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# Modeling pedestrian crossing speed profiles considering speed change behavior for the safety assessment of signalized intersections

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A R T I C L E I N F O

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A B S T R A C T

Pedestrian safety is one of the most challenging issues in road networks. Understanding how pedestrians maneuver across an intersection is the key to applying countermeasures against traffic crashes. It is known that the behaviors of pedestrians at signalized crosswalks are significantly different from those in ordinary walking spaces, and they are highly influenced by signal indication, potential conflicts with vehicles, and intersection geometries. One of the most important characteristics of pedestrian behavior at crosswalks is the possible sudden speed change while crossing. Such sudden behavioral change may not be expected by conflicting vehicles, which may lead to hazardous situations. This study aims to quantitatively model the sudden speed changes of pedestrians as they cross signalized crosswalks under uncongested conditions. Pedestrian speed profiles are collected from empirical data and speed change events are extracted assuming that the speed profiles are stepwise functions. The occurrence of speed change events is described by a discrete choice model as a function of the necessary walking speed to complete crossing before the red interval ends, current speed, and the presence of turning vehicles in the conflict area. The amount of speed change before and after the event is modeled using regression analysis. A Monte Carlo simulation is applied for the entire speed profile of the pedestrians. The results show that the model can represent the pedestrian travel time distribution more accurately than the constant speed model.

## 1. Introduction

Pedestrian safety is one of the main challenges that city planners and policy makers face. Pedestrian–vehicle crashes have become a major safety problem that has resulted in a high rate of fatalities (National Police Agency in Japan, 2015). Worldwide, 22% of total road crash fatalities are pedestrians (World Health Organization, 2015). In Japan, 37% of total road fatalities in 2015 were pedestrians (National Police Agency in Japan, 2015). In Tokyo alone, the traffic police department reported that 48% of total road crash fatalities were pedestrians (Metropolitan Police Department in Japan, 2016). These percentages are increasing with time owing to the growth of pedestrian activities and the expansion of urban areas. Therefore, pedestrian safety is a critical issue and concrete measures should be taken to improve the current situation. Various speed calming measures, control policies, and geometric improvements have been implemented, combined with different technologies from various countries worldwide in order to provide pedestrians with a safer crossing experience. In spite of all these extensive efforts, pedestrian safety remains one of the main problems that transportation engineers face, especially in urban areas.

Although pedestrians have the right-of-way over vehicles both at unsignalized and signalized crosswalks where the priority is given by signal indication, drivers still compete with pedestrians over the right-of-way and put pedestrian safety at risk. Understanding pedestrian and vehicle behaviors is crucial to provide rational and reliable safety assessments. In reality, road users anticipate other users' behavior in order to avoid collisions. Thus, widely varying pedestrian and/or vehicle maneuvers may result in a misunderstanding of each other's decisions, which can lead to safety problems. Pedestrians are subject to behavioral changes while crossing, as reported by Iryo-Asano et al. (2014). Crosswalk geometry and signal time settings, among other contributing factors, may cause pedestrians to suddenly change their velocity without paying attention to the surrounding conditions (Iryo-Asano et al., 2014; Alhajyaseen and Iryo-Asano, 2017). Such behavioral changes cannot be predicted by drivers, and they may lead to severe conflicts.

This study aims at developing a method for the estimation of pedestrian speed profiles at signalized crosswalks, considering possible

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behavioral changes such as abrupt acceleration and/or deceleration. The developed model takes into account the impact of crosswalk geometry, signal settings, and the interaction with turning vehicular traffic. The availability of a reliable model that can reproduce realistic pedestrian maneuvers at crosswalks is crucial to provide a dependable assessment of pedestrian–vehicle conflicts and their severity.

## 2. Literature review

A majority of the existing studies related to pedestrian–vehicle conflicts concentrate on the microscopic parameters of vehicle behavior, such as speed profiles including acceleration and deceleration events, assuming that vehicles are the main contributing element in pedestrian–vehicle crashes. In this regard, Alhajyaseen et al. (2013a, 2013b, 2012a, 2012b) intensively analyzed turning vehicle maneuvers at intersections including paths, speed profiles, and gap acceptance for better assessment of pedestrian–vehicle conflicts. They identified significant variations in vehicle paths and speeds at conflict points with pedestrians. The presence of significant variations in the turning maneuvers of vehicles considerably affects the probabilities and severities of conflicts with pedestrians.

On the other hand, pedestrian behavior plays an important role in conflicts with vehicular traffic. Many studies have analyzed pedestrian crossing behavior at intersections including stop-go decisions, compliance with signal indications, and average crossing speed. However, the analysis of instantaneous behavior of pedestrians while crossing, particularly the velocity profile to identify possible behavioral changes, is lacking. Such analysis is important because sudden behavioral changes cannot be predicted by other road users who will probably fail to react appropriately to avoid conflicts with pedestrians.

In a previous study in Japan, Iryo-Asano et al. (2015) and Alhajyaseen and Iryo-Asano (2017) videotaped several signalized crosswalks to collect the microscopic characteristics of pedestrian maneuvers. They used image-processing software to collect pedestrian position and timing information at 0.5 s time intervals. They identified empirical evidence that some pedestrians exhibit sudden speed changes while crossing, which could be a reaction to pedestrian signal indications, the crosswalk layout, or a combination of different factors. Many of the identified acceleration and deceleration events occur near conflict areas, which may cause pedestrians to arrive more quickly at these areas or stay longer in them. In either case, drivers cannot anticipate such abrupt behavioral changes, which may lead to severe conflicts with pedestrians. Such differing behaviors make it difficult for drivers to correctly predict the pedestrian reactions. This increases the probability of improper maneuvers that put pedestrian safety at risk. However, a method to predict the location and timing of such speed changes and to integrate them with vehicle maneuvers for the safety assessment of intersections was not developed in their study.

In another study, Alhajyaseen (2014) studied average pedestrian crossing speeds at signalized crosswalks in Japan considering the impact of signal timing and crosswalk geometry. He found that pedestrian crossing speed increases as the pedestrian green (PG) phase proceeds, especially at the end of the PG and the onset of pedestrian flashing green (PFG) phase. Furthermore, he demonstrated empirically that pedestrians hurry when entering crosswalks as the green light flashes and then tend to significantly decrease their speed while crossing, which is in accordance with other recent studies (Iryo-Asano et al., 2014a; Iryo-Asano and Alhajyaseen, 2014). Iryo-Asano et al. (2014) proposed a method to estimate pedestrian travel speeds in the first and second halves of the crosswalk considering crosswalk geometry and signal settings. However, these travel speeds are useful in the estimation of crossing time but not in the analysis of pedestrian–vehicle conflicts. Instantaneous pedestrian speeds are crucial for the estimation of pedestrian arrival time at the conflict area and the safety assessment of conflicts with vehicles.

Koh and Wong (2014) analyzed pedestrian crossing speeds in Singapore and obtained similar results, where they found that crossing speeds significantly differ during the PG phase compared to the pedestrian flashing green (PFG) phase. Schmitz (2011) also confirmed the significant impact of pedestrian signal settings on pedestrian behavior from empirical data in the US; for instance, he concluded that pedestrian countdown timers significantly increase the pedestrian crossing speed.

Other studies in different countries have confirmed the significant impact of crosswalk layout, including width, length, position, and the usage of channelization, on pedestrian compliance to signals (Supernak et al., 2013; Yang and Sun, 2013; Xu et al., 2013), which is in accordance with the authors' previous studies (Iryo-Asano et al., 2014a, 2014bIryo-Asano and Alhajyaseen, 2014Iryo-Asano et al., 2014a, 2014b; Iryo-Asano and Alhajyaseen, 2014). Pedestrian compliance to signals was also analyzed by Wang et al. (2011) who identified several contributing factors to pedestrian violation of traffic signals, such as the waiting time or delay, personal characteristics (e.g., age and gender), trip purpose, and traffic conditions (e.g., pedestrian flow rate and vehicular traffic volume).

All previous studies analyze the pedestrian behavior in terms of decision-making and average crossing speeds without developing methodologies to produce their maneuvers for a realistic representation of pedestrian-vehicles conflicts. In this study, a method to predict the location and timing of possible acceleration and deceleration events is developed considering the impact of crosswalk layout, signal indication, pedestrian arrival time to the crosswalk, pedestrian approaching speed, and others. The availability of a reliable model that can produce realistic maneuvers of pedestrians can facilitate the development of proper safety countermeasures, such as improving intersection layouts and signal control or developing safety-information provision systems. Moreover, it can be utilized in autonomous vehicles for the detection of pedestrians and prediction of any possible behavioral changes, so that vehicles can make appropriate maneuvers to avoid severe conflicts with crossing pedestrians.

## 3. Modeling pedestrian speed profile considering sudden speed change events

### 3.1. Speed profile using stepwise functions

According to Iryo-Asano et al. (2015), the profiles of pedestrian longitudinal speed on crosswalks under low demand conditions can be expressed by the stepwise functions $v_s(t)$ as Eq. (1).

$$v_s(t) = \begin{cases} v_1 & \text{where } t < t_1 \\ v_2 & \text{where } t_1 \le t < t_2 \\ & \cdots \\ v_{m+1} & \text{where } t_m \le t \end{cases} \tag{1}$$

where $m$ is the number of speed changing events, $t_i$ is the timing of the speed change event $i$, and $v_i$ is the constant speed during the time period between $t_i$ and $t_{i+1}$. The value of $m$ differs for each individual speed profile and should be 0 if there are no speed changes. The speed profiles of each pedestrian can be fit to this stepwise function by determining $t_i$, $v_i$, and $m$.

This implies that the pedestrian speed change events are approximated by a set of discrete events. Thus, in this study, it is assumed that pedestrians have a discrete choice to determine whether they will accelerate/decelerate or not at each time and location. Therefore, the proposed pedestrian speed profile model in this study consists of two sub models. The first one represents the pedestrians' reaction, i.e., when and where they accelerate or decelerate. The other sub model is to calculate the actual amount of speed change at the event.

### 3.2. Sudden speed change sub model

At each time interval $\Delta t$, it is assumed that pedestrians choose their