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Comparison of proposed countermeasures for dilemma zone at signalized intersections based on cellular automata simulations

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ABSTRACT

The Type II dilemma zone describes the road segment to a signalized intersection where drivers have difficulties to decide either stop or go at the onset of yellow signal. Such phenomenon can result in an increased crash risk at signalized intersections. Different types of warning systems have been proposed to help drivers make decisions. Although the warning systems help to improve drivers' behavior, they also have several disadvantages such as increasing rear-end crashes or red-light running (RLR) violations. In this study, a new warning system called pavement marking with auxiliary countermeasure (PMAIC) is proposed to reduce the dilemma zone and enhance the traffic safety at signalized intersections. The proposed warning system integrates the pavement marking and flashing yellow system which can provide drivers with better suggestions about stop/go decisions based on their arriving time and speed. In order to evaluate the performance of the proposed warning system, this paper presents a cellular automata (CA) simulation study. The CA simulations are conducted for four different scenarios in total, including the typical intersection without warning system, the intersection with flashing green countermeasure, the intersection with pavement marking, and the intersection with the PMAIC warning system. Before the specific CA simulation analysis, a logistic regression model is calibrated based on field video data to predict drivers' general stop/go decisions. Also, the rules of vehicle movements in the CA models under the influence by different warning systems are proposed. The proxy indicators of rear-end crash and potential RLR violations were estimated and used to evaluate safety levels for the different scenarios. The simulation results showed that the PMAIC countermeasure consistently offered best performance to reduce rear-end crash and RLR violation. Meanwhile, the results indicate that the flashing-green countermeasure could not effectively reduce either rear-end crash risk or RLR violations. Also, it is found that the pavement-marking countermeasure has positive effects on reducing the rear-end risk while it may increase the probability of RLR violation. Lastly, the implementation of the proposed warning system is discussed with the consideration of connected-vehicle technology. It is expected that the dilemma zone issues can be efficiently addressed if the proposed countermeasure can be employed within connected vehicle technology.

1. Introduction

In the United States, intersection-related crashes are among the most frequently occurring types of accidents. In 2012, there were 2,498,000 vehicles involved in intersection or intersection-related crashes at signalized intersections (NHTSA, 2012). Among all the intersection-related crashes, yellow-phase-related crashes are of significant concern to transportation engineers. At the onset of the yellow light, drivers who are approaching the intersection must make a quick decision to either stop or cross the intersection. Typically, when far from the intersection, drivers tend to stop while others would like to pass the intersection if they are closed to the stop line. However, it was found that drivers may hesitate to make decision due to the dilemma zone and the decisions may vary by different drivers under different situations (Elhenaway et al., 2015). Hence, serious yellow-light related problems arise due to drivers' wrong decisions. The differences in drivers' decision can lead to read end crash while the false stop/go judgment can cause red light running (RLR) violations. Due to huge losses caused by dilemma zone, it is urgent to devote efforts to improve drivers' behaviors and enhance the safety at signalized intersections.

1.1. Previous efforts in dilemma zone protection

There are two types of dilemma zone defined at signalized

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intersections. The first type of dilemma zone may arise because of the insufficient length of yellow as well as all red interval (Liu and Herman, 1996). Herman et al. (1959) defined the Type I dilemma zone "yellow light dilemma", where a driver can neither stop safely nor be able to cross the intersection at the yellow interval. The yellow interval is usually 3 s–6 s in duration or longer on approaches with higher speed according to the Manual on Uniform Traffic Control Devices (MUTCD (Manual of Uniform Traffic Control Devices), 2009). The Type II dilemma zone was first introduced by Parsonson et al. (1974) which is mainly based on the lack of competence of some drivers. Specifically, Type II dilemma zone describes segments at signalized intersection where drivers may have difficulty to make decisions to go or cross an intersection at the onset of yellow signal. The wrong decisions may result in rear end crashes or red light running (RLR) violations. The problem with the Type II dilemma zone is more prevalent at high speed intersections, encouraging studies of the drivers' behaviors at intersections with high speed (Hurwitz, 2009). It was found that the vehicles' condition such as speed and location in dilemma zone and the characteristics of drivers have significant impacts on drivers' stop/go decisions (Elhenawy et al., 2015). Besides the decisions by the drivers, it was found that the increase of the Type II dilemma zone length can also lead to an increasing rear-end crashes (Mahadlel et al., 1985; Newton et al., 1997; Liu et al., 2007; Li et al., 2015). In order to improve drivers' stop/go decisions when encountering a signal change, several warning systems were introduced to reduce the potential crash risk. Generally, the strategies can be divided into two types: time-warning systems and distance-warning systems.

The time-warning systems integrate with signals to give drivers advanced information about the coming yellow indication at the end of green phases. The pre-signal indication system (PSIS) is one type of time-warning systems which uses a flashing green or yellow signal during the last few seconds of the green phase. Previous research found that the PSIS might reduce right angle collision (Quiroga et al., 2003; Köll et al., 2004) and contribute to increasing rear-end crash risk (Newton et al., 1997; Köll et al., 2004; Factor et al., 2012; Wu et al., 2017). Another time-warning system is the green-phase countdown timer which can show how many seconds left until the termination of green phase (Lum and Halim, 2006; Chiou and Chang, 2010; Ni and Li, 2014). Some studies indicated that the countdown timers can reduce RLR rate (Lum and Halim, 2006) while others studies showed that the countdown timers might increase the crash risk since the duration of dilemma zone will be longer. Also, some research results suggested that the countdown timers may lead drivers to speed up to beat the red signal to avoid a delay for stopping at the intersection (Long et al., 2011).

As for the distance-warning system, the pavement marking and advance warning signs or flashers (AWF) were developed. The system is to place the markings or signs upstream of signalized intersection to help drivers to decide whether to stop or go at the onset of the yellow light. The pavement marking is to locate marking with a word message "SIGNAL AHEAD" based on stopping sight distance to the intersection (MUTCD, 2009). According to the previous studies (Sayed et al., 1999; Yan et al., 2009; Elmitiny et al., 2010), both the marking and AWF countermeasure can improve drivers' stop/go decisions and significantly reduce rear-end and angle crashes. However, since the system is designed for the drivers with the specified speed, the drivers with lower speed may fail to beat the red signal resulting in the RLR violation.

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

Traditionally, the traffic simulation models can be classified into three levels: macroscopic, mesoscopic, and microscopic models (Sommer et al., 2011). The macroscopic model describes continuous macro-phenomenon of traffic flow such as volume, speed, and density (Zhong and Chen, 2009). The mesoscopic model captures the essentials of the vehicle dynamics which does not consider the movement of individual vehicle but the movement of vehicle platoons. The microscopic simulation is to analyze the motions of each individual vehicles such as acceleration, deceleration, and lane changes. For the analysis of dilemma zone, various factors including traffic volume, signal setting, geometric design, and drivers' behaviors need to be considered (Cai et al., 2014; Wang et al., 2016; Elmitiny et al., 2010). Thus, the microscopic simulation is found to have advantages since it is more flexible for different intersection layouts and individual vehicle's movements. With the development of computation technology, the cellular automata (CA) model as a microscopic simulation which require massive computations are becoming popular to analyze complex scenarios. In CA models, roads are represented by a series of cells and each of them can be either occupied by a vehicle or not occupied. Each vehicle movement is simulated by flexible transition rules. Thus, the CA models can accurately simulate microscopic traffic behaviors including drivers' stop/go decision in a dilemma zone (Clarridge and Salomaa, 2010). The CA models have been gradually employed for crash analysis at intersections (Marzoug et al., 2015) and segments (Moussa, 2003). In the conventional CA models, the speed change rules are set to ensure all vehicles move with no collisions and enough gaps. In order to conduct safety assessment, Jiang et al. (2004) defined risky situations which can reflect the occurrence of rear-end crashes. Besides, Chai and Wong (2014) proposed a new indicator called "deceleration occurrences caused by conflicts" (DOC) to evaluate the safety at signalized intersections. However, the CA models have not been widely used to analyze to effects of warning systems for dilemma zones. The main reason is that the rules of vehicles' movements and stop/go decisions in dilemma zone with warning systems are not available.

In this study, a new warning system for Type II dilemma zone is proposed to improve drivers' stop/go decision. In order to compare the proposed warning system with conventional warning systems, a CA-simulation based analysis is conducted. Four scenarios (a typical signalized intersection without warning systems, an intersection with the flashing green indication, an intersection with pavement marking before the stop line, and an intersection with the proposed warning system) were simulated in CA models. Also, a logistic regression model is calibrated based on field data to predict drivers' general stop/go decision and the rules of drivers' movement and stop/go decision with the influence of different warning systems are developed in CA models. Proxy indicators of the rear-end crash and RLR violation are estimated and employed to evaluate the performance of different warning systems. Through various simulation scenarios, relationships between risk levels and warning systems of dilemma zones are investigated and compared. Based on the comparison results, the warning system with the best performance is recommended and its potential implementation is discussed.

2. Description of different warning systems

2.1. Time-warning system

As discussed in the previous section, the flashing green is a time-warning system which provides warning message to drivers during the last seconds of the green phase by using flashing signal (see Fig. 1). By seeing the flashing-green warning message, drivers can have more time to be prepared for the coming yellow or red light. In this study, the flashing green is adopted as a time-warning system in the simulation

Fig. 1. Illustration of intersection with time-warning system.