Efficiently Using Micro-Simulation to Inform Facility Design – A Case Study in Managing Complexity

Erin Morrow
Arup Canada Inc.,
2 Bloor St. West
Toronto, ON M4W 1A8 Canada
Corresponding author: erin.morrow@arup.com

Abstract

At major transit terminals large, volumes of people, intricate operational procedures, and complex built environments present significant challenges to effective pedestrian facility design. Transbay Terminal in San Francisco is a prime example of layered complexity. It is a multi-modal transit terminal designed to serve commuter rail, commuter bus, local bus, and eventually high speed rail passengers in downtown San Francisco. With the existing facility already near capacity and new transit modes being planned it is essential that the terminal facility is upgraded. This paper will present a new crowd simulation technology called MassMotion and describe how this toolset was applied to inform the design of a new Transbay terminal.

Introduction

Pedestrian micro-simulation enables understanding of complex design problems and confidence in design solutions. The MassMotion pedestrian simulation system has been designed from the ground up to provide planners and designers with the tools to predict the performance of their designs. This is accomplished through a holistic consideration of:

- Dynamic crowd interactions
- Network assignment and predicted loads
- Capacity planning for predicted loads

MassMotion is an autonomous agent based crowd system that operates within three dimensional virtual environments. The following sections will describe the basic architecture of the MassMotion crowd simulation system and then explore how this tool can be used to enhance the planning and design process using the Transbay Terminal project as a case study.

Architecture

MassMotion separates the calculation of crowd activity into two distinct processes. The first component is referred to as “reflexive” and governs the individual agents’ basic movements and responses to the environment. This reflexive component navigates the agents through open space while avoiding obstacles and other agents. The second component is referred to as “contemplative” and governs the agents’ network path planning between origins and destinations. This component analyzes distance, congestion, and terrain to develop costs for all available routes to the agent goal and to select an appropriate route based on these costs.

Reflexive agent motion

The reflexive component of MassMotion agent movement is broken down into spatial analysis and movement toward areas of high utility. As described by Kuffner1 each individual agent is made aware of their environment through bit map representations of free and obstructed space on all walk-able surfaces of the

3D simulation environment. This approach uses a 2D projection of all static obstacles within a defined volume to map obstructed areas and then uses a modified version of Dijkstra’s2 algorithm to describe all complete paths between a starting and goal location within the map. Each agent is also aware of other agents within their immediate neighbourhood using a global space partitioning structure to improve the efficiency of neighbor discovery within a specified range.

Using a combination of information from the path/obstruction map and the positions and velocities of the neighbouring agents, each agent determines their best available target location for the next frame of the simulation and adjusts their velocity and orientation to achieve that position. This calculation is executed at five frames per second of simulated time which is frequent enough to allow agents to adjust to dynamically changing conditions within the environment without encroaching on locations occupied by obstructions or other agents.

While the computational methods used are well documented, the practice of pedestrian planning requires that the results of the simulation of agent motion conform to industry standards. The Level of Service (LOS) standard developed by Fruin3 for pedestrian planning and design defines performance thresholds A through F. These thresholds describe the expected motion and interactions between people in a crowd for densities ranging from completely unimpeded in free space (LOS A) to packed shoulder to shoulder and chest to chest (LOS F). The reflexive motion of MassMotion agents has been calibrated to the Fruin walkway and bulk queuing LOS standards for level passages, restricted passages, stairs, and escalators. While the reflexive agent motion of the MassMotion system does not in and of itself help to manage complexity, it is the foundation of reliable reporting on crowd conditions within a complex network.

Network Construction & Assignment

The contemplative component of the MassMotion system is based on a sparse network description of the overall simulation environment. As shown in Figure 1 the environment is broken up into a series of floors and links with floors typically representing rooms, plazas, corridors, etc. and links representing doorways, thresholds, stairs, escalators, etc. The floors and links of the environment model constitute the nodes in the sparse network.

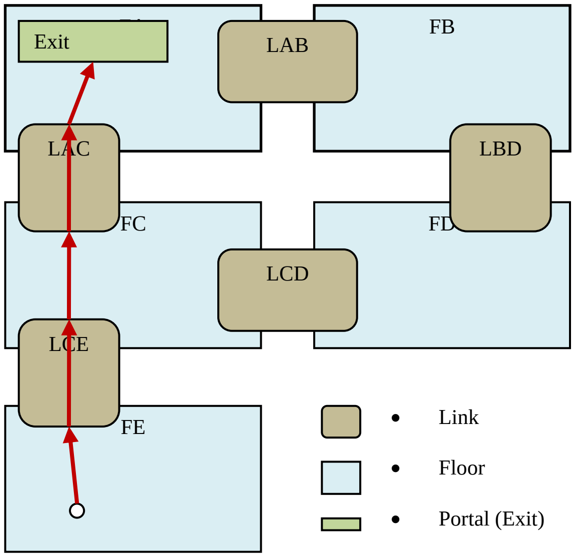

Figure 1 - Example of MassMotion environment comprised of floors and links

The first way in which MassMotion helps to manage the complexity of simulating a pedestrian environment is in the automatic association of floors and adjacent links. Simple geometric tests are carried out to establish which two floors are connected by a specific link. For example, in Figure 1 floors FE and FC are implicitly connected by link LCE which touches both floors. In this way the modeler is relieved of the task of defining the organization of the network beyond the geometric definition of the environment and specifying the type of each element/node.

Figure 2 shows an example of the relationships implicit in the floors-links sparse network including the direction of travel permitted on each link. In this case all links are bi-directional with the exception of link FD which could represent a turnstile or escalator. To facilitate the consideration of possible routes by agents in the simulation a pre-computing of distances to exits from each node is carried out (again using a modified implementation of Dijkstra's algorithm) and stored on the link nodes. Directionality is considered and routes with no viable forward path (e.g. LCD to LBD) are ignored. These pre-computed distances are made available to the agents at run time through direct querying of the link objects.

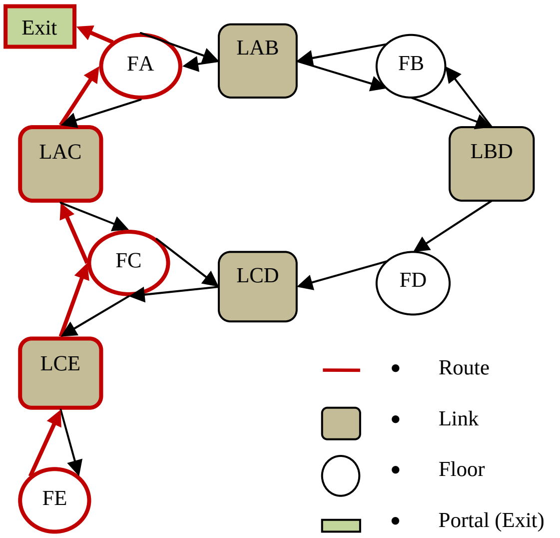

Figure 2 - Sparse network diagram including link directions

In MassMotion all agent journeys are defined by origin and destination pairs. Each agent is given autonomy over the route it will take between its origin and destination points. This is the second significant way that MassMotion helps manage complexity. Because the software will manage the network assignment of agents on an individual basis there is no need for the modeler to specify assignments at junctions. In Figures 1 and 2 for example, the shortest distance path from floor FE to the exit on floor FA is via floor FC. This is particularly advantageous when simulating complex interconnected environments, where the effort required to manually assign volume splits at junctions per destination would result in an unmanageable number of permutations to be defined.

The route self-assignment process at any junction will be based on the perceived cost of all available routes. Available is defined as a route that leads to the agent's ultimate goal without using a previously traversed node. Cost perception is randomized per agent through the use of randomized weights for the cost components of routes. The simplified algorithm for total route cost is as follows:

$$cost = W_D * \left(\frac{D_G}{V}\right) + W_Q * Q + W_L * L$$

Where,

W_D = Distance Weight (random agent property)
D_G = Total distance from agent position to ultimate goal
V = Agent's desired velocity (random agent property)
W_Q = Queue Weight (random agent property)
Q = Expected time in queue before reaching link entrance
W_L = Link Traversal Weight (random agent property)
L = Link Type Cost (level, ramp, stair, etc.)

Based on the results of the costing of all available routes, the agent will generate a probability list with the best cost route having the greatest chance of being selected and the worst cost route having the least chance of being selected. The agent then uses a randomizing function to select their route. This process, including the randomized selection of a rote based on probability has been shown4 to result in statistically similar network activity as surveyed at complex, high volume transit facilities. A significant advantage of the MassMotion system, that results from the automatic organization and costing of routes through a pedestrian network, is that design alternatives may be explored by simply replacing or modifying environment geometry. The sparse node network will update itself based on the new geometric relationships, while the availability and cost of routes within the network will likewise adjust to new structure. As pedestrian planning and design work is fundamentally concerned with the testing and refinement of design ideas this ability to rapidly adjust design models and run simulations is exceptionally valuable both in terms of effort saved and confidence gained through extensive testing.

Transbay Terminal Case Study

The design for a new Transbay Terminal in San Francisco needed to demonstrate effectiveness in three key areas of pedestrian activity:

- Transit boardings and alightings
- Interchange between transit modes
- Neighbourhood impacts

The new terminal will be a multi-modal transit hub designed to serve commuter rail, commuter bus, local bus, and eventually high speed rail passengers in downtown San Francisco. The variety of modes, degree of interchange between modes, and density of the surrounding urban fabric required an analysis approach that would consider the interaction of people with disparate destinations and patterns of movement within a complex environment. MassMotion models were constructed to assist the design team in analyzing the proposed layout of the station. The intended use of the model was to predict:

- Capacity of platforms and vertical circulation
- Demand on internal circulation routes
- Neighbourhood dispersion patterns

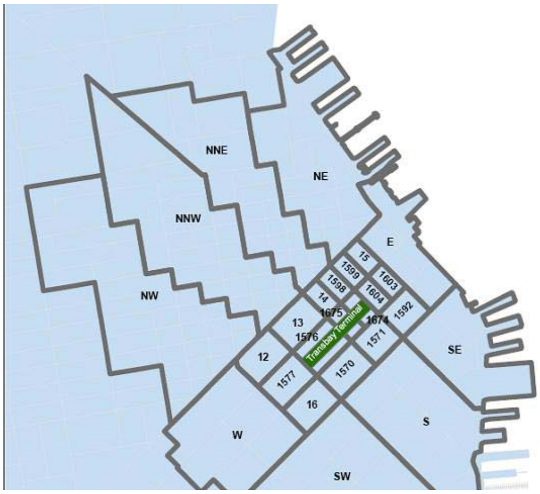

Figure 3 - Transbay neighbourhood TAZs showing aggregations outside of immediate site

Input Data

Projected ridership and transit schedules were provided to the design team for inclusion in the simulations. Much of this data was derived from regional transit models that provided distributions between various transit modes and the surrounding Traffic Analysis Zones (TAZs). The TAZs are based on census data including residential and workplace densities which inform the regional transit models in terms of mode assignment and volume of traffic.

A matrix of origin and destination (O/D) pairs was developed that described the relationships between the various transit modes at the terminal building and the block in the surrounding neighbourhood.

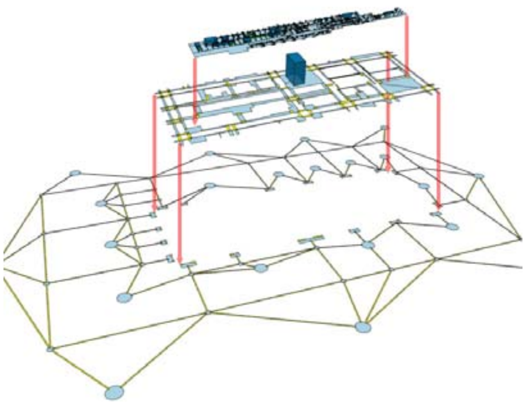

Figure 4 - Exploded network diagram of Transbay MassMotion model showing terminal building, immediate site, and surrounding neighbouhood layers

3D Model of the Terminal & Neighbourhood

With the origin and destinations entered into the MassMotion model based on transit activity (and including schedule timings for train and bus arrivals and departures) a 3D model of the terminal and neighborhood was developed. As with the O/D pairs, the construction of the 3D model was based on incremental reductions in level of detail as distance from the terminal building increased. As shown in Figure 4, all public circulation spaces and elements were modeled within the terminal building while sidewalks and crosswalks were modeled in the immediate site area. A simplified 3D representation of the aggregated TAZs from the outer neighbourhood (as defined in the O/D matrices) was developed that would provide reasonable approximations of overall distances without incurring a significant burden of modeling effort.

Results

The simulation results indicated that early designs of the terminal building contained problem areas from a pedestrian circulation point of view due to insufficient channel widths in what were predicted to be high volume routes. Subsequent design iterations contained changes which eliminated areas of congestion according to the simulation results. At the end of schematic design the simulations were predicting that there would be no significant concerns regarding the boarding and alighting of passengers, that the internal circulation of the terminal building would accommodate projected traffic, and that there would not be significant impact to neighbourhood sidewalks.

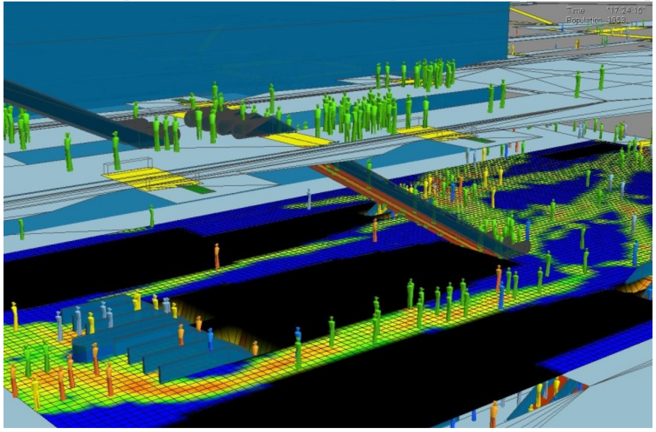

Figure 5 - Screen capture of running simulation including average crowd density mapping

It is clear from the Transbay case study that a simulation tool that minimizes the amount of modeler effort and provides a predictive view of design effectiveness is exceptionally valuable to the planning and design process. It enables the design team to devote less time to modeling more time to analysis and alternatives exploration which in turn increases confidence in the effectiveness of the design.

In addition to providing the design team with analysis of particular conditions and comparisons with desired outcomes it turns out that there are significant communications advantages to the MassMotion system. During the design process it became standard practice to bring the simulation model to design meeting for on the spot querying of particular issues and to gain insight into the overall functioning of the pedestrian network. The 3D models and animated motion of the agents provided a clear depiction of projected conditions and in a number of cases eliminated extra design effort and construction expenses that might have been required without such a tool.

Next steps

While MassMotion has proven to be a very valuable design and capacity planning tool on Transbay and on similar projects around the world there are performance issues that need to be addressed. The modeling of thousands of individual agents in a complex virtual environment is computationally intense and there are hardware and software opportunities such as multi-core processors and 64-bit addressing that should be explored. In addition there are specific implementation approaches which could be done in alternative and perhaps more efficient ways. The work done by Helbing et al.5, Lakoba et al.6 and others on Social Forces looks very promising as an efficient means of describing the reflexive component of agent motion. Work has already begun on the next generation of MassMotion to address some of these possibilities.

Acknowledgements

Much gratitude is extended to Wendy Tao and Andrew McCulloch for their work on developing the input data and simulation models for Transbay terminal designs and to Micah Zarnke for his ongoing contribution to the development and documentation of the MassMotion suite of simulation and analysis tools. The development of MassMotion has been made possible by ongoing research funding provided by the Design and Technical Executive of Arup and Oasys.

References

[1] Kuffner, James J. Jr. Goal-Directed Navigation for Animated Characters Using Real-Time Path Planning and Control in the Proceedings of CAPTECH ’98, November 1998

[2] Fruin, John J. Pedestrian Planning & Design, Revised Edition Chapt. 4, Elevator World, 1987

[3]Dijkstra, E. W. "A note on two problems in connexion with graphs". Numerische Mathematik 1: 269–271, 1959

[4]Morrow E. MassMotion: Simulating Human Behavior in the Proceedings of the Design for Human Perfromance Conference, Royal Society, London, January 2009

[5]Dirk Helbing and Péter Molnár Social force model for pedestrian dynamics II. Institute of Theoretical Physics, University of Stuttgart, 70550 Stuttgart, Germany, January 1995

[6]Taras I. Lakoba, D. J. Kaup and Neal M. Finkelstein
“Modifications of the Helbing-Molnár-Farkas-Vicsek Social Force Model for Pedestrian Evolution” SIMULATION 2005; 81; 339