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Micro-simulation of vehicle conflicts involving right-turn vehicles at signalized intersections based on cellular automata

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ABSTRACT

At intersection, vehicles coming from different directions conflict with each other. Improper geometric design and signal settings at signalized intersection will increase occurrence of conflicts between road users and results in a reduction of the safety level. This study established a cellular automata (CA) model to simulate vehicular interactions involving right-turn vehicles (as similar to left-turn vehicles in US). Through various simulation scenarios for four case cross-intersections, the relationships between conflict occurrences involving right-turn vehicles with traffic volume and right-turn movement control strategies are analyzed. Impacts of traffic volume, permissive right-turn compared to red-amber-green (RAG) arrow, shared straight-through and right-turn lane as well as signal setting are estimated from simulation results. The simulation model is found to be able to provide reasonable assessment of conflicts through comparison of existed simulation approach and observed accidents. Through the proposed approach, prediction models for occurrences and severity of vehicle conflicts can be developed for various geometric layouts and traffic control strategies.

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1. Introduction

Intersections are bottlenecks of road capacity and hot spots of safety. Conflicts between road users will reduce road safety as well as add extra travelling time. For an urban environment as Singapore, there are more than 1,400 signalized intersections while noting that motorists drive on the left side of the road as similar to United Kingdom driving convention. In 2009, about one in five (21%) road traffic accidents occurred at the signalized intersections (Hau and Ho, 2010). Among all vehicle movements, right-turn vehicles are considered to be the most difficult and complex vehicle movements at the signalized intersections, not only because of the turning movement, but also because of the conflict with other road users. Right-turn vehicles colliding with opposing straight-through or along-side straight-through vehicles are severe and very frequent (Wang and Abdel-Aty, 2008). Therefore, the objective of this study is to develop a new approach to estimate vehicle conflicts by microscopic simulation based on cellular automata (CA). Through conducting simulation experiments, the impacts of intersection design and traffic factors on conflicts involving right-turn vehicles at signalized intersections are studied.

2. Previous research

2.1. Factors affecting the occurrence of vehicle conflicts

Numerous researchers have found that efficient geometric and signal setting will significantly increase intersection safety level. Based on Poisson regression and negative binomial regression analyses, it has been found that road environment, lane arrangement at intersection approaches as well as number of signal phases, are significant factors for crash risk (Wong et al., 2007). Kumara and Chin (2005) found that, total traffic flow, right-turn flow as well as number of signal phases significantly affected the occurrence of crashes.

For vehicle conflicts involving right-turn vehicles, a series of study have found factors affecting the occurrence of right-turn crashes (Wang and Abdel-Aty, 2008). Those factors include traffic volume of conflicting flows, the application of shared right-turn lane, and permissive right-turn signal control. It has been found that the application of protected right-turn signal phasing scheme significantly reduced crashes between right-turn vehicles and pedestrians. An 85% reduction in right-turn accidents was found after a permissive right-turn was replaced by a protected signal phase (Zhang and Prevedouros, 2003).

2.2. Conflicts involving right-turn vehicles

Conflicts involving vehicles with right-turn movement that occur most frequently can be classified into 2 types: (I) conflicts between right-turn vehicles and straight-through vehicles along

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the same approach; and (II) conflicts between right-turn vehicles and opposing straight-through vehicles.

Type (I) conflicts between right-turn and straight-through vehicles occur at approaches with shared lanes. Opportunity for this type of vehicle conflict is very common because according to an observation survey of 154 cross-intersections spread over the Singapore island, over 54% of the approaches contain shared straight-through and right-turn lane. A right-turn vehicle can be blocked by a straight-through vehicle ahead of it during right-turn green phase and vice versa. According to study conducted by Fitzpatrick and Schneider IV (2004), number of rear-end crashes along shared lane is 0.04 cases per approach per year from 2001 to 2003 at 8 studied approaches.

Type (II) conflicts between right-turn vehicles and opposing straight-through vehicles occur under permissive right-turn signal control. At straight-through green phase, the right-turn vehicle needs to wait for appropriate gaps in opposing straight-through traffic stream to make a right-turn (Wang and Abdel-Aty, 2007). There is a risk of collision if the right-turn vehicle moves without enough gap or when the opposing straight-through vehicle travelled too fast. Compared to Type (I) conflicts, consequences for Type (II) conflicts are more severe for traffic safety as accidents involving right-turn and opposing straight-through vehicles can lead to a grid-lock of the whole intersection, and such collisions have constituted over 40% of accidents at signalized intersections (Ng et al., 1997; Wee, 2004).

2.3. Right-turn control methods

Conflicts involving right-turn vehicles are closely related to signal control type for right-turn vehicles. Most commonly used right-turn control methods are right-turn signal phase, lane markings, and right-turn waiting area.

In Singapore, the most common right-turn signal phases are straight-through green phase with permissive right-turn followed by a protected right-turn green phase, and straight-through green phase followed by a protected right-turn phase, the so called red-amber-green (RAG) arrow control. Under permissive right-turn arrangement, right-turn vehicles are permitted to make a turn during straight-through green phase (Qi et al., 2010). Vehicles making permissive right-turn movements experience shorter delay, but conflicts with other vehicle movements and hence collision risks are higher (Chen et al., 2012). On the other hand, under RAG arrow control, right-turn vehicles only have an exclusive right-turn green phase and are not allowed to filter through during straight-through green phase. Such kind of signal settings will be able to reduce vehicle conflicts but result in a higher overall delay (Al-Kaisy and Stewart, 2001). Therefore, whether to allow permissive right-turn is a trade-off between intersection capacity and safety (Chen et al., 2012).

Many approaches at intersections in Singapore contain shared right-turn and straight-through lanes. The arrangement of shared lane is usually based on traffic volumes of the two movement streams, especially right-turn traffic volume. Having a shared lane can help to increase right-turn capacity and to balance vehicle flows of diverging movements at an approach (Liu et al., 2008). However, at approaches with a shared lane, blockage may occur and thus results in Type (I) conflicts. Some large intersections with permissive right-turn also apply right-turn waiting area to give right-turn vehicles a guided waiting area and a better sight line when making right-turn.

2.4. Current safety assessment models

A series of studies estimated road safety performance of signalized intersections for different intersection types (Persaud et al., 2002; Oh et al., 2003, 2010). For example, an ordered Probit model relating crashes at signalized intersections with road attributes was calibrated by Abdel-Aty and Keller (2005). For Singapore's local context, an accident prediction model based on time series analysis has been developed by Kusumawati (2008).

Al-Ghamdi (2002) applied the binary logit model to examine the effect of crash characteristics and their causes to study the injury levels of crashes involving right-turn vehicles. Instead of real collisions, some researchers have used vehicle conflicts involving right-turn movement to assess the quantity of risk and safety level of specific intersection design (Zhang and Prevedouros, 2003; Kirk and Stamatiadis, 2012; El-Basyouny and Sayed, 2013).

In essence, there have been numerous studies analyzing conflicts involving right-turn vehicles at signalized intersections. However, most current studies are based on statistical analysis methods of crash occurrences or quantitative approaches to estimate the number of conflicts. Modeling of microscopic vehicle movements and vehicle interactions to study safety performance has seldom been attempted. Essentially, it is very hard to assess safety level and predict conflict occurrences because interaction behavior of vehicles at signalized intersection is a very complex process.

2.5. Micro-simulation based on cellular automata (CA)

As many factors such as traffic volume, signal settings, and geometric design have to be considered when designing a signalized intersection, micro-simulation is found to have more advantages than traditional quantitative models due to micro-simulation models being more flexible in intersection layout and more accurate for dynamic traffic demand (Nagel and Schreckenberg, 1992). PTV VISSIM has been calibrated by Genetic Algorithm, to estimate safety performance through micro-simulation (Cunto and Saccomanno, 2008; Huang et al., 2013). A software called Surrogate Safety Assessment Model (SSAM) has been developed by Federal Highway Administration (FHWA) to estimate conflicts by identifying critical safety indicators, such as time to collision (TTC) through trajectory files from simulation packages such as VISSIM (Huang et al., 2013). However, as the calibration is conducted in particular traffic conditions, a more flexible and generalized simulation tool is needed.

With increasing computation technology, cellular automata (CA) models that require massive computations are becoming popular for modeling and simulating complex scenarios. Based on flexible transition rules, it is becoming easier to use CA models to simulate microscopic traffic behavior accurately while leveraging on parallel CA computation (Clarridge and Salomaa, 2010; Kerner et al., 2011). The developments of CA model have increased the flexibility of modeling road traffic. Currently, it is not widely used for safety assessment because in most conventional CA models, velocity change rules are set to ensure all vehicles are travelling with no collisions and enough gaps.

In this study, an improved model that involves new features for safety assessment is established. With the application of improved CA model, safety performance can be estimated directly by simulation of vehicle interactions and conflicts. Occurrences of vehicle conflicts are estimated by detection and computation of a proxy indicator, namely declaration occurrences caused by conflicts (DOC). Through various simulation scenarios, relationship between safety level and control strategy of right-turn vehicles are analyzed. Simulation results are able to predict the risk of collisions related to right-turn vehicles and thereby identify intersections prone to such collisions.

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