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Safety evaluation of driver cognitive failures and driving errors on right-turn filtering movement at signalized road intersections based on Fuzzy Cellular Automata (FCA) model

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ABSTRACT

This paper proposes a simulation-based approach to estimate safety impact of driver cognitive failures and driving errors. Fuzzy Logic, which involves linguistic terms and uncertainty, is incorporated with Cellular Automata model to simulate decision-making process of right-turn filtering movement at signalized intersections. Simulation experiments are conducted to estimate the relationships between cognitive failures and driving errors with safety performance. Simulation results show Different types of cognitive failures are found to have varied relationship with driving errors and safety performance. For right-turn filtering movement, cognitive failures are more likely to result in driving errors with denser conflicting traffic stream. Moreover, different driving errors are found to have different safety impacts. The study serves to provide a novel approach to linguistically assess cognitions and replicate decision-making procedures of the individual driver. Compare to crash analysis, the proposed FCA model allows quantitative estimation of particular cognitive failures, and the impact of cognitions on driving errors and safety performance.

1. Introduction

Signalized road intersections are locations where complicated decision-making is prevalent. They are also the most dangerous spots of the road system. There are over 1400 signalized intersections in Singapore's road network. In 2011, about one in four (23.4%) road traffic accidents in Singapore occurred at the signalized intersections (Chai and Wong, 2015). Over the three years from 2009 to 2011, 112 fatal accidents in Singapore occurred at the signalized intersections. Over 71% of fatal and 86% of injury accidents at signalized intersections are between vehicles and do not involve pedestrians. Signalized intersections are inherently high-risk locations for motorized vehicles as resulting from the interactions of different movements. Therein, failures in the driving process such as driver cognitive failures and driving errors are more prevalent at signalized intersections.

This study focuses on the relationship between driver cognitive failures and driving errors as predictors of conflicts between vehicles. Among different movements at signalized intersections, right-turn filtering maneuver is chosen for modeling drivers' decision-making process. Section 2 introduces right-turn signal control strategies in Singapore and reviews previous studies on driver cognitive failures and driving errors. In Section 3, a Fuzzy Cellular Automata (FCA) model that combines Fuzzy Logic and Cellular Automata is developed to model cognition and decision-making associated with right-turn filtering movement. Section 4 evaluates and discusses simulation results of various simulated cognitive failures and driving errors. The last concluding section summarizes key findings and discussions of the proposed simulation-based approach.

2. Literature review

2.1. Right-turn filtering movement at signalized intersections

In Singapore, where driving is on left-side of road, the most common signal phases are straight-through green phase (green lantern) with permissive right-turn followed by a protected right-turn green phase (red lantern and green arrow), or alternatively a straight-through green phase (green lantern and red arrow) followed by a protected right-turn phase under 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 experi-

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ence shorter delay, but at the risk of conflicts with opposing straight-through vehicle movements (Chen et al., 2012).

During green lantern with permissive right-turn, the right-turn vehicle needs to wait for appropriate gaps in the 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 moved without sufficient gap or when the opposing straight-through vehicle travelled very fast in closing the gap. It is found that conflicts 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 (Chai and Wong, 2014; Ng et al., 1997; Wee, 2004).

2.2. Occurring mechanism of driving errors

Several studies have examined driving errors at signalized intersections based on crash record analysis (Lee et al., 2004; Schepers et al., 2011). A Driving Reliability and Error Analysis Method (DREAM) has been developed to analyze contribution factors of crashes at 26 intersections (Ljung, 2002). Causation charts were aggregated for six defined risk situations based on the most common errors and violations occurring at intersections (such as failure to yield, or running a traffic light or sign). It is found that misjudgment and distraction play very important roles in driving errors and crashes.

However, studies based on crash analysis have several limitations. Firstly, in most studies of driving errors, accident databases are not sufficiently detailed to identify driving errors and accident contributory factors. Another limitation is that the data are often focused on the driver and thus it is difficult to identify the system-wide factors that may also have contributed to the driving error (Salmon et al., 2010).

System approaches have been applied to understand driving errors that considered the road system including traffic control and neighboring road users (Larsson et al., 2010; Wegman et al., 2008). However, such studies are not focused on driving errors themselves, but more on the interactions of other parts of the system. Considering that driving behavior primarily governs the successful operation of a traffic system, it is pivotal that ever more efficient methods are applied to analyze driving errors and vehicle interactions.

2.3. Cognitive failures as predictors of driving errors

Researchers have advanced cognitive antecedents to explain differences in the driving behavior (Ajzen, 1988; Parker et al., 1998; Rosenstock, 1974; Hu et al., 2013). It is found that a range of personalities variables such as age, gender, and experience as well as cognitive variables, such as misjudgement, are associated with driving errors (Wiesenthal and Singhal, 2006; Taubman-Ben-Ari et al., 2004).

Drivers' misjudgement can be caused by inattention and distraction. Previous studies have shown that inattention is a significant risk factor of crash and harms driver performance (Farmer et al., 2010; Lemercier et al., 2014). Previous study shows inattention is involved in between 10% and 33% of total crashes in the United States (Ranney, 2008). On the other hand, distraction while driving is also found to have significant impact on driving errors. Harbluk et al. (2002) estimated the impact of drivers' distraction based on on-road experiment. Drivers are asked to drive an 8 km city route and to perform three different secondary tasks as distractors at the same time. The experiment found that distracted drivers checked mirrors less often, had reduced eye-scanning, and tended to brake more frequently.

Misjudgment while driving, which are identified as cognitive failures, are used to explanation driving errors (Wiesenthal and Singhal, 2006; Strayer and Johnston, 2001). It is found that cognitive failures are significantly associated with driving behavior and understanding of cognitive failures can serve as an important first step in understanding the occurrences of driving errors (Wicken et al., 2008).

2.4. Surrogate safety assessment based on simulation

In estimating vehicle interactions and conflicts, surrogate safety assessment based on micro-simulation is found to have more advantages than traditional quantitative models, given that micro-simulation models are more flexible in modelling intersection layout and being more responsive in estimating dynamic traffic demand (Nagel and Schreckenberg, 1992). For example, PTV VISSIM has applied Genetic Algorithm in micro-simulation model to estimate safety performance (Cunto and Saccomanno, 2008; Huang et al., 2013). An application software package 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), in the trajectory files from simulation packages such as VISSIM (Huang et al., 2013). However, existing models are calibrated for limited traffic conditions, and a more flexible and generalized simulation tool is desired.

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 reliably while leveraging on parallel CA computation to handle the large computations (Clarridge and Salomaa, 2010; Chai and Wong, 2014a). The developments of CA model have increased the flexibility of modeling road traffic with high computational efficiency. In recent years, CA models are applied in surrogate safety assessment, with conflict frequency and conflict severity analyzed using simulation outputs (Chai et al., 2014; Chai and Wong, 2015; Young et al., 2014).

However, in determinate simulation models, decision-making process of road users that involves cognition and judgment are not modeled. Herein, a novel approach based on Fuzzy Logic and Cellular Automata is developed to examine the relationship between drivers' misjudgment and driving errors. Compared to traditional simulation models with exact and fixed solution, the proposed FCA model allows for uncertainty and approximation which are well suited to representing complex decision-making process of drivers (Chiou and Huang, 2013; Jahani et al., 2014). Moreover, unlike other simulation models, linguistic terms are used to describe the environment and responses. These linguistic terms can be used to describe driver cognitions, such as perception, intention and attitude. In this way, decision-making procedure of individual drivers can be modeled in a clear and straight-forward way.

3. Methodology

3.1. Fuzzy Cellular Automata (FCA) model for right-turn filtering

A Fuzzy Cellular Automata (FCA) model is proposed to apply fuzzy sets of linguistic terms on simulating right-turn filtering behavior, as shown in Fig. 1. The right-turn filtering fuzzy set (F) is developed to decide whether to filter through opposing straight-through vehicles. Firstly, input factors that affect a driver's filtering movement decision are identified as Current velocity (v_n); Velocity of the opposing straight-through vehicle (v_n^o); Gap provided by opposing straight-through flow (g_n^o). Decision of right-turn vehicle is whether to filter through (Y/N). Different factors and linguistic terms used are shown in Table 1.

Therefore, the right-turn filtering fuzzy set (F) is developed for right-turn vehicles to decide whether to stop or move according to the velocity and position of the subject and opposing straight-through vehicles. Input factors are current velocity of the subject vehicle (v_n), velocity of the opposing straight-through vehicle (v_n^o), and the gap provided by opposing straight-through flow (g_n^o). Fuzzy rules are created as right-turn filtering drivers will decide to filter through when enough gap is provided or when the velocity of opposing vehicle is slow, as shown in Table 2.