INDOOR PEDESTRIAN NAVIGATION SIMULATION VIA A NETWORK FRAMEWORK

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ABSTRACT
The Intermodal Simulator for the Analysis of Pedestrian Traffic (ISAPT) is being developed for the purpose of modeling pedestrian traffic within intermodal facilities, such that designers may evaluate the impact of building design on the Level of Service provided. The navigational and decision-making behaviors that influence a pedestrian's travel rely heavily on the functional attributes defined within the facility model. An associated network delineates the principal path structure between nodes that represent waypoints and locations of pedestrian resources such as ticket counters, food service vendors, and restrooms. This paper describes the network framework employed by ISAPT and illustrates the necessity of key features it affords to the simulation. Several examples are given that demonstrate various applications of the capabilities provided by the framework in the context of intermodal facilities.

Keywords: pedestrian traffic simulation, micro-simulation, behavioral modeling.

1. INTRODUCTION
In the process of facility engineering and construction, designers must evaluate overall building design considerations in the context of their effective impact on Level of Service and other factors. The Intermodal Simulator for the Analysis of Pedestrian Traffic (ISAPT) system models each pedestrian's behavior individually within the context of a facility defined by its architecture and available resources that offer services to the travelers within it. Using agents to represent the individual pedestrians, the collective behavior of the crowd emerges from the interactions between them. Pedestrian navigation choices are simulated using a probabilistic approach that takes into account those factors considered by humans as they move about their environment.

The overall trip of each pedestrian is governed by an agenda that is generated when they enter the system. This agenda defines the tasks they would like to accomplish and requires real-time decision-making based on the environmental conditions they encounter within the facility. The navigational and decision-making behaviors that influence the pedestrian's travel rely heavily on the functional attributes defined within the facility model. A network of nodes delineates the principal path structure with the nodes representing waypoints and locations of resources (services) such as ticket counters, food service vendors, and restrooms.

This paper describes the network framework employed by ISAPT and illustrates the necessity of key features it affords to the simulation. Several examples are provided that demonstrate various applications of the capabilities provided by the framework in the context of intermodal facilities.

2. BACKGROUND
Capturing realistic pedestrian behavior in simulation is useful for evaluation and planning in building design (Daamen, Bovy, and Hoogendoorn 2001), urban design (Jiang 1999), design of the area around an outside memorial (Monteleone et al. 2008), land use (Parker et al. 2003), marketing (Borgers and Timmermans 1986), facility operational assessment (Daamen, Hoogendoorn, and Campanella 2009), city wide regional planning (Raney et al. 2002), and evacuation evaluation (Sagun, Bouchlaghem, and Anumba 2011).

Popular schemes for simulating pedestrian crowds include cellular automata, social forces and rule-based systems – each of which has certain tradeoffs (Pelechano, Allbeck, and Badler 2007). The first of these relies on a grid cell-based division of space for pedestrian travel, occupancy and consideration of movement alternatives (Kirchner et al. 2003). Using a force strategy attempts to distribute motion via physically motivating forces such as forward movement, steering and avoidance of obstacles.

Rule-based systems enact logical choices when a certain set of conditions or overall criteria have been met. 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 (Helbing, Farkas, and Vicsek 2000; Williams and Huang 2006), 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 (Kirchner et al. 2003; Blue and Adler 2001) or representative combinations of direction and speed (Bierlaire, Antonini, and Weber 2003; Antonini, Bierlaire, and Weber 2006). When simulated movement choices are not viable or have already resulted in an undesirable state, however, it is up to the individual system to allow for braking force, stop-and-wait conditions, and other actions to enable individual pedestrians (and the system overall) to re-adjust, for example, after one or more collisions have been encountered.

3. SYSTEM DESCRIPTION

The ISAPT simulation system is designed to simulate pedestrian traffic within intermodal facilities (e.g., airports, train stations, etc.). Based on the overall travel schedule for the facility, the system generates a dynamic pedestrian population representative of those arriving, departing, and connecting transit points. Since pedestrian traffic in a facility is not limited to travelers only, ISAPT also provides the capability to simulate what is termed “non-travelers” representing persons that enter the facility for the express purpose of picking up or dropping off travelers. At this time, the system does not consider the contribution of employee traffic within the facility.

ISAPT is implemented as a 3D OpenGL-based application written in the C++ programming language with an objective of supporting cross-platform use. The system simulates the behavior of each individual pedestrian, employing probabilistic navigation at the local level and route based planning at the strategic level. Each pedestrian moves in continuous 3D space, planning their trip inside the facility determined by an agenda defining a list of activities they intend to complete during their visit. An example activity set would include check-in at the ticket counter, checking of bags, passing through security, obtaining food, a visit to the restroom, and waiting in the gate area prior to the boarding call. Agendas are defined for each individual within the facility, with the system simulating and collecting data on the traffic flow and resource utilizations that arise as the result of the pedestrians executing their agendas. For additional details, the reader is referred to associated publications (Usher and Strawderman 2010; Usher, Kolstad, and Liu, 2010).

4. SYSTEM FRAMEWORK

As opposed to grid-based approaches, pedestrians in ISAPT are able to move freely in any direction within the navigable space of the facility model. A structured network of nodes within the facility provides a navigational framework defining generalized paths interconnecting the available resources of the facility. The resulting network provides a basis for performing route based planning to decide the overall path a pedestrian will follow in order to perform the tasks on their agenda. Pedestrians are not bound to the paths initially selected, but instead are permitted to re-assess their activity schedule based on the conditions they encounter as they proceed with their tasks in the facility. Each pedestrian must thus possess a certain awareness of the potential paths defined by the network, along with current conditions on that path and resources within visual range (e.g., congestion, queue lengths, etc.). It is the job of the system framework to provide these capabilities.

Conceptually, network nodes within the system can be divided into three categories: (1) those that actively represent physical entities within the system, (2) those primarily used to define path connectivity, and (3) those that provide needed support for the simulation itself (e.g., data collection). A general node object acts as a base prototype to represent all these types of nodes and its respective attribute values define its specific purpose, capabilities, and influence on pedestrian behavior. A node is not limited to a particular function, but can provide a flexible range of components to serve multiple purposes. For example, a user can define a single node to represent a physical queue that is part of a pedestrian’s path and collects data on its operation.

The sections that follow discuss this framework along with the nodes and attributes that define the network that provides these capabilities.

4.1. Physical Entities

As indicated earlier, a pedestrian’s trip within a facility is determined by their current agenda, which results in a list of activities they intend to complete during their visit to the facility. Each activity has one or more corresponding resource locations where it may be performed (e.g., ticket counters, food service areas, boarding gates, retail stores, restrooms, etc.). These resources are represented by *resource nodes* that act as primary objects on the underlying network used as waypoints along potential routes planned by pedestrians. Figure 1 shows a queue formation in front of a ticket counter, involving two node-based structures common to many simulations. The queue itself is comprised of a series of directionally linked nodes along a navigation route. Each ticketing location is represented by a resource node requiring a variable service time to complete.

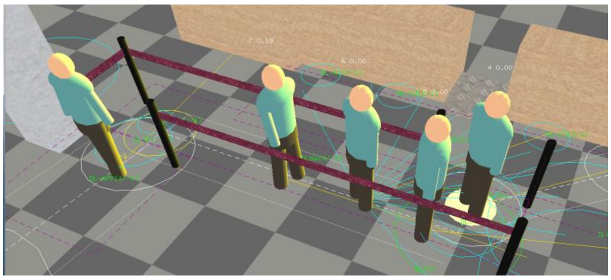

Figure 1: Simulated Pedestrians Arriving at Queue, in Front of Ticket Counters

4.2. Path Connectivity

When a pedestrian first enters the system, they are assigned a planned initial route from their origin to final destination (e.g., the boarding gate for their departing flight). This route is defined by a set of nodes they intend to visit from start to finish. An extensive set of intermediary nodes connects the space between resource nodes, acting as a navigation framework that provides a structural description of the building's thoroughfares to enable pedestrian route-based navigation. Consider the simple layout shown in Figure 2 defining the location of several resources (ticket counter locations K1-K2 and C1-C2). If a pedestrian were approaching at the lower left with intent to visit the ticket counter area, they would typically be observed to follow an indirect path (such as the curving dashed line) that is somewhat impeded due to obstacles along the way. Without more detailed connectivity information, a navigational decision might suggest a planned travel path (shown as a straight dashed line) that does not realistically represent typical behavior for an actual pedestrian. *Intermediate navigation nodes* are thus arranged within the network as needed to increase the spatial resolution of successive waypoints located between resource locations. Figure 2 shows several dotted-outline nodes added to the graph for secondary navigation detail.

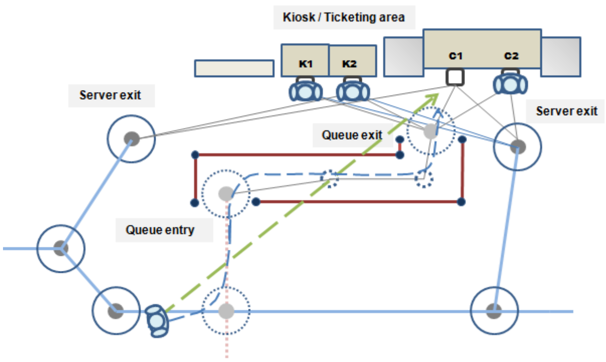

Figure 2**:** Nodes of an Airport Ticket Counter Area

As can be seen in Figure 2, it is possible that multiple connecting links (pathways) will be associated with a given node. We refer to these nodes as *decision nodes*, as they will trigger pedestrian decision logic in association with path-based routing through that node. A decision node in effect is an intermediate navigation node with two or more alternative links that may be considered for outbound traffic. The routing logic will assess which path is best utilized at the point when such a node is approached. This becomes necessary in situations where:

- Pedestrians have the choice of several branching routes through (sometimes crowded) areas,
- A pedestrian approaches an area with multiple queue lines for a resource (i.e., alternative vendors in a food court), and
- Exit paths lead to variously distanced resources with different priorities.

In the first situation, the pedestrian will evaluate the congestion and approximate travel time for each region ahead and make an informed path decision. Where multiple queues are observed, they will estimate the waiting times for the available options and select one they believe will provide the best service. Similarly, the choice amongst multiple paths and available resources will be based on priority and time required to obtain them. Estimates made by the pedestrians in each of these cases may take into account region-based data maintained by associated *data collection nodes* (discussed below).

4.3. Simulation Support

At this point, we have additional nodes that provide simulation support which are used for data collection and compilation of statistics. These nodes may appear within the system either as stand-alone nodes (i.e. not connected as part of the navigation structure) that define regions such as a corridor area of interest for traffic analysis, or as part of the overall node network.

The data collection region can be defined as either a radial extent or a rectangular zone of a certain width and length. The region encompassed by any one node is permitted to overlap with other nodes, and can automatically collect data on all behavior within its region without interference.

A representative list of the types of data that can be requested to be logged for each pedestrian is given in Table 1. Some of this data is available to pedestrians for decision-making purposes, e.g. in the form of an observed queue line length and estimated wait time. Any pedestrian estimates, however, are subject to variability in the form of added noise representing a degree of uncertainty.

Table 1: Information Logged in Association with Data Collection Nodes

• Tacked location over time
• Time spent in regions
• Pedestrian speed
• Distance traveled
• List of node visited (travel history)
• Travel time between nodes
• Wait time in queue(s)
• Service time
• Levels of needs (e.g., hunger, thirst, etc.)
• Decisions made

4.4. Node Attributes

The attributes of a node define its features, parameter values, behavioral effect, and limitations for a given region. To enable navigational or other decision-making use, node attributes can also be marked to indicate an association with a larger structure.

The common attributes of a node are its *name*, *location*, and *connectivity*. The name of a node provides a unique identifier used for general reference, while its location provides a relative locale within the 3D geometry representing the facility. A node's connectivity describes its relation to other nodes in the navigation network via incoming and outgoing links.

While a node's general function is to support path-based routing and navigation behavior, more specialized attributes are available to help represent varied service-related resources found within intermodal centers. These act together to simulate larger system processes involved with services such as ticket counters, security gates, food courts, restrooms and so on.

The principal functional node attributes consist of:

- Active region extent (rectangular or circular)
- Navigable zones for nodes and pathways
- Conditional entry requirements
- Resource type notation (used primarily in decision logic)
- Behavioral influence factors
- Data collection within an associated region

An overview of the use of these attributes and their influence on pedestrian behavior and general system operation is discussed below.

4.4.1. Active Region and Navigable Zones

Each node in the system occupies a define space, which pedestrians must cross into for purposes of navigation and/or resource use. With an active route plan in mind, pedestrians will follow their path traveling from one node to the next. As they do, their local movements are guided primarily by collision avoidance as they progress towards their next objective (target node). The actual path traveled by the pedestrian is also a function of the presence of other pedestrians in proximity. If each pedestrian were asked to follow such a path exactly, this would result in unnatural behavior and traffic congestion along the route, with further convergence towards waypoints (intermediate nodes) that represent the navigational targets, as shown in Figure 3a.

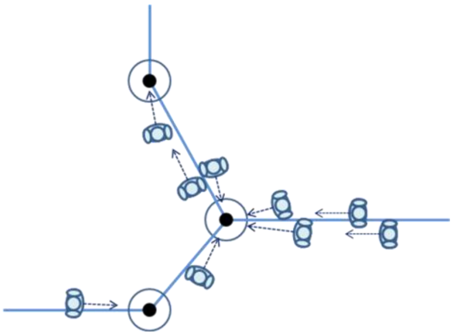

Figure 3a: Pedestrians Following in Proximity to Network Structure (tendency to converge at nodes)

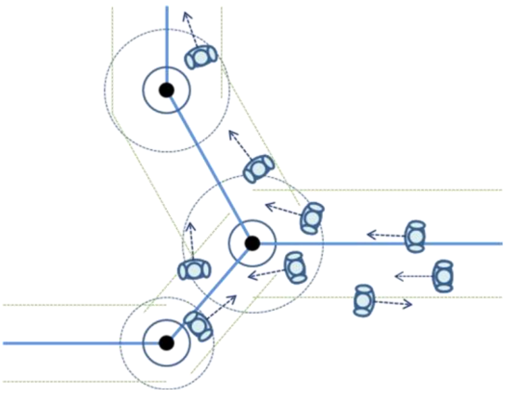

Figure 3b: Network Structure with Navigational Extent Region Hints Added for Nodes and Connecting Paths

To overcome this problem, the system permits the user to define greater navigable extents along paths and within the vicinity of node regions. A connected route may be considered to have a collective region of space encompassing its nodes and pathways that represents an area of more likely travel under certain constraints. Pedestrians will generally attempt to stay within a reasonable *proximity* of the path segments between and regions surrounding waypoints. Figure 3b's dashed *navigation zones* (above) can be interpreted as regions of relatively preferred movement.

When a pedestrian moves within the *active range* of an upcoming target node (i.e. shown in the figure as a larger radius around the node), they are considered to have effectively reached that node for navigation purposes en-route. At this point, the next node on the pedestrian's path becomes its waypoint and travel continues towards the next location on the current route, or into the node's *physical limits* if it is an intended resource they plan to utilize. Similarly, there exists a buffer zone of space around inter-connecting paths (specific to certain node connections) where travel en-route is relatively more preferred, although not strictly confining. The result is a more natural representation of traffic through the facility (Figure 3b, above) as pedestrians are encouraged to go with the overall flow and direction of the network structure, and may take shortcuts past recognized waypoints. The factors that encourage this behavior are adjustable for individual nodes and connections (e.g. for a single-occupancy resource vs. a wide-open area, or a corridor junction with a diverse range of traffic relative to a queue line) and act to direct pedestrian focus when approaching resources.

4.4.2. Conditional Entry

These properties permit the user to limit entry into a region defined by a node based on the region's capacity, conditions, and/or specific requirements of the pedestrian expressed in terms of their attributes. Being able to limit access based on the current occupancy is important in situations such as forcing a pedestrian to wait in line before approaching a ticket counter until the area in front of the agent in open.

At times a pedestrian's attributes will influence their navigation decisions and access to resources. A passenger may, for example, need to have presented an ID and acquired a ticket (ahead of time or at a kiosk/counter) prior to receiving their boarding pass, which in turn is necessary to proceed through security and enter the terminal areas. It is also possible to require that node attributes match a certain value or range to be valid, and for overlapping regions to impose combined limits.

4.4.3. Resource Type

In today's modern intermodal facilities, there are many resources available to the traveler that provide a wide variety of services. In some instances a pedestrian must make decisions based on information related to the type of resource and the current conditions of their environment. To enable the decision logic to ascertain the function of a larger structure, or mark parts of it that are relevant for a particular use, attributes defining the resource type and its service parameters can be assigned. For example, marking a node as the entrance to a queue would indicate its connection with upcoming servers to the route decision logic for use in resource acquisition, and provide key details when a pedestrian wants to choose which queue to enter based on observed statistics.

4.4.4. Behavioral Influence (Region of Effect)

These attributes act to modify pedestrian behavior by adjusting the relative influence of certain navigational factors, decision-making factors, and/or by altering the logic utilized. For example, when a pedestrian enters a queue, given the need to form a line and stand next to others, they will effectively reduce the size of their personal space. Their criteria for obstacle avoidance also changes in that they are more willing to stand right next to (or even touch) an obstacle such as a wall, column, or turnstile. The distance they look ahead to avoid obstacles is similarly reduced. To accommodate the capability to alter pedestrian behavior, each node can specify a set of factor adjustments that are active while a pedestrian is present within that node's active region, thereby altering one or more of the area-based influences and attenuating the pedestrian's characteristic response. Once the pedestrian leaves the node, the pedestrian's factors return to their original settings. Another example would be a region with a distracting element (i.e., window display, food vendor, etc.) that might influence passing pedestrians by causing them to slow down and/or adjust navigation behavior. In addition, a turn-taking behavior could be enforced to prevent a traffic jam in an area with limited space.

4.4.5. Data collection

A designated node may likewise be tasked to actively record data, based on pedestrians that pass within its node boundaries. The node may either be linked within the navigation network or exist as a stand-alone node.

Given that the overall attributes of a node define what it can do, it is viable to have a single node that performs multiple functions. For example, facility resources are often modeled using nodes that represent physical entities that provide services, but these nodes likewise place conditions on who can use them while influencing the behavior of those present, and collecting data on their usage patterns. This effectively allows ISAPT to:

- Enforce occupancy requirements to facilitate arrival/departure and parking locations (for seating, etc.),
- Influence navigational decisions within node regions and connected routes,
- Enable pedestrians to obtain resource benefits according to a user-specified service time distribution,
- Modify decision factor influence and/or behavior within proximity to a node,
- Provide the planning module with current data updates for dynamic route planning and resource use,
- Gather region-based statistics,
- Represent the dynamic input sources for arriving populations, and
- Modify the navigation network to include additional structures e.g. for temporary use (such as in dynamic queue formation)

5. NAVIGATIONAL DECISION-MAKING

Given the availability of a navigation network of nodes with such attributes, the following traversal criteria (relative to current node status) may be actively considered by the pedestrian when determining their an ongoing course of action:

- When the proximate node is a point with multiple decision choices, what are the currently navigable nodes connected to resources of interest?
- If the next planned node acts as a server, is its region clear and available for use?
- When an upcoming node is a queue entry node, which potential resources are available at the end?
- When the next node is a queue entrance, how many people are now in the queue (i.e. to estimate wait time)?
- Which related resource nodes should be obtained [in sequence] to properly satisfy a resource need (e.g., selection of ticketing Kiosks, Counters, Kiosk-to-Counter-to-TSA, Counter-to-TSA, etc.)?
- Is it viable to traverse a node region when it is conditional use zone (permitting occupancy only under certain conditions, such as capacity limits, pedestrian attribute, etc.) or while it may have a region of effect (whereby certain travel factors are affected)?

Given these capabilities, the ISAPT system is able to support the simulation of a wide variety of services offered within intermodal facilities along with the pedestrian traffic that results.

6. IMPLEMENTATION EXAMPLES

This section provides several practical examples of how the nodes may be collectively assembled to define areas of functionality common to intermodal facilities.

6.1. Ticket Counter

A simple ticket counter, as seen in Figures 1 and 2, can be constructed as follows. An initial node at the entrance of a queue (marked as a “queue entry” node, with a capacity of 1) is associated with a region-based statistics node for collecting data on the queue for later analysis as well as real-time use for pedestrian decision making (e.g., line length and estimated wait time). The queue entry node connects a sequence of nodes within the line barriers to an exit node that is linked to one or more ticket resource server nodes. A free-form extendable line might likewise be configured for the entrance node to handle additional visitors beyond a strictly enclosed path. A resource node is used to represent each service point at the counter area (kiosk terminal, ticket agent, baggage scanning). The attributes of each resource node define their respective characteristics such as capacity, service time distribution, task handling ability and resource type. Real-world scenarios such as shown in Figure 1 may require a node region space in front of the counter to enforce conditional entry zone, enacting a *waiting* behavior that prevents people in line from traversing the limited corridor space until a server (resource node) becomes available. These nodes may also be linked to other resource nodes nearby (e.g. if additional processing is required for check-in following kiosk use, or if luggage must be scanned at another station) along with navigation nodes defining potential points for departure.

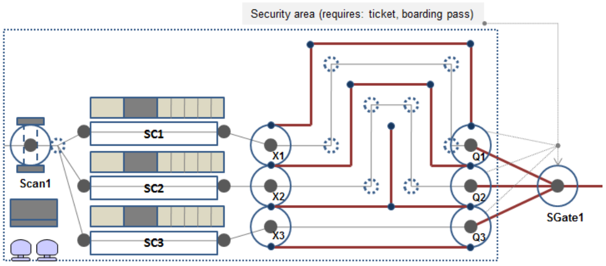

Figure 4: Security Processing Area

6.2. Security Gate

The security gate area in Figure 4 depicts a structure with several queues. A node defining the security area’s surrounding region (dotted line) will not permit pedestrian entry without a valid ticket and boarding pass. The main entry node, SGate1, is connected to several queue lines. The three nodes at the entrances to the queues (Q1-Q3) provide detail on their current occupancy and maximum capacity for decision-making purposes. Q3 might have an added conditional entry requirement, e.g. for flight crew status or passengers needing assistance in processing. At the end of each line, a conditional entry node (SC1-SC3) is used to define a capacity limited service area where persons empty their belongings into bins and then wait for their turn to pass through a common node (Scan1) of capacity one that represents a personal screening device.

6.3. Food Court

A food court might be comprised of multiple queue lines attached to food and drink resources, which have exit points linked back to the larger court area. The court area in turn may have individual seating resources (e.g. tables) each with several available positions that a pedestrian may occupy for a time (as required to eat), and an overall region-based occupancy may be enforced by a capacity-limited node surrounding the court. While individual seating occupancy depends on a given pedestrian’s requirements, the seats at the same table (when occupied by a group) may further enact an overall waiting behavior or preferred seat selection.

6.4. Restroom

Larger enclosed-spaced resources such as restrooms – where concern is focused primarily on capacity rather than individual dynamics – would typically require a single resource node associated with the entrance (enforcing some capacity limit for total occupancy). This node would often be tagged such that pedestrians entering do not remain within the node’s physical extent, but rather “park” outside of the observable simulation space while service is underway. To a simulation observer, the pedestrian avatar disappears as they pass through the door and then later reappears as they exit after completing service. A linked exit node – slightly offset from the entrance location to encourage flow of traffic due to simulation limits with narrow openings – would thereafter return the individual pedestrians back to the system.

Such a configuration enables the system to simulate services that do not require physical modeling or graphical representation of the service being performed, i.e., that are able to be represented as a self-contained “black box”. A similar setup might be used with stores along a terminal where the customer will enter or exit through a doorway.

6.5. Dynamic Queues

The waiting behavior at the end of demarked queue-like zones (such as cordoned lines leading up to a ticket counter) or near certain resources that have particular demand (e.g., a water fountain), may not be sufficiently represented with a single node region (of limited or unlimited capacity) or a simple group of nodes. While there are many cases when a small crowd will gather around a resource waiting for it to become available, it is common that a temporary line formation of sorts will occur. In our observation and more commonly, these lines often take two basic forms: the *free-form* style line that arcs away from the resource in one direction or another (as in Figure 5), and a more linearly *stacked* variety where the line begins to form side-to-side and outward as space permits. ISAPT allows either type of line to form starting at an arbitrary node configured as its root, with control over the directional parameters, spatial extent and permitted line length. A series of temporary nodes dynamically added to the graph structure act to enforce regular directed line formation along with their own specific evolving directional flow. Node connectivity changes are communicated to pedestrians en-route for ongoing route adjustment and re-targeting, as needed.

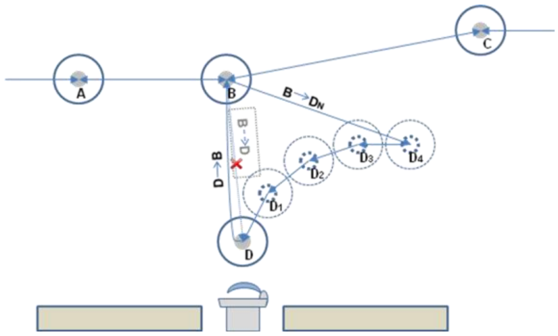

Figure 5: Dynamic Queue Formation

7. SUMMARY

ISAPT provides the means to enact a crowd-based simulated environment by modeling agent-based behavior via individuals' reactions to their environment, based on observed real-world behavior. Data obtained in both experimental trials and on-site studies of real-world facilities have been incorporated in the modeling process – including route-based decision logic. The location and availability of resources in a structured node network are central to how pedestrians interact with the larger system, in obtaining their planned objectives and choosing a preferred course of action from moment to moment. The flexible array of node-based attributes in the ISAPT system is designed to enable a broad range of possible resource configurations and behaviors, without imposing substantial limits on design. Apt resources matching real-world structures and facility-specific data may be constructed with a model-appropriate set of attributes for varied scenarios and activity levels. This gives rise to a modeling platform that is highly adaptable and able to easily represent a wide range of intermodal facilities.

We are presently involved in site studies and modeling of several transportation facilities and experimental scenarios, focused on inter-modal facilities and pedestrian traffic through common areas. The network-based attributes that have been discussed here are subject to further expansion, as it becomes apparent that certain modeling tasks and varied facility types benefit from added functionality. Current and future applications will utilize these to define their own unique system of interconnected resource nodes to model additional facilities.

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REFERENCES

Antonini, G., Bierlaire, M., and Weber, M., 2006. Discrete choice models of pedestrian walking behavior. *Transportation Research Part B: Methodological*, 40(8), 667-687.

Bierlaire, M., Antonini, G. and Weber, M. 2003. Behavioral dynamics for pedestrians. In *Moving through nets: the physical and social dimensions of travel*, Elsevier.

Blue, V.J., and Adler, J.L., 2001. Cellular automata microsimulation for modeling bidirectional pedestrian walkways. *Transportation Research Part B: Methodological*, 35(3), 293-312.

Borgers, A., and Timmermans, H., 1986. A model of pedestrian route choice and demand for retail facilities within inner-city shopping areas, *Geographical Analysis*, 18 (2) 115–128.

Daamen, W., Bovy, P.H.L and Hoogendoorn, S.P., 2001. Modelling Pedestrians in Transfer Stations. In Schreckenberg, M., and Sharma, S.D. eds., *Pedestrian and Evacuation Dynamics*, Duisburg: *Springer Verlag*, 59-74.

Daamen, W., Hoogendoorn, S.P. and Campanella, M.C., 2009. Ticket reservation posts on train platforms: an assessment using the microscopic pedestrian simulation tool Nomad. *Proc. of Transportation Research Board*, Jan. 11-14, Washington, D.C., paper no. 09-1853 CD-ROM.

Helbing, D., Farkas, I., and Vicsek, T., 2000. Simulating Dynamical Features of Escape Panic. *Nature*, 407, 487-490.

Kirchner, A., Namazi, A., Nishinari, K. and Schadschneider, A., 2003. Role of Conflicts in the Floor Field Cellular Automaton Model for Pedestrian Dynamics. *2nd International Conference on Pedestrians and Evacuation Dynamics*, 51-62.

Monteleone, M. F., Veraart, N., Chough, S., and Aviles, W., 2008. Pedestrian Simulation Modeling Study for World Trade Center Memorial. *Transportation Research Record: Journal of the Transportation Research Board*, 2073, 49-57.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann M.J., and Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. *Annals of the Association of American Geographers*, 93(2), 314-337.

Pelechano, N., Allbeck, J.M. and Badler, N.I., 2007. Controlling Individual Agents in High-Density Crowded Environments. *Eurographics/ACM SIGGRAPH Symposium on Computer Animation.*

Raney, B., Cetin, N., Vollmy, A., and Nagel, K., 2002. Large Scale Multi-agent Transportation Simulations, *Computer Physics Communications*, 147, 559-564.

Sagun, A., Bouchlaghem, D., and Anumba, C., 2011. Computer simulations vs. Building guidance to enhance evacuation performance of buildings during emergency events, *Simulation Modelling Practice and Theory*, 19, 1007-1019.

Usher, J.M., and Strawderman, L., 2010. Simulating Operational Behaviors of Pedestrian Navigation. *Computers and Industrial Engineering*, 59, 736-747.

Usher, J.M., Kolstad, E., and Liu, X., 2010. Simulation of Pedestrian Behavior in Intermodal Facilities. *International Journal of Agent Technologies and Systems*, 2(3), 66-82.