes them according to a given schedule that contains all trains between 6:18 a.m. and 8:30 a.m. that run into the SBB station Bern and leave it. The train leaves solely depending on the schedule and independent of simulated pedestrians who wait at the doors. No delays in departure were admitted as we used the number of agents that could not alight as an evaluation criteria. There is no heterogeneity in rolling stock beyond the number of doors or schedule.
- Transfer areas "beam" simulated pedestrians from the stairways or ramps to the underpass or traverse level. They react to simulated pedestrians stepping on the area and immediately beam them to the corresponding area on the other level, if there is sufficient space on the other side. Thus, indirect perception of densities is possible.
- Entry/Exit points generate simulated pedestrians and delete the pedestrians who have this as their exit-point in their plan. Entry/Exit points may be the doors of a train or the general station access. The generation of simulated pedestrians is described below.

Simulated Pedestrians

The behavior of a simulated pedestrian is tackled on two different levels: actual locomotion with sub-goal selection for obstacle by-passing and secondly, flexible path-planning at the area level. Figure 3 summarizes the general architecture. The atomic time advance was set to 1 second as a compromise between low-level interaction and re-planning processes.

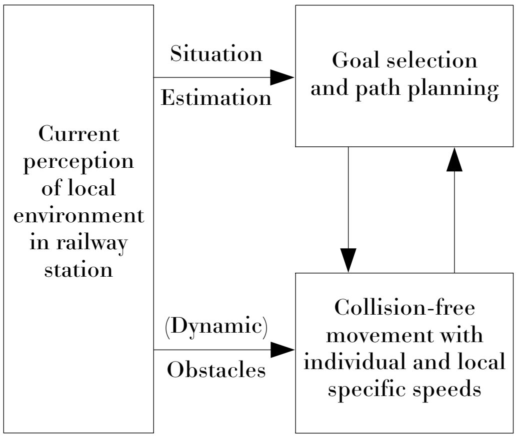

Fig. 3: General architecture of the behavior program of a simulated pedestrian.

Simulated Boarding Pedestrians

For every simulated pedestrian that heads towards a train, a random arrival time before train departure is drawn from a normal distribution with characteristics derived from data provided by SBB. The distributions are distinct according to properties of the train (long or short distance). A fixed time interval is added for the walk from the gate to the platform. Also, a desired speed is initially drawn from a distribution.

The path that the simulated pedestrian may want to take to its train cannot be completely planned all the way to the doors of the trains as the exact position of the doors is not known to the simulated passenger when it is generated at the gate. The plan is completed when the train arrives, and its doors appear on the platform edge. For waiting pedestrians, a random position on the platform is determined in the area where the train will stop. The underlying equal distribution is justified as we concentrate on commuters who usually know about train positions. This is also supported by anecdotal observations in the SBB station in Bern.

When a train arrives, all waiting agents select one of the doors as their immediate goal area. Initially, the nearest door is selected. Passengers that arrive at the platform when the train is already there, also select the nearest door from the position where they step onto the platform. If the queue in front of the door becomes too large, the decision for a particular door is reconsidered.

Before boarding, all alighting agents are generated; therefore, simulated pedestrians may only enter one of the doors after the alighting passengers have exited. We assume that only one agent may enter or leave the door per second, however, when too many agents block the area in front of the door, this frequency may decrease.

Train departures completely adhere to the schedule, even if there are still passengers heading for this train or preparing to board. These "lost" pedestrians are deleted from the simulation even though it reduces the overall density. However, we decided in favor of this for several reasons: This number is an important quality measure for the simulation. In addition, the pedestrian must have a particular destination and must then select the next train that passes this destination. Consequently, the representation of the simulated traveller as well as the data concerning train stops has to be elaborated.

Simulated Alighting Pedestrians

Simulated alighting pedestrians may be generated either to leave the station or to be transfer passengers. The former select one of the gates randomly, following general frequencies based on SBB counts. The goal of the latter is also randomly drawn from the overall list of transfer goals provided by SBB. The door-agents first generate the transfer passengers, followed by the passengers who will leave the railway station through the exit gates. This has been done because the evaluation focuses on transfer times. It thus ensures that the numbers provided by SBB are actually reproduced for connecting passengers. In very dense situations with tight schedules, not all passengers may be able to alight.

Locomotion

After being generated by the door of a train or one of the station gates, and after determining its goal area, a simulated pedestrian generates an area level path and sets its individual desired speed (drawn from a normal distribution with characteristics, as in Daamen 2004). A share of simulated pedestrians, 10% for short-distance trains, 30% for long-distance trains (numbers from SBB), is assumed to be unfamiliar with the station layout which results in a halved desired speed for the initial 10 seconds on the platform.

After determining the (initial) path, the simulated passengers use some standard model for collision-free movement. It is basically a continuous form of the PEDFLOW model (Willis et al., 2000). This module is exchangeable; in the next version of the model, we will use a social force-based locomotion model (Helbing, Molnár, 1995). To avoid deadlocks, we used some dynamically generated temporal sub-goals within the areas where the agents are moving. The determination of these sub-goal positions is based on fixed rules.

Re-Planning

The simulated pedestrians on the platforms continuously evaluate the situation they perceive around them and in front of their next-planned area. Based on threshold-based rules, a re-planning procedure is triggered that enables the simulated pedestrians to change the intended door for boarding the train or to adapt their plan by changing the stairways or ramps they previously planned to use. These rules not only consider queues in front of the goal area or between the agent and the goal area, they also consider the densities around the agent and between the agent and a potential new goal. Thus, they tackle both the question of whether rerouting is useful and if it is actually feasible.

A full documentation of the model with all details can be found in Klügl and Rindsfüser (2006).

Basic Simulation Environment SeSAm

The agent-based pedestrian simulation was implemented using SeSAm 2.1 (shell for simulated agent systems), which is a high-level modeling and simulation environment for agent-based simulations. Due to its visual programming environment, it allows for rapid prototype testing of a variety of model variants. In addition, the simulation is quite efficient, despite its explicit model interpretation, due to the use of code optimization techniques from compiler construction. The basic system is open source and can be downloaded at: www.simsesam.de. As SeSAm is not a tool for a particular pedestrian model, it allows complete flexibility in modeling.

Calibration and Validation of the Model

For calibration and validation, data was provided by SBB consisting of layout information, traveler numbers and train schedules. We augmented this data with PDA-based observations at several stairways inside the railway station. During simulation experiments, simulated agents were used to collect data analogous to a real-world situation, which resulted in comparable figures.

We calibrated the parameters, in particular the parameters of the actual locomotion model of the simulated pedestrians together with thresholds for re-planning, using the automatic calibration tool described in Fehler et al. (2005). We used a black-box optimization technique (simulated annealing) for setting these parameter values, minimizing the delta between passenger counts in the model and the real world. Validation beyond this parameter optimization was basically done by face validation techniques, integrating human experts in evaluating whether passenger movement and decision-making appear to be plausible. Unfortunately, the overall budget of the project did not allow a more detailed and formal validation procedure. Therefore, our results have the quality of plausible hints rather than specific advice supported by a thorough statistical validation. However, we could generate a reasonably good resemblance between the real pedestrians counted and the simulated ones, although some small delay of the peaks of passing pedestrians after train arrivals remained.

6. Short Review of the Results

One advantage of the high level of detail incorporated into this simulation is the production of a huge amount of data that can be used for analyses. Each attribute of each agent in every single time step may be stored during simulation and is thus accessible for analysis. Therefore, it is possible to answer new questions that arise during analysis or to further develop the measures and ideas for the different scenarios.

In Figure 4, the distribution of stopping times for simulated alighted travellers is displayed for Scenarios 2006RE and 2030RA, showing the result of the changed train schedules. Here, some unexpected effects can be seen. The expected and desired shift to shorter travel times from Scenario 2006RE to Scenario 2030RA can be seen for the "short" times, whereas some 7% of the pedestrians will actually need longer times. It turned out that the tense schedule in 2030RA, in combination with the increase of agent numbers, did not allow the station to be almost empty between train arrivals. In the simulation, this builds up a more and more populated station, making it more difficult to get through due to increased overall density. This is illustrated in Figure 5. As expected, densities were generally high at the entry areas to the stairways. However, in Scenario 2030RA, the entire underpass was jammed at around 8 a.m., leading to higher overall stopping times.

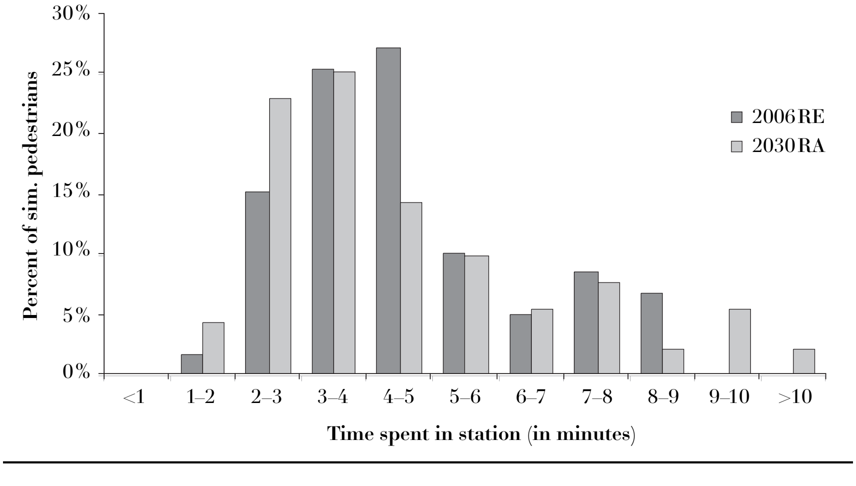

Fig. 4: Time spent in the railway station by alighting agents (without waiting times).

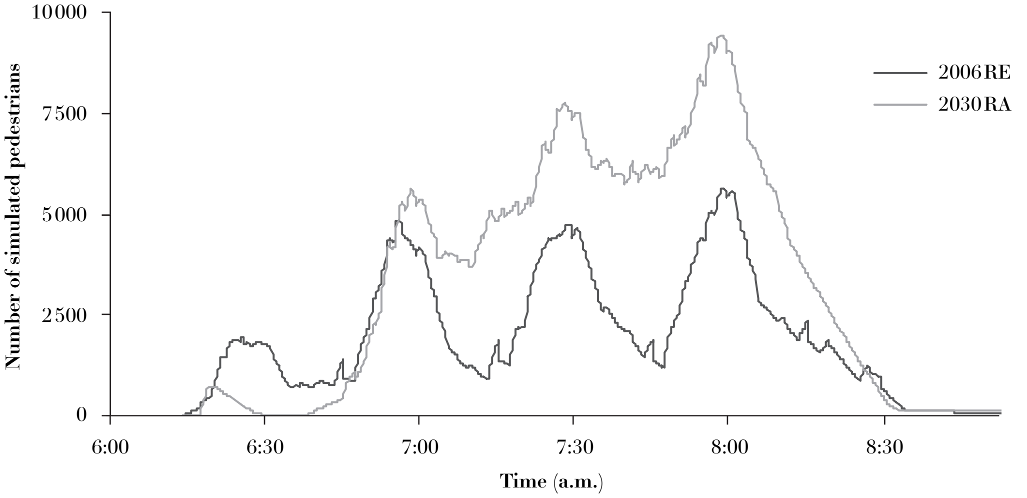

Fig. 5: Occupancy of the railway station.

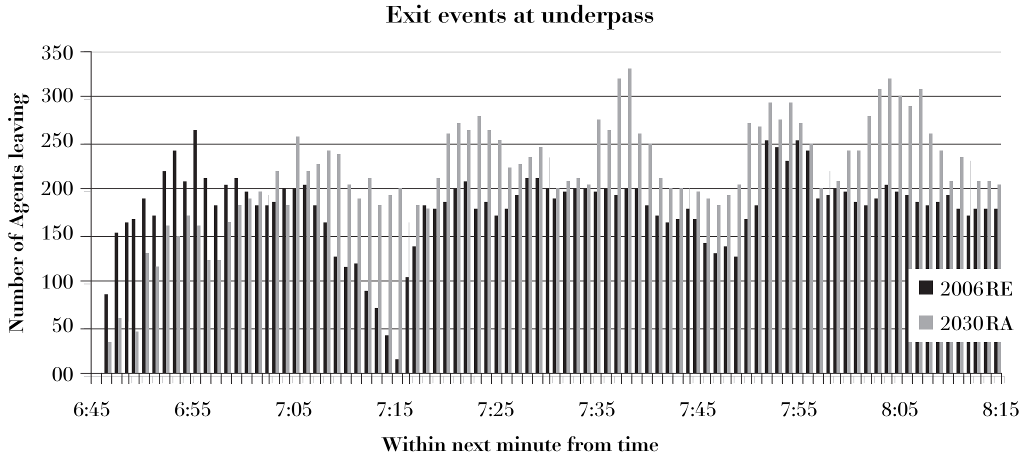

Fig. 6: Pedestrians counted passing the exit at the underpass for two different scenarios.

The possibility of placing simulated sensors as counting elements in front of stairs or exits allowed even more analyses. Figure 6 shows the number of pedestrians leaving the station at the exit at the underpass. The comparison of the current Scenario 2006 and Scenario 2030 reflects the changed schedule with additional peaks. In combination with Figure 5, one notices that, although the overall numbers of simulated pedestrians are increasing, the exit events at the underpass stay about the same. This indicates that there is an increase of density in some areas within the railway station, this happens particularly in the underpass and the stairways where passenger flows meet.

In addition to the data analyses and visualizations like those described above, the simulator allows the simulation run to be saved as a video. Animation is in general not only useful for validation, but also for visualization and thus for face validation.

In practical terms, the model and its produced events were useful on a qualitative level. We concluded that the additional traverse could provide some relief, although main passenger flows concentrated toward the underpass. For a detailed assessment, additional data concerning urban context and the destinations of passengers, resulting in an improved model of gate selection, would need to be collected and integrated. This is highly dependent as different gates open to different areas of the city.

Another recommendation, or better said, a warning, could be illustrated concerning the planned halting positions and times that would result in longer walking distances on the platform, increased densities on the platforms and almost concurrent meeting of peaks of passengers in the underpass. The resolution of jam situations will be faster in reality than in the model, but nevertheless, attention has been drawn to the problematic issues of the planned schedule.

Finally, one may conclude that the simulation model produces interesting and plausible results. The pedestrian behavior is at least plausible, for empirically valid results, more effort has to be invested in data collection, calibration and validation. However, the rule-based approach for modeling collision-free locomotion is sub-optimal, not only concerning the details of the resulting behavior and effort in modeling, but also in the simulation times such as situations with higher densities where a lot of conditions have to be tested. Therefore, we are currently experimenting with a social force-based model that combines short-distance and long-distance perception.

7. Conclusion and Future Work

The development and use of a multi-agent-simulation to investigate pedestrian movement in a railway station shows that modeling complex individual behavior and the simulation of more than 40 000 individuals is conceptually and technically feasible. Thus, it offers hope of being able to integrate even more realistic aspects. Such simulations can provide valuable data for analysts and offer a useful tool for planning complex pedestrian facilities.

However, from our experience, one of the main problems, as with all kinds of microscopic modeling, was to get the necessary detailed data about travel and train-change demands as well as the underlying behavioral data. Empirical validation of microscopic pedestrian simulation is generally quite problematic. The usefulness of the data on the aggregate level is unquestioned, for example, counts and image-based density measurements. However, for behavioral dynamics, automatic methods are more complex, compared to image-based techniques in traffic flow models, as pedestrian movement involves more degrees of freedom. Much research will still have to be devoted to the validation of agent-based pedestrian simulation.

Our future work will tackle different improvements and extensions of the described model. On a technical level, it will include an optimization of simulation speed based on some model "refactoring". Also, the calibration of different parameters that until now has not been done will have to be performed. An example is the influence of the basic time unit of 1 second that seems to be quite high for interactions between pedestrians. This has to be tested and adapted if necessary.

We are already experimenting with alternative collision-free locomotion model components, as mentioned before. This will also involve a more detailed treatment of agent orientation in space with reference to short- and long-distance perception. Another extension of the model concerns the integration of new movement areas as well as the extension by urban areas near the station to include the access routes to the station and the connection to a new planned underground station. Integrating more spatial context into the model, this may result in a better representation of travel demand and distribution beyond the originally simulated railway station. Another extension planned in this context is the explicit representation of train and pedestrian destinations, enabling an improved treatment of passengers who miss their trains.

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Guido Rindsfüser
Emch+Berger AG Bern
Gartenstrasse 1
CH-3001 Bern
Guido.Rindsfueser@emchberger.ch

Franziska Klügl
Lehrstuhl für Künstliche Intelligenz und Angewandte Informatik
Universität Würzburg
Am Hubland
D-97074 Würzburg
kluegl@informatik.uni-wuerzburg.de

at the 4th Swiss Transport Research Conference (STRC04) in Monte Verità / Ascona, Switzerland March 25–26, 2004.

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