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Estimation of left-turning vehicle maneuvers for the assessment of pedestrian safety at intersections

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ABSTRACT

Improving pedestrian safety at intersections remains a critical issue. Although several types of safety countermeasures, such as reforming intersection layouts, have been implemented, methods have not yet been established to quantitatively evaluate the effects of these countermeasures before installation. One of the main issues in pedestrian safety is conflicts with turning vehicles. This study aims to develop an integrated model to represent the variations in the maneuvers of left-turners (left-hand traffic) at signalized intersections that dynamically considers the vehicle reaction to intersection geometry and crossing pedestrians. The proposed method consists of four empirically developed stochastic sub-models, including a path model, free-flow speed profile model, lag/gap acceptance model, and stopping/clearing speed profile model. Since safety assessment is the main objective driving the development of the proposed model, this study uses post-encroachment time (PET) and vehicle speed at the crosswalk as validation parameters. Preliminary validation results obtained by Monte Carlo simulation show that the proposed integrated model can realistically represent the variations in vehicle maneuvers as well as the distribution of PET and vehicle speeds at the crosswalk.
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1. Introduction

The operational efficiency of vehicular and pedestrian flows is an important concern, especially at signalized crosswalks where both have to share the same space. Crosswalks are designated portions of a road that are used to assist pedestrians desiring to cross the street, and they play a significant role in the safety and mobility performance of signalized intersections.

Pedestrian-vehicle conflicts are a common safety problem at signalized intersections since pedestrians are less protected than drivers. According to a report by the Japan National Police Agency [1], one-third of the total traffic accident fatalities in 2009 were pedestrians at signalized and unsignalized crosswalks. There are many reasons for such collisions, for instance, visibility, intersection geometry, traffic signal control policy, and user behavior.

The safety performance of intersections is usually evaluated through two approaches: before–after studies using accident statistics and traffic conflict analysis based on empirical data. However, in both approaches, the analysis is based on data collected after implementing the countermeasures, which means that an assessment before their implementation is not possible. Simulation tools are often used in practice as an alternative analysis tool to overcome the limitations of existing procedures, and they are more flexible and promising. However, existing simulation software is basically aimed toward mobility assessments; thus, they simplify the traffic flow at intersections to an extent that safety assessment is not reliable. The models described in this study are part of a comprehensive research project aimed at developing a simulation tool for the safety assessment of signalized intersections.

In general, the main threat to pedestrian safety comes from interaction with turning vehicles since, in common signal plans, pedestrians and turning vehicles share the same phase. Vehicles are expected to yield to pedestrians in such cases; however, because of the surrounding environment, pedestrian direction of movement, and geometric layout of the intersection, drivers might take risky decisions by looking to pass through small gaps or not yielding to pedestrians, which might threaten pedestrian safety. The Manual on Intersection Accident Countermeasures of Japan [2] suggests modifying intersection corner geometry or the crosswalk position to improve the safety performance regarding accidents between left-turning vehicles (left-hand traffic) and pedestrians. These measures clearly suggest that understanding the effects of intersection layouts, for instance, on driver turning maneuvers is essential.

In Japan, vehicles drive on the left side of the road (left-hand traffic), while in the US, they drive on the right side (right-hand traffic). The positions of the driver relative to the road curb in both cases are symmetric. Therefore, it is expected that in terms of similar intersection geometries, operations, and driver characteristics, the traffic systems

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do not have a significant impact on pedestrian–vehicle conflicts. The definition of turning movements throughout this study is based on left-hand traffic system. Since left-turners have more frequent conflict with pedestrians in common signal plans, this study concentrates on their maneuvers and aims to develop an integrated model to represent the variations in the maneuvers of left-turners considering intersection geometry and crossing pedestrians.

This paper starts with an introduction and literature review; it then describes the method to represent the maneuvers of left-turners. The proposed method consists of several sub-models that are briefly discussed. A validation for the proposed model and a case study are presented. Finally, conclusions and future works are discussed.

2. Literature review

Many studies use historical accident data and take different kinds of influencing factors into account as an approach to analyzing the changes in safety levels of signalized intersections after a specific countermeasure is implemented [3]. However, it takes a very long time to obtain statistically sufficient data. Furthermore, ex-ante safety assessments are not possible through such approaches.

Microscopic simulations are considerably effective tools to overcome the shortcomings of accident analysis approaches. They can virtually represent situations in the planning stage to evaluate improvements in intersection layouts. Gettman and Head [4] investigated surrogate safety measures that were obtained from microscopic simulation tools. They listed several requirements for the simulations to fulfill in order to obtain reliable safety measures that have not yet been achieved by existing simulation tools. Archer [5] conducted a more detailed analysis of the opportunities and shortcomings of microscopic simulations for safety assessments. He concluded that crucial behaviors, including the speed of vehicles around intersections and yielding decisions to other users, are yet not realistically represented in existing simulations. These behaviors are affected by intersection layouts and/or the surrounding users' behavior.

Several studies have empirically modeled the yielding behavior of vehicles. Sun et al. [6] applied logit and probit models for a vehicle's choice to yield at an unsignalized pedestrian crossing site. Gap acceptance models are frequently used to represent a driver's decision of whether to stop. Logit gap acceptance models [7,8] and probit models [9,10] have been proposed that consider the surrounding conditions of vehicles. Conceptually, these models could represent inconsistent driver behavior and a heterogeneous population by using random distributions. However, those models are based on binary choice, though some do consider the approaching speed of vehicles as an influencing factor [6]. They also do not consider the arrival timing of the vehicle to the crosswalk and the speed at the crosswalk, which are essential factors for evaluating safety.

Vehicle speed at intersections is affected not only by pedestrians but also by intersection geometries. Viti et al. [11] compared the observed trajectories of vehicles near the stop line with results obtained by microscopic simulations and found conspicuous differences. In another study, Xin et al. [12] proposed a collision-inclusive car-following behavior model called the “Less-Than-Perfect Driver.” Their proposed model aims to capture the variations in driver maneuvers in order to represent unsafe behavior. However, their model does not cover vehicles turning at intersections. In general, it can be concluded that, to date, no realistic model has been proposed to represent the variations in the maneuver of a turning vehicle at a signalized intersection.

Alhajyaseen et al. [13] analyzed and modeled the gap acceptance of left-turning vehicles as Weibull distributions that considered the pedestrians' walking directions. Turning vehicle maneuvers, in terms of parameters such as the path and speed around intersections, were also modeled as functions of the intersection layout [14,15]. However, these path and speed models were only developed under free-flow conditions without pedestrians. The present study aims to integrate those models to reproduce the overall conflict conditions between left-turners and pedestrians; this will enable the distribution of vehicle trajectories to be represented depending on the intersection layout and give more reliable surrogate measures for safety assessment.

The traffic conflict technique, initially proposed by Perkins and Harris [16], is widely used to evaluate safety. This method assesses the safety through conflict frequency and severity, which are usually indicated by certain measures, such as the post-encroachment time (PET) and time to collision [17,18]. Tang and Nakamura [19] supported the use of PET for evaluating conflict severity, especially when analyzing conflicts involving turning traffic. They explained that a lower PET indicates a higher severity of corresponding conflict; however, other studies refuted that argument, primarily because speed is not included in the measure [20,21]. In fact, a lower PET certainly indicates a higher probability of collision, but it cannot be directly linked to the severity of the collision. Vehicle speed at the crosswalk is also an important measure for evaluating the severity of conflicts. Several previous studies found that the vehicle speed when a crash occurs (crash speed) significantly contributes to the severity of the crash [22,23]. Kloeden et al. [22] found that the risk of involvement in a casualty crash increases more than exponentially as the free traveling speed increases above the mean traffic speed on rural roads. Hence, it is reasonable to use the speed of the vehicle at the crosswalk as an indicator for the severity of the conflict, assuming that the clearing speed is very close to the crash speed if the conflict becomes a real crash. Therefore, in this study, PET and the vehicle speed at the conflict point are chosen to evaluate safety and validate the proposed model.

3. Scope and assumptions

The analyzed conflict situation in this study is depicted in Fig. 1. Green indications for left-turning vehicles and pedestrians crossing at the exit approach of the corresponding left-turners are given at the same time (permitted green phase). Note that turning on red is not allowed in Japan and that left-turners can only turn when a shared pedestrian–vehicle phase is provided. Pedestrian–vehicle interactions significantly vary from one country to another depending on the traffic conditions and the compliance of users to traffic rules. However, in general, drivers must yield to crossing pedestrians at signalized crosswalks in order to avoid colliding with them.

In this study, a conflict area is defined as the area occupied by the body of a vehicle on a crosswalk (Fig. 1). All potential conflicts with pedestrians occur within the conflict area. In order to assess the safety in this area, the maneuvering of left turners, such as the turning path and speed inside the intersection, is modeled in the latter part of the study. The subject area of the developed model is from the stop line to the end of the conflict area. This study mainly examines vehicles entering the conflict area that reach the intersection after the queuing vehicles at the stop line have been discharged. The subject vehicles have relatively less probability of meeting pedestrians at crosswalk, and thus, they might be less careful while turning. Moreover, their approach speed to intersections is higher than that of queuing vehicles. Thus, it is reasonable to assume that these vehicles are at higher risk of severe collisions. Since queuing vehicles also have a probability of encountering pedestrians, they will be considered in the future. Furthermore, the effects of signal timing on driver behavior, especially during the intergreen time, are not yet reflected in the proposed model.

In order to explain the mechanism of a turning vehicle's maneuver, the following major assumptions are presented below.

Assumption 1. Each driver has his/her own free-flow speed and path profiles.

The free-flow speed profile is defined as the speed profile of a vehicle for the overall turning maneuver at the intersection when

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