Exploring Area-Wide Dynamics of Pedestrian Crowds: Three-Dimensional Approach

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Exploring Area-Wide Dynamics of Pedestrian Crowds Using a Three-Dimensional Approach

Meead Saberi and Hani Mahmassani

Abstract

The main objective of this paper is to evaluate the existing measurement methods of pedestrian traffic flow and propose a three-dimensional approach, extending Edie’s definitions of fundamental traffic variables to multi-directional walking areas using three-dimensional pedestrian trajectories. It is found that similar to the notion of the Network Fundamental Diagram (NFD) of vehicular traffic, pedestrian crowds have an area-wide fundamental diagram. It is also shown that pedestrian traffic in a multidirectional area, exhibits hysteretic behavior similar to some other many-particle physical systems. Moreover, this paper explores some of the underlying dynamics of bidirectional pedestrian streams using empirical data. We show that pedestrian streams behave somewhat differently from ordinary fluids with regard to the viscosity concept in the models based on fluid dynamics. It is found that the velocity profile for both unidirectional and bidirectional pedestrian streams is hyperbolic with higher values on the boundaries and lower values in the middle, in opposite of the velocity profile of fluids. This paper also explores the formation and dissipation of self-organized pedestrian lanes. Thus, a modification to Helbing’s social force model is proposed with regard to the attractive force between pedestrians.
INTRODUCTION

Crowd dynamics and pedestrian traffic flow characteristics have been attractive research topics for physicists, behavioral scientists, safety and traffic engineers, planners and others. In the past two decades, several models have been developed to simulate and reproduce dynamics of pedestrian streams in different situations such as airports, train stations, stadia, concerts, parades, Muslims pilgrimage in Makkah (Hajj), evacuation, etc. Generally, pedestrian models in the literature can be categorized into six classes:

- Gas-kinetic/fluid based models (1-3)
- Cellular automata based models (4,5)
- Social force models (6)
- Continuum macroscopic models (7-11)
- Agent-based models (12-14)
- Area-wide (network-wide) models (15)

In the 1970’s, Henderson (1) developed a pedestrian model based on the gas-kinetic equations. Later in the 1990’s, Helbing (2) extended Henderson’s work and developed a theory for pedestrians’ movement based on fluid dynamics, taking into account pedestrian interactions and intentions. Helbing (2) used the concept of viscosity to model pedestrian intentions. He stated that in pedestrian traffic flow, “the effect of viscosity is not compensated by a gradient of pressure as in ordinary fluids, but instead by the tendency of pedestrians to reach their intended velocity.” He concluded that in the case of unidirectional stationary flow, the velocity profile for pedestrian crowds is expected to be hyperbolic with lower values on the boundaries and higher values in the middle. In this paper, we empirically examine this phenomenon and find that pedestrian streams behave differently from ordinary fluids with regard to viscosity (2).

Al-Gadhi and Mahmassani (7) developed a model of crowd dynamics, with particular reference to the Hajj system, by decomposing the walking area into cells as the basic units of analysis, and specifying the mechanisms governing the transmission of flows across cell boundaries. The model effectively provided a numerical solution to a finite-difference form of a first-order bi-directional continuum model of crowd flow. The associated equilibrium bi-directional speed-density relation was calibrated using actual video-based observations (8). Other studies in the 2000’s modeled pedestrian behavior based on cellular automata, such as Burstedde et al. (4) whose model considered local and long-range interactions between pedestrians. They assumed that pedestrian interactions are repulsive for very short distances and often attractive for longer distances. The former prevents occupation of a cell by multiple people and the latter helps reproducing formation of self-organized lanes in bidirectional streams. This is consistent with the social force model proposed by Helbing and Molnar (6). In this paper, we use experimental data to explore the underlying dynamics of pedestrian crowds and hypothesize that attractive force between pedestrians.

More recently, Hoogendoorn et al. (9) established relationships for pedestrian traffic flow similar to network traffic flow (16-20). They extended the generalized Edie’s definition of density to walking areas as the number of pedestrians \( n \) that are in an area \( A \) at any time in interval \( T \) multiplied by the fraction of the period length \( T \) that pedestrians spent in area \( A \). They defined the generalized flow using the fundamental identity where \( q \) is flow (1/m/sec), \( k \) is density (1/m\(^2\)), and \( v \) is speed (m/sec):

\[
q = k \cdot v
\]  

(1)
Crowd behavior is a complex phenomenon. Despite the growing body of literature on crowd dynamics, our understanding of multi-directional movements of pedestrians in high densities is still limited. The main objective of this paper is to evaluate the existing measurement methods of pedestrian traffic flow in the literature and propose a three-dimensional approach, extending Edie’s definitions of fundamental traffic variables to multi-directional walking areas using pedestrian three-dimensional trajectories. Overall, this paper explores some of the underlying dynamics of bidirectional pedestrian streams using empirical data.

BACKGROUND

Fundamental pedestrian traffic flow variables including flow, density, and speed can be measured with different methods, and thus could produce inconsistencies in results and in the shape of the pedestrian fundamental diagram. A recent study by Zhang et al. (21) compared four different measurement methods (A-D) to calculate fundamental quantities of traffic flow. In method A, a fixed location \( x \) in a corridor is specified and mean values of flow \( q \) and speed \( v \) are calculated over a fixed time interval as the following:

\[
q = \frac{N}{\Delta t} \quad \text{and} \quad v = \frac{1}{N} \sum_{i=1}^{N} v_i(t)
\]  

where \( N \) is the number of people passing the specified location \( x \) during the time interval \( \Delta t \) and \( v_i(t) \) is the instantaneous speed of person \( i \).

Method B calculates density \( k \) over time and space (by taking a segment \( \Delta x \) in the corridor) as the following:

\[
k = \frac{1}{\Delta t} \int_b^x \frac{N}{\Delta x} dt
\]  

where \( b \) and \( \Delta x \) are the width and length of the measurement area, respectively. Individual space-mean speeds are also calculated as follows where \( \Delta t_i \) is the time interval for pedestrian \( i \):

\[
v_i = \frac{\Delta x}{\Delta t_i}
\]  

The average speed within the measurement area is then calculated by taking the average of individual speeds.

Method C calculates density as the number of people in the area of measurement section as the following:

\[
k = \frac{N}{b \cdot \Delta x}
\]  

Also speed is calculated as in equation 4.

Method D uses Voronoi diagrams which decomposes the space by distances between pedestrians into discrete set of objects in the space. See Zhang et al. (21) and Steffen and Seyfried (22) for details.
Here, we first discuss the validity and correctness of the proposed measurement methods. Later, we propose a three-dimensional approach to correctly measure fundamental quantities of pedestrian traffic in multidirectional environments. In method A, pedestrian flow is measured over a specified location and the calculated speed is the time-mean speed. Therefore, the fundamental identity (Equation 1) cannot be used to calculate density. Method B correctly calculates density in a space and is consistent with Hoogendoorn et al. (15). However, the speed of individual persons is calculated incorrectly. In a walking area, even in a straight corridor, the distance traveled by a pedestrian is not necessarily equal to the length of the corridor. Therefore, equation 3 underestimates pedestrian speeds. Later in the paper, we empirically show that the distance traveled by pedestrians, even in a straight corridor, follows a non-uniform distribution. Pedestrians tend to deviate from the straight line when density is high. Also, both density and speed as measured by method C and D are inconsistent with Edie’s definitions of density and speed as discussed in the next section.

Zhang et al. (23) also studied the pedestrian fundamental diagram in bidirectional streams. Using data from controlled laboratory experiments, they examined the effects of different corridor widths and flow types (including stable separated lanes, dynamical multi-lanes, balanced flow ratio, and unbalanced flow ratio) on the shape of the pedestrian fundamental diagram. No significant difference was found in the fundamental diagram for densities below 2.0 m$^2$. They also observed that the maximum flow of unidirectional pedestrian flows is higher than the bidirectional flows. A comprehensive background exposition on the effects of multidirectional movements on crowd dynamics is given in Zhang et al. (23).

MEASURING PEDESTRIAN FUNDAMENTAL TRAFFIC VARIABLES: A THREE-DIMENSIONAL APPROACH

Edie (24) proposed definitions of flow and density for unidirectional vehicular traffic as the following:

\[
q(A) = \frac{\sum_{n \in N} d_n}{|A|} \tag{6}
\]

\[
k(A) = \frac{\sum_{n \in N} \tau_n}{|A|} \tag{7}
\]

where $d_n$ is the total distance traveled by vehicle $n$ in region $A$, $\tau_n$ is the total time spent by vehicle $n$ in region $A$, and $|A|$ is the area covered by region $A$ as shown in Figure 1(a). Since the area $A$ is defined in a two-dimensional time-space diagram, it has the dimension of $[distance][time]$. Therefore, $q(A)$ and $k(A)$ have the dimensions of $1/time$ and $1/distance$, respectively. Unlike the common application of two-dimensional time-space diagrams when studying vehicular movements on individual facilities, pedestrian traffic can be visualized and studied in a three-dimensional time-space diagram. The three-dimensional space of walking areas can be defined as a space in which the $x$ and $y$ axes represent the walking surface and the $z$ axis represents time, as illustrated in Figure 1(b).
For example, Figure 2(a) shows a three-dimensional illustration of trajectories of three pilgrims in a circular environment during the Hajj in Makkah, Saudi Arabia. Similarly, Figure 2(b) shows a three-dimensional illustration of pedestrian trajectories in an experiment performed by Zhang et al. (23). In their experiment, two groups of pedestrians (red and blue) walk through a corridor with a length of 8 m and width of 3.6 m as shown in Figure 3. To better illustrate the evolution of trajectories, top and side views of the trajectories are shown in Figure 4. Movement direction of each pedestrian is marked with a color (blue or red).
Figure 4 (a) Top view and (b) Side view of Bidirectional Pedestrian Trajectories (n=100)

In a three-dimensional space (see Figure 5), the mathematical equation of a flat plane with non-zero normal vector of $n=(a,b,c)$ through the point $(x_0,y_0,t_0)$ can be generally expressed as:

$$ax + by + ct + d = 0$$

where $d = -ax_0 - by_0 - ct_0$.

In physics and applied mathematics, flux is the rate of flow of a property per unit area, and has the dimension of $[\text{quantity}] / (\text{area}.\text{time})$. In theory, for any flat plane in the defined three-dimensional space, the general flux of pedestrian trajectories can be measured. However, only flux through specific planes provides meaningful and practical measures of crowd dynamics.

Figure 5 Schematic Illustration of a Flat Plane in a Three-Dimensional Space
Concentration

If the normal vector of the specified plane is parallel to the $z$ (or time) axis, where $a=0$, $b=0$, $c=1$ and $d=-t_m$, then the flux of trajectories represents pedestrian concentration (or density) at time $t_m$ as the following:

$$k(t) = \frac{N dt}{|A| dt} = \frac{N}{[A]}$$

(9)

where $N$ is the total number of pedestrians passing through the plane $t=t_m$ regardless of their movement direction, $|A|$ is the area of the specified plane. Here $|A|$ is the geometrical area of the walking area. Note that unlike the density of vehicular traffic in which the dimension is $1/\text{distance}$, density of pedestrian traffic has the dimension of $1/\text{distance}^2$. This is consistent with Edie’s definition of concentration in a three-dimensional context for pedestrians, as given in Hoogendoorn et al. (15):

$$k = \frac{\sum \tau_n}{|V|} = \frac{\sum \tau_n}{T.|A|} = \frac{\sum \tau_n}{T.(X.Y)}$$

(10)

where $\tau_n$ is the total time spent by pedestrian $n$ in shape $V$ shown in Figure 1(b) and $|V|$ is the spatial volume covered by shape $V$. Also, $|V|$ can be expressed as the geometric area of the walking area ($|A|=X.Y$) multiplied by the time interval $(t_1-t_0)$ as illustrated in Figure 1(b). If all the pedestrians have the same travel time of $(t_1-t_0)$, then Equation 10 can be rewritten as:

$$k = \frac{\sum \tau_n}{(t_1-t_0).|A|} = \frac{N.(t_1-t_0)}{(t_1-t_0).|A|} = \frac{N}{|A|}$$

(11)

Flow

If the normal vector of the specified plane is vertical to the $z$ (or time) axis, where $c=0$, then the flux of trajectories represents pedestrian flow over the specified plane.

$$q = \frac{N dm}{dm|A|} = \frac{N}{|A|}$$

(12)

where $N$ is the total number of pedestrians passing through the plane $ax+by+d=0$, $m$ is the normal vector of the specified plane, and $|A|$ is the area of the specified plane. Here $|A|$ has the dimension of $[\text{distance}].[\text{time}]$, different from the $|A|$ when measuring concentration. Therefore, for the $dx$ plane, as shown in Figure 6, pedestrian flow can be expressed as:

$$q(x) = \frac{N dx}{dx|A|} = \frac{N dx}{dx.T.y} = \frac{N}{T.y}$$

(13)

This is consistent with Edie’s generalized definition of flow in a three-dimensional space for pedestrians as the following:
where $\tau_n$ is the total time spent by pedestrian $n$ in shape $V$ and $|V|$ is the spatial volume covered by figure $V$. If all the pedestrians have the same walking distance of $D$, then Equation 14 can be rewritten as:

$$q = \frac{\sum_{n=N} d_n}{|V|} = \frac{\sum_{n=N} d_n}{Y.X.T}$$

(14)

Unlike the horizontal plane when measuring concentration, in which trajectories move only in one direction with time, pedestrian trajectories in a multi-directional environment can move forward or backward through any specified plane when measuring flow. See Figure 6. Note that the pedestrian flow has the dimension of $1/[\text{time}\cdot\text{distance}]$, unlike the vehicular flow of traffic that has the dimension of $1/\text{time}$. Also the definitions of forward and backward can vary. Therefore, pedestrian flow of each direction can be separately defined as the following:

$$q_f = \frac{N_f dm}{dm|A|}$$

(16)

$$q_b = \frac{N_b dm}{dm|A|}$$

(17)

where $N_f$ and $N_b$ are the number of pedestrians passing through the specified plane in forward and backward directions, respectively.
AREA-WIDE FUNDAMENTAL DIAGRAM OF PEDESTRIAN CROWDS

Building upon the study by Hoogendoorn et al. (15), we further explore the characteristics of pedestrian crowds in large areas. In this section, we use empirical data collected by Zhang et al. (23) as described and illustrated earlier in Figure 2-4. Here, we calculate fundamental pedestrian traffic variables including flow, density, and speed using three-dimensional extension of Edie’s definitions as discussed in the previous section for a 28.8 m$^2$ wide area.

Figure 7 shows the time-series of area-wide density, flow, and speed. As the selected area gets loaded with pedestrians from both directions, area-wide density and flow increase while speed decreases. The area-wide flow breaks down at about a density of 2 persons per m$^2$. During the breakdown period, area-wide speed decreases to 0.4 m/s. Unlike the breakdown phenomena in vehicular traffic, the breakdown in pedestrian traffic does not occur as abruptly. Rather, the reduction in speed takes place gradually.

To further explore the dynamics of pedestrian crowds in bidirectional environments, area-wide fundamental diagrams are plotted and shown in Figure 8. Similar to vehicular traffic flow on both individual facilities and networks, pedestrian traffic exhibits hysteretic behavior too. The observed hysteresis formed a clockwise loop in which the area-wide pedestrian flow during the loading period was higher compared to the unloading period. Pedestrian crowds seem to behave similarly to other many-particle systems. Similar hysteretic behavior has been observed in vehicular networks (18, 19, 25, 26, 27).

Based on empirical observations, the capacity drop phenomenon seems to exist in pedestrian crowds too, similarly to individual freeway segments and vehicular networks, albeit with possibly a different mechanism. Earlier studies by Cepolina and Tyler (28) and Cepolina and Farina (29) have also observed capacity drop in unidirectional pedestrian flow. The capacity drop in bidirectional pedestrian crowds is likely associated with two main reasons. First are the inherent characteristics of many-particle transportation systems in which the flow decreases when density exceeds a critical level. Second is the increased interaction (or friction) between pedestrian streams from opposite directions when density is high. Moreover, the observed capacity drop (from t=9 sec to t=17 sec) is followed by a relatively stable period in which the area-wide flow remains roughly constant while density continues to increase. It is known that when density increases in bidirectional environments, pedestrians tend to form self-organized lanes to increase their speed (and thus, flow) (30). However, due to the self-organizing nature of such behavior, the formed lanes are not necessarily stable over time. Therefore, self-organized lanes may form in different locations and disappear after some time. Our qualitative empirical observations suggest that
the observed stability in flow after the initial breakdown is mainly due to the formation of stable lanes. Further quantitative analysis is required to verify this conjecture.

Also, based on experimental data of a narrow and wide bottleneck, Hoogendoorn et al. (15) suggested that there is a strong linear relationship between pedestrian flow and outflow (also known as production or trip completion rate) as shown in Figure 9(a). However, our results suggest that the linear relationship holds only for flows smaller than 1/m/s while the relationship becomes scattered for flows greater than 1/m/s (See Figure 9(b)). Note that the observed linear relationship by Hoogendoorn et al. (15) does not include flows greater than 1/m/s, suggesting that their observations were limited to the uncongested regime.

One possible reason associated with the observed scatter for higher flows is the non-uniform distribution of distance traveled by pedestrians when density is high. Remember that according to the three-dimensional extension of Edie’s definition of flow, area-wide flow is calculated as the ratio of the total sum of the distance traveled by all the pedestrians in the specified walking area divided by the volume of the specified shape in time and space as expressed in equation 14. Therefore, for the same number of pedestrians in the area, area-wide pedestrian flow increases if the distance traveled increases. However, the increase in the distance traveled does not necessarily mean more pedestrians reach their destinations.
because the distribution of the distance traveled by pedestrians is not constant and follows a non-uniform distribution even in a straight corridor, as shown in Figure 10(a). Also, Figure 10(b) shows that pedestrians who enter the system early, while density is still low, travel shorter distances compared to the pedestrians who enter the corridor while the system is congested. Thus, we postulate that pedestrians tend to zigzag more when density is high. This “zigzagging effect” results in a higher area-wide nominal flow but does not necessarily increase the system outflow.

![Figure 10 (a) Distribution of Distance Traveled by Pedestrians and (b) Distance Traveled vs. Entrance Time to the System](image)

**EVOLUTION OF SELF-ORGANIZED LANEs: UPDATING THE SOCIAL FORCE MODEL**

The self-organizing behavior of pedestrian crowds has been modeled to some extent by the social force model proposed by Helbing and Molnar (6) and Helbing et al. (30). Helbing et al. (30) introduced an attractive force which reproduces the case in which “families, friends, or tourists often move in groups.” In their model, they assume that such attractive forces are often temporally decaying because of declining interest. The attractive force in Helbing and Molnar (6) and Helbing et al. (30) model is expressed as:

\[
\vec{f}_{\alpha i}(\vec{r}_\alpha, \vec{r}_i, t) = -\nabla_{\vec{r}_\alpha} W_{\alpha i}(\vec{r}_\alpha - \vec{r}_i, t)
\]  \( (18) \)

where \( \vec{f}_{\alpha i} \) is the social force between pedestrian \( \alpha \) and \( i \), \( \vec{r}_\alpha \) is the location of pedestrian \( \alpha \), \( \vec{r}_i \) is the location of pedestrian \( i \), and \( t \) is time. On the right hand side of the equation, \( \nabla_{\vec{r}_\alpha} \) is the attractive force parameter and \( W_{\alpha i}(\vec{r}_\alpha - \vec{r}_i, t) \) reflects the relationship between the attractive force, distance between pedestrian \( \alpha \) and \( i \), and time. Helbing and Molnar (6) and Helbing et al. (30) did not propose a specific formulation for \( W_{\alpha i} \).

In this section, based on empirical data, we note that, when density is high, the attractive force in pedestrian crowds is not limited to people who have a social relationship with each other. Pedestrians tend to move in self-organized lanes or groups when they perceive that they can walk with a speed closer to their desired speed when walking in a lane or group. Also, such joining behavior is not necessarily decaying with time because of declining interest. Rather, interruption by the intersecting stream(s), drop in demand, and differing destinations are the main reasons associated with the dissipation of self-organized lanes. Figure 11 illustrates the evolution of a self-organized lane including formation, growth,
and dissipation. The lane began forming at about t=8.125 sec and grew until t=13.125 sec. The self-organized lane fully dissipated at t=23.125 sec while demand still existed and density was relatively high. The dissipation of the lane occurred mainly because of the interruption caused by the intersecting stream from the opposite direction.

Self-organized lanes can be stable or unstable. A stable self-organized lane sustains its spatial and temporal development while demand exists. Instability in self-organized lanes can cause permanent or temporary dissipation of a lane. The dissipation of the illustrated lane in Figure 12 is an example of a permanent dissipation due to instability in pedestrian traffic flow. Toward this end, we propose that at any given time, the attractive force in pedestrian crowds can be expressed as a function of the distance between two consecutive pedestrians and their speed difference.

\[
\vec{f}_a (\vec{r}_a, \vec{r}_i, \vec{v}_a, \vec{v}_i) = W_a (\vec{r}_a - \vec{r}_i, \vec{v}_a - \vec{v}_i) \tag{19}
\]

If \( \vec{v}_i \geq \vec{v}_a \) and \( \vec{r}_i - \vec{r}_a \leq \eta \), then pedestrian \( a \) follows pedestrian \( i \). Note that \( \eta \) is the maximum critical distance between two consecutive pedestrians that encourage them to move together and form a self-organized lane. Unlike the assumption made in Helbing and Molnar (6) and Helbing et al. (30), the attractive force, as defined in equation 19, does not decay with time. Further research is required to validate this finding.

![Figure 11 Evolution of a Self-Organized Lane: a) Formation, b) Growth, and c) Dissipation](image)

**Figure 11 Evolution of a Self-Organized Lane: a) Formation, b) Growth, and c) Dissipation**

**PEDESTRIAN CROWDS VERSUS FLUIDS: A NOTE ON VISCOSITY**

As mentioned earlier in the paper, Helbing (2) used the concept of viscosity to model pedestrian intentions. He assumed that pedestrian crowds have a similar velocity profile to ordinary fluids in which the lower values are on the boundaries and higher values are in the middle, as shown in Figure 12. In this section, we empirically show that both unidirectional and bidirectional pedestrian streams indeed have behavioral similarity with fluids with regard to the viscosity concept but the velocity profile of pedestrian streams seems to have an entirely opposite shape.
Figure 12 Effect of Viscosity in Fluids and Pedestrian Crowds as in Helbing (2)

Figure 13 shows the measured velocity profile of unidirectional and bidirectional pedestrian streams using empirical data collected by Zhang et al. (23). As can be seen, unlike the velocity profile of ordinary fluids as illustrated in Figure 12, pedestrian streams seem to have an opposite profile of velocity in a bounded corridor in which lower values are in the middle and higher values are on the boundaries. The velocity differences over the width of a corridor in unidirectional streams are observed to be smaller compared to the bidirectional streams. However, they both have a similar polynomial shape. However, making a strong conclusion on the effect of viscosity in pedestrian crowds versus fluids require further empirical analysis of pedestrian streams. The reproducibility of the observed pattern in this study needs to be further examined using data collected in other locations.

CONCLUSION

This paper evaluated the existing measurement methods of pedestrian traffic flow and proposed a new three-dimensional approach. The proposed method extends Edie’s definitions of fundamental traffic variables to multi-directional walking areas. It is confirmed that a pedestrian crowd in an area has an area-wide fundamental diagram similar to the notion of the Network Fundamental Diagram (NFD or MFD). Using empirical data of uni- and bi-directional pedestrian streams, it is shown that hysteresis phenomenon exists in the area-wide fundamental diagram of pedestrians. It is also shown that pedestrian streams
behave somewhat differently from ordinary fluids with regard to the viscosity concept. The pedestrian velocity profile for both unidirectional and bidirectional streams is found to be hyperbolic with higher values on the boundaries and lower values in the middle, in opposite of the velocity profile of fluids. This paper also explores the formation and dissipation of self-organized pedestrian lanes. Future research using additional observations in different locations is needed to verify the findings of this study.

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