Generalized Macroscopic Fundamental Diagram for Pedestrian Flows

Winnie Daamen, Victor L. Knoop, and Serge P. Hoogendoorn

Abstract It has been shown that a relation exists between the number of pedestrians in an area and the average flow in that area (production); this is called the Macroscopic Fundamental Diagram (MFD). Using this relation, we can express the average production of a network as a function of the average density (or accumulation) of the network. One of the assumptions under which a proper shape of the MFD is found, is that the congestion is spread homogeneously over the network. In vehicular traffic, it is shown that when this assumption is relaxed, the spatial variation of density within the network leads to a decreased production. This paper shows to which extent a function of accumulation and an aggregated variable of the spatial spread can predict the performance of a pedestrian traffic flow.

1 Introduction

Traffic congestion is not only a local problem: due to route choice behaviour it spreads out over the network. To increase insights into network dynamics and how to characterise these dynamics, the concept of the Macroscopic Fundamental Diagram (MFD) has been re-introduced [1]. One of the assumptions under which a proper shape of the MFD is found, is that the congestion is spread homogeneously over the network [1]. Knoop and Hoogendoorn [3] show the effect of inhomogeneity by deriving the so-called *generalised macroscopic fundamental diagram* (GMFD).

Hoogendoorn et al. [2] have shown that a similar relation exists between the number of pedestrians in an area and the average flow in that area (production). However, the effects of spatial inhomogeneity of the density has not been considered. In the paper at hand we show to which extent a function of the number of pedestrians and an aggregated variable of the spatial spread can predict the performance of a large scale pedestrian traffic flow. Similar to vehicular traffic, we found that a larger spatial variation in density leads to higher flows in the network (at the same density).

W. Daamen (✉) • V.L. Knoop • S.P. Hoogendoorn
Delft University of Technology, Stevinweg 1, Delft, The Netherlands
e-mail: w.daamen@tudelft.nl; v.l.knoop@tudelft.nl; s.p.hoogendoorn@tudelft.nl

M. Chraibi et al. (eds.), *Traffic and Granular Flow '13*,
DOI 10.1007/978-3-319-10629-8_5

Next to providing insights into network pedestrian traffic dynamics, MFDs can be important for (on-line) applications such as pedestrian traffic control. Busy pedestrian facilities (e.g., metro and train stations, airports and shopping centres) need to be monitored for safety and operational performance. The use of pedestrian counting devices combined with a reliable MFD could provide a good estimator for the traffic state in real time applications.

The paper starts with an experimental design (Sect. 2), then shows the resulting MFDs (Sect. 3) and ends with conclusions.

2 Experimental Design

In the experimental design we introduce the simulation set-up and data used to derive the Generalized Macroscopic Fundamental Diagram for pedestrians for a specific network layout. Section 2.1 gives an overview of the corresponding layout, while Sect. 2.2 shows the traffic demand for the two data sets. Section 2.3 shows how the characteristics of the MFD (flow and density) are calculated.

2.1 Layout

In order to control the data and to identify the effects of different flow patterns on the shape of the MFD we have chosen to model both one-directional traffic and crossing traffic flows. Figure 1a, b show an overview of these two layouts, where the red pedestrians walk from left to right and the blue pedestrians walk from top to bottom. The area measures 10×10 m, while the exits have a width of 1 m. In order to create congestion upstream of the exits, the entrances have a width of 6 m. To make sure that the capacity of the exit is correct, we have added a short corridor downstream of the exit, having the same width. However, the observations are made only for the central area.

2.2 Traffic Demand

Traffic demand is increased in a stepwise way, until a largest flow of 1.65 P/s is generated. This demand is maintained during 30 s, to let congestion set in, after which demand is gradually decreased. This way, both the effects of congestion onset and its resolution are included in the GMFD. For the crossing flow scenario, the crossing flow (from top to bottom)is much smaller than the main flow (from left to right). The main flow in this scenario is 2 P/s, while the crossing flow is equal to 0.5 P/s. An overview of these demand profiles is shown in Fig. 2. The total duration of the simulation is 900 s.

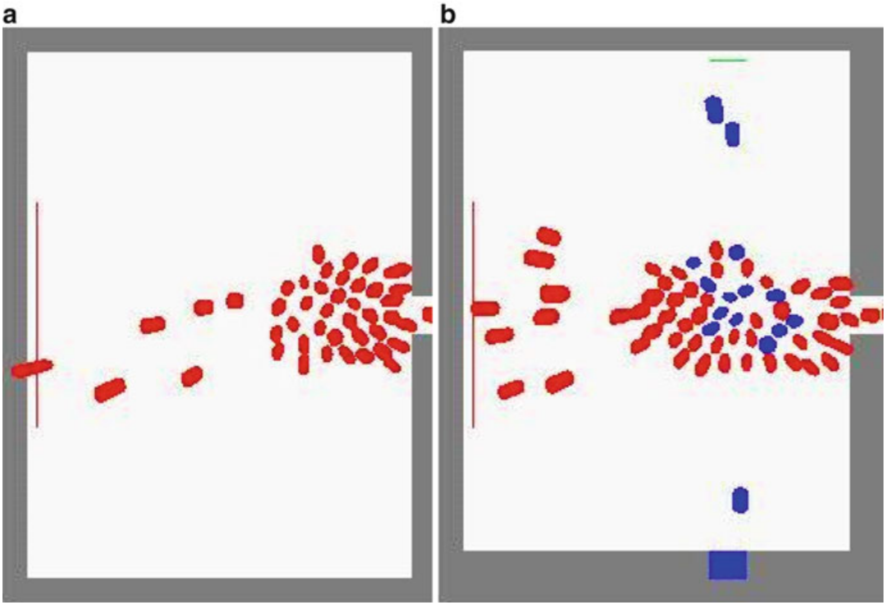

Fig. 1 Layout for the two data sets. (**a**) One directional. (**b**) Crossing flows

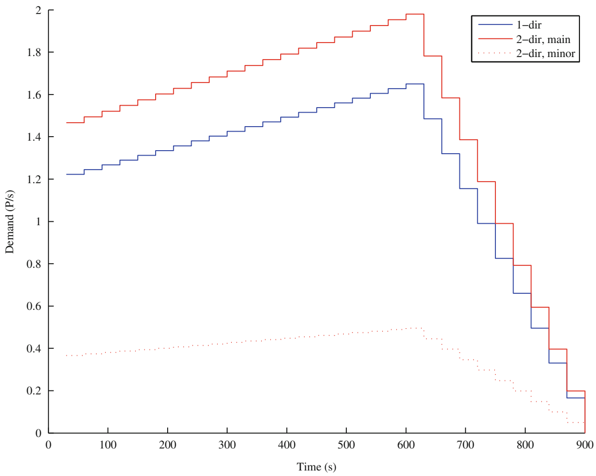

Fig. 2 Traffic demand over time in both scenarios

2.3 *MFD Characteristics*

To visualise the effect of spatial variation in the density on the density and the flow, both density and flow need to be calculated. As the application of the GMFD is to see whether sufficient space is available to cope with the existent pedestrian flows and how efficiently this space is used, we include the empty areas in the density calculation. The local or individual density k_i is equal to the inverse of the empty space around an individual pedestrian A_i

$$k_i = \frac{1}{A_i} \tag{1}$$

Then, we calculate the so-called space mean density, where all local densities k_i are weighed:

$$k(t) = \frac{1}{\frac{\sum_i 1/k_i}{N}} = \frac{N}{\sum_i 1/k_i} = \frac{N}{\sum_i A_i} = \frac{N}{A} \tag{2}$$

where A is the area of the whole surface. Note that by this weighting of individual pedestrian's individual space we obtain a consistent equation for the density, expressed as the number of pedestrians divided over the area in space.

The speed for each individual pedestrian is calculated directly from the trajectory data:

$$v_i = \sqrt{v_{xi}^2 + v_{yi}^2} \tag{3}$$

Here, we take the absolute speed, as we want to discard the walking direction. To calculate the flow, we use the previously calculated density and speed:

$$q(t) = \frac{\sum_i k_i \cdot v_i}{n} \tag{4}$$

3 Generalized Network Fundamental Diagrams

First, we show the resulting densities (accumulation) of the simulation runs for both scenarios in Fig. 3. It can be seen that in both scenarios the accumulation slightly increases, although a lot of variation in the accumulation is visible as well. We can see a rather short period in which the accumulation is relatively constant, after which the density decreases further.

The resulting Generalized Network Fundamental Diagrams are shown in Fig. 4a, b. The axes show the density and the density variation respectively, while the color of each dot indicates the corresponding flow (high flows in green, low flows in red). As we can see in both configurations, when the density increases, also the

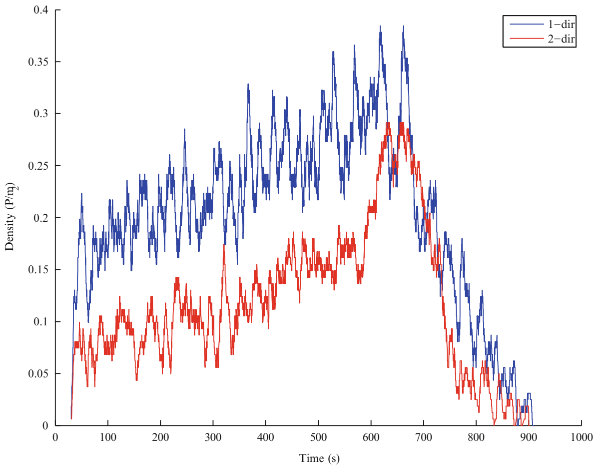

Fig. 3 Accumulation of both scenarios over time

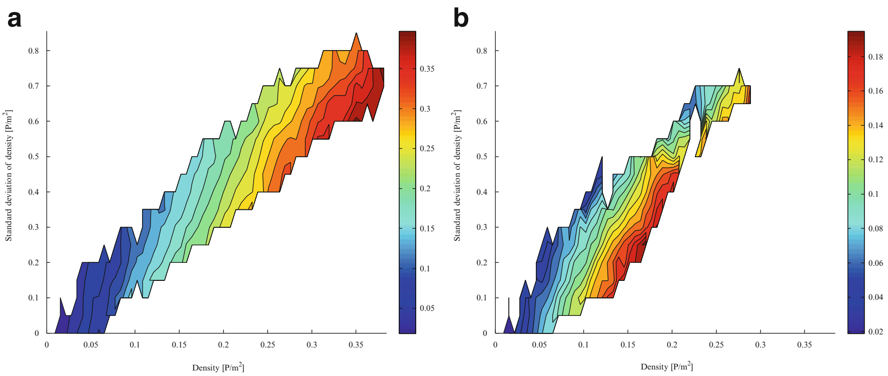

Fig. 4 Generalized macroscopic fundamental diagram. (**a**) One directional. (**b**) Crossing flows

standard deviation of the density increases. This can be expected, as the reason of the density increase is the onset of congestion, which causes high densities and low speeds just upstream of the exit, while the remaining part of the area remains almost empty. In the latter areas the pedestrians can walk with their free speeds. For a given density, it can be seen that flow increases with an increase in density variation. A smaller spatial variation of density implies less variation in conditions (being the experienced densities), and thus on average lower flows. For crossing flows, the spatial variation in density is even larger. In this case, the crossing flow, even though it is only small, is hindered by the congestion in the main flow, leading to a lower speed than would be expected according to volumes. The hinder caused by the crossing pedestrians causes disturbances in the queue, leading to a longer, and also more spatially distributed queue. The tendency of larger flows corresponding to a larger spatial distribution of the density also holds for this crossing scenario. As the spatial distribution is larger, this tendency is even better visible in the crossing flow scenario.

Conclusions
In this paper we have shown the Macroscopic Fundamental Diagrams also exist in pedestrian traffic. When the assumption of homogeneously distributed congestion over the area is dropped, the spatial variation in density appears to affect the MFD: a lower spatial variation implies lower flows, and higher variation implies higher flows. The exact shape of the MFD and the influence of the spatial variation in the density depends on the flow pattern (one-directional versus crossing flows). A reliable MFD combined with the use of pedestrian counting devices could provide a good estimator for the traffic state in real time applications.

Acknowledgements The research presented in this paper has been sponsored by the Dutch Foundation of Scientific Research MaGW-NWO and is part of the Aspasia subsidy Understanding emergent crowd behaviour: from individual behaviour dynamics to macroscopic phenomena, and the VENI subsidy Space to Change Lane and the VICI subsidy Modeling and Management of Traffic and Transportation in case of Exceptional Events.

References

1. C.F. Daganzo, Urban gridlock: macroscopic modeling and mitigation approaches. Transp. Res. Part B: Methodol. **41**(1), 49–62 (2007)
2. S.P. Hoogendoorn, M.C. Campanella, W. Daamen, Fundamental diagrams for pedestrian networks, in *Pedestrian and Evacuation Dynamics* (Springer, New York, 2011), pp. 255–264
3. V.L. Knoop, S.P. Hoogendoorn, Empirics of a generalised macroscopic fundamental diagram for urban freeways. Transp. Res. Rec. 2391, 133–141 (2013)