Pedestrian Traffic Characterization Based on Pedestrian Response

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ABSTRACT There are significant differences in pedestrian behavior between normal and emergency conditions. Further, this behavior varies with age. Therefore, in this paper, pedestrian behavior is studied during normal and emergency evacuation of two groups of students from classrooms. One group consists of grade nine high school students while the other includes diploma (college) students. The evacuation time, number of steps, step frequency, and velocity are observed. It is found that the number of steps, step frequency, and velocity are larger during an emergency evacuation. Further, pedestrian response to forward conditions is based on the step size and velocity. These results are used to develop a macroscopic pedestrian response model. The performance of this model and the Lighthill, Whitham, and Richards (LWR) model for pedestrian traffic is compared using the First Order Centered (FORCE) scheme. Pedestrian parameters from the experiments are used for model evaluation. The direction of pedestrian movement is changed multiple times to observe pedestrian alignment behavior. The results obtained show that pedestrians follow changes in direction and align to forward conditions. The behavior with the LWR model is uniform for all changes in direction and alignment is instantaneous, which is impossible. Conversely, pedestrian behavior with the proposed model is realistic.

INDEX TERMS Pedestrian behavior, evacuation, LWR model, two-dimensional pedestrian model.
to a panic situation. A similar event in Shanghai, China on December 31, 2015, resulted in 35 fatalities [16], [17]. Thus, effective pedestrian models are required to provide better crowd control strategies.

Experimental results reveal that exit locations also impact pedestrian behavior. For example, traffic flow at corner exits is more efficient than in the middle of walls [18]. The time for pedestrians to align to forward conditions is smaller at corner exits when running slow or normally.

Step size is an important factor in pedestrian movement [18], [19]. The step size is the distance between consecutive steps of the left and right feet [20]. The step frequency is the number of steps per unit time [21], [22]. Pedestrian conditions affect the step size, step frequency (cadence), and velocity. The step size decreases with an increase in density as the distance between pedestrians is smaller. Thus, the flow is reduced [21] while the number of steps increases. When the density is high pedestrians tend to follow each other according to the velocity of those in the lead [23]. The pedestrian step size is uniform and does not change. As the distance between pedestrians increases, following may not occur and the step size varies [13]. The evacuation time is higher for a fixed step size compared to a variable step size [13]. During an emergency, pedestrian dynamics change such that the step size decreases while the number of steps increases [24].

Pedestrian traffic bottlenecks occur due to an increase in arrival rate and this results in a decrease in velocity [11]. Pedestrians adjust their velocity and step size at bottlenecks to avoid collisions and maintain distances between them. They accelerate when emerging from bottlenecks by increasing the step frequency [18]. When the density is low, pedestrians can maintain their desired velocity. As the density increases, the velocity decreases until movement is stop-and-go [25], [26], [27], [28], [29]. Pedestrians adjust their velocity according to their surroundings to avoid collisions and maintain comfort [26].

Pedestrian response to forward conditions depends on age, gender, and disabilities [27]. For example, males typically cross roads faster than females, and senior citizens are slower than young adults. Moreover, profession [28] and location also affect velocity [29], [30]. It has been observed that pedestrian velocity in Khulna, Bangladesh, is 51.7 m/min, while in Asian cities it ranges from 52.0 m/min to 93.6 m/min, and in American and European cities between 79.0 m/min and 88.0 m/min [29]. The time of day also impacts pedestrian velocity. During working hours, this velocity is greater than at other times [25]. Moreover, pedestrian behavior can differ according to location conditions [31]. In some situations, sidewalks are used by merchants and vendors, and there are parked vehicles, so pedestrians are forced to walk on the road or shoulders which leads to bottlenecks [26]. Thus, accurate modeling of pedestrian behavior during normal and emergency conditions is necessary for effective control of pedestrian flow. This modeling should realistically characterize the spatial and temporal changes in flow.

Microscopic, mesoscopic, and macroscopic traffic flow models have been developed [32], [33]. Microscopic models characterize individual pedestrian behavior. They predict the velocity and trajectory of pedestrians along with their interactions. Macroscopic models consider aggregate behavior based on speed, density, and flow. These models are used to predict effects such as congestion, delay, and queue formation [33]. Thus, they are appropriate to model crowd dynamics. Mesoscopic models combine the properties of microscopic and macroscopic models. These models consider individual pedestrian parameters and are used to predict aggregate behavior. Macroscopic models have low computational complexity and are easy to implement in software. Further, they can predict parameters such as flow [34], [35], [36], [37], which is important during an evacuation. Therefore, in this paper, a macroscopic pedestrian traffic model is developed for flow prediction.

The first macroscopic model is the Lighthill, Whitham, and Richards (LWR) model [38], [39]. However, it ignores pedestrian dynamics [40]. Further, it assumes only small changes in velocity [41], [42], [43] and does not consider delay [44] or stop-and-go behavior [44], [45], [46]. A fluid dynamic pedestrian model was proposed in [47] which is based on the Boltzmann gas kinetic model. However, it provides inaccurate results when the density is low.

Payne and Whitham developed the Payne Whitham (PW) model which characterizes traffic acceleration to align to forward conditions. However, the response is based on a constant which is unrealistic [48]. This model was improved [49] to incorporate interactions as there are more interactions with a higher density [50]. However, fluid-like behavior is assumed which is not suitable so the results obtained are poor. Further, the computational complexity of this model is high. The Zhang model is based on changes in the equilibrium velocity distribution [51]. However, pedestrian characteristics such as step size, step frequency, and transition velocity are ignored. The Berg, Mason, and Woods model [52] considers the distance between pedestrians and includes parameters such as diffusion and viscosity to smooth large changes. However, the characterization is inappropriate as other pedestrian parameters are ignored.

In [53] a higher-order macroscopic pedestrian flow model was proposed which considers pedestrian groups as anisotropic. However, pedestrians exhibit isotropic behavior, and this model ignores the interaction dynamics in a crowd. In [54], a macroscopic pedestrian model was developed which incorporates the effect of panic. This model can be employed in both panic and non-panic situations. However, there are many variables, and the psychological behavior of pedestrians is ignored. A macroscopic model was developed in [17] based on the concept of crowd convergence. A T-shaped junction was considered for evaluation. Mesoscopic approaches have also been developed [55], [56]. However, most models focus on higher-order dynamics rather than improving first-order models such as the LWR model by considering pedestrian parameters. Thus, a two-dimensional...
A macroscopic pedestrian model is proposed based on the step frequency, step size, and pedestrian response to characterize pedestrian behavior during evacuations accurately and realistically.

In this paper, the results of four experiments to observe crowd dynamics considering age and scenario are presented. The groups are Grade 9 school students and third-year college students. The scenarios are normal and emergency evacuations. Velocity, step frequency, and the number of steps were recorded during the experiments. Then, a macroscopic model is developed to characterize pedestrian behavior which has lower computational complexity than existing mesoscopic and microscopic models [14], [57]. This model is based on step frequency, step size, and transition velocity during alignment. The proposed and LWR models are numerically discretized using the first-order upwind scheme to compare their performance. The simulations are performed in an area of size $30 \times 30$ m ($900$ m$^2$).

The rest of this paper is organized as follows. Section II presents the crowd evacuation experiments and the corresponding results are used in Section III to develop a pedestrian flow model. The performance of the proposed and LWR models is evaluated in Section IV. Finally, Section V gives some concluding remarks.

II. CROWD EVACUATION EXPERIMENTS

During emergency evacuations, significant behavioral changes occur and the interactions among pedestrians increase which affect the velocity [31], [16]. To capture and understand these changes, evacuation experiments were performed during emergency and normal situations. Students were chosen for the experiments to provide homogeneous groups for comparison purposes. There were two groups of students, 40 students in the first group with ages between 14 and 16 years and 30 students in the second group with ages between 17 and 20 years. Four pedestrian evacuation experiments were conducted, two with each group considering normal and emergency situations.

A. FIRST GROUP EVACUATION

The first group was in a classroom on the first floor of a school. The width and length of the classroom is 9.20 m with an exit to a corridor. Two doors open to this corridor, each of width 0.92 m and height 1.83 m. Only one door is used for evacuation. The layout of the classroom is shown in Figure 1. An area of $1.00 \times 1.00$ m was marked at the egress to record pedestrian density for both the normal and emergency evacuation experiments. It is shown as a red line in Figure 2.

To enable better tracking and collection of data, each student had a pedometer in their pocket to provide the number of steps, step size (length), step frequency, time, and distance covered. Two cameras were also used to record their behavior. They were installed inside the classroom opposite the exit door and outside the classroom in front of this door. The positions of the cameras are shown in Figure 1. The elapsed time was also monitored using a stopwatch. Pedestrian density is the number of pedestrians per unit area and so is expressed as pedestrians per square meter [60]. The density was determined manually using data from the cameras. The step frequency was obtained from the number of steps recorded by the pedometer and the time for evacuation.

For normal evacuation, the students were directed to move at their typical (or comfortable) speed and not to endanger their safety as shown in Figure 3. A person was located outside the classroom to observe the students and ensure their safety. The evacuation time for each student is given in Table 1 along with the corresponding distance covered. This information was used to determine the velocity. The number of steps is also given in the table. The step length was fixed in the pedometer at 0.60 m based on their average height of 1.66 m [20]. Moreover, the density at the exit was observed to be 2.00 p/m$^2$.

For emergency evacuation, the students were directed to move as in a panic situation when the emergency alarms began to ring. They were told to act as though they were in...
TABLE 1. Time, step length, step frequency, velocity, and density for normal evacuation with the first group.

| Student No. | Time (s) | No. of Steps | Distance Covered (m) | Cadence (steps/s) | Step Length (m) | Velocity (m/s) | Density (p/m²) |
|-------------|----------|--------------|----------------------|-------------------|----------------|---------------|---------------|
| 1           | 49.0     | 56.0         | 33.0                 | 1.14              | 0.67           |               |               |
| 2           | 53.0     | 63.0         | 36.0                 | 1.18              | 0.68           |               |               |
| 3           | 55.0     | 59.0         | 35.0                 | 1.07              | 0.64           |               |               |
| 4           | 50.0     | 50.0         | 31.0                 | 1.00              | 0.62           |               |               |
| 5           | 50.0     | 65.0         | 38.0                 | 1.30              | 0.76           |               |               |
| 6           | 48.0     | 58.0         | 33.0                 | 1.20              | 0.69           |               |               |
| 7           | 52.0     | 60.0         | 31.0                 | 1.15              | 0.60           |               |               |
| 8           | 56.0     | 53.0         | 28.0                 | 0.95              | 0.50           |               |               |
| 9           | 48.0     | 58.0         | 33.0                 | 1.20              | 0.69           |               |               |
| 10          | 53.0     | 62.0         | 32.0                 | 1.16              | 0.60           |               |               |
| 11          | 49.0     | 55.0         | 32.0                 | 1.12              | 0.65           |               |               |
| 12          | 48.0     | 49.0         | 28.0                 | 1.00              | 0.58           |               |               |
| 13          | 53.0     | 52.0         | 31.0                 | 1.00              | 0.58           |               |               |
| 14          | 54.0     | 53.0         | 32.0                 | 0.98              | 0.59           |               |               |
| 15          | 46.0     | 54.0         | 32.0                 | 1.17              | 0.70           |               |               |
| 16          | 56.0     | 55.0         | 33.0                 | 0.98              | 0.59           |               |               |
| 17          | 55.0     | 63.0         | 37.0                 | 1.45              | 0.67           |               |               |
| 18          | 51.0     | 54.0         | 32.0                 | 1.00              | 0.63           |               |               |
| 19          | 55.0     | 55.0         | 33.0                 | 1.00              | 0.60           |               |               |
| 20          | 54.0     | 62.0         | 37.0                 | 1.14              | 0.69           |               |               |
| 21          | 53.0     | 56.0         | 33.0                 | 1.00              | 0.62           |               |               |
| 22          | 52.0     | 61.0         | 36.0                 | 1.17              | 0.69           |               |               |
| 23          | 54.0     | 55.0         | 33.0                 | 1.00              | 0.61           |               |               |
| 24          | 55.0     | 51.0         | 30.0                 | 0.92              | 0.55           |               |               |
| 25          | 56.0     | 60.0         | 36.0                 | 1.00              | 0.64           |               |               |
| 26          | 54.0     | 56.0         | 33.0                 | 1.00              | 0.61           |               |               |
| 27          | 47.0     | 47.0         | 28.0                 | 1.00              | 0.60           |               |               |
| 28          | 57.0     | 53.0         | 32.0                 | 0.92              | 0.56           |               |               |
| 29          | 48.0     | 51.0         | 31.0                 | 1.00              | 0.65           |               |               |
| 30          | 54.0     | 56.0         | 34.0                 | 1.00              | 0.63           |               |               |
| 31          | 56.0     | 57.0         | 34.0                 | 1.00              | 0.61           |               |               |
| 32          | 51.0     | 61.0         | 37.0                 | 1.20              | 0.75           |               |               |
| 33          | 53.0     | 56.0         | 34.0                 | 1.10              | 0.64           |               |               |
| 34          | 54.0     | 53.0         | 31.0                 | 0.98              | 0.57           |               |               |
| 35          | 48.0     | 62.0         | 37.0                 | 1.30              | 0.77           |               |               |
| 36          | 51.0     | 57.0         | 34.0                 | 1.12              | 0.67           |               |               |
| 37          | 54.0     | 59.0         | 35.0                 | 1.10              | 0.65           |               |               |
| 38          | 55.0     | 52.0         | 31.0                 | 0.98              | 0.56           |               |               |
| 39          | 54.0     | 59.0         | 35.0                 | 1.10              | 0.65           |               |               |
| 40          | 53.0     | 62.0         | 37.0                 | 1.16              | 0.70           |               |               |
| Average     |          |              |                      |                   | 0.63           |               |               |

FIGURE 4. First group egress during emergency evacuation.

danger and thus disregard their safety as shown in Figure 4. A person was located outside the classroom to observe the students and ensure their safety. The evacuation time for each student is given in Table 2 along with the corresponding distance covered. The step length was reduced to 0.40 m as the step length decreases with increasing density [21], [61]. Moreover, the results obtained indicate that the density at the exit increased to 5.00 p/m² during the emergency evacuation from 2.00 p/m² during the normal evacuation.

B. SECOND GROUP EVACUATION

Normal and emergency evacuation experiments were also conducted with the students in the second group. Figure 5 shows the normal evacuation, while Figure 6 shows the emergency evacuation. They were in a ground-floor classroom with dimensions 7.62 m × 10.66 m and one exit.
FIGURE 5. Second group egress during normal evacuation.

FIGURE 6. Second group egress during emergency evacuation.

to a corridor. This exit is in the front of the room and has width 0.92 m and height 1.83 m. The rest of the experimental setup was the same as with the first group, and pedometer, manual, and video data were obtained. Table 3 gives the normal evacuation results and Table 4 gives the emergency evacuation results.

For normal evacuation, Tables 1 and 3 indicate that the average evacuation time for the first and second groups is 53.0 s and 52.0 s, respectively. The corresponding average number of steps is 56.0 and 57.3, respectively, while the average distance covered by the first group is 33.0 m and the second group is 34.0 m. The average frequency is 1.06 steps/s for the first group and 1.10 steps/s for the second group. The average velocity during normal evacuation for the first group is 0.63 m/s, while for the second group it is 0.66 m/s.

For emergency evacuation, Tables 2 and 4 indicate that the average evacuation time for the first and second groups is 26.0 s and 30.3 s, respectively. The corresponding number of steps is 82.0 and 84.0, respectively. The average distance covered by the first group is 33.0 m and by the second group is 34.0 m. The average frequency is 3.18 steps/s for the first group and 2.80 steps/s for the second group. The average velocity during normal evacuation for the first group is 1.27 m/s, while for the second group it is 1.12 m/s. Thus, this model cannot accurately characterize traffic at abrupt changes such as traffic capacity drops and stop-and-go traffic [43], [62]. The LWR model for one-dimensional flow is given by

$$\frac{\partial (\rho)}{\partial t} + \frac{\partial (\rho V_{eq})}{\partial x} = 0,$$

where \( \rho \) is density and \( V_{eq} \) is the equilibrium velocity distribution. Several equilibrium velocity distribution models have been developed. The Greenshields model [63] is the simplest and most commonly used which is given \( V_{eq} = V_m \left( 1 - \frac{\rho}{\rho_m} \right) \), where \( \rho_m \) is the maximum traffic density and \( V_m \) is the maximum velocity. Equation (1) characterizes traffic flow in a single direction. For pedestrians moving in different directions, this model can be extended to two dimensions [38], [64]

$$\frac{\partial (\rho)}{\partial t} + \frac{\partial (\rho V_{eq})}{\partial x} + \frac{\partial (\rho V_{eq})}{\partial y} = 0.$$
due to a stampede [65]. The two-dimensional LWR model (2) ignores the pedestrian response to a stimulus such as congestion. This results in instantaneous changes in traffic which is unrealistic. To adequately characterize spatial and temporal traffic evolution, pedestrian response must be considered in the model.

Pedestrians can walk independently or follow others. Pedestrian behavior is based on stimuli that can be classified as sensory, state, or event based [66]. Pedestrian reaction to a stimulus is called sensitiveness [67]. A pedestrian is more reactive during an emergency. Typically, a sensory stimulus causes a behavioral reaction that depends on personality [10]. Pedestrian response can be characterized as the product of reaction and stimuli [68], [69]

reaction \times \text{stimuli.} \tag{3}

During an emergency, behavior is driven by fear which results in reactions such as a stampede towards an egress [9]. Pedestrian response can be characterized by the number of steps [21] so that when the density is large the number of steps increases [24]. Thus, in an emergency

\[
\frac{N_n}{N_e} < 1,
\]

where \(N_n\) is the step size in normal conditions and \(N_e\) is the step size during an emergency. In a normal situation \(N_e = N_n\), so that

\[
\frac{N_n}{N_e} = 1.
\]

The step frequency (cadence) will change in response to local conditions resulting in a transition. During a transition, pedestrians react to forward conditions with a transition velocity \(V_{tr}\). This is analogous to wave velocity where the wave frequency \(f\) is the step frequency. A larger step frequency and larger step size mean the velocity at transitions is greater [8], [25], so

\[
V_{tr} = fN, \tag{4}
\]

where \(f\) is the step frequency and \(N\) is the step size. Pedestrian response to forward conditions based on (3) is then

\[
\frac{N_n}{N_e} V_{tr}. \tag{5}
\]

The step size [18] is affected by the group size due to interactions within the group [14]. The pedestrian step size decreases with an increase in density as there is less clear space ahead [21], while the number of steps increases. Pedestrian behavior is affected by the speed of the lead pedestrians in the group [23]. Pedestrian response is also influenced by backward conditions [14]. The response to the backward conditions can be expressed as

\[
(1 - \frac{N_n}{N_e}) V_{tr}. \tag{6}
\]

Thus, the pedestrian transition velocity \(V_t\) is a function of both the forward (5) and backward conditions (6) given by

\[
V_t = \left(1 - \frac{N_n}{N_e}\right) V_{tr} + \frac{N_n}{N_e} V_{tr}. \tag{7}
\]

Substituting (4), (5), and (6) in (7) gives

\[
V_t = \left(1 - \frac{N_n}{N_e}\right) fN + \frac{N_n}{N_e} fN. \tag{8}
\]

Pedestrian response at a transition can be expressed as \(\rho \frac{V_{eq}^2 V^2}{V_t} \) [70]. This indicates that pedestrians align to the equilibrium velocity distribution and changes during the transition occur at velocity \(V_t\). Substituting \(\rho \frac{V_{eq}^2 V^2}{V_t} \) in (2) gives

\[
\frac{\partial (\rho)}{\partial t} + \frac{\partial (\rho)}{\partial x} \left[\frac{V_{eq}^2 - V^2}{V_t}\right] \frac{\partial V_{eq}^2 - V^2}{\partial y} V_t = 0 \tag{9}
\]

where \([V_{eq}^2 V^2]\) is the pedestrian traffic flow alignment to the equilibrium velocity distribution at transitions [18], [70], [71], and results in a homogeneous flow [2]. Substituting (8) in (9) to include the impact of forward and backward conditions results in

\[
\frac{\partial (\rho)}{\partial t} + \frac{\partial (\rho)}{\partial x} \left[\frac{V_{eq}^2 - V^2}{\left(1 - \frac{N_n}{N_e}\right) fN + \left(\frac{N_n}{N_e}\right) fN}\right] + \frac{\partial (\rho)}{\partial y} \left[\frac{V_{eq}^2 - V^2}{\left(1 - \frac{N_n}{N_e}\right) fN + \left(\frac{N_n}{N_e}\right) fN}\right] = 0. \tag{10}
\]

This indicates that pedestrian traffic evolves temporally and spatially according to the difference in velocity and local pedestrian conditions. However, the LWR model ignores both transitions and pedestrian behavior. Thus, this model is inadequate and so results in unrealistic pedestrian traffic characterization as will be shown in the next section.

IV. PERFORMANCE RESULTS

In this section, the proposed model is compared with the LWR model as it is a first-order model and thus has similar computational complexity. Further, both models conserve changes in pedestrian behavior [33]. Pedestrian macroscopic traffic flow models are a system of partial differential equations. Thus, the proposed and LWR models can be numerically discretized using the First Order Centered (FORCE) scheme for performance evaluation [72], [73], [74]. This scheme was implemented in MATLAB. The maximum speed in the \(x\) direction is 1.36 m/s, while in the \(y\) direction it is 1.40 m/s. The simulation step size is 0.20 m in both directions over an area of 30 m \(\times\) 30 m. To ensure accurate results, the time step is set to 0.02 s which satisfies the Courant-Friedrichs-Levy (CFL) condition [75]. The simulation time is 4.00 s. The pedestrian step sizes are the same as in Tables 3 and 4. From 0 s to 0.20 s they move in the \(x\) direction, from 0.20 s to 1.00 s in the negative \(y\) direction, from 1.00 s to 2.00 s in the negative \(x\) direction, and from
2.00 s to 4.00 s in the y direction. The simulation parameters are given in Table 5. The maximum density is \( \rho_m = 1 \) which means pedestrians cover 100\% of the area [33]. The target is Greenshields equilibrium velocity distribution to align to forward conditions.

### TABLE 4. Time, step length, step frequency, velocity, and density for emergency evacuation with the second group.

| Student No. | Time (s) | No. of Steps | Distance Covered (m) | Cadence (steps/s) | Velocity (m/s) |
|-------------|----------|--------------|----------------------|-------------------|---------------|
| 1           | 31.0     | 81.0         | 32.0                 | 2.61              | 1.03          |
| 2           | 36.0     | 93.0         | 37.0                 | 2.58              | 1.03          |
| 3           | 30.0     | 80.0         | 32.0                 | 2.66              | 1.07          |
| 4           | 31.0     | 82.0         | 32.0                 | 2.64              | 1.03          |
| 5           | 27.0     | 76.0         | 30.0                 | 2.81              | 1.11          |
| 6           | 29.0     | 73.0         | 29.0                 | 2.51              | 1.00          |
| 7           | 32.0     | 93.0         | 37.0                 | 2.90              | 1.16          |
| 8           | 30.0     | 90.0         | 36.0                 | 3.00              | 1.20          |
| 9           | 32.0     | 87.0         | 35.0                 | 2.71              | 1.09          |
| 10          | 28.0     | 83.0         | 33.0                 | 2.96              | 1.18          |
| 11          | 31.0     | 91.0         | 36.0                 | 2.93              | 1.16          |
| 12          | 32.0     | 90.0         | 36.0                 | 2.81              | 1.13          |
| 13          | 29.0     | 79.0         | 32.0                 | 2.72              | 1.10          |
| 14          | 34.0     | 91.0         | 36.0                 | 2.67              | 1.06          |
| 15          | 32.0     | 82.0         | 33.0                 | 2.56              | 1.03          |
| 16          | 32.0     | 85.0         | 33.0                 | 2.59              | 1.03          |
| 17          | 25.0     | 77.0         | 31.0                 | 3.08              | 1.24          |
| 18          | 30.0     | 71.0         | 28.0                 | 2.36              | 0.93          |
| 19          | 30.0     | 91.0         | 36.0                 | 3.03              | 1.20          |
| 20          | 32.0     | 89.0         | 36.0                 | 2.78              | 1.13          |
| 21          | 29.0     | 89.0         | 36.0                 | 3.06              | 1.24          |
| 22          | 30.0     | 85.0         | 34.0                 | 2.83              | 1.13          |
| 23          | 29.0     | 93.0         | 37.0                 | 3.20              | 1.28          |
| 24          | 30.0     | 89.0         | 36.0                 | 2.96              | 1.20          |
| 25          | 28.0     | 80.0         | 32.0                 | 2.85              | 1.14          |
| 26          | 34.0     | 91.0         | 36.0                 | 2.67              | 1.06          |
| 27          | 27.0     | 84.0         | 34.0                 | 3.11              | 1.26          |
| 28          | 34.0     | 83.0         | 33.0                 | 2.44              | 0.97          |
| 29          | 29.0     | 79.0         | 32.0                 | 2.72              | 1.10          |
| 30          | 31.0     | 75.0         | 30.0                 | 2.41              | 0.97          |
| Average     | 30.3     | 84.0         | 34.0                 | 2.8               | 1.12          |

**FIGURE 7. Initial pedestrian density distribution.**

Figures 7 and 8 show the initial density distribution for both models. Figure 8 gives the contours of the density in Figure 7. The density at 20 m in the x and y directions is 0.90, and at 15 m in the x direction and 20 m in the y direction, it is 0.50.

Figures 9 and 10 show the LWR model pedestrian density at 0.18 s. The pedestrians move in the x direction. The maximum density is 0.90, which occurs at 20 m in the x and y directions. At 15 m in the x direction and 20 m in the y direction, the density decreases to 0.50. The contours in Figure 10 show that the pedestrian behavior is very similar to the initial conditions, so there is no significant change in movement after 0.18 s, which is unrealistic.

### TABLE 5. Simulation parameters.

| Parameter                                      | Value   |
|------------------------------------------------|---------|
| Maximum velocity in the x direction            | 1.36 m/s|
| Maximum velocity in the y direction            | 1.40 m/s|
| Simulation step size                           | 0.2 0m  |
| Simulation time                                 | 4.00 s  |
| Time step                                      | 0.02 s  |
| Maximum density \( \rho_m \)                   | 1.00    |
| Equilibrium velocity distribution \( v(\rho) \)| Greenshields |
| Normal evacuation step size \( N_n \)          | 0.60 m  |
| Emergency evacuation step size \( N_e \)       | 0.40 m  |
| Area                                           | 30 m \( \times \) 30 m |
| Pedestrian direction 0 s to 0.20 s              | positive x |
| Pedestrian direction 0.20 s to 1.00 s           | negative y |
| Pedestrian direction 1.00 s to 2.00 s           | negative x |
| Pedestrian direction 2.00 s to 4.00 s           | positive y |
| Step frequency                                 | 1.50 steps/s |

**FIGURE 8. Initial pedestrian density contours.**

**FIGURE 9. LWR model density after 0.18 s with maximum velocity 1.36 m/s in the x direction and pedestrian movement in the x direction.**
Figures 11 and 12 show the LWR model pedestrian density after 0.98 s. The pedestrians now move in the negative y direction. The maximum density is 0.80. The density contours in Figure 12 show that the pedestrians are spread over an area between 7 m and 30 m in both directions.

Figures 13 and 14 show the LWR model pedestrian density after 1.98 s. The pedestrians now move in the negative x direction. The maximum density is 0.90 at 21 m in both the x and y directions. There are small variations in density in both directions even though pedestrians move in the negative x direction. Further, the contours in Figure 14 show that they exit the area in both directions. The density gradually decreases in all directions. The contours lie between 9 m and 30 m in the x direction and 12 m and 30 m in the y direction. Thus, pedestrian behavior is close to uniform which is not realistic.

Figures 15 and 16 show the LWR model pedestrian density after 3.98 s. Movement is in the negative x direction, but Figure 16 indicates that there are only small variations in density in both directions. This is unrealistic as there are no significant changes in density even though there are abrupt changes in movement. This is because the LWR model cannot characterize such changes.

Figures 17 to 24 present the pedestrian density with the proposed model after 0.18 s, 0.98 s, 1.98 s, and 3.98 s. Figures 17 and 18 give the results after 0.18 s with movement in the x direction. The maximum density is 0.90 and the direction of movement is in the x direction. The minimum density is 0.10 which occurs at 9 m and 30 m in the x and y directions,
respectively. The pedestrian contours lie between 9 m and 30 m in both directions.

Figures 19 and 20 present the density with the proposed model at 0.98 s. Pedestrian movement is now in the negative y direction. These results indicate that the maximum density is 0.80. The pedestrian contours lie between 7 m and 28 m in the x direction and 7 m and 27 m in the y direction. The 0.10 and 0.20 density contours are at 7 m and 10 m, respectively, in the y direction at 20 m in the x direction. The distance between these contours is 3 m. In the opposite direction of pedestrian flow, at 20 m in the x direction, these contours lie at 28 m and 26 m, respectively, in the y direction, so the distance between them is 2 m. The 0.20 and 0.30 density contours are at 10 m and 12 m, respectively, in the y direction at 20 m in the x direction. The distance between these contours is 2 m. In the opposite direction of pedestrian flow, at 20 m in the x direction, these contours lie at 26 m and 25 m, respectively, in the y direction. The distance between these contours is 1 m.
The 0.30 and 0.60 density contours are at 12 m and 15 m, respectively, in the y direction at 20 m in the x direction. The distance between these contours is 3 m. In the opposite direction of pedestrian flow, at 20 m in the x direction, the 0.30 and 0.60 contours lie at 25 m and 23.5 m, respectively, in the y direction. The distance between these contours is 1.50 m. Thus, the proposed model follows the direction of pedestrian movement.

Figures 21 and 22 present the density with the proposed model at 1.98 s. Pedestrian movement is in the negative x direction. The contours lie between 5 m and 26 m in both directions and the minimum and maximum densities are 0.10 and 0.90, respectively. The maximum density contour lies between 16 m and 18 m in the x direction. The 0.10 and 0.50 density contours are at 5 m and 12 m, respectively, in the x direction at 15 m in the y direction. The distance between these contours is 7 m. In the opposite direction of pedestrian flow, at 15 m in the y direction, the 0.10 and 0.50 contours lie at 26 m and 22 m, respectively, in the x direction. The distance between these contours is 4 m, thus there is a difference of 3 m between the contours depending on the direction of flow. This shows that the proposed model follows the direction of flow.

Figures 23 and 24 present the density with the proposed model at 3.98 s. Pedestrian movement is in the y direction. The maximum density is 0.80 while the minimum is 0.10. The maximum density contour lies between 13 m and 16 m in the x direction at 10 m in the y direction. The minimum density contour lies between 3 m and 23 m in the x direction at 15 m in the y direction. The contours lie between 3 m and 23 m in the x direction and 6 m and 27 m in the y direction. The 0.10 and 0.50 density contours are at 27 m and 10 m, respectively, in the y direction at 10 m in the x direction. The distance between the 0.10 and 0.50 contours is 17 m. In the opposite direction of flow, these contours lie at 6 m and 8 m, respectively, in the y direction. The distance between these contours is 2 m, so there is a difference of 15 m in this direction depending on the direction of flow. Thus, pedestrian movement with the proposed model follows the direction of flow.

The center of the contours with the LWR model at 0.18 s lies at 20 m in both directions as shown in Figure 10, and remains at 20 m after 0.98 s as shown in Figure 12. At 1.98 s it is at 19 m in both directions as shown in Figure 14, and remains there at 3.98 s as shown in Figure 16. Thus, from 0.18 s to 3.98 s, the center of the contours moves only 1 m in both directions. The center of the contours with the proposed model at 0.18 s also lies at 20 m in both directions as shown in Figure 18, and remains there after 0.98 s as shown in Figure 20. At 1.98 s it is at 17 m in both directions as shown in Figure 22, and moves to 13 m in the x direction and 10 m in the y direction at 3.98 s as shown in Figure 24. From 1.98 s to 3.98 s, the center of the contours moves 4 m in the x direction and 7 m in the y direction. From 0.18 s to 3.98 s, it moves 7 m in the x direction and 10 m in the y direction. This shows that pedestrians move a greater distance with the proposed model. Further, they follow the changes in direction whereas with the LWR model the movements are almost uniform, which is unrealistic.

V. CONCLUSION

In this paper, emergency and normal evacuation experiment results for two groups of students (Grade 9 and college), were presented. They indicate that the number of steps, step frequency, and velocity are larger during an emergency evacuation, and the evacuation time is smaller than in a normal evacuation. These results were used to develop a new pedestrian response model. The behavior of this model was compared with the well-known LWR model. The results obtained indicate that the proposed model is more realistic than the LWR model. In particular, pedestrians move according to direction and velocity, whereas movement with the LWR model is much smaller and almost uniform. This is because the LWR model cannot characterize pedestrian behavior during transitions and as a result alignment to forward conditions occurs instantaneously.

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