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Evaluation of pedestrian safety at intersections: A theoretical framework based on pedestrian-vehicle interaction patterns

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ABSTRACT

Pedestrians are the most vulnerable road users, and pedestrian safety has become a major research focus in recent years. Regarding the quality and quantity issues with collision data, conflict analysis using surrogate safety measures has become a useful method to study pedestrian safety. However, given the inequality between pedestrians and vehicles in encounters and the multiple interactions between pedestrians and vehicles, it is insufficient to simply use the same indicator(s) or the same way to aggregate indicators for all conditions. In addition, behavioral factors cannot be neglected.

To better use information extracted from trajectories for safety evaluation and pay more attention on effects of behavioral factors, this paper develops a more sophisticated framework for pedestrian conflict analysis that takes pedestrian-vehicle interactions into consideration. A concept of three interaction patterns has been proposed for the first time, namely "hard interaction," "no interaction," and "soft-interaction." Interactions have been categorized under one of these patterns by analyzing profiles of speed and conflict indicators during the whole interactive processes. In this paper, a support vector machine (SVM) approach has been adopted to classify severity levels for a dataset including 1144 events extracted from three intersections in Shanghai, China, followed by an analysis of variable importance. The results revealed that different conflict indicators have different contributions to indicating the severity level under various interaction patterns. Therefore, it is recommended either to use specific conflict indicators or to use weighted indicator aggregation for each interaction pattern when evaluating pedestrian safety.

The implementation has been carried out at the fourth crosswalk, and the results indicate that the proposed method can achieve a higher accuracy and better robustness than conventional methods. Furthermore, the method is helpful for better understanding underlying levels of safety from the behavioral perspective, which can also provide evidence for targeted traffic education on proper behaviors.

1. Introduction

Pedestrians are the most vulnerable road users and are at risk of severe consequences when involved in traffic accidents. Accident statistics from The Ministry of Public Security of China (2011) indicated that pedestrians accounted for 30 percent of total traffic fatalities in China in 2011. Not only in China, but worldwide, pedestrian safety has become a major concern in recent years.

Because of data quality and quantity limitations of collision-based safety analysis, as being proposed by Ismail et al. (2009, 2010), the use of surrogate safety measures has been advocated and the traffic conflict technique (TCT) has been developed for pedestrian-vehicle conflict analysis.

The most common way to do such analysis is to use individual or aggregate indicators of temporal proximity (Tourinho and Pietrantonio, 2003; Lord, 1996; Archer, 2005; Rodriguez-Seda et al., 2008; Tarko et al., 2009; Ismail et al., 2009, 2011; Kaparias et al., 2010; Laureshyn et al., 2010; Salamati et al., 2011; Ren et al., 2012; Saunier, 2013). In recent years, the development of computer vision has made it possible to apply automated conflict analysis to pedestrian safety evaluation— For example, Ismail et al. (2009, 2010) and Laureshyn et al. (2009a) have demonstrated the potential to acquire and process trajectory data for conflict analysis.

Compared to encounters between vehicles, pedestrian-vehicle encounters are of strong "inequality", since pedestrians move at relatively low speeds and have the potential to stop or accelerate quickly (Van der Horst and Kraay, 1986). Furthermore, pedestrian-

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vehicle encounters are more complicated, because of the multiple interactions that are quite often observed. This makes it impossible to use the same indicator(s) or their aggregation in the same way for all conditions. Additionally, behavioral factors cannot be neglected. For these reasons, this paper aims to develop a more sophisticated framework for vehicle-pedestrian conflict analysis that accounts for their interactions and efficiently uses of extracted trajectories. A literature review of pedestrian conflict analysis and interaction study is presented in the next section, followed by sections on data acquisition, methodology, implementation, and finally conclusions and future work.

2. Literature review

Surrogate safety measures have been used widely to estimate road user safety. The most commonly used indicators of temporal proximity include but are not limited to the following measures:

- Time to Collision (TTC), which is defined as the time until two road users collide if they continue at their present speed and along the same paths (Hayward, 1971),
- Deceleration-to-Safety Time (DST), which is the deceleration required so that a second road user reaches the conflict point no earlier than when the first user leaving it (Hupfer, 1997),
- Post-Encroachment Time (PET), which is the time between the first road user leaving a common spatial zone and the second user arriving in that zone (Allen et al., 1977), and
- Gap Time (GT), or the time difference between the second user arriving at the conflict point after the first user leaves it when both continue at the same speed and along the same paths (Vogel, 2002), which is also recognized as a predicted PET.

Given the assigned values of some measures of traffic events, the severity of traffic events can be evaluated and traffic conflicts will be registered once the value reaches a predetermined threshold. However, no consensus has been reached on what measures should be used because the various measures differ in their natures and are applied preferentially according to road conditions (Guido et al., 2011). For example, *The Dutch Manual for Conflict Observation* (DOCTOR) pointed that a minimum TTC value of less than 1.5s indicates a potentially dangerous situations in urban areas, and PET values of 1.0s and lower indicate a possibly critical traffic situation (Van der Horst and Kraay, 1986). In a vehicle-bicycle interaction study done by Sayed et al. (2013), traffic events with associated minimum TTC of less than 3s were considered for safety evaluation. Ismail et al. (2010) classified vehicle-pedestrian traffic events into traffic conflicts, important events, and uninterrupted passages, and declared that PET was the most reliable parameter for detecting both conflicts and important events when analyzing pedestrian safety. Hupfer (1997) divided severity analysis into four DST thresholds of 1, 2, 4, and 6 m/s^2, with 1 m/s^2 as a threshold of normal encounter and 6 m/s^2 as the threshold of the most severe conflict. Other researchers suggest that the integration of various indicators is a better approach (Ismail et al., 2009, 2011; Kaparias et al., 2010; Laureshyn et al., 2010; Salamati et al., 2011; Ren et al., 2012).

Taking another approach, some research has used a safety continuum instead of only traffic conflicts via behavior analysis to better understand the underlying level of safety (Svensson and Hydén, 2006) In one of the early studies on automated pedestrian conflict analysis, Ismail et al. (2009, 2010) used trajectory processing to generate profiles of indicators (TTC and GT) of the interactive process. Laureshyn et al. (2010) proposed a theoretical framework to evaluate traffic safety based on micro-level behavioral data. They continuously calculated a set of indicators from trajectory data and generated curves, which together allowed for a continuous description of the interactive process.

However, despite the research on pedestrian conflict analysis mentioned above, there are still some gaps to fill.

(1) Few studies have clearly argued that different conflict indicators should be used, depending on the interaction. At the same time, a single indicator can represent different severity levels if interaction varies. For example, a small PET can appear either when a vehicle passes perilously close behind a pedestrian, which is risky, or when a pedestrian enters the conflict zone as soon as a vehicle clears it. Small TTCs can be observed when either party takes corrective action at urgent situations, or when a vehicle moves through a pedestrian group at very low speed.
(2) Previous studies based on micro-level behavioral data proposed useful ideas for analyzing indicator profiles throughout the interactive process, but these studies focused only on individual events. Given the large number of traffic events recorded from trajectories, to categorize traffic events in terms of interaction features will probably provide more information about the relationship between behavior and safety.

Therefore, unlike the conventional process of analyzing pedestrian conflict, in which conflict indicators are calculated by processing trajectories and the same individual or multiple indicators are used to identify conflicts for all conditions (see Fig. 1(a)), this paper attempts to develop a more sophisticated process that takes pedestrian-vehicle interactions into consideration (see Fig. 1(b)). A conceptual interaction pattern is proposed that represents different behavioral features when pedestrians and vehicles encounter. In this model, interaction pattern recognition is required prior to determining indicators for conflict identification, since conflict indicators can vary from interaction patterns.

3. Data acquisition

Data acquisition was carried out at four intersections in Shanghai, China: Jianhe Rd-Xianxia Rd, Dalian Rd-Siping Rd, Siping Rd-Zhangwu Rd, and Zhongshan Rd-Quyang Rd. Note that data collected at the first three intersections are used to develop the method proposed in the paper, and the last intersection is used for implementation. Video cameras were installed on tall buildings nearby intersections to record a view of the entire intersection. Information for each of the three intersections, including geometric layout, signal timing, and traffic volume information, is listed in Table 1.

All three intersections employ permissive or prohibited/permissive right-turn phasing, so that pedestrians are signaled to begin crossing as the same time adjacent motorized vehicles can make a turn. In such cases, encounters between right-turning vehicles and pedestrians occur frequently. Despite the regulation that grant pedestrians priority at crosswalks, mixed priorities exist in reality, and multiple interactions between pedestrians and vehicles can be observed. To simplify the conditions, pairwise interactions with only one pedestrian and one vehicle involved are analysed in this study. Data acquisition included the following two steps.

3.1. Step 1: trajectory extraction and indicator calculation

Trajectories of pedestrians and vehicles were extracted from video data using Traffic Analyzer (Suzuki and Nakamura, 2006), which is a semi-automated video image processing tool. Video calibration was conducted at the beginning, and the video was played by refreshing the image at a time interval of 0.12s. Vehicles and