Safety Science 82 (2016) 68–76

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Interaction between vehicles and pedestrians at uncontrolled mid-block crosswalks

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ARTICLE INFO

Article history:
Received 12 April 2015
Received in revised form 8 August 2015
Accepted 10 September 2015

Keywords:
Crosswalk
Pedestrian
Vehicle
Cumulative prospect theory
Evolutionary game

ABSTRACT

Pedestrian crossing safety has attracted increased attention in recent years. However, little research has been conducted for examining the interaction between vehicles and pedestrians at uncontrolled mid-block crosswalks. In this paper, both a decision model and a motion model are developed for simulating this interaction process. Cumulative prospect theory is embedded in the evolutionary game framework for modeling the decision behaviors of drivers and pedestrians during the interactions, which can capture the phenomenon of disagreement among a pedestrian crossing group. Cellular automata-based moving rules are used to depict the motion of vehicles with consideration of the three-second rule, and a modified bidirectional pedestrian model is developed in order to consider the right-moving preference and resolve the deadlock among mixed flows. Results of calibration and validation of the proposed model are also presented. An application is designed for the purpose of illustrating the model's capabilities. The results demonstrate that the proposed model can well replicate actual observed traffic.

1. Introduction

The interaction between vehicles and pedestrians at crosswalks may induce not only traffic congestions of vehicle flow but also accidents. Thus, analysis of the interaction between pedestrians and vehicles has been the subject of numerous studies focused on road design, traffic signals, and road users' behaviors (de Lavalette et al., 2009; Guo et al., 2012; Koh et al., 2014; Li, 2013; Liu and Tung, 2014).

In the last decade, limited studies have been conducted for attempting the modeling of mixed pedestrian–vehicle flows at uncontrolled crosswalks. For example, Zhang et al. (2004) used cellular automata to simulate pedestrians' crossing and introduced the concept of a "stop point" for resolving conflicts among pedestrians or between pedestrians and vehicles at a crosswalk. Further, Helbing et al. (2005) proposed a macro model for analytically investigating the oscillations and delays of pedestrian and vehicle flows. Sun et al. (2012) used cellular automata to model the behavior of mutual interferences between pedestrians and vehicles at a crosswalk by introducing conflict interference rules between pedestrians and vehicles. Jin et al. (2013) developed a modified car-following model and pedestrian crossing rules so as to analyze the interaction between vehicle traffic and pedestrian flow. Xin et al. (2014) proposed a pedestrian–vehicle cellular automata model to study the characteristics of the mixed traffic, in which the heterogeneity of pedestrians is taken into account.

The aforementioned studies focused primarily on modeling of the behavior characteristics of vehicle drivers and pedestrians. None of these studies, however, considered the decision process of vehicle drivers and pedestrians during the interaction. This shortcoming resulted in a failure to understand the interaction between vehicles and pedestrians from the perspective of the entire system. The relationship between conflicting traffic streams at a mid-block crosswalk is essentially a game of competing for limited time and space resources. Thus, game theory is applicable to the analysis of the interaction between vehicles and pedestrians. Classical game theory is based on rational behavior exhibited in interpersonal conflicting situations. In order to deal with the limited rationality in the selection and decision processes, evolutionary game theory is proposed as an extension of the classical paradigm toward bounded rationality. However, the payoff matrix in evolutionary game theory is composed of the payoff based on expected utility theory, which is contrary to the assumption of bounded rationality. In order to overcome the shortcoming of expected utility theory, prospect theory is proposed for handling the decision behavior under risk and uncertainty. Most studies on prospect the-

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http://dx.doi.org/10.1016/j.ssci.2015.09.016
0925-7535/

ory in the field of transportation focus on the route choice, network equilibrium, and departure time choice (Gao et al., 2010; Hjorth and Fosgerau, 2012; Jou et al., 2008; Kemel and Paraschiv, 2013). A recent study (Wang et al., 2013) embedded the prospect theory model into the replicator dynamics framework in order to model the evolution of the traveler route choice under risk. The framework for that study was developed at the macro level.

Different from the work of Wang et al. (2013), in the present work, we model the interaction between vehicles and pedestrians from a micro-dynamics viewpoint, in order to provide a more detailed analysis of individual behavior. The micro-level dynamics of the system is usually defined by strategy update rules. A huge variety of microscopic update rules has been defined and applied in game theory (Szabo and Fath, 2007). These update rules can be divided into two categories of learning paradigms: one is the social learning paradigm, in which players update their strategies based on imitation of strategies of those players who have performed better in the past, and the other is the individual learning paradigm, which is based on an individual's learning and updating of strategies based only on his/her own experience (Arifovic and Karaivanov, 2010). In this study, we consider mainly social learning paradigms in order to describe the player's learning process, which may help us better understand the herd mentality (Jin et al., 2013) and capture the phenomenon of disagreement among a pedestrian crossing group, which previous works failed to reflect.

Moreover, the aforementioned studies on the modeling of the motion of pedestrians and vehicles have the following three shortcomings. First, in China, pedestrians prefer to walk or move along the right-hand side of the road (Yang et al., 2008). However, this asymmetrical behavior has been ignored in the abovementioned studies. Second, a waiting pedestrian may not cross the conflict area with a vehicle and exchange his/her position with an opposing crossing pedestrian in accordance with the existing model, which results in the pedestrian and the vehicle stopping in the conflict area. Therefore, the deadlock among mixed flows should be resolved. In this study, we develop improved rule sets for simulating the motion of pedestrians. Finally, our observation suggests that drivers driving on the road usually follow the "three-second rule" (New Jersey Motor Vehicle Commission, 2015) to avoid tailgating, which should be considered in the vehicle-following model.

The remainder of this paper is organized as follows. Section 2 describes the framework of the proposed model. Section 3 describes the decision model of the interaction between vehicles and pedestrians at uncontrolled mid-block crosswalks. Section 4 introduces a motion model for vehicles and pedestrians. Sections 5 and 6 respectively present the calibration and validation of the proposed model. Section 7 describes an application of the proposed model. Finally, Section 8 concludes the paper with a summary and outlook for further research.

2. Model framework

The model consists of two modules: a decision model and a motion model (see Fig. 1). The objective of the decision model is to describe the perception and judgment of pedestrians and drivers during street crossing. Then, the motion model determines the microscopic movements of vehicles and pedestrians. The moving rules for vehicle and pedestrian flows are extended from the existing cellular automata model. In the following, each model is described in detail.

3. Decision model

In this section, we describe the decision model of the interaction between vehicles and pedestrians at uncontrolled mid-block crosswalks. First, we define the interaction within the framework of game theory. Then, we present three key components in the decision model based on the evolutionary game: payoff based on cumulative prospect theory (Tversky and Kahllemna, 1992), dynamic topology, and microscopic update rules.

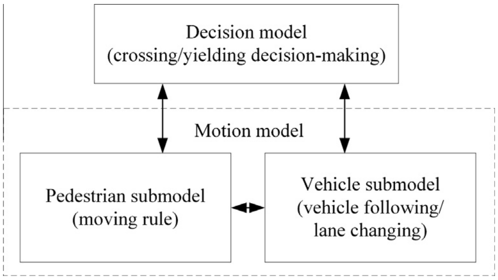

Fig. 1. Model framework.

3.1. Definition and notation

We formulate the game to take into account the population, players, strategy, and payoff.

(1) *Population:* The two populations are vehicles and pedestrians. Let C denote the population of vehicles and let S denote the population of pedestrians.
(2) *Players:* For a certain uncontrolled mid-block crosswalk, each user in the population is a player of the game. Let C_i and S_i $(i = 1, \ldots, l)$ denote the players in the populations of C and S, respectively.
(3) *Strategy:* The vehicle chooses whether or not to yield to the pedestrian. The pedestrian chooses whether or not to accept the gap. For simplicity, the set of strategies for all players is taken as {crossing, yielding}. Let $M = \{(p_1, p_2)|p_j \geq 0, \sum_{j=1}^{2} p_j = 1.\}$ be the set of probability distributions over the two pure strategies, where p_j represents the proportion of users choosing strategy j.
(4) *Payoff:* The payoffs for the vehicle and pedestrian are described in Section 3.2.

3.2. Payoffs based on cumulative prospect theory

3.2.1. Assumption

(1) *Delay costs:* When the vehicle and pedestrian are in conflict, the driver may yield to the pedestrian or the pedestrian may wait for a chance to cross; thus, at least one of the two sides would spend more time, which can be described by the delay. Let t_C^D and t_S^D denote the delay costs for the vehicle and pedestrian, respectively.
(2) *Risk costs:* When the vehicle and pedestrian are in conflict, both the driver and the pedestrian may choose to cross, and thus, both of them would face potential losses, which can be described by the risk. For drivers, accidents will lead to economic losses. For pedestrians, accidents will lead to physical injury or loss of life. Let t_C^R and t_S^R denote the risk costs for the vehicle and pedestrian, respectively. Note that $t_C^R < t_S^R$.

We also assume that each player is bounded rational and chooses the strategy according to cumulative prospect theory.