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Quantification of the level of crowdedness for pedestrian movements

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HIGHLIGHTS

- Comprehensive review of measures to estimate the level of crowdedness in a crowd.
- Quantitative comparison of the measures w.r.t. pedestrian movement behaviours.
- Most of the studied measures introduce large errors in the 'fundamental relations'.
- The Voronoi Diagram measure and the X-T measure are 'best' estimating crowdedness.

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ABSTRACT

Within the realm of pedestrian research numerous measures have been proposed to estimate the level of crowdedness experienced by pedestrians. However, within the field of pedestrian traffic flow modelling there does not seem to be consensus on the question which of these measures performs best. This paper shows that the shape and scatter within the resulting fundamental diagrams differs a lot depending on the measure of crowdedness used. The main aim of the paper is to establish the advantages and disadvantages of the currently existing measures to quantify crowdedness in order to evaluate which measures provide both accurate and consistent results. The assessment is not only based on the theoretical differences, but also on the qualitative and quantitative differences between the resulting fundamental diagrams computed using the crowdedness measures on one and the same data set. The qualitative and quantitative functioning of the classical Grid-based measure is compared to with the X-T measure, an Exponentially Weighted Distance measure, and a Voronoi-Diagram measure. The consistency of relating these measures for crowdedness to the two macroscopic flow variables velocity and flow, the computational efficiency and the amount of scatter present within the fundamental diagrams produced by the implementation of the different measures are reviewed. It is found that the Voronoi-Diagram and X-T measure are the most efficient and consistent measures for crowdedness.

1. Introduction

Numerous empirical studies have researched the interactions between pedestrians in order to understand, assess, predict and manage the resulting movement dynamics. Understanding pedestrian movements is essential in order to manage and control crowd movements. In vehicular traffic engineering a fundamental diagram exists that relates density experienced

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by drivers to their driving velocity and the overall flow on the road. Using this fundamental diagram one is capable of predicting the capacity and behaviour of a road traffic system, allowing proactive rather than reactive traffic management. For pedestrian traffic this fundamental relation between the level of crowdedness, velocity and flow is still not understood completely. As a result, effective management of pedestrian facilities is still mainly based on vehicular traffic flow theory and the experience and intuition of the crowd manager.

In vehicular traffic engineering, density has been defined as the number of cars on a certain stretch of roadway at a certain time instance. Due to a different use of the available space, and a different ratio between vehicle length and road length for which the density is determined, computing the density of pedestrian traffic flows is less straightforward. Even without the answers to these questions, within the realm of pedestrian research numerous methods have been proposed to compute density [1–4]. However, no comprehensive answer is yet provided for issues such as computing densities near physical boundaries, the validity of necessary assumptions with respect to sight and interaction distances, and the best parameter sets to use to describe the relative weight of the presence of one pedestrian on the total density experienced by a pedestrian. A debate about which measures can be used, based on not only the theoretical differences but also the qualitative and quantitative differences of their respective results, is currently lacking. As such, at the very least a discussion about the measures that are to be preferred is necessary in order to create a scientific language when considering research into pedestrian movement dynamics. While vagueness surrounds the measures of density, fundamental diagrams, which relate the walking velocity of individuals to the level of crowdedness experienced by the individual, are frequently used to analyse pedestrian walking behaviour. Several fundamental diagrams for pedestrian traffic were presented over the years (e.g. Refs. [5–9]). In the diagrams the walking behaviour of different samples of the population, taking part in both empirical and laboratory studies featuring different flow situations, is depicted. The curves of these fundamental diagrams all have similar parabola-like shapes. However, the characteristic properties of these fundamental diagrams (i.e. the capacity, jam density and free speed) differ a lot. As an explanation of the found differences, researchers have mentioned culture (e.g. Ref. [10]), interactions with the physical infrastructure (e.g. Ref. [5]) and physical characteristics of the pedestrian themselves (e.g. Ref. [7]). Johansson [11] and Zhang et al. [12] did, however, show that also the measures used to compute the density experienced by a pedestrian might introduce dissimilarities between the resulting fundamental diagrams. In accordance with both previous attempts, this paper also shows that part of the dissimilarities between the previously presented fundamental diagrams are not only due to the previously mentioned factors, but are instead also due to the currently used measures.

The aim of this paper is to provide a comprehensive overview of measures that can be used to quantify the level of crowdedness experienced by a pedestrian within a crowd and to accordingly assess which of the found measures provide both an accurate estimation of crowdedness and a consistent way of relating crowdedness to the other two macroscopic flow variables. The authors specifically do not refer to the term density, since Johansson [11] showed that the level of crowdedness experienced by pedestrians can be determined in other SI-units than P/m^2. As a consequence, the current area-based definition of density would limit the scope of the inventory of measures. Furthermore, as with any computation measure, the usefulness of measures is dependent on the question one wants to answer and what one wants to measure. Density can be computed at different scales. This study attempts to derive specifically local measurements of crowdedness which can be used to deduce trends in the microscopic movement behaviour of pedestrians from a fundamental diagram. That is to say, the level of crowdedness experienced by an individual pedestrian at a given moment in time.

Both Johansson [11] and Zhang et al. [12] performed similar studies. Yet, where Johansson [11] transposes the available data sets to show the similarities in pedestrian movement behaviour captured by differently shaped fundamental diagrams, this research has quite the opposite goal. This study aims at visualizing the differences in the resulting fundamental diagrams produced by the measures to compute the density instead of the underlying data sets. In order to do so, the fundamental diagrams presented later on in this paper are computed based on one and the same data set. Therefore, the differences between the fundamental diagrams are solely due to the used measure of density. Factors which were previously mentioned to influence the results such as culture, physique and environment, are hence taken out of the equation. As a result, differences between the computed fundamental diagrams will be solely due to the implementation of the measure of crowdedness. A similar approach as Zhang et al. [12] followed. However, while Zhang et al. [12] compares methods in which the mathematical definitions of the velocity, as well as the density and the flow are varying between methods, this study assesses the influence of only using distinct measures of density while keeping the velocity computation method stable. Furthermore, where Zhang et al. [12] compares only measures of density that produce results with the units $\frac{P}{m^2}$, this study casts a wider net. More and also other measures that can be used to compute the level of crowdedness are studied with respect to the previous study. Additionally, a different flow situation is studied, i.e. a bottleneck situation instead of a uni-directional flow. Since, different movement phenomena arise during bottleneck situation than during a uni-directional flow situation [13,12], it is expected that also the shape of the fundamental diagrams computed based on the results of the two distinct movement situations differs.

This paper starts with a brief literature review of measures the can be used to estimate the level of crowdedness experienced by a pedestrian. Section 2 also introduces both the theory and mathematical formalization of the measures under assessment. The advantages and disadvantages of all measures of crowdedness are established. This section elaborates upon the assumptions imposed by each measure, the discrete/continuous nature of the solution, the resulting SI-units and the consistency of the density estimates. In Section 3 the data sets, gathered during pedestrian bottleneck experiments performed by Daamen and Hoogendoorn [13], which are used as grounds of comparison are discussed. Subsequently, Section 4