Fundamental Diagram and Validation of Crowd Models

Armin Seyfried[1] and Andreas Schadschneider[2]

[1] Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany
a.seyfried@fz-juelich.de
[2] Institut für Theoretische Physik, Universität zu Köln, 50937 Köln, Germany
as@thp.uni-koeln.de

Abstract. In recent years, several approaches for crowd modeling have been proposed. However, so far not much attention has been paid to their *quantitative* validation. The fundamental diagram , i.e. the density-dependence of the flow or velocity, is probably the most important relation as it connects the basic parameter to describe the dynamic of crowds. But specifications in different handbooks as well as experimental measurements for the fundamental diagram differ considerably. We give a review of the experimental data base and the causes for the discrepancies discussed in the literature. Up to now it was neglected that the way of measurement can cause variations between the results of different studies. To shed some light on this problem we studied by means of experimental trajectories of the single file movement how different measurement methods influence the resulting fundamental diagram.

Keywords: empirical data, model validation, fundamental diagram.

1 Introduction

The number of models for pedestrian dynamics has grown in the past years, but the experimental data to test them and to discriminate between these models is still to a large extent uncertain and contradictory (see e.g. [1]). In most models, pedestrians are considered to be autonomous mobile agents, hopping particles in a cellular automaton or self-driven particles in a continuous space. However, if one wants to make quantitative predictions (e.g. evacuation or travel times) the model has to be calibrated with empirical data, independent from the model type. One of the most important characteristics of pedestrian dynamics is the fundamental diagram giving the relation between pedestrian flow and density. Beside its importance for the dimensioning of pedestrian facilities it is associated with every qualitative self-organization phenomenon, like the formation of lanes or the occurrence of jams. However, specifications of different experimental studies, guidelines and handbooks, display non negligible differences concerning maximal flow values, the assigned density and the density where the flow is expected to become zero due to overcrowding. Although a large variety of models for pedestrian dynamics has been proposed, so far there have been only limited attempts to calibrate and validate these approaches with the fundamental

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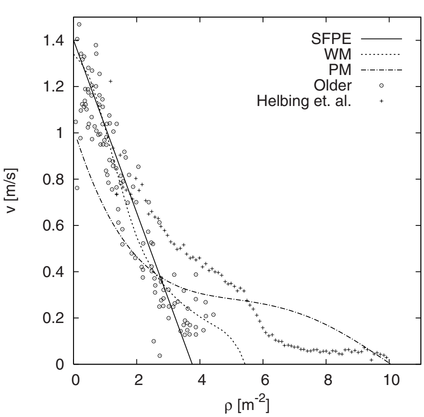
diagram. In part, one reason is the unclear situation of the empirical data, as described above. This situation is very unsatisfactory and poses serious limitations to the use of such models e.g. in the area of safety planning. To improve the current state of affairs it is necessary to have more reliable data that can be used as basis for validation and calibration which then would allow to make even quantitative predictions based on computer simulations.

2 Specifications and Measurements

The fundamental diagram describes the empirical relation between density ρ and flow J (or specific flow per unit width $J_s = J/b$). Due to the hydrodynamic relation $J = \rho v b$ there are three equivalent forms: $J_s(\rho)$, $v(\rho)$ and $v(J_s)$. In applications the relation is a basic input for engineering methods developed for the design and dimensioning of pedestrian facilities [2,3,4]. For various facilities like floors, stairs or ramps the shape of the diagrams differ, but in general it is assumed that the fundamental diagrams for the same type of facilities but different widths merge into one diagram for the specific flow J_s. In this contribution we will concentrate on planar facilities like sidewalks, corridors or halls. The comparison in Fig. 1 reveals that specifications and measurements disagree considerably. In particular the maximum of the function giving the capacity $J_{s,\max}$ ranges from 1.2 (ms)$^{-1}$ to 1.8 (ms)$^{-1}$, the density value where the maximum flow is reached ρ_c ranges from 1.75 m^{-2} to 7 m^{-2} and, most notably, the density ρ_0 where the velocity approaches zero due to overcrowding ranges from 3.8 m^{-2} to 10 m^{-2}. Several explanations for these deviations have been suggested, including cultural and population differences [7], differences between uni- and multidirectional flow [10,8], short-ranged fluctuations [8], influence of



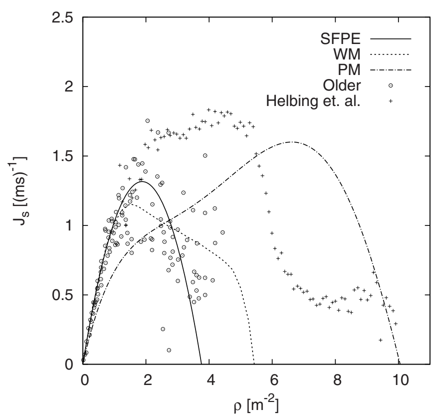


Fig. 1. Fundamental diagrams for pedestrian movement in planar facilities. The lines refer to specifications according to planing guidelines (SFPE Handbook [4] [SFPE], Predtechenskii and Milinskii [2] [PM], Weidmann [5] [WM]). Data points give the range of experimental measurements (Older [6] and Helbing *et al.,* [7]).

psychological factors given by the incentive of the movement [2] and, partially related to the latter, the type of traffic (commuters, shoppers) [9].

The most elaborate fundamental diagram has been given by Weidmann who collected 25 data sets. An examination of the data which were included in Weidmann's analysis shows that most measurements with densities larger then $\rho = 1.8$ m^{-2} are performed on multidirectional streams. Weidmann neglected differences between uni- and multidirectional flow in accordance with Fruin, who states in his often cited book [3] that the fundamental diagrams of multidirectional and unidirectional flow differ only slightly. This disagrees with results of Navin and Wheeler [10] who found a reduction of the flow in dependence of directional imbalances. But bidirectional pedestrian flow includes unordered streams as well as lane-separated and thus quasi-unidirectional streams in opposite directions. Another explanation is given by Helbing et al. [7] who argue that cultural and population differences are responsible for the deviations between Weidmann and their data. In contrast to this interpretation the data of Hanking and Wright [11] gained by measurements in the London subway (UK) are in good agreement with the data of Mori and Tsukaguchi [12] measured in the central business district of Osaka (Japan), both on strictly uni-directional streams. This brief discussion clearly shows that up to now there is no consensus about the origin of the discrepancies between different fundamental diagrams and how one can explain the shape of the function.

3 Influence of the Measurement Method

Partially the discussion outlined in the previous section loose it's importance due to two reasons. First it is important to notice that in the majority of cases the data come without fluctuations and error margins and thus, strictly speaking, there is no contradiction between the data. Second it is well known in vehicular traffic that different measurement methods can lead to deviations for the resulting relations [13,14]. The deviations depend on the fact that the velocity distributions measured at a certain location and averaged over time do not necessarily conform with velocity distributions measured at a certain point of time averaged over space. For pedestrian traffic it was never analyzed whether there exits or how large the deviations due to different measurement methods are.

Fig. 2 shows a comparison of fundamental diagrams for the single file movement. In our experiment [15] we performed 12 runs with varying number of pedestrians, $N = 17$ to $N = 70$. It is important to note that the different measurements shown in Fig. 2 are basing on the same set of trajectories determined automaticaly from video recordings of the measurement area with high accuracy ($x_{err} \pm 0.02m$). The data analysis is restricted to the stationary state. More details will be given in [16]. Even at this very simple and regular system of pedestrians moving along a line it is astounding how large the deviations are. Thus it is important to consider the measurement method for the validation of models as well as for the comparison of different experimental studies.

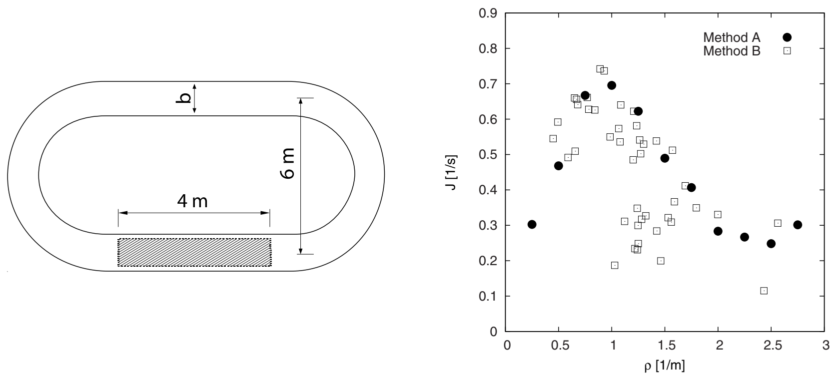


Fig. 2. Left: Sketch of the experimental setup to determine the fundamental diagram for the movement of pedestrians along a line ($b = 0.7m$). The measurement area is dashed. **Right:** Fundamental diagram determined by different measurement methods. *Method A:* Measurement of the density ρ and velocity v at a certain point of time t averaging over space Δx. The flow is given by $J = \rho v$. *Method B:* Measurement of the flow $J = N/\Delta t$ and velocity v at a certain location x averaging over a time interval Δt. The density is given by $\rho = J/v$.

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