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Modelling the Pedestrian's Perception for the Social Force Model to Reproduce Experimental Data

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Abstract: The social force model which belongs to the microscopic pedestrian studies has been considered as the supreme model by many researchers and engineers due to the main feature of its capability in reproducing the self-organization phenomena resulting from pedestrian dynamics. Recently, some principles of this model have been modified by other researchers to overcome a shortcoming that the model could not reproduce experimental data in normal situations such as the fundamental diagram. In this article, we argue that these principles are not the reasons for this shortcoming. And we clarify that the actual reason for this shortcoming is due mainly to the misunderstanding of the role of the pedestrian's perception of the objects surrounding him. And then, we present a typical approach to find the relation between the pedestrian's perception and the local density which helps in reproducing the fundamental diagram which conforms to the empirical data while conserving the principles of the social force model.

Key words: Social force model · Fundamental diagram · Perception · Repulsive parameter · Density

INTRODUCTION

Over the last few decades, researchers have devoted much attention to pedestrian studies to provide solutions for some pressing problems such as congestion [1]. Microscopic studies, which are essentially a branch of pedestrian studies, are mainly concerned with the interactions among pedestrians and their effects upon each other [1]. One of the most important models in the microscopic level of pedestrian studies is the Social Force Model. The most important feature in this model is the representation of a pedestrian's motivations exerted by other objects (pedestrians and obstacles) surrounding him as social forces [2]. The sum of these forces is implemented in Newtonian equation which, in turn, leads to acceleration to the pedestrian's motion. An extension by the authors of [3] incorporated the physical forces arising in case of contact occurring amongst the pedestrians into the model. A modification of some aspects of the model has been done in [4-7]. The model is characterized by reproducing the self-organization phenomena of pedestrian dynamics flow in normal and panic situations [8]. The main equations of the model are

$$\frac{d\vec{x}_i(t)}{dt} = \vec{v}_i(t) \quad (1)$$

$$m_i \frac{d\vec{v}_i}{dt} = \vec{f}_i + \varepsilon_i = \vec{f}_i^{\,pref} + \sum_j \vec{f}_{ij} + \sum_{object} \vec{f}_{i,object} + \varepsilon_i \quad (2)$$

$$\vec{f}_i^{\,pref}(t) := \gamma\left(\vec{v}_i^{\,0}(t) - \vec{v}_i(t)\right) \quad (3)$$

$$\vec{f}_{ij}(t) = \vec{f}_{ij}^{\,att}(t) + \vec{f}_{ij}^{\,rep}(t) + \vec{f}_{ij}^{\,push}(t) + \vec{f}_{ij}^{\,friction}(t) \quad (4)$$

$$\vec{f}_{i,object}(t) = \vec{f}_{i,object}^{\,att}(t) + \vec{f}_{i,object}^{\,rep}(t) + \vec{f}_{i,object}^{\,push}(t) + \vec{f}_{i,object}^{\,friction}(t) \quad (5)$$

Where $\frac{d\vec{x}_i(t)}{dt}$ is the rate of change of the location of pedestrian i; $\vec{v}_i(t)$ represents his actual velocity which is numerically computed by solving Eq. (1) and (2); $d\vec{v}_i/dt$ is the acceleration of pedestrian i resulting from the sum of total forces upon him; $\varepsilon_i(t)$ is the fluctuation of individual i; $\vec{f}_i^{\,pref}(t)$ is the preferred force modeled to express the motivation inside the pedestrian to adapt his actual velocity $\vec{v}_i(t)$ to reach another velocity $\vec{v}_i^{\,0}(t)$ at which he prefers to walk, called the preferred velocity; $\gamma = m_i/\tau$ where m_i and τ represent the mass of the pedestrian i and

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the relaxation time respectively; The function $\vec{f}_{ij}(t)$ is the sum of all forces exerted by pedestrian *j* upon *i* (the social and the physical forces). The social forces are the repulsion force $\vec{f}_{ij}^{rep}(t)$ and the attraction force $\vec{f}_{ij}^{att}(t)$ that represent the model of the repulsive and attractive motivations inside pedestrian *i* against and toward *j*, respectively [2]. They are modeled as exponential functions with different values of the parameters and opposite directions; the physical forces are $\vec{f}_{ij}^{push}$ and $\vec{f}_{ij}^{friction}$ which are modeled as linear functions in [3] in analogy with the granular forces; $\vec{f}_{i,object}(t)$ is analogous with $\vec{f}_{ij}(t)$ but regarding walls.

The repulsive social force $\vec{f}_{ij}^{rep}(t)$ plays an essential role in the work done in this article. This force is modeled in [2] by

$$\vec{f}_{ij}^{rep}(t) := A^{rep} e^{(R_{ij}-d_{ij}(t))/B^{rep}} \vec{n}_{ij}.W\left(\phi_{ij}(t)\right) \tag{6}$$

Where A^{rep} and B^{rep} are constant parameters that denote the strength and the characteristic distance of the corresponding force, respectively; $\vec{n}_{ij}$ is the normalized vector which points from the object *j* to the pedestrian *i*; R_{ij} and d_{ij} are the sum of the radius of *i* and *j* and the distance between the centers of *i* and *j* respectively; *W* is a weight function to take into account the effect of the angle made between the individual direction of motion and the vector pointing from him to the source j. With this weight function, the source located in front of individual *i* has different (higher) effect on individual *i* than that the source is aside or behind.

Although the original model has reproduced the various dynamical phenomena in pedestrian crowds well [3, 8], the model has attracted significant criticisms [6, 7], that the model could not reproduce the fundamental diagram and the pedestrian flow rate to fit the empirical data reproduced by [9] and stated in [7], respectively. For this reason, certain components in the Social Force Model have been modified by those researchers to overcome the claimed shortcoming. In this article, we argue that the fundamental diagram can be reproduced based on the Social Force Model without modifying the principles whether by changing basic terms or incorporating new components into the model. This article is organized as follows: in the second section, we introduce a brief description of the essential variables frequently used as quantitative measurements in the relevant experimental data. The relation between the repulsive distance force and the density factor is described in the third section. Based on the latter, simulations are performed to formulate this relation by adopting curve fitting approach which helps reproduce the fundamental diagram. Finally, the conclusion is introduced

The Macroscopic Characteristics and the Fundamental Diagram

Macroscopic Characteristics: The essential macroscopic variables, frequently used by most pedestrian studies, are the density, the flow and the mean speed [10].

The density is defined as the number *N* of pedestrians within a specific area *A* at any given moment. Dividing this number N by the area A presents the average number in one square meter. It is calculated by:

$$\sigma = \frac{N}{A}. \tag{7}$$

The unit of the density is represented by P/m^2 where P denotes the pedestrian and m denotes a meter.

The instantaneous mean speed is defined as the average value of the pedestrians' speeds (the components of the velocities into the considered direction) that are present in an area A at a given moment. It is computed by the formula:

$$\bar{V}_{inst}(t) = \sum_{i\in A} \frac{v_i(t)}{N}. \tag{8}$$

The speed is assumed to follow normal or lognormal distribution with a mean m and deviation *s*, as proposed in [11]. However, in [12], it was found that the speed is Gaussian distributed. An inverse relation between the deviation and the density was proposed in [13].

The flow rate is defined as the number of pedestrians passing a cross-section of an area during specified period of time. It is directly computed by:

$$f = \frac{N}{L.T}, \tag{9}$$

Where *N* is the number of pedestrians passing the cross-section which has length L meters during the time period *T* seconds. It is denoted by (P/m/s). This measurement is helpful to examine the capacity of pedestrian facilities. It was studied in detail in [10]. The flow has also its specific applications (such as the maximum flow) in vehicular traffic [14].

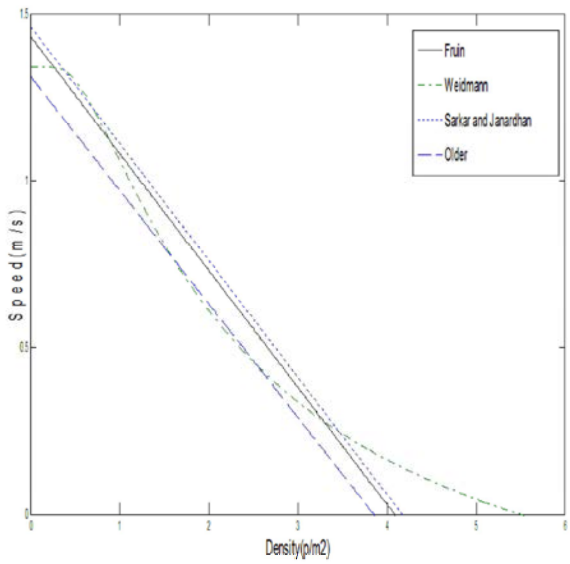

Fig. 1: Estimated speed-density relations for unidirectional pedestrian traffic flow. Fruin [15], Sankar [16] and Older [11] used a linear speed-density relation, while Weidmann [9] used a double S-bended curve.

The aforementioned three macroscopic variables: the flow, density and mean speed are main components composing the fundamental traffic flow formula:

$$f = \sigma.\bar{V}. \quad (10)$$

This formula is very helpful with introducing the relationship between speed, flow and density [10].

The Fundamental Diagram: The fundamental diagram is a graphical representation to describe the relation between two macroscopic variables such as the mean speed and the density $\bar{V} = \bar{V}(\sigma)$, the flow and the density $f = f(\sigma)$ and the flow and the mean speed $f = f(\bar{V})$. Based on the traffic flow formula (9), obtaining one relation will induce the other relations. These relations are useful for the assessment of the models whether it can describe the pedestrian stream appropriately with respect to the empirical studies. Moreover, these diagrams have a great benefit to optimize some parameters of the model in consideration for the calibration. For that reason, researchers have conducted their simulations to fit their models with the fundamental diagrams resulting by empirical studies as calibration to their models. However, due to the varying pedestrian environments where the empirical studies have been conducted, the conditions that the researchers adopted in their empirical studies

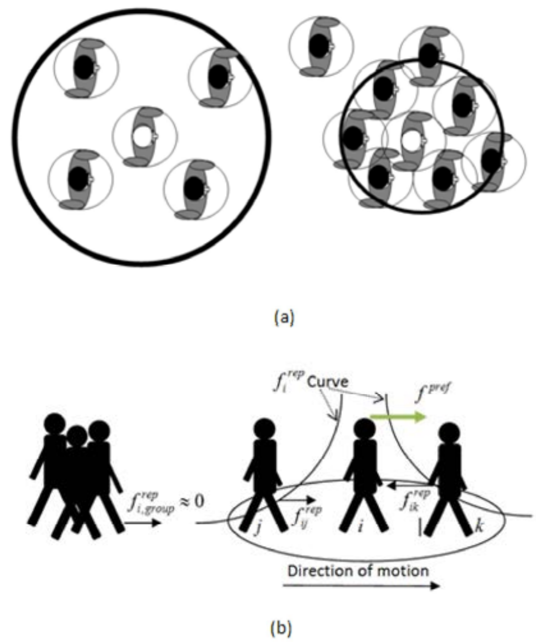

Fig. 2: The perception area of a pedestrian is represented as a circle centered at his location. It is an estimated area that the repulsive forces exerted by the other pedestrians have significant values as depicted in (b). In (a) it is shown how the effect of the local crowd density would change the awareness of the white-head pedestrian of those who surround him. Accordingly, the values of the repulsive forces exerted by other objects which located at the same distance from the white-head pedestrian would be changed also.

were varied. This has led the resulting relations and the corresponding fundamental diagrams to be varied from one study to another as shown in Fig. 1.

On the other hand, the empirical studies cannot be conducted in emergency situations because of the difficulty of controlling the conditions of such situations. Accordingly, most researchers have conducted their empirical studies to obtain fundamental diagrams for their models with the common achievable conditions: homogeneous and stationary flow in unidirectional walkway and normal situations where no repulsive or attractive sources are inside.

The Relation Between the Repulsive Distance Parameter and the Density: In this section, in contrast to the works of [6, 7], a typical approach is presented in reproducing the fundamental diagram while conserving the principles of the Social Force Model which are responsible for reproducing the self-organization phenomena.

The pedestrian, as a social human being, possesses social attributes such as respect for others, believes that his awareness to avoid collision with the immediate adjacent pedestrians decreases with the increase in the surrounding local crowd density (Fig. 2-a), Namely, there is an inverse relationship between the pedestrian's awareness area and his surrounding local crowd density. Accordingly, the objects which become located outside the pedestrian's awareness area due to the increase in the crowd density must not be considered as significant repulsive sources.

On the other hand, the pedestrian in the Social Force Model has limited perception (which refers to the pedestrian's awareness area described in the above paragraph) imposed by the repulsive distance parameter β^{rep} in $\vec{f}_{ij}^{rep}(t)$ of Equation (6). The objects located outside the pedestrian's perception area exert insignificant repulsive forces on him (see Fig. 2-b). According to the curvature of the repulsive social force function, illustrated in Fig. 2-b, there is a direct relationship between the value of β^{rep} and the size of this perception (awareness) area. Combining this relation with the relation introduced in the first paragraph of this section, we can assume that there is an inverse relationship between the size of the pedestrian's perception area and his surrounding local crowd density. Based on this argument, we confirm that taking into account the change in the pedestrians' perception areas with respect to the change in the corresponding local crowd densities of these areas could further introduce real aspects to their walking behaviors. One of these aspects is the fundamental diagram.

In the next section, simulations are conducted to investigate the appropriate relationships between the repulsive distance parameter β^{rep} (dependent variable) and the density factor (independent variable), based on reproducing a fundamental diagram which conforms to the empirical ones [9].

Simulations and Results

Simulations: In this section, the simulations to explore the relationship between the repulsive distance parameter and the density are conducted, which help reproduce an appropriate fundamental diagram identical with the one obtained by Weidmann [9] as shown in Fig. 1. For various densities, the value of β^{rep} which approximately produces the corresponding mean speed, according to the diagram obtained by Weidmann [9] are computed. Using the curve fitting approach, this relationship is formulated as the calibration of the repulsive distance parameter.

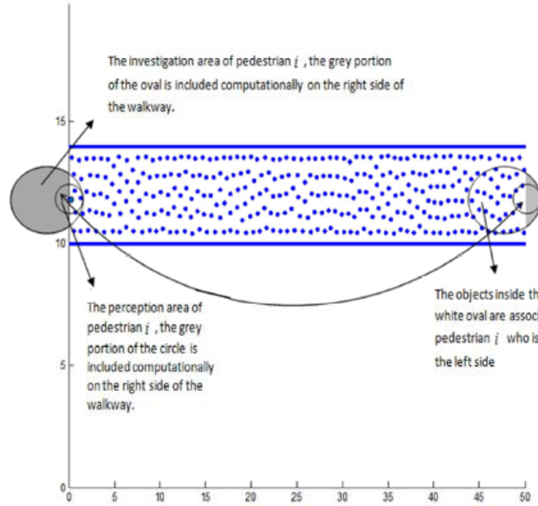

Fig. 3: The simulated environment is a unidirectional walkway. The particles were initialized randomly. The curved line indicates that the shadowed investigation and perception areas of particle i which exceeds the vertical left boundary is computed on the right side. The shadowed areas are imaginary areas for demonstration.

Unlike the approach adopted in [6, 7], where the environment of the simulations were set up as a closed walkway (racetrack), the walkway of the current simulations is straight, instead of elliptical as in a racetrack. However, when the areas possessed by particle *i* (the investigation and perception areas) exceed the left vertical line of the walkway, it is automatically computed to be on the right part of the walkway as shown in Fig. 3. Therefore, the particles on the left side before reaching the vertical line (the boundary), preserve the forward forces exerted by the forward pedestrians who are apparently on the right side. Subsequently, when the particle reaches the end of the left side of the walkway, it is regenerated to the right side with identical y-component of its previous location; which is the actual velocity and forces exerted by the followers.

Invariably, the particles keep following their motion inside the walkway from the right side again as though they are in a closed walkway. Thus the walkway is considered to be a closed loop, with regards to the implementation.

The specification of the simulated pedestrians (particles) is as follows: The positions of all particles (simulated pedestrians) are initialized randomly in the simulated area (walkway) simultaneously (Fig. 3) and their motion instantaneously directed towards the left (the destination). Analogous to the characteristics of

Table 1: The pedestrian and Social Force Model parameters

The pedestrians' parameters:	
m = [77 – 83]kg	The pedestrians' mass: uniformly distributed within the range [77 - 83] kg
r = [0.25 – 0.30]kg	The pedestrians' radius: uniformly distributed within the range [0.25 - 0.30] m
The parameters of the social force model:	
A^{rep} = 2000N	The strength of the repulsive social force
v^0 1.34m/s	The preferred speed
τ = 0.5s	The pedestrian reaction time
$\varepsilon \in [v^0/\tau, 0.05*v^0/\tau]$	The fluctuation source of the pedestrian's acceleration is randomly assigned to each individual

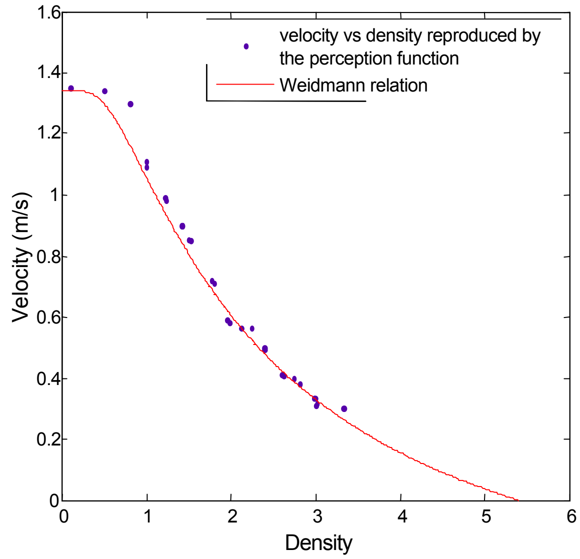

Fig. 4: Comparison between Weidmann's graph and the data obtained by the simulations made in this section by governing the value of the repulsive distance parameter β^{rep}.

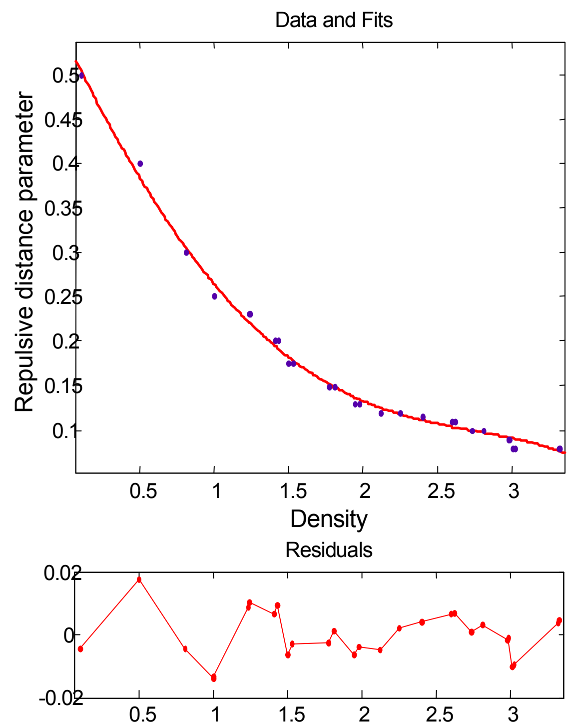

Fig. 5: The best fitting curve for the β^{rep} – relation is given by the equation

$$\beta^{rep}(\sigma) = -0.003\sigma^4 + 0.011\sigma^3 + 0.062\sigma^2 - 0.34\sigma + 0.538$$

the pedestrians in the previous experimental studies [9], all pedestrians have the same preferred direction; with preferred mean speed and deviation. The values of the pedestrians' parameter are shown in Table 1.

RESULTS

By controlling the value of the parameter β^{rep} (the repulsive distance parameter), the data (velocity-density points) which fit the fundamental diagram obtained by Weidmann [9] were obtained and fitted, as shown in Fig. 4.

Similarly, the corresponding values of the repulsive parameter obtained and the density were used to generate the graph in Fig. 5. Using the nonlinear least squares method, the best fitting curve for the repulsive distance parameter in terms of the density is given by

$$\beta^{rep}(\sigma) = -0.003\sigma^4 + 0.011\sigma^3 + 0.062\sigma^2 - 0.34\sigma + 0.538. \quad (11)$$

CONCLUSION

In this article, a brief description of the Social Force Model is introduced. The most essential macroscopic variables and the fundamental diagram have been described, as well. The notion that the pedestrians are changing their perceptions of the surrounding objects and areas according to the local densities in these areas has been considered as a real behaviour adopted by the pedestrians. The approach chosen to model the latter behaviour is by calibrating an essential parameter (the repulsive distance parameter) and formulating it as a relation in terms of the local density. From this work, the fundamental diagram conformed to the empirical studies has been reproduced.

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