An Implementation of a Macroscopic Network-Based Simulation for Large-Scale Crowd Management

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Abstract Current state-of-the-art macroscopic pedestrian models effectively simulate large-scale traffic, yet they focus primarily on descriptive analyses of pedestrian interactions rather than on implementing real-time control algorithms. Consequently, there is a need for a large-scale pedestrian simulation platform with integrated crowd intervention capabilities to support the development of network-wide control strategies.

Keywords Macroscopic pedestrian modeling, network model, crowd management

Introduction

Effective crowd flow management at large events to ensure pedestrian safety and preventing congestion. Existing research has focused mainly on managing crowds in localized areas such as corridors, intersections, or individual venues (e.g. [4, 5]). These studies primarily offer insights into micro-level pedestrian behavior. They often overlook the need for a comprehensive approach to coordinate the crowd in multiple interconnected locations, such as urban footpath networks and stadium complexes. This may limit the efficiency of the coordinating algorithm in a broader pedestrian network. Two key challenges currently hinder progress in network-wide controllers for crowd management. First, agent-based microscopic simulation models though rich in behavioral detail, are computationally prohibitive for simulating large crowds in large public areas. Second, macroscopic network-based models for pedestrian dynamics are underdeveloped. Existing frameworks such as the Link Transmission Model (LTM) [6] and other network-based pedestrian models (e.g. [1, 3]) are either adapted from vehicular traffic (ignoring pedestrian-specific behaviors) or not efficient enough for real-time control algorithms such as serving as the environment for reinforcement learning. This disconnect between simulation and control hinders the development of adaptive, network-wide crowd management.

To bridge this gap, we implemented a Python-based macroscopic pedestrian simulation model that is readily applicable to large-scale pedestrian simulation and can be integrated with real-time crowd management strategies (e.g. crowd redirect, capacity adjustment and flow separator). Compare to the continuum-based models, which are less suited for scenarios with complex route choices, our model can offer a more granular representation of pedestrian movement within a network. The model comprises two main modules: network loading, which simulates the propagation of pedestrian flows, and route split, which simulates the direction of the movement of the crowd. The subsequent sections will provide a detailed explanation of these modules.

Network Loading

Following Lilasathapornkit et al. [3], we implemented network loading using the LTM model. The pedestrian traffic propagation on links is assumed to follow kinematic wave theory and the conservation law, the link model in LTM defines the constraints of sending flow (upstream demand) and receiving flow (downstream supply) and the flow from upstream to downstream is constrained by the supply and demand. Detailed mathematical formulas for calculating the sending and receiving flow can be found in the original paper [6]. Note that the travel time on the link changes dynamically based on the link speed, which is influenced by the bidirectional pedestrian density and also the density-speed fundamental diagram on each link.

Turning Fractions

To simulate the route choice behavior of the pedestrians, we apply the route choice model described in [2] to calculate the turning fraction of the intersections (the nodes). First, k-shortest paths would be generated for each OD pairs. Then, the path condition such as the distance from the current node to the destination, the travel time, the comfort level of the path would be used to determine the utility of choosing a downstream link from a given upstream link, it is calculated using $U_i = \theta_i^T x_i + \epsilon$. In the equation, U_i represents the utility of choosing path i, and ϵ denotes the random error term, which follows a Gumbel distribution. The terms θ_i and x_i correspond to the calibrated coefficient and route condition factors, respectively. The conditional probability $P(\text{down} \mid \text{up}, \text{od})$ is computed using the softmax function: $P(\text{down} \mid \text{up}, \text{od}) = \frac{e^{U_i}}{\sum_j e^{U_j}}$.

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The turning fraction $P(\text{down} \mid \text{up})$ is then obtained by applying the law of total probability:

$$P(down \mid up) = \sum_{od \in S} P(down \mid od, up) P(od \mid up). \tag{1}$$

Here, $P(od \mid up)$ depends on the real-time OD demands. The set S represents all ODs that can be reached by passing through the upstream node.

Preliminary Results

Figure 1 simulates the spill-back effect in the network caused by a bottleneck. To replicate this scenario, we intentionally set the capacity of the downstream link to a very low value to create the bottleneck condition. Figure 2 shows the simulation in a large sidewalk network in the center of Delft. There are two origins in the network and we can see the pedestrian propagate slowly from the origins (red nodes).

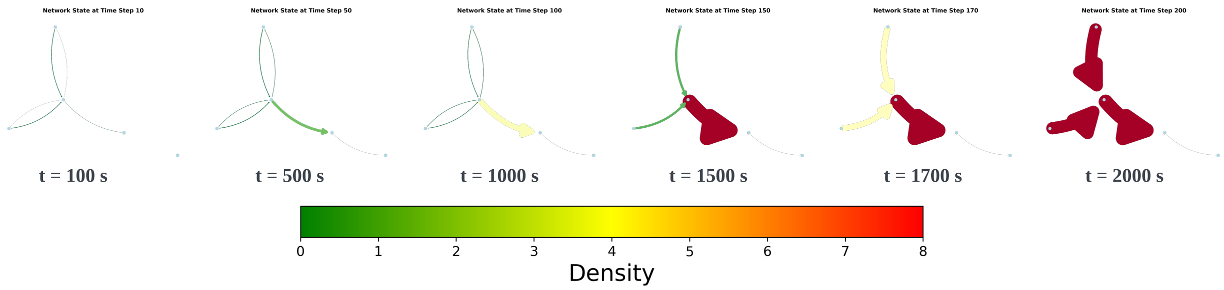

Figure 1: Simulating the spill-back of the flow in the forky intersection due to the bottleneck.

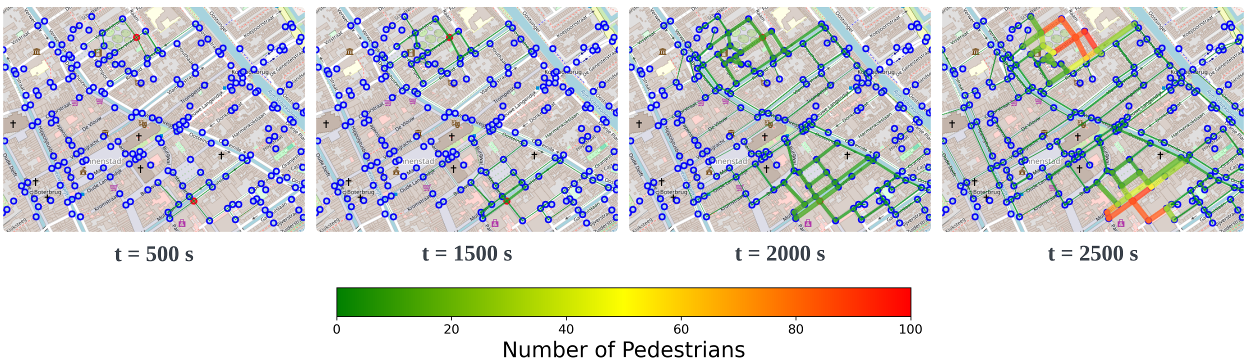

Figure 2: The evolution of the traffic state of the sidewalk network in Delft city center.

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