Towards Safer Pedestrian Traffic: Investigation of the Impact of Social Field Characteristic on Crowd Dynamics

Jingwan Fu, Boxiao Cao, Samer H. Hamdar, and Tianshu Li

Abstract The objective of this paper is to investigate pedestrian safety on vehicle-free platforms. Towards realizing such objective, a microscopic pedestrian movement model is expanded to analyze the implications of different pedestrian behavioral characteristics on pedestrian movement under different density levels. This microscopic modeling approach is flexible and may be efficiently implemented while accounting for different traffic dynamics caused by complex geometric and operational features, such as those observed in transit stations, football stadiums, and rallies. The integrated modeling framework is built based on the Social Field method (i.e., the social force model): the surrounding stimulus is considered, while adding a stopping/vibration module and a tangential force module to the basic Social Field method to account for additional behavioral dimensions based on atomistic interactions between particles. C++ was used to build a simulator to obtain the trajectory of pedestrians in the system. The research has been already translated to two simulated scenarios: the bottleneck scenario and the bi-direction flow scenario. Realistic flow patterns have been produced with a triangular fundamental diagram (flow-density curve) as observed in real-life conditions. When the density goes up, the flow will go up then go down to meet the capacity of the system. The expanded social force model provided improved (lower) error levels once the simulated pedestrian trajectories are compared to the observed pedestrian trajectories. Results show the expanded model produces high-density congestion dynamics that are not captured by the traditional social force model. The dynamics represented the higher clustering of flow-density data points at low flow and high pedestrian levels represent these dynamics.

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1 Introduction

In the recent decades, pedestrian safety has become a significant problem in metropolitan areas both on roadways (mainly due to pedestrian-vehicle collisions) and on pedestrian platforms (mainly due to overcrowding and lack of supply with respect to demand: as is the case crowded metro stations, stadiums, concert halls ..., etc.). Using Washington, D.C. as an example, there were 2624 collisions from 01/01/2013 to 01/01/2015.[1] The report of National Highway Traffic Safety Administration (NHTSA) may indicate that increased volumes for all types of traffic (bicycles, pedestrian, motor vehicles, etc.) create an increase in exposure to risky conflict conditions and the safety of all users requires examination [4].

Towards performing such investigation, the authors explore an integrated modeling approach that captures pedestrian walking behavior in congested and uncongested conditions. The modeling approach is flexible and may be efficiently implemented in order to account for different traffic dynamics caused by complex geometric and operational characteristics, such as those observed in transit stations, football stadiums, and rallies. The integrated modeling framework is built using concepts from the social force model [6, 10, 11, 13], behavioral heuristics [5, 12], and material science [14, 15]. Daamen and Hoogendoorm have done some of the experiments to capture the behavior of pedestrian [2, 3, 8]. C++ was used to build a simulator to obtain the trajectory [1, 9] of pedestrians in the system. From these trajectories, flow-density fundamental [7, 16, 17] diagrams can be derived and analyzed.

2 Methodology

The two behavior modules that are added to Helbing's social force model [6] in order to capture the movement behavior at different density levels are: the tangential force module and the stopping module. The details of the social force model, the tangential force module, and the stopping module are presented next.

2.1 *The Basic Social Force Model*

According to the social force model [6], we can calculate this directional acceleration or movement. Since the social force model is physics based model, the acceleration is determined through a force vector. The sum of all social force vectors determines the movement of pedestrians.

[1] http://dc.ms2soft.com/tcds/tsearch.asp?loc=dc&mod=tmc.

When a pedestrian wants to reach a destination, the desired direction is determined by

$$\mathbf{e} = \frac{\mathbf{x_i^0} - \mathbf{x_i}}{\|\mathbf{x_i^0} - \mathbf{x_i}\|} \tag{1}$$

where $\mathbf{e_i}$ ≡ desired direction, $\mathbf{x_i^0}$ ≡ the original location of pedestrian i, $\mathbf{x_i}$ ≡ the destination of pedestrian i.

The comfortable velocity and the desired velocity are defined as following:

$$\mathbf{v_i^0} = v_i^0 \mathbf{e_i^0} \tag{2}$$

where $\mathbf{e_i^0}$ ≡ desired direction of pedestrian, i v_i^0 ≡ the value of desired velocity, $\mathbf{v_i^0}$ ≡ desired velocity.

The social force is proportional to the difference between the desired velocity and current velocity and is scaled by a relaxation time

$$\mathbf{f_i} = \frac{1}{\tau_i}(\mathbf{v_i^0} - \mathbf{v_i}) \tag{3}$$

where $\mathbf{f_i}$ ≡ social force, τ_i ≡ relaxation time, $\mathbf{v_i^0}$ ≡ desired speed of pedestrian i, $\mathbf{v_i}$ ≡ current speed of pedestrian i.

Moreover, a pedestrian prefers to keep a distance away from other pedestrians through a repulsion potential. The direction of repulsion force is defined by

$$\mathbf{e_{ij}} = \frac{\mathbf{x_i} - \mathbf{x_j}}{\|\mathbf{x_i} - \mathbf{x_j}\|} \tag{4}$$

$$\mathbf{f_{ij}} = \mathbf{e_{ij}} \frac{\partial v}{\partial r} \|\mathbf{x_i} - \mathbf{x_j}\| \tag{5}$$

where $\mathbf{U_{ij}}$ ≡ repulsion potential between $i$and$j$, $\frac{\partial v}{\partial r} \equiv V$ is a monotonic decreasing function of r, $\mathbf{x_i}$ ≡ current location of pedestrian i, $\mathbf{x_j}$ ≡ current location of pedestrian j, r ≡ euclidean distance between pedestrian $i$and$j$, $\mathbf{f_{ij}}$ ≡ repulsion force.

In our research, we considered the surrounding stimulus, then added a tangential force module and a stopping module to the basic social force model to account for additional behavioral dimensions.

2.2 Tangential Force Module

The previous social force model considered repulsion force, but did not consider the collision avoidance. Pedestrians would keep distance away from others while moving towards a destination. When we detected the direction of pedestrian i is different of the direction of pedestrian j, we will force pedestrian i to "detour"

$$\mathbf{e_i} \cdot \mathbf{e_{ij}} < 0 \tag{6}$$

where $\mathbf{e_i} \equiv$ desire direction of i, $\mathbf{e_{ij}} \equiv$ desire direction of j with respect to i.

In order to bypass pedestrian j, the force on pedestrian i should be perpendicular to $\mathbf{e_ij}$, in the direction of

$$\frac{\mathbf{f_i}}{\|\mathbf{f_i}\|} = \mathbf{e_{ij}} \times (\mathbf{e_i} \times \mathbf{e_{ij}}) \tag{7}$$

where $\mathbf{f_i} \equiv$ social force for pedestrian$i$, $\mathbf{e_i} \equiv$ desire direction of i, $\mathbf{e_{ij}} \equiv$ desire direction of j with respect to i.

2.3 Stopping Module

The stopping module is introduced to account for the difference between the human behavior during every-day congested regimes (waiting in lines, stopping with no contact) and particle movements. Particles oscillate at equilibrium position while pedestrians have zero velocity/acceleration at equilibrium position. The velocity at time t is $\mathbf{v}(t)$ and the velocity at the subsequent time step dt becomes $\mathbf{v}(t + dt)$. When $\mathbf{v}(t)$ and $\mathbf{v}(t + dt)$ have different directions

$$\mathbf{v}(t) \cdot \mathbf{v}(t + dt) \le 0 \tag{8}$$

where $\mathbf{v}(t) \equiv$ velocity at time t, $\mathbf{v}(t + dt) \equiv$ velocity at the subsequent time step dt.

In such situation, the pedestrian is forced to make "full stop".

To move again, a pedestrian's movement is governed by a gap acceptance function that can be described as

$$\| \int_0^\infty \mathbf{f}(t - \xi) g(\xi) \| \ge F_0 \int_0^\infty g(\xi) d\xi \tag{9}$$

where $F_0 \equiv$ pre-set starting force magnitude for a pedestrian, $\xi \equiv$ infinitesimally small time period/duration.

3 Results

The fundamental diagrams for the different narrow bottleneck scenario for the different models adopted were extracted from trajectory data and plotted through the use of MATLAB.

Different fundamental diagram under the bottleneck scenario was produced depending on the type of walking model adopted and the measurement area. The original size of the playground is $25 \times 25\,\text{m}$ and with 5 m-width bottleneck. As a first study area (Area1 shows in Fig. 1): the focus was on the coordinates from $x = 3\,\text{m}$ to $x = 23\,\text{m}$ and from $y = 20.5\,\text{m}$ to $y = 4.5\,\text{m}$ (area width = 20 m and arealength $= 16\,\text{m}$).

To reach higher congestion levels, Area2 (shows in Fig. 2) is considered: the point of consideration has the coordinates from $x = 5\,\text{m}$ to $x = 10\,\text{m}$ and from $y = 20\,\text{m}$ to $y = 15\,\text{m}$.

As mentioned earlier, two types of models were tested: the Modified SF models [13] and the basic social force model [6]. In the Modified SF model-1 (i.e., without the tangential force and the stopping modules), two assumptions were made: the first assumption considered that the movement of each pedestrian was impacted by the forces resulting from the nearest three pedestrians who are within a subject's sight-distance; the second assumption considered the nearest three pedestrians irrespectively of the sight-distance. In the Modified SF model-2, all the surrounding forces within a given sight-distance to a target pedestrian were accounted for. Moreover, the stopping module and the tangential force module were incorporated into the basic social force model.

In order to compare the differences between the fundamental diagrams for all the SF model versions, we plot the plow/density fundamental diagrams of these three models on the same graph in Fig. 3.

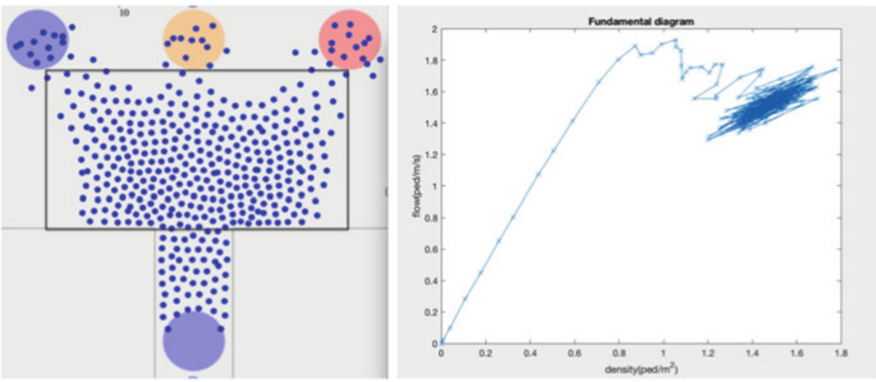

Fig. 1 Area 1: the expanded model fundamental diagram/flow/density relationship under the narrow bottleneck scenario

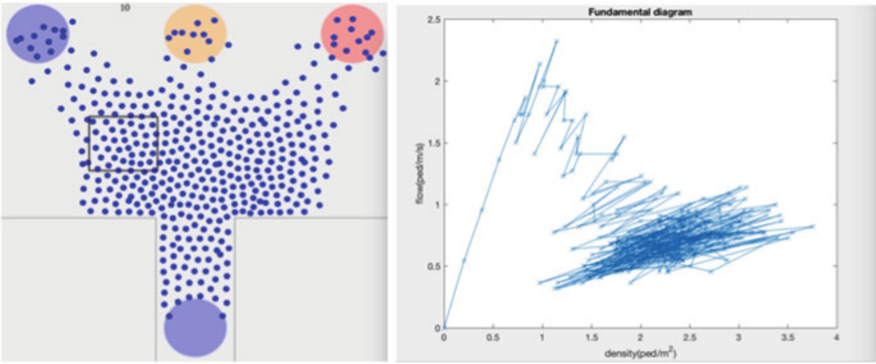

Fig. 2 Area 2: the expanded model fundamental diagram/flow/density relationship under the narrow bottleneck scenario

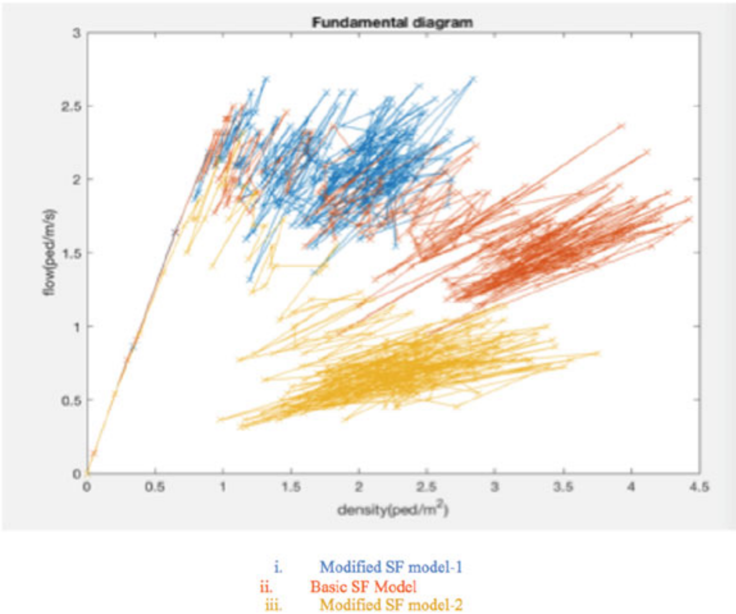

Fig. 3 Comparative illustration of different SF model versions studied in this thesis

The resulting Fig. 3 shows that only the Modified SF model-2 allows the formation of a complete triangular fundamental diagram.

For added insights, the trajectory data for some pedestrians were extracted from both the experimental TU Delft data and the simulation tool in Fig. 4. The X axis represents the time step while the Y axis represents the horizontal directional displacement. A clear shock wave phenomenon (consistent decrease in the slope of the space-time/x-y function) is seen in the first figure of Fig. 4. The only model that

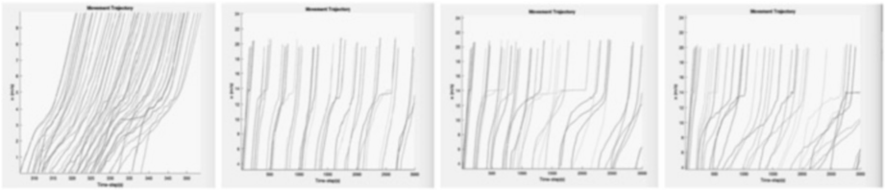

Fig. 4 Trajectory data extracted from the experimental data, the Basic SF model, the Modified SF model-1, and the Modified SF model-2

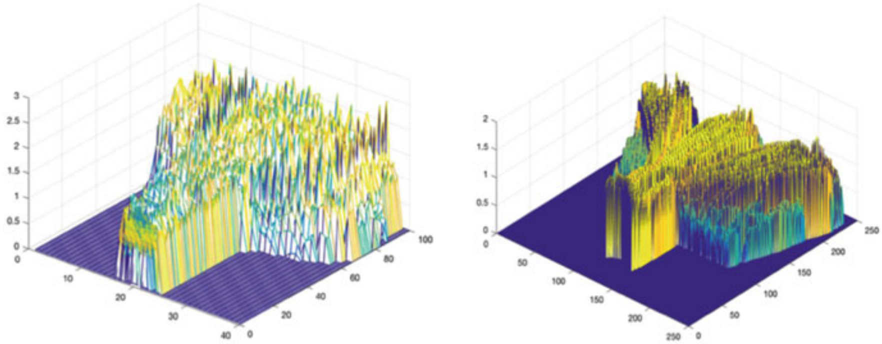

Fig. 5 3D diagrams for the experimental trajectories and the SF model-2 simulated trajectories

captures similar shockwave phenomena is the Modified SF model-2 (the last figure of Fig. 4).

In order to observe the distribution of the average speed in the bottleneck scenario, the 3-Dimensional trajectory figures (with speed represented by the z-axis) are offered in Fig. 5. The 3D diagrams record the average speed for each time step (0.1 s) for both the experimental data and the simulated data generated by the Modified social force model-2. It can be observed that the average speeds are similar in both diagrams.

4 Conclusion

Two modules have been added to expand on the basic social force model while incorporating perception related constraints associated with the cognitive and physiological capabilities of pedestrians (i.e., number of pedestrians considered and sight-distances). The modules added are a tangential force module to allow avoidance maneuvers and a stopping module allowing waiting and gap acceptance maneuvers in crowded situations. Different versions of the SF model (along with the proposed expanded SF model) are implemented and simulated. From the simulation exercise, by comparing the expanded SF model with the remaining versions of the

SF model, it was deduced that the formulation suggested in this thesis leads to more realistic pedestrian trajectories and thus behavior. The fundamental flow/density diagram resulting from the expanded SF model captured jamming and shockwave conditions observed in real-word crowded conditions. In other words, the model suggested in this thesis can efficiently be implemented while accounting for different crowd dynamics caused by complex geometric and operational features. In the future works, we will concentrate on the model calibration via genetic algorithm and combine the pedestrian traffic with bicycle and vehicle traffic.

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