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Continuum modelling of pedestrian flows — Part 2: Sensitivity analysis featuring crowd movement phenomena

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HIGHLIGHTS

- We present a sensitivity analysis of the continuum model.
- The model's capabilities to predict crowd movement phenomena are studied.
- Only under very specific conditions all phenomena can be reproduced.
- The local route choice component is essential to predict dispersion.
- Self-organization arises as a result of the local route choice.

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ABSTRACT

In recent years numerous pedestrian simulation tools have been developed that can support crowd managers and government officials in their tasks. New technologies to monitor pedestrian flows are in dire need of models that allow for rapid state-estimation. Many contemporary pedestrian simulation tools model the movements of pedestrians at a microscopic level, which does not provide an exact solution. Macroscopic models capture the fundamental characteristics of the traffic state at a more aggregate level, and generally have a closed form solution which is necessary for rapid state estimation for traffic management purposes. This contribution presents a next step in the calibration and validation of the macroscopic continuum model detailed in Hoogendoorn et al. (2014). The influence of global and local route choice on the development of crowd movement phenomena, such as dissipation, lane-formation and stripe-formation, is studied. This study shows that most self-organization phenomena and behavioural trends only develop under very specific conditions, and as such can only be simulated using specific parameter sets. Moreover, all crowd movement phenomena can be reproduced by means of the continuum model using one parameter set. This study concludes that the incorporation of local route choice behaviour and the balancing of the aptitude of pedestrians with respect to their own class and other classes are both essential in the correct prediction of crowd movement dynamics.

1. Introduction

The fatally and severely injured pedestrians of the New Years stampede in Shanghai (2015) demonstrate that docile large-scale crowd movements during music, sports and religious events can develop into highly dangerous unpredictable

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crowd crushes at a moments notice. The newspaper headlines illustrate that managing pedestrian crowd movements is, due to the complex nature of these movements, a very intricate and complex task.

In recent years numerous pedestrian simulation tools have been developed that can support crowd managers and government officials in their tasks. Many of these tools simulate the movements of pedestrians at a microscopic level. These microscopic models determine the speed and direction of each pedestrian as a direct result of the characteristics of the pedestrian and its interactions with its environment. As a result of the high level of detail, microscopic simulation models tend to have long computation times. But more importantly, since these models predict the traffic state as a summation of the actions of individual particles, no exact solution exists that is necessary for management purposes.

Next to microscopic models, also macroscopic models exist. However, up to this moment only a few macroscopic simulation models have been presented. This type of model captures the fundamental characteristics of the traffic state at a more aggregate level. Consequently, a closed form description of crowd movement behaviour can be achieved.

New technologies to monitor pedestrian flows are in dire need of models that allow for rapid state-estimation. Consequently, these new technologies can potentially benefit from the core properties of macroscopic models. One promising macroscopic modelling attempt to be used for such endeavours has been detailed in Ref. [1].

This contribution presents a next step in the development of this continuum model. In this paper represents the second step in the calibration process of a pedestrian simulation model. That is to say, a comprehensive sensitivity analysis of the continuum model is presented. The influence of global and local route choice parameters on the development of crowd movement phenomena, such as dissipation, lane-formation and stripe-formation, is studied. The main contribution of the presented work is an improved understanding of the influence of the density gradient on the development of crowd movement phenomena in the proposed continuum model.

The paper starts with a brief overview of crowd movement phenomena, macroscopic modelling approaches and contemporary calibration attempts (Section 2). At the end of this section a framework for the calibration and validation of pedestrian simulation models is briefly introduced which will serve as point of departure during the remainder of this paper. A description of the continuum model is provided in Section 3. Subsequently, Section 4 details the sensitivity analysis methodology and the case studies. The simulation results, used in this research to assess the sensitivity of the continuum model, are presented and discussed in Section 5. The last section reviews the key findings of this contribution and presents some directions of future research.

2. Background

In this section, the key studies that feature attempts to model pedestrian movements in a continuous fashion and calibrate pedestrian simulation models are presented, which jointly form the foundation of this research. The main types of macroscopic modelling approaches are discussed in Section 2.1. Accordingly, Section 2.2 presents a brief overview recent attempts to ascertain whether pedestrian simulation models predict crowd movement dynamics accurately. Given that only limited calibration endeavours have been undertaken, Section 2.2 does not distinguish between microscopic and macroscopic modelling attempts.

2.1. Macroscopic modelling of operational walking behaviour

While new microscopic modelling approaches are presented frequently, the development of macroscopic pedestrian simulation models has been slow and sporadic. Nevertheless, several instances of macroscopic models have been presented in the last decade, such as network models, hybrid models and continuum models.

The first type of macroscopic simulation models, i.e. network models, makes use of graph theory to simulate the movements of pedestrians through a network. Examples of this type of models are Chalmer et al. [2], Lovas [3] and Daamen [4]. Due to the typical simplistic description of the network and/or the movement dynamics of the pedestrians, many network models use mathematical procedures borrowed from operational research to determine optimal management strategies swiftly. However, due to the lack of detail in the description of the movement dynamics these models are not capable of predicting the effect key features of crowd movements, such as for instance phase transitions and self-organization patterns.

A second type of macroscopic models, i.e. hybrid models, attempts to tap into the benefits of both microscopic and macroscopic simulation models. The microscopic and macroscopic part of a hybrid model are either entirely overlapping in time and space and used sequentially, or used separately at different time intervals or at different areas of the infrastructure depending on the stability of the traffic state. Banerjee et al. [5] and Xiong et al. [6] are examples of this type of macroscopic modelling. In complicated flow situations (i.e. intersecting flow situations) most hybrid models tend to fall back on the microscopic part of the simulation model. Consequently, the computation speed of hybrid models tends to decrease especially at the instances where the complexity and scale of the flow situation renders microscopic modelling impractical.

Models of the last type, continuum models, attempt to describe pedestrian movements as continuous flows in space and time. The inspiration of this type of aggregate simulation models, which feature the movements of large crowds without detailing the agent-based dynamics, has often been found in nature. Hughes [7] was the first to describe the analogy between pedestrian flows and soil mechanics, and used a potential field approach. Several other studies, Treuille et al. [8] and Xiong et al. [9], have further developed these ideas. Several researchers have found other sources of inspiration; such as for instance