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Developing a safety heatmap of uncontrolled intersections using both conflict probability and severity

Yingying Ma[a], Xiaoran Qin[a,*], Offer Grembek[b], Zhiwei Chen[a]

[a] South China University of Technology, Department of Transportation Engineering, Guangzhou, Guangdong, 510640, PR China
[b] University of California, Berkeley, Safe Transportation Research and Education Center, Berkeley, CA 94720, United States

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ABSTRACT

This paper presents a method to assess the safety of uncontrolled intersections considering two major properties of traffic conflicts—conflict probability and severity. This method assesses both the safety level of the entire intersection in addition to the distribution of safety within it. Intersections are modeled by a two-dimensional Cartesian coordinate system and the internal space of intersections is divided into cells. First, the vehicle movement characteristics of an uncontrolled intersection are modeled. Second, the conflict probability of each cell within the intersection is estimated considering the approaching probability and lateral migration probability of vehicles. The quantification of conflict severity is based on kinetic energy loss of potential crashes. Cluster analysis is used to combine conflict probability and severity to model the safety assessment of each cell. Third, the application of the method is discussed, and an overall safety index of intersections is proposed which considers weighted safety level and relative value of areas of different safety levels. Finally, a case study, which includes three different designs, is presented along with safety heatmaps to demonstrate the results. The results not only demonstrate the validity of the model, but also indicate that the proposed method can be applied to: i) safety evaluation of build-up intersections; ii) dangerous position management within an intersection; iii) safety assessment of designed intersections, and iv) safety level comparison among different intersections or various designs for a single intersection. Using this method, engineers and planners can better evaluate and improve the safety of existing or future uncontrolled intersections.

1. Introduction

Intersections are bottlenecks of urban roads and junctions of pedestrian, bicycle and vehicle flows, apart from being nodes where road users change their directions, and traffic conflicts and accidents are concentrated. Statistics reveal that from 2013 to 2015, head-on collisions, broadside collisions and vehicle-pedestrian collisions that occurred primarily at intersections accounted for 47.1% of 9859 traffic accidents in San Francisco (SafeTREC, 2016), while 50% of vehicle crashes in Vitoria, Australia took place at intersections (Cornelissen et al., 2013). The safety problem of intersections has always been of great public concern, and is therefore an extremely important issue in the domain of traffic conflict analysis and safety assessment.

The uncontrolled intersection is common in rural areas of China. There is neither signal control nor stop sign at this kind of intersection to control and manage the traffic flow. Therefore, during the design stage the intersection can be regarded as an uncontrolled intersection. When crossing vehicles arrive at the intersection, the driver can continue through the intersection without any control measures. However, drivers should not only focus on driving through the intersection, but must also pay more attention to the surrounding environment to determine whether they can proceed without any conflicts with other vehicles, pedestrians or bicyclists. This requires increased attention and discretion of drivers compared with those crossing controlled intersections. Unfortunately, this requirement is not always fulfilled due to personal or environmental factors, and therefore conflicts and collisions are more likely to occur at uncontrolled intersections.

Previous research on uncontrolled intersections safety problems analyzed various aspects of driver behavior, including gap acceptance and traffic conflict analysis based on conflict points. When addressing traffic safety problems at uncontrolled intersection based on gap acceptance, video data should be collected and analyzed. Previous studies analyzed the behavior of drivers facing available gaps, how they determined whether it was acceptable or not, and their critical gap out of safety concern. Based on these outcomes, Nagalla et al., 2017 applied support vector machines, decision tree and random forests to predict

* Corresponding author at: South China University of Technology, Department of Transportation Engineering, 381 Wushan Road, Jiaotong Building, Guangzhou, Guangdong 510640, PR China.
E-mail address: xqinad@connect.ust.hk (X. Qin).

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the gap acceptance behavior of drivers at uncontrolled intersection, and to evaluate the accuracy of different methods. Maurya et al., 2016 determined the influence of waiting time, occupancy and speed on gap acceptance. Additionally, Kaysi and Abbany, 2007 investigated aggressive driver behavior at uncontrolled intersections, and described the aggressive phenomenon of minor street drivers with high risk. Sayed et al. (1994) built a model to study traffic conflicts in critical situations, and described the behavior of drivers with conventional gap acceptance. Other researches used conflict theory to measure the safety level and conditions at uncontrolled intersections. There are several ways to describe conflict. First, researchers used points to represent the conflict location—for example, conflict point, merging point and separation point (Ceder and Eldar, 2002). This simplified the problem, but was too abstract to accurately express actual crashes. Later, safety surrogate indices were proposed, such as delay and deceleration, which were unable directly reflect the safety problem. Subsequently, two important indices based on field observation were introduced—TTC and PET. These two indices are respectively suitable for measuring rear-end conflicts and angle conflicts and are widely used to address safety problems (Machiani and Abbas, 2016).

Safety assessment, which incorporates direct assessment approaches based on traffic accident statistics, and indirect assessment based on traffic conflict analysis, was introduced in England in 1987. Direct assessment approaches refer to the regression modeling approach, grey evaluation approach and experience modeling approach, which produce results by analyzing data such as accident numbers and accident rates. The generalized linear regression modeling (GLM) approach is now quite common in crash prediction modeling and is used to relate crashes to traffic volume and geometric factors (Lorion and Persaud, 2015). The regression modeling approach conducts a statistical test on variables including traffic volume, delay and conflict categories and achieves results through analysis and prediction (Ma et al., 2010). Some scholars use the binary probit model to measure the risk of hotspots based on the data of crashes per year per kilometer (Ferreira and Couto, 2015). The grey evaluation approach assesses the degree of safety of intersections with gray clustering analysis, using indicators such as Traffic Conflict and Mixed Passenger Car Units (TC/MPCU) as evaluation factors (Niu, 2005; He et al., 2010). Experience modeling approaches are based on large quantities of data. Although indicators of the above methods are direct, their drawbacks are also conspicuous, not only because of their limited assessment results, but also due to their high demand for statistics, long assessment periods and low efficiency.

Indirect assessment approaches based on traffic conflict analysis can be divided into four types based on: statistical data of traffic conflict, hybrid fuzzy clustering, system analysis, and traffic simulation, respectively. Traffic conflict technique is a non-accident based approach widely applied in traffic safety analysis throughout the world. In 1968, traffic conflict was introduced at General Motor and used as a safety assessment approach (Allen et al., 1978). In addition, validity (Minderhoud and Bovy, 2001), estimation methods (Brown et al., 1986; Zhang et al., 2015) and applications (Brown et al., 1986) of traffic conflict technique are also studied. Safety assessment based on statistical data of traffic conflict generally makes evaluations using characteristics of conflict points and conflict probability (Zhang et al., 2015; Wang and Huang, 2014; Lu et al., 2008). Safety assessment approaches based on hybrid fuzzy clustering include two branches, which use fuzzy C-means clustering algorithm (Cheng, 2004) and classical membership (Zhou et al., 2008), respectively. Similarly, safety assessment based on system analysis can also be divided into two branches. Analytic hierarchy process (AHP) (Qu, 2011) and principal component analysis (Zhang, 2012) are used respectively to assess traffic safety comprehensively. Safety assessment based on traffic simulation uses microscopic traffic simulation to obtain traffic conflict data (Sun and Zhao, 2011; Zhou and Huang, 2013).

Studies on safety assessment of uncontrolled intersections are prolific, but several problems have yet to be solved. First, previous studies simplified the vehicle as a particle and the vehicle trajectory as a line, neglecting the actual size of the vehicle, which is inconsistent with real-world circumstances. Second, in most studies the entire intersection is assessed as a whole, based on historical crashes, while details about the intersection, such as traffic conflict, safety degree and the impact of unreasonable design on accidents, are completely omitted, weakening its potential role in intersection design. However, traffic accidents are not a complete indicator of safety of intersections—crash risk is another significant indicator. Therefore, conflict probability and severity should be integrated to ameliorate the safety assessment of intersections. More importantly, the assessment studies or methods mentioned above largely rely on conflict field data or historical accident data. It is obvious that when the design scheme of an intersection needs to be assessed, such studies may not be effective. However, it is significant in conducting safety assessments on intersection schemes before they are put into service—for example, identifying dangerous locations and avoiding design problems in advance. The major goal of this paper is to determine how to assess an intersection in a visual way closer to reality, particularly one that can be applied to an intersection design scheme without any operation field data. The findings in this paper can provide reference and support for road planning and design.

This paper presents a safety assessment approach of uncontrolled intersections considering conflict probability and severity. Previous works generally conducted research from a single aspect. However, conflict probability and severity both affect a crash. Conflict probability shows how likely a crash is to happen at a certain position within the intersection, while conflict severity reflects the type of crash it may be and how serious the crash is. Intersections are divided into cells to detail the safety information of the intersections. The safety level of each specific cell within the internal space of an intersection can be calculated and shown in a visualization picture. To evaluate the safety level of the entire intersection, an overall safety assessment method for intersections is presented, which could be used for comparing safety situations of multiple intersections or alternatives for a single intersection.

2. Modeling movement characteristics of vehicles at uncontrolled intersections

The running characteristics of vehicles at uncontrolled intersections determine the distribution of traffic conflicts, and have a crucial impact on the safety level of intersections. Therefore, the analysis and modeling of vehicle movement characteristics are the foundation work of safety assessment.

2.1. Assumptions

This paper takes a four-leg intersection as an example, but the methodology can also be applied to intersections with various geometric shape and lane width. The basic assumptions are as follows:

i) Only automobile (cars only, buses and trucks are excluded) are taken into consideration, the impacts of pedestrian and non-motor vehicle are excluded.
ii) Vehicles stay in one lane and do not change lanes when they pass through intersections.
iii) Width of lanes at each approach and exit are the same.
iv) Only conflicts in the internal space of the intersection are considered, merging and diverging conflicts at approaches and exits of the intersection are excluded.

2.2. Modeling intersection and vehicle trajectories

The modeling process includes building a two-dimensional Cartesian coordinate system: the center of the intersection is defined as the coordinate origin, the center line of the west-to-east road as the x-