G Model
AAP-4036; No. of Pages 9

ARTICLE IN PRESS

Accident Analysis and Prevention xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Exploring stop-go decision zones at rural high-speed intersections with flashing green signal and insufficient yellow time in China

Keshuang Tang[a,*], Yanqing Xu[a], Fen Wang[a], Takashi Oguchi[b]

[a] Department of Transportation Information and Control Engineering, Tongji University, No. 4800, Cao'an Road, Shanghai 201804, China
[b] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 1538505, Japan

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form
12 November 2015
Accepted 19 January 2016
Available online xxx

Keywords:
Flashing green
High-speed intersections
Stop-go decision behavior
Fuzzy Logic
Dilemma Zone

ABSTRACT

The objective of this study is to empirically analyze and model the stop-go decision behavior of drivers at rural high-speed intersections in China, where a flashing green signal of 3 s followed by a yellow signal of 3 s is commonly applied to end a green phase. 1, 186 high-resolution vehicle trajectories were collected at four typical high-speed intersection approaches in Shanghai and used for the identification of actual stop-go decision zones and the modeling of stop-go decision behavior. Results indicate that the presence of flashing green significantly changed the theoretical decision zones based on the conventional Dilemma Zone theory. The actual stop-go decision zones at the study intersections were thus formulated and identified based on the empirical data. Binary Logistic model and Fuzzy Logic model were then developed to further explore the impacts of flashing green on the stop-go behavior of drivers. It was found that the Fuzzy Logic model could produce comparably good estimation results as compared to the traditional Binary Logistic models. The findings of this study could contribute the development of effective dilemma zone protection strategies, the improvement of stop-go decision model embedded in the microscopic traffic simulation software and the proper design of signal change and clearance intervals at high-speed intersections in China.

1. Introduction

In China, a flashing green indication of 3 s followed by a yellow indication of 3 s is commonly applied to end a green phase at signalized intersections in many cities. It is understandable that the length of yellow time is usually too short for approaching drivers to avoid Dilemma Zone (DZ) at the high-speed intersections, where speed limits are usually set above 60 km/h in China. Meanwhile, the use of flashing green may become more effective in influencing stop-go behavior of drivers at the change of phases and thus has greater impact on intersection safety.

The stop-go decision in the conventional DZ theory is based on a deterministic relationship between the maximum crossing distance and the minimum stopping distance (Gazis et al., 1960). The theory has been the basis of prevalent modeling and simulation of stop-go behavior at the end of green phase. However, past studies have indicated that the flashing green signal could provide an early decision opportunity to drivers before the onset of yellow (Mahalel et al., 1985; Köll et al., 2004; Factor et al., 2012). Therefore, drivers are likely to accelerate or decelerate in order to avoid DZ, based on the perceived surrounding traffic environment. Accordingly, the stop-go decision making process becomes more dynamic and the stop-go decision zones might be significantly different from those assumed in the conventional DZ theory (Prashker and Mahalel, 1989; Hamaoka et al., 2010).

The identification of stop-go decision zones and the modeling of such a dynamic decision making process have important implications, such as the proper design of signal change and clearance intervals, the improvement of stop-go decision models embedded in the microscopic traffic simulation software and the development of effective DZ protection strategies. Hence, the objective of this study is to empirically analyze and model the stop-go decision behavior of drivers at rural high-speed intersections with flashing green signal and insufficient yellow time in China. 1, 186 high-resolution vehicle trajectories collected at four typical high-speed intersection approaches in Shanghai were used for statistical analysis of contributory factors related to the determination of stop-go decisions zones, the identification of actual decision zones and the modeling of stop-go decision behavior of drivers at the onset of flashing green and yellow.

The rest of the paper is organized as follows. Firstly, the related past research is reviewed to position the study; secondly, data

* Corresponding author.
E-mail address: tang@tongji.edu.cn (K. Tang).

http://dx.doi.org/10.1016/j.aap.2016.01.011

collection and reduction of high-resolution vehicle trajectories are described; thirdly, the method and results of identifying stop-go decision zones are introduced, followed by the modeling of stop-go decision behavior based on the Binary Logistic model and Fuzzy Logic model respectively; finally, conclusions and future works are summarized.

2. Literature review

Stop-go behavior at the end of a green phase was initially modeled by Gazis et al. (1960) which is usually referred to as the GHM model. A driver approaching a signalized intersection during the phase transition period will either have to stop at the stop-line or proceed to cross the intersection. The stopping distance, X_S, is the distance required for the vehicle to stop before the stop-line. The crossing distance, X_C, is the distance on the approach within which the vehicle can proceed before the end of yellow. X_S and X_C can be computed by Eqs. (1) and (2), respectively.

$$X_S = v\tau + \frac{v^2}{2a_1} \quad (1)$$

$$X_C = vY + \frac{1}{2}a_2(Y-\tau)^2 \quad (2)$$

where, v = the vehicle's approach speed (m/s); τ = the driver's perception-and-reaction time (s); a_1 = the maximum deceleration rate (m/s^2); a_2 = the maximum acceleration rate (m/s^2); Y = the duration of yellow interval (s).

The basic hypothesis of the GHM model is that a driver makes his or her decision based on a deterministic relationship between X_S and X_C, without accelerating (i.e., $a_2 = 0$). A DZ, in which drivers can neither comfortably stop at the stop-line nor safely pass the intersection, will occur if X_C is smaller than X_S; otherwise, an option zone will occur. As DZ may induce abrupt stop and red-light-running, leading to rear-end and right-angle collisions, the primary purpose of yellow time is to eliminate the occurrence of DZ. The elimination of DZ is possible only when X_S and X_C are equal.

Liu et al. (1996) extended the GHM model by taking the decreasing relationship between acceleration and instantaneous speed into account. In addition, several other notable calibrations were reported such as Crawford and Taylor (1961), Chang et al. (1985), and Lin and Vijaykumar (1988). The GHM model and its extensions are essentially kinematic and deterministic models that assume that all vehicles will stop, if they can, at the yellow onset. However, Olson and Rothery (1961) observed that some vehicles used the yellow interval as the green extension. May (1968) found that some vehicles accelerated/decelerated to escape DZ. Liu et al. (2007), Wei et al. (2011) and Gates et al. (2012) observed that DZ driver behavior was considerably different from the theoretical assumption.

Generally, the main disadvantage of the GHM model is lack of capability to tackle the randomness and anxiety of driver's stop-go decision behavior (Easa and Said, 1993). Therefore, some researchers (e.g., Newton et al., 1997; Köll et al., 2004; Papaioannou, 2007) attempted to explain the stop-go decision behavior based on the Binary Logistic models, in which the stopping probability was regarded as a function of the approaching speed, the distance or travel time to the stop-line at the onset of yellow, vehicle type, driver characteristics, etc. In addition, Elmitiny et al. (2010) used classification tree models to analyze how the probabilities of a stop or go decision and of red-light-running are associated with the traffic parameters. Meanwhile, other researchers applied the Fuzzy Logic theory to model the stop-go behavior, such as Rakha et al. (2007), Hurwitz et al. (2010) and Moore (2012). Furthermore, the behavioral parameters related to the determination of stopping decision zones may vary with site conditions, driver characteristics as well as vehicle performance. Those contributory factors are also often correlated with each other. Hence, the distribution of decision zones might become stochastic, rather than deterministic as described in the conventional DZ theory. A few researchers have made good efforts to explain the dynamics of decision zones, such as Prashker and Mahalel (1989), Moon and Coleman (2003), Li and Abbas (2009), Wei et al. (2011) and Tang et al. (2011).

Meanwhile, many studies have been done to investigate the impacts of flashing green on the stop-go decision behavior as well as DZ occurrences. It was reported that intersections with a flashing green signal apparently have a lower proportion of drivers crossing during the red, as compared to those without a flashing green (Mahalel et al., 1985; Newton et al., 1997). Moreover, the maximum accelerations and decelerations (i.e., a_1 and a_2 in Eqs. (1) and (2)) were found to be reduced in the presence of a flashing green (Newton et al., 1997). In other words, adding a flashing green light is similar to increasing the length of the yellow interval. On the other hand, several theoretical and empirical studies have reported drawbacks of flashing green signal. Firstly, the likelihood of rear-end collisions increased with introduction of the flashing green (Mahalel and Zaidel, 1985; Mahalel et al., 1985; Newton et al., 1997); secondly, relative to intersections without a flashing green, there was a marked increase in the proportion of stopping decisions (Mahalel et al., 1985; Köll et al., 2004; Factor et al., 2012).

Past research has also investigated the impacts of green signal countdown devices and advance warning systems on the stop-go decision behavior. Such systems are expected to have similar effects on driver behavior to the flashing green signal, by providing an early decision opportunity to drivers before the onset of yellow. Advance warning systems that provide advance warning to motorists by using signs mounted on the roadside have been implemented in the United States to improve safety at high-speed intersections. These signs (i.e., Be Prepared To Stop When Flashing) would hash a beacon about 5–6 s before the onset of the yellow signal. McCoy and Pesti (2003), Sunkai et al. (2005) and Appiah et al. (2011) investigated the effects of the advance warning systems on driver behavior and DZ occurrence through empirical studies. Their conclusions are generally consistent that such warning systems enhanced the DZ protection and reduced red-light-running. Yan et al. (2009) proposed a pavement marking with word message "Signal Ahead" that is placed on the pavement upstream of a signalized intersection. Results indicated that the marking can reduce the probabilities of both conservative-stop and risky-go decisions.

In summary, in spite of tremendous research efforts on the stop-go behavior and decision zones, few studies can be found in literature to address those issues at the high-speed intersections, where a flashing green signal is implemented together with an insufficient yellow interval. Hence, this study was intended to address such a unique safety issue in China and fill in that research gap.

Such a fact is quite different from regular situations presented in literature, because of the following two reasons:

(1) In most of the cases presented in previous studies, the flashing green was not used as a part of the signal phase transition time interval and the yellow time is basically set based on the local conditions such as speed limit and vehicle composition, not a constant length of 3 s for all conditions. Worldwide practice support that a 3 s of yellow might be appropriate for the intersections with a speed limit not greater than 50 km/h. But it is usually too short for approaching drivers to avoid DZ at the intersections with a speed limit greater than 50 km/h.
(2) The flashing green signal together with the yellow signal is implemented in a few countries only, e.g., Austria and Switzerland. Even in those countries, yellow time is also designed largely based on the speed limit, not a constant length of 3 s.