Simulation of Pedestrian Behavior in Intermodal Facilities

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Abstract
Planning pedestrian environments requires that designers understand how pedestrians interact with their environment and one another. With improved knowledge, the design and planning of pedestrian areas can provide improvements in safety, throughput, and utility. This paper provides an overview of the Intermodal Simulator for the Analysis of Pedestrian Traffic (ISAPT). It focuses on the methodology and approaches used in simulation of the pedestrian traffic, including route planning and navigation.

1. INTRODUCTION
Capturing realistic pedestrian behavior in simulation is useful for evaluation and planning in building design [1], urban design [2], design of the area around an outside memorial [3], land use [4], marketing [5], facility operational assessment [6] and city wide regional planning [7].

The goal of our research is to develop a system that can be used as an aid for designers and planners in the evaluation and operation of intermodal facilities. The design of such facilities is often based on “rules of thumb” gained over the years from experience in the observation of operations within such facilities. It is believed that the availability of a simulation system that can realistically model the behavior of pedestrians and crowds will permit the exploration and discovery of new guidelines for design and operations planning while providing a scientific basis for those existing rules proven valid over the years.

When planning pedestrian environments it is necessary that designers take into consideration how pedestrians will respond to their environment as they navigate in order to complete their individual and sometimes joint missions. This poses unique challenges, given that you have a crowd of persons simultaneously navigating towards specific destinations for various purposes. Some may be in a hurry to get to a particular location, while others are visiting intermediate points primarily to occupy time prior to reaching their intended goal. As crowd density increases, the path a person takes to reach their destination becomes convoluted as they make numerous divergences in their journey while navigating the crowds. In general, the environment is one that is highly dynamic.

Route planning and navigation are somewhat instinctive abilities for humans, but simulating this capability in a virtual environment is no easy task; it has likewise been of interest to researchers for nearly a decade. This paper provides an overview of the intermodal simulator for the analysis of pedestrian traffic (ISAPT). The ISAPT system provides a simulation tool to evaluate the influence of the architectural design and layout of new and existing intermodal facilities on pedestrian traffic within a large-scale structure. The system models each pedestrian’s behavior individually and the collective behavior of the crowd is allowed to emerge from the interactions that take place between individuals. In the sections that follow, an overview of the ISAPT system is given providing some background on the functionality and the methodology employed by the ISAPT pedestrian simulation model.

2. ISAPT SYSTEM
Broadly speaking, ISAPT has the capability to simulate pedestrian traffic within a facility taking into account the diversity one might find in such a facility from the view point of pedestrian characteristics, as well as their trip purpose. The system is able to generate different pedestrian populations exhibiting specific traits at multiple entry points within a facility. Each of these pedestrians enters the system with particular objectives in mind (e.g., reach departure gate by 1:30 pm) and a tentative route to meet those goals, being provided with the capacity to utilize one or more other resources in the facility (e.g., restaurants, restrooms, etc.). While en route a pedestrian is able to dynamically re-plan, altering their route based on the environmental conditions that exist (e.g., long queues at the restaurant). Once the pedestrian reaches their final departure point they proceed to exit the system. In addition to the resources within the system, statistics are collected on each pedestrian as they traverse the system.
3. PEDESTRIAN DEFINITION

In support of routing and navigation capabilities, ISAPT represents pedestrians within the system as individual agents, where each pedestrian is defined in terms of their physical attributes, navigation capabilities and preferences, agenda, current state(s), and simulation event history. Their physical attributes are based on characteristics such as gender, age, and size. The navigation capabilities and preferences of each pedestrian define their behavior, incorporating preferred and maximum speed as well as navigation space and lead time preferences. The system makes it possible for a user to either directly generate attribute values for each pedestrian according to a stated distribution, or to use some a predefined function that assigned values based on the pedestrian’s gender, age, size and so on. Both the space preference and lead time values of a pedestrian, for example, influence collision detection and avoidance. Allowed navigation space can influence movement choices based on individual preference, environmental factors, and whether they are in a hurry or not. The lead time enacts a look-ahead distance based on the pedestrian’s current speed, adding to the distance a pedestrian scans ahead for potential obstacles. Although these values can be altered in real time as a function of the environmental factors, the current system maintains them as constants at this stage in development.

A pedestrian’s agenda denotes the list of resources and locations that they plan to visit during their trip to the facility, including such entities as ticket counters, the baggage claim area, restaurants, and restrooms. The history of the pedestrian provides a record of the actual pedestrian’s travelogue as they move through the facility, e.g. path-based decisions, which resources they visited and the statistics at each stop. The pedestrian’s current state provides basic variables to track their position and velocity, along with flags as whether they currently carry luggage, and a list of their personal needs such as the level of hunger, thirst, and hurriedness a pedestrian feels, along with intent to use the restroom. These variables influence initial route plans as well as re-routing that can take place during their trip. Needs levels are similarly dynamic and adjusted based on the specific resources a pedestrian is able to visit.

4. ENVIRONMENTAL ATTRIBUTES

Environmental attributes at a facility influence both general navigation behavior and individual pedestrian choices. These include a physical layout of the building structure and the location of resources, along with convenient travel and route alternatives. Current localized crowd density and traffic flow/direction factors (described below) both act to influence individuals’ navigation choice, as do route-planning factors such as observed resources' proximity, availability and potential wait time. Information sources such as signs, announcements and flight status displays can likewise affect individuals' decisions. System adjustments are generally subject to changing variables within the facility, e.g. pedestrians at a subway station during rush hour would expect more traffic in-between resource points, thus anticipating less personal space and slower overall movement, with longer resource wait times and so on.

Pedestrians respond to the physical system model such as current nearby obstacles (e.g. other pedestrians, facility walls) with a limited awareness, filtered based on field of view and a perceptual distance, where each object has a spatial location and extent. The pedestrian’s knowledge of the facility layout, resource information and potential route connections is stored within the node data structures, along with statistical factors and other conditions that may be observed. Statistical distributions are likewise set up for model variables in order to generate individual pedestrians from populations along with their individual characteristics and system entry time/locations. This information is provided via a flexible set of XML-based information structures that describe the overall experimental setup in conjunction with marked features in the facility’s 3D geometry file.

5. PEDESTRIAN ROUTING

Hoogendoorn and Bovy [8] have defined pedestrian travel behavior as determining which activities a pedestrian will perform, where they will perform them, and how they will get there. This reveals the three general planning phases: activity scheduling, destination choice and route choice. Hoogendoorn and Bovy [8] note that activity scheduling and route choice both involve tactical level planning that leads the pedestrians to make decisions that maximize their efficiency as represented by a utility value. Given a specific purpose for the pedestrian, an initial schedule is defined that includes all possible activities to be performed inside the transportation facility. However, this initial schedule may be modified at a later planning stage. Disutility acting as penalty increases whenever either an unfinished mandatory activity occurs or an inappropriate route is chosen. An inappropriate route choice implies that an activity has been performed in an area where the expected walking time is longer than if it had been performed in other areas. In planning, the model varies the activities, their sequence and location where performed, selecting the plan with the minimal disutility value.

The ISAPT system uses a similar approach partitioning planning into two stages; an initialization stage and a re-planning stage, each of which provides one or more of the three general planning phases. The initialization stage occurs when a pedestrian is first generated at a particular entry point. For each pedestrian the system will assign a specific agenda defining their
initial activity sequence. In light of the growing number of resources and services available within transportation facilities there are many possible activities that a pedestrian can perform. Similar to Yagi et al. [9], our research divides these principle activities into the three types: mandatory, auxiliary and discretionary as shown in Table 1. In our application, pedestrians are classified as either travelers or non-travelers. Travelers are those pedestrians whose trip purpose is to board, alight, or transfer between two flights within the facility. The group of pedestrians defined as non-travelers are those who enter the facility for non-travel related purposes such as to pick-up or drop-off one or more persons who are traveling. Currently, each pedestrian that enters the system is assigned an initial activity schedule from one of 18 potential choices based on the observed likelihood of occurrence for a specific facility. If data on a specific facility is not available, then an empirical distribution can be used to define these likelihood values.

Table 1. Principle activities of a pedestrian.

<table>
<thead>
<tr>
<th>Activity type</th>
<th>Instances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandatory activities</td>
<td>Visit service counter or kiosk (ticketing, etc.)</td>
</tr>
<tr>
<td></td>
<td>Baggage check/claim</td>
</tr>
<tr>
<td></td>
<td>Security check</td>
</tr>
<tr>
<td>Auxiliary activities</td>
<td>Checking flight monitors</td>
</tr>
<tr>
<td></td>
<td>Informational inquiry</td>
</tr>
<tr>
<td>Discretionary activities</td>
<td>Shopping (gift shop)</td>
</tr>
<tr>
<td></td>
<td>Eating (bar, restaurant, cafe)</td>
</tr>
<tr>
<td></td>
<td>Restrooms</td>
</tr>
<tr>
<td></td>
<td>Resting/Waiting</td>
</tr>
<tr>
<td></td>
<td>Other (e.g., ATM, viewing exhibits)</td>
</tr>
</tbody>
</table>

Although the initial path defines the nearest resource locations to perform each of the activities, the nearest resource may not always be the best in terms of utility (e.g. total travel time). Therefore, alternatives should be considered. Lam and Huang [10] utilize a time-dependent equilibrium model and combine the activity-scheduling and destination choice problem together. They compute the joint probability for each possible destination and activity pair. This probability takes into consideration factors of the activity, destination, and travel time. Although their approach is time-dependent, the concern is that it may ignore the priority of mandatory activities in transportation scenarios. For instance, if a time constraint exists for a traveler they will need to complete the check-in activity first, no matter how hungry they are and attractive the airport café might be.

In the ISAPT system, re-planning is triggered whenever a pedestrian reaches a decision node. These nodes exist at points in the system that define entry points to resources. Due to the randomness in a pedestrian’s arrival time, as well as the time required to perform various activities, it is possible for a traveler to be late for time-critical activities, therefore it is necessary that the system keep track of the remaining time available to complete their agenda. A time availability mechanism was created that can adjust the activity sequence with a focus on trying to ensure the completion of the mandatory activities within an agenda. The completion time of a single activity is estimated taking into consideration travel time, wait time and service time. Once a traveler is released into the system, their total available time (difference between final departure time and the current time) is updated dynamically at decision points. When they reach a decision point, the estimated completion of the activity is compared with the available time remaining. Using a tolerance level value that simulates the pedestrian’s personal preferences, if the waiting time in a service queue being considered is too long, the pedestrian begins formulating a plan change. If the activity is a mandatory activity and the estimated completion time of the subsequent activity exceeds the available time, the pedestrian will consider switching the order of the current mandatory activity with the next non-mandatory activity in the agenda, and update next destination on the path with the nearest resource point to perform next activity. However, if the current activity being evaluated is a non-mandatory activity, then the system will search for alternative resource points that can provide the same functionality but potentially a shorter completion time. If this search fails, then this non-mandatory activity will be dropped from agenda indicating that there just isn’t enough time to complete it prior to departure. The overall logic is represented in Figure 1.

Given the new pedestrian’s initial activity sequence, the system then generates an initial route connecting their entry point to their final destination. This route arises from the consideration of the shortest-path between the origin and destination taking into account the alternative locations (resource points) where the specific activities may be performed. The destination choice and route choice phases are combined with the route and resource points chosen based on a desire to minimize the pedestrian’s overall travel distance. Therefore, the results of the initialization stage is an initial plan for each new pedestrian representing the agenda (activity sequence) and path (resources and route) they hope to follow during their visit to the facility. However, based on the actual crowds and service levels they eventually find available within the facility, this initial plan may need to be modified. It is for this reason that the re-planning stage becomes active as the pedestrian travels through the facility.
Within this decision making activity, a pedestrian’s personal needs are considered together with the time availability mechanism, and the sequence of activities can be changed due a pedestrian’s personal needs (e.g., hunger, etc.). However, changes to the agenda based on their needs are given less priority than those based on time availability, which means that a pedestrian’s needs will be overridden when time is short and they are running late. For example, a traveler may have on their agenda the desire to get a snack prior to entering the security gate. However, if the time availability mechanism perceives that the estimated completion time of this activity violates the current available time, indicating that the pedestrian may not catch their flight, then the activity will be ignored.

As the pedestrian travels between two resource points, the initial path they were given might be modified for one of two possible reasons: the availability of alternative resource points or the discovery of alternative routes that have a better utility value. These alternatives arise since routes that are not necessarily the shortest are considered. As mentioned above, given that the current environmental factors (e.g., area congestion levels) are dynamically changing within the facility, the initial path of the pedestrian may need to be modified. Given the actual conditions the utility of “longer” routes may be better than the current route selected when the pedestrian first entered the system. Based on the length of a route, we seek to estimate the relative walking speed in a particular environment for a pedestrian that into account crowd density. Cheung and Lam [11] developed a BPR function that describes the speed-flow/speed-density relationship for pedestrian traffic. Therefore the system will generate alternative paths with different lengths by relaxing the shortest path constraint; then use the adapted BPR function to evaluate the relative walking speed for a particular pedestrian based on factors such as distance, congestion level, and their personal characteristics. Given the availability of the distance and relative walking speed, the selection criterion is the minimal travel time. This use of the BPR function acts to simulate real world outcomes where that the shortest path may not be the fastest path.

Overall, the initial agenda is changed according to pedestrians’ personal needs and available time, which may cause alternative resource points and alternative routes to be chosen since they minimize the total completion time of activities.

6. PEDESTRIAN NAVIGATION

Three major interaction schemes are often seen in simulating crowds of agents: cellular automata, social forces and rule-based systems – each of which has certain tradeoffs [12]. The first of these relies on a grid cell-based division of space for pedestrian travel, occupancy and consideration of movement alternatives [13]. Using a force strategy attempts to distribute motion via physically motivating forces such as forward movement, steering and avoidance of obstacles [14]. Rule-based systems enact logical choices when a certain series of conditions or overall criteria have been met [15]. Overall system models are somewhat divided as to whether choices are examined in terms of a continuous space of motion alternatives (as with social forces systems modeled as repulsive forces [16, 17] or these are focused on several discrete combinations of base navigation factors during a given time step – for example, discrete spatial regions in cellular automata [18, 19] or representative combinations of direction and speed [20, 21].
In the near future for a given movement, representing the speed and direction movement choices is deconstructing large-scale facilities with dense traffic (akin to findings by others, e.g. Pelechano et al. [12]), it was apparent that case-based logic was not sufficient in itself to describe the range of possible conditions in these environments. We felt it was important to represent a variety of pedestrian behaviors that varied based on individual choice, while allowing an acceptably realistic range of movement options that could be evaluated based on navigation factors. We have opted to model pedestrian navigation as a series of choices made based on current environmental conditions. This model is based on the concepts developed by Antonini et al. [21] and Robin et al. [22], where a continuous set of combined speed and direction movement choices is deconstructed into a discrete set of radial and angular sector divisions.

The basic idea of the navigational system is to provide each pedestrian agent with a range of alternative decisions they can choose from for their next step. In this scenario there are 33 alternative movement decisions (plus stop) that represent potential combinations of direction and speed. The pedestrian’s field of view (FOV) is split into 11 angular divisions whose sizes differ based on their position (see Figure 2). Potential travel range is divided into three zones centered at 0.5, 1.0 and 1.5 times current speed, representing three possible choices: deceleration (0.5), no change (1.0), or acceleration (1.5). Each of the resulting regions represents a continuous space (as shown in the diagram) for purposes of computing collision avoidance and other factors involving other pedestrians.

Given the availability of alternatives that a pedestrian can choose from, a utility function is employed to indicate the value of each alternative based on their current environmental attributes. The utility function used in this project is composed of a weighted sum of individual utility factors that each focus on some aspect that influences the navigational decisions of a pedestrian. The overall utility function is:

\[
\text{Utility} = w_1\text{UKD} + w_2\text{UTD} + w_3\text{UFF} + w_4\text{UPA} + w_5\text{UOA}
\]  

(1)

The individual utility factors include maintenance of current travel direction (KD), movement towards the current goal (TD), free-flow acceleration based on crowd density (FF), along with collision avoidance with pedestrians (PA) and obstacles (OA). The KD factor is motivated by the innate desire for the pedestrian to maintain their current direction and minimize the need for angular displacements. The TD factor arises from the observed behavior where once a trajectory change has been made, the pedestrian will tend to return to a trajectory in the direction of their original path. The desire of the pedestrian is to not deviate too far from their destination throughout their journey, but to make continual progress toward their goal. This factor supports the basic concept of efficiency of movement. The “free-flow” speed for a pedestrian is that at which they normally travel when not faced with any imposing traffic. Their “preferred” speed takes into account the need for them to adjust their speed to fit the overall situation; this is a pedestrian’s desired speed for the given density independent of the need to adjust speed in the face of impending collisions. The utility equation for the FF factor rewards alternatives where a pedestrian makes a speed adjustment that brings them closer to their preferred speed. The PA utility factor is a measure of the potential for a collision with another pedestrian if they were to choose a specific alternative, while the OA factor gauges the relative threat of colliding with a non-yielding obstacle in the near future for a given movement alternative.

Each of these factors makes use of a different function employ a range of variables to compute a value that reflects the utility of each of the 33 alternatives available to the pedestrian. The types of variables considered include the pedestrian’s current, preferred and maximum speeds, their direction of travel, time and distance to collision, and the location and direction of movement of other pedestrians and potential obstacles. Several of these utility factor equations are an outgrowth of the work by Antonini et al. [21] and Robin et al. [22],

Figure 2: Speed and direction alternatives.
and additional details on these factors can be found in Usher et al. [23]. Given the individual factors an overall utility value is computed for each sector/speed combination corresponding to a decision alternative. The alternative with the maximum utility represents the best sector and speed that results in beneficial movement.

While real-world pedestrians attempt to arrive at the best working solution, it won’t necessarily be a perfect or near-optimal one. Particularly where discrete movement models are used, probabilistic navigation may be incorporated to simulate pedestrians’ incomplete knowledge or attention in decision-making. Based on their knowledge of the system and assessment of movement factors, raw values are initially computed for each of the discrete movement alternatives. The resulting set of decision factor values and overall utility are summarized vs. the range(s) of results and used to produce an initial likelihood distribution, which can be modified via function. A random number generator then determines which option is selected.

Each of the alternatives is assumed to be independent of one another. It is not possible to select a direction and separately consider a speed, since each specific combination of speed and direction impacts utility differently. The pedestrian is modeled as selecting the alternative with the greatest utility, taking into account the pedestrian’s environment at that moment. The actual utility values of the alternatives, \( U_i \), represent random variables and the probability of that alternative being the best is computed using a multinomial logit model (MNL) where the probability pedestrian \( n \) chooses alternative \( i \) from among the set of alternatives \( C_n \) is:

\[
P_n(i) = \frac{e^{\beta U_{in}}}{\sum_{j \in C_n} e^{\beta U_{jn}}} \quad \text{where} \quad 0 \leq P_n(i) \leq 1
\]

and \( \sum_{i \in C_n} P_n(i) = 1 \) for all \( i \in C_n \)

All alternative choices are assumed to have the same scale parameter, \( \beta \), which has been set to 9 in our initial trials. Lowering the value of \( \beta \) raises the probabilities of additional alternatives being manifested, with the pedestrian switching from one decision to the next. Raising the value of \( \beta \) has the opposite effect, resulting in fewer alternatives with stronger probabilities, thus decreasing the likelihood that the pedestrian will select another option on successive iterations when there is little change in their environment. On each ISAPT iteration, an alternative is selected according to the computed probabilities. Relative to our previous rule-based navigation method [24], this approach permits a pedestrian to make a less than optimal decision, which mimics the reality of navigation as evidenced by the fact that it is not unusual to see pedestrians run into other pedestrians and obstacles on occasion.

7. NAVIGATION OUTCOME

Given that the overall utility equation and individual factor equations include variables and weights, the system has the capacity to be fine-tuned to correspond more directly to certain types of crowds and/or environmental conditions observed at a certain place or time. In these tests, however, initial values were chosen for the weights and parameters based on observations of the system under varied scenarios.

To illustrate this navigational approach we set up two common corridor examples. In each case, the time between arrivals of pedestrians follows an exponential distribution, and their start position along the width of the corridor follows a uniform distribution. An equal number of pedestrians are generated for each direction; once a pedestrian exits the system, they will be reintroduced again back at their lateral start location, with their initial position along the width of the corridor set akin to where they exited. The first example (Figure 3) simulates a corridor 27 meters in length and 8m wide with a 4m doorway in the middle of the corridor. Even though traffic began with a random pattern, in less than
a minute’s simulation time lanes start to form as the pedestrians begin to work out efficient traffic patterns. The second example, Figure 4, depicts a corridor of the same size, but with 3 columns located in the center. Again starting with random entry placement, after roughly 735 seconds have passed, the pedestrians were observed to have organized themselves into two uniform lanes.

8. CONCLUSIONS
While the ISAPT system is not yet fully operational, it has shown great promise in advancing the modeling of pedestrian traffic in intermodal facilities. The navigational component is operational and we are presently completing integration of the route planning capabilities into the system. The use of an agent-based approach to model individual pedestrians within the system has provided a mechanism that supports the development of realistic capabilities on the part of the behavior of the individual and permits the representation of a diversity of pedestrian characteristics that one would normally find in such an environment. The emergent behaviors that have been observed from the interaction of the simulated pedestrians (e.g., lane formation, striping at intersections, etc.) add supporting evidence to the validity of the overall simulation.

We have recently completed a large scale experimental study that we plan to use as a means for validating the simulation, and likewise for the purpose of further tuning the behavior of the individual pedestrians. Once the route planning component is completed, we will begin efforts at validating the system using a medium sized airport as a test case, initially focusing on its main concourse area.

9. ACKNOWLEDGEMENTS
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10. REFERENCES
Activity Scheduling Decision Rules”, Research Record: Journal of the Transportation Research Board, 2076, 123-131.


