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Impact of road environment on drivers' behaviors in dilemma zone: Application of agent-based simulation

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ABSTRACT

At a signalized intersection, there exists an area where drivers become indecisive as to either stop their car or proceed through when the traffic signal turns yellow. This point, called a dilemma zone, has remained a safety concern for drivers due to the great possibility of a rear-end or right-angle crash occurring. In order to reduce the risk of car crashes at the dilemma zone, Institute of Transportation Engineers (ITE) recommended a dilemma zone model. The model, however, fails to provide precise calculations on the decision of drivers because it disregards the supplemental roadway information, such as whether a red light camera is present. Hence, the goal of this study was to incorporate such roadway environmental factors into a more realistic driver decision-making model for the dilemma zone. A driving simulator was used to determine the influence of roadway conditions on decision-making of real drivers. Following data collection, each driver's decision outcomes were implemented in an Agent-Based Simulation (ABS) so as to analyze behaviors under realistic road environments. The experimental results revealed that the proposed dilemma zone model was able to accurately predict the decisions of drivers. Specifically, the model confirmed the findings from the driving simulator study that the changes in the roadway environment reduced the number of red light violations at an intersection.

1. Introduction

At the onset of the yellow phase, drivers often come across a dilemma situation where they are unable to stop comfortably before the stop line or clear the intersection (without excessive acceleration) prior to the onset of the red signal phase (Gazis et al., 1960). The Institute of Transport Engineers (ITE) has named the area where drivers face this uncertain situation as the Type I dilemma zone. If the Type I dilemma zone is removed, it is hypothesized that the risk of any probable car crashes around the intersection (e.g., rear-end crashes and right-angle crashes) will turn to zero as uncertainty of the decisions is eliminated (Hurwitz et al., 2012). The Type I dilemma zone equation is as follows:

$$x_{dz} = x_c - x_0 \quad (1)$$

where $x_c = V_0\delta_2 + (V_0^2/2a_2)$ and $x_0 = V_0\tau - (w + L) + (1/2)a_1(\tau - \delta_1)^2$.

The following factors are present in the equation: the approaching speed of the vehicle (V_0), the maximum deceleration rate when stopping (a_2), maximum acceleration rate when proceeding (a_1), the reaction time for the perception of the drivers (PRT) for proceeding (δ_1) and stopping (δ_2), length of yellow phase (τ), width of intersection (w), and average vehicle length (L). The distance of the dilemma zone (x_{dz}) can be calculated by subtracting the maximum yellow passing distance (x_0) from the minimum stopping distance (x_c). Theoretically, the size of dilemma zone can be reduced by adjusting the length of yellow phase (τ).

Nonetheless, collisions still happen when drivers are in the dilemma zone because drivers' decision-making involves uncertainty. To resolve this issue, the Type II dilemma zone was proposed, which considers the stopping probability of drivers at the onset of the yellow phase (Zegeer, 1977). It defines the dilemma zone from the position where 90% of drivers stop to the position where 10% of drivers stop so that the uncertainty aspect of drivers' decisions can be covered. However, because it only focuses on the results of observations (i.e., stopping and proceeding) without

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considering the impact that roadway environmental factors may have on drivers' decisions, controlling the length of the yellow phase is regarded as the only way to solve the dilemma zone problem. This means the Type II dilemma zone model has difficulty in handling the case where drivers are affected by other roadway factors, such as traffic conditions.

According to Wierwille (1993), drivers visually sample their surroundings while driving so they are able to change their behavior based on other vehicles' movements and the roadway environment. This implies that drivers' behaviors are affected by surrounding factors such as other vehicles' movements or intersection conditions. In the dilemma zone, drivers' decisions are influenced not only by their own condition (e.g., distance to the stop line, speed) but also by the surrounding environment at an intersection. From an empirical study with eight intersections in Madison, Wisconsin, Gates et al. (2007) found that actions of vehicles in an adjacent lane affect drivers' decisions in dilemma zone. Huey and Ragland (2007) found that the pedestrian countdown signal makes drivers' behaviors more conservative (i.e., less likely to enter the intersection at the end of the yellow phase) from observations of two intersections, one with pedestrian countdown signal and one without. Likewise, red light photo enforcement cameras are known to be useful to mitigate red light running of vehicles, therefore reducing the possibility of a collision (Retting et al., 1999).

In this study, a dilemma zone model considering the effects of roadway surroundings is proposed. In addition to factors that were included in the Type I dilemma zone model, such as subject vehicle speed and distance to the stop line, other surrounding environment factors addressed in literatures (Gates et al., 2007; Huey and Ragland, 2007; Retting et al., 1999) are also incorporated. Specifically, the influence of a pedestrian countdown signal, a red light photo enforcement camera, and adjacent vehicle behavior on the driver decision-making process are all examined. To represent uncertain decision making of drivers in dilemma zone, a probabilistic framework known as Extended Belief-Desire-Intention (E-BDI) is used. The E-BDI framework mimics perception and decision behaviors regarding the uncertainty of human decision-making via probabilistic models (Lee et al., 2010). It predicts states of road conditions (Beliefs) from perceived information via Bayesian network and makes a decision regarding psychology aspect of a driver via Extended Decision Field Theory (EDFT) (see Section 2.2 for more details). To analyze impact of the five factors on drivers' decisions under different levels of traffic conditions, the proposed E-BDI based dilemma zone model is calibrated with human-in-the-loop experiment data collected by a driving simulator and implemented in AnyLogic® ABS software. This highly detailed cognition based decision-making model in ABS will help traffic engineering to accurately predict drivers' behaviors in dilemma zone under various hypothetical traffic situations without potential risks of experiments (e.g., car accidents).

The rest of the paper is organized as follows. In Section 2, data collected during the driving simulator experiment on driver behavior in the dilemma zone and conclusions derived from that experiment are briefly described. Moreover, the E-BDI based dilemma zone model will be introduced. In Section 3, the results of experiments conducted using the proposed model implemented in AnyLogic are then provided. Conclusions and future applications are discussed in Section 4.

2. Methods

2.1. Empirical driving simulator experiment

To analyze impact of the five factors on driver decision-making in dilemma zone, the high fidelity driving simulator at the Turner-Fairbank Highway Research Center of U.S. Federal Highway Administration (FHWA) was used. The driving simulator equipped with a compact car chassis mounted on a six degree-of-freedom motion base (tilt, roll, and heave). The compact car chassis included all functions of a real vehicle such as accelerating, steering, and breaking capabilities, along with audio (driving noise) and video (side mirror) functions. It provided realistic driving experience to participants. Fig. 1 shows the driving simulator used in this experiment.

Fig. 1. Driving simulator used in the current study.

The advantage of experiments with the high fidelity simulator is to easily enable control experiment environment for accurate analysis of the impact of the five factors. Although the decision-making model of drivers can be developed based on a data set of field observations, the field observations involving various uncontrollable road and driving conditions (e.g., vehicle type, level traffic flow, and driving purpose or psychological status of a driver) tends to have many outliers and cause incorrect analysis results. In addition, the driving simulator is able to conduct experiments without concerning about potential risk of car accidents associated with dilemma zone. The following sections will explain more details of the human-in-the-loop experiments with the driving simulator.

2.1.1. Design factors

Given below are the key factors that were examined while assessing the influence of the roadway environment on driver decision-making within the dilemma zone.

- *F* – Facility speed limit: 40 mi/h (64.37 km/h) and 55 mi/h (88.51 km/h).
- *H* – Degree of driving in a hurry (hurry or not): Recommended time for a participant to finish a drive when in a hurry was within 22.5 min for the 40 mi/h (64.37 km/h) case and within 18.5 min for the 55 mi/h (88.51 km/h) case.
- *R* – Presence of red light photo enforcement camera (present or not): Four of the dilemma zone intersections and eight of the non-dilemma zone intersections had red light photo enforcement cameras.
- *P* – Presence of pedestrian countdown signal (present or not): In four of the dilemma zone intersections and eight of non-dilemma zone intersections, pedestrian countdown signals were present.
- *A* – Decision of adjacent vehicle (proceed or stop): In all of the dilemma zone intersections and eight of the non-dilemma zone intersections, an adjacent vehicle was present.
- *D* – Distance to stop line of subject vehicle (m): There was a constant recording of the distance to the stop line of a subject vehicle at the start of the yellow phase.
- *V* – Speed of subject vehicle (m/s): A continuous recording was also made for speed of the subject vehicle at the start of yellow phase.