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Bidirectional pedestrian fundamental diagram

Gunnar Flötteröd [a,*], Gregor Lämmel [b]

[a] Department of Transport Science, KTH Royal Institute of Technology, Stockholm, Sweden
[b] Institute for Advanced Simulation, Forschungszentrum Jülich, Jülich, Germany

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ABSTRACT

This article presents a new model of stationary bidirectional pedestrian flow. Starting out from microscopic first principles, a bidirectional fundamental diagram (FD) is derived that defines direction-specific flow rates as functions of direction-specific densities. The FD yields non-negative and bounded flows and guarantees that the instantaneous density changes that would result from these flows stay bounded between zero and jam density. In its minimal configuration, it uses just as many parameters as a unidirectional triangular FD: maximum walking speed, jam density, a collision avoidance parameter (from which the backward wave speed can be derived). A one-on-one mapping between the parameters guiding uni- and bidirectional pedestrian flows is proposed and both conceptually and empirically justified. Generalizations of the FD that maintain its desirable properties turn out to be straightforward by making its parameters density-dependent. The FD performs very well in comparisons against simulated and real data.

1. Introduction

The modeling of pedestrian traffic flow is relevant for the design and operation of pedestrian facilities as well as for emergency and evacuation planning. The present work exclusively focuses on the modeling of bidirectional flow. This phenomenon is separated from higher-level walking processes such as path following or route/destination choice by considering flows in long channels only. Within this scope, the following body of literature is of relevance.

1.1. Pedestrian cellular automata

The cellular automaton (CA) approach to pedestrian flow modeling has received much attention in the literature; Zheng et al. (2009) review more than 20 pedestrian CA models in the evacuation context. Pedestrian CAs were preceded by CAs for vehicular flow, initiated by the work of Nagel and Schreckenberg (1992), who introduce a CA model for single lane vehicular movements. The model yields realistic dynamics and a plausible fundamental diagram (FD). Exact and approximate expressions for different guises of this FD have been derived (Schadschneider, 1998). Rickert et al. (1996) extend the CA of Nagel and Schreckenberg (1992) into a two-lane model that allows for passing. Simon and Gutowitz (1998) introduce bidirectional flows into this model. Moussa (2008) also presents a CA model for bidirectional vehicular traffic. Daganzo (2006) establishes the equivalence of certain unidirectional CAs and the Kinematic Wave Model (KWM; Lighthill and Witham, 1955; Richards, 1956). Laval and Leclercq (2013) summarize this and other results under the umbrella of Hamilton–Jacobi theory.

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* Corresponding author.
E-mail addresses: gunnar.floetteroed@abe.kth.se (G. Flötteröd), g.laemmel@fz-juelich.de (G. Lämmel).

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Applications of CAs to the modeling of pedestrian flows began in the late 1990s. Blue and Adler (1998) present a unidirectional CA model for a multi-lane ring road. The pedestrians differ by their desired speed and can perform lane changes. This model produces an FD similar to that proposed by Weidmann (1993). Fukui and Ishibashi (1999) develop a bidirectional CA model. Conflicts (two pedestrians facing each other) are resolved by lateral movements. For low densities, the model exhibits lane formation behavior; as densities increase, it produces a rapid state transition from free flow to total jam. The bidirectional pedestrian CA proposed by Baek et al. (2009) exhibits the same phenomenon. Muramatsu et al. (1999) and Muramatsu and Nagatani (2000) investigate this state transition in detail, identifying a stable critical density for large systems. Blue and Adler (2000a) also specify a CA model for bidirectional pedestrian flow with multiple lanes. Apart from allowing for lateral movements, they also enable pedestrians to switch positions under dense conditions, avoiding the previously observed breakdowns. Blue and Adler (2000b) develop a four-directional extension of this model. Blue and Adler (2001) compare bidirectional FDs obtained from CA simulations to standard shapes found in the literature and identify the rate at which conflicting pedestrians move around each other as decisive for the shape of the FD. Tajima et al. (2002) present a CA for bidirectional flows in a channel with open boundary conditions. The model yields a triangular FD mapping entrance densities on total flows. Kirchner et al. (2003b); Kirchner et al. (2003a) introduce “friction” into a model of bidirectional flow, such that speed is reduced when conflicts occur. However, the model is evaluated for evacuation scenarios only, in which bidirectional flows rarely occur. Nowak and Schadschneider (2012) consider bidirectional pedestrian flows in channels with periodic and open boundary conditions and analyze quantitatively the occurrence of free flow, disordered flow, lane formation, and gridlock.

1.2. Cell-transmission models

The cell-transmission model (CTM) was introduced by Daganzo (1994, 1995) and Lebacque (1996) as a numerical solution scheme for the KWM. Asano et al. (2007) propose a multi-directional CTM of pedestrian flow that acknowledges speed reductions due to directional conflicts. Their approach is based on the use of a “conversion function” that turns a cell’s multi-directional density into a unidirectional one, to which then the standard CTM’s flow transmission rules are applied. However, no concrete functional form for this conversion function is given, and the presented simulation studies ignore multi-directional effects within the cells. Guo et al. (2011) specify a two-dimensional CTM of pedestrian evacuations. Directional conflicts are not explicitly modeled, but a congestion-dependent branch is included in the FD. Both studies present simulation results but do not validate those against real data. Hänseler et al. (2014) adopt the approach of Asano et al. (2007) in a model system for pedestrian flows in public walking areas. They observe a good performance of their model when calibrating it against real densities and travel times but acknowledge that the use of unidirectional flow propagation rules is a simplification.

1.3. Force-based models

Force-based models describe the movements of individual pedestrians in continuous space and time as the consequence of a force vector pointing to a destination location and repellent forces avoiding collisions. A prominent instance is the social force model (Helbing and Molnár, 1995; Helbing et al., 2000), where the repellent forces depend on Euclidean distances to obstacles and other pedestrians. Alternative formulations assume elliptical (Johansson et al., 2007; Shukla, 2010), velocity-dependent (Chraibi et al., 2010) or predicted (Zanlungo et al., 2011) force fields. Validations against empirical data have been performed by Chraibi et al. (2010) for unidirectional flows and by Zanlungo et al. (2011) for crossing pedestrian streams. Lane formation and oscillations in bottlenecks can be reproduced by these models given low or medium densities. Köster et al. (2013) discuss numerical problems arising in social force models for higher densities.

1.4. Empirical studies of bidirectional pedestrian flows

Isobe et al. (2004) compare an extended version of the CA model of Tajima et al. (2002) with experimental data. The CA model reproduces flows and velocities of bidirectional pedestrian experiments with a 50/50 directional flow split around an average density of 2.5 pedestrians per square meter in a channel. Similar experiments are performed by Nagai et al. (2005) for exceptional walking situations (e.g. evacuations during earth quakes or fire evacuations).

Cheung and Lam (1997) study bidirectional pedestrian flows in the Hong Kong Mass Transit Railway. Focusing on the effect of the directional distribution of pedestrian flow, they observe that capacity and speed of the minority stream decrease with increasing majority stream. Lam et al. (2002, 2003) study bidirectional pedestrian flows in in- and outdoor walkways and estimate a modified BPR function (Bureau of Public Roads, 1964) that captures the effect of counter-flow through a flow-composition dependent capacity parameter. Helbing et al. (2005); Kretz et al. (2006) support the hypothesis that flow composition matters. They conduct bidirectional flow experiments with various flow compositions and densities and find that the sum of directional flows in the bidirectional case is higher than in the unidirectional case for similar densities.

Wong et al. (2010) develop and estimate a bidirectional FD mapping direction-specific densities for different intersection angles onto direction-specific flows. Xie et al. (2013), Xie and Wong (2014) develop the model of Wong et al. (2010) further and introduce velocities as additional explanatory variables. The endogenous velocity variable cannot be isolated in their model, requiring numerical solution techniques. It should be noted that the FD developed in the present paper also starts