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Macroscopic Fundamental Diagram for pedestrian networks: Theory and applications

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ABSTRACT

The Network or Macroscopic Fundamental diagram (MFD) has been a topic receiving a lot of attention in the past decade. Both from a theoretical angle and from a more application-oriented perspective, the MFD has proven to be a powerful concept in understanding and managing vehicular network dynamics.

In particular, the application in traffic management has inspired the research presented in this contribution, where we explore the existence and the characteristics of the pedestrian Macroscopic Fundamental Diagram (p-MFD). This is first of all done from a theoretical perspective, which results in the main contribution of this research showing how we can derive the p-MFD from assumed local fundamental diagrams (FDs). In doing so, we show that we can relate the average (out-)flow from a pedestrian network as a function of the average spatial density $\bar{\rho}$ and the density spatial variation σ^2. We show that the latter is essential to provide a reasonable description of the overall network conditions. For simple relations between density and speed (i.e. Greenshields and Underwood fundamental diagrams), we derive analytical results; for more commonly used FDs in pedestrian flow theory, such as the triangular FD of Newell or the FD of Weidmann, we show the resulting relation by proposing a straightforward simulation approach.

As a secondary contribution of the paper, we show how the p-MFD can be constructed from pedestrian trajectory data stemming from either microsimulation or from experimental studies. We argue that the results found are in line with the theoretical results, providing further evidence for the validity of the p-MFD concept. We furthermore discuss concepts of hysteresis, also observed in vehicular network dynamics, due to the differences in the queue build up and recuperation phases.

We finally present some applications of the presented concepts in crowd management, network level-of-service determination, and coarse-scale modelling.

1. Introduction

The Network or Macroscopic Fundamental Diagram (MFD) for vehicular networks has received a lot of attention in the past decade, gradually leading to a comprehensive theory of network dynamics (Daganzo, 2007; Daganzo and Geroliminis, 2008). Hoogendoorn et al. (2011) has shown that a similar relation exists between the number of pedestrians

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in an area and the average flow in that area (production). Saberi and Mahmassani (2014) builds upon Hoogendoorn et al. (2010) and also shows that pedestrian crowds have an area-wide fundamental diagram that is similar to a network fundamental diagram of vehicular traffic, using empirical data from experiments. Moreover, they show that in a multidirectional area pedestrian traffic exhibits hysteresis behaviour similar to that of some other many-particle physical systems. The observed hysteresis formed a clockwise loop in which the areawide pedestrian flow was higher during the loading period than during the unloading period.

Pedestrian dynamics are known for its sensitivity to homogeneity of the pedestrian flow composition. Campanella et al. (2009) and Yang et al. (2014) show the consequences of heterogeneity on e.g. breakdown probability (capacity). Similar effects of the spatial variability of vehicle density on urban capacity are found by a.o. Mazloumian et al. (2010) and Daganzo et al. (2011). Homogeneity also plays an important role in the MFD, as the condition that the congestion is spread homogeneously over the network is one of the assumptions under which a proper shape of the MFD is found. Knoop et al. (2015) shows the effect of inhomogeneity by deriving the so-called generalised macroscopic fundamental diagram (GMFD). This effect of inhomogeneity is also found for MFDs for pedestrian traffic. Daamen et al. (2015) considers the effects of spatial inhomogeneity of the density and found that at the same density, a larger spatial variation in density leads to reduced network flows.

However, a thorough theoretical underpinning of the MFD and a quantification of the effect of the spatial distribution of density does not exist yet. This contribution builds upon the before-mentioned exploration of the pedestrian macroscopic fundamental diagram by Hoogendoorn et al. (2011). We explore the concept of the MFD for region-wide pedestrian flow operations (referred to as the p-MFD in the ensuing) and derive a relation between flow, (average network) density and spatial distribution of density. Next to performing several theoretical analyses, we investigate the characteristics of the p-MFD using both experimental and simulation data.

This contribution starts with an overview of the main definitions, followed by theoretical considerations on the p-MFD. Then, the properties of the p-MFD are investigated using data from micro-simulation (Section 4) and data from laboratory experiments (Section 5). We end with an overview of applications of the MFD for pedestrian networks, and conclusions and recommendations.

2. Definitions and nomenclature

Pedestrian flows are two (and in some cases even three) dimensional. This implies that common concepts from – generally one-dimensional – vehicular traffic flow theory, such as flows, speeds, and densities, need to be re-considered carefully before they can be used in a pedestrian flow context. From a macroscopic (or rather, continuum) perspective, concepts such as density, flow and average speed are relatively straightforward to interpret. For an introduction into the key variables for continuum multi-directional pedestrian flow modelling, we refer to Hoogendoorn et al. (2015).

For microscopic analyses using either simulation data or experimental data, concepts are somewhat more ambiguous. Duives et al. (2015) compares nine different definitions of density and shows that the results differ considerably when using the same underlying data set. Johansson (2009) and Zhang et al. (2011) show that these measures to compute the density might introduce dissimilarities between the resulting fundamental diagrams.

In this contribution, we use the concept of Voronoi diagrams (Zhang and Seyfried, 2013) to the microscopic data from either simulations or from experiments to determine the local density and the spatial density variation. Fig. 1 shows an example of the Voronoi diagram. In a Voronoi diagram, each cell corresponds to a single pedestrian p and includes all points in the area closer to pedestrian p than to any other pedestrian. The crosses indicate the locations of the individual pedestrians i at a time instant t_k. The cells are the local regions that reflect the area Ω_i that is available to the pedestrian. For the concepts discussed in this paper, we will modify the standard Voronoi approach in such a way that $\cup_{i=1}^{n}\Omega_i = \mathcal{A}$, where $\mathcal{A}$ is the (two-dimensional) walking area. Having computed the Voronoi diagram, we can define a pedestrian specific density $\rho_i(t_k)$:

$$\rho_i(t_k) = \frac{1}{|\Omega_i(t_k)|}. \tag{1}$$

The average density $\bar{\rho}(t_k)$ for time instant t_k is then given by averaging the pedestrian specific densities $\rho_i(t_k)$:

$$\bar{\rho}(t_k) = \frac{1}{n}\sum_{i=1}^{n}\rho_i(t_k), \tag{2}$$

where n is the amount of pedestrians in the area. As a measure of the spatial density variation $\bar{\sigma}(t_k)$, we use the standard deviation of the local densities, i.e.:

$$\bar{\sigma}(t_k)^2 = \frac{1}{n}\sum_{i=1}^{n}(\rho_i(t_k) - \bar{\rho}(t_k))^2 \tag{3}$$

The region-wide instantaneous mean speed is determined by taking the average speed of all pedestrians present in the region at time instant t_k. For a more thorough discussion on the impact of this definition, as well as alternative definitions, we refer to Duives et al. (2015).

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