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SIV-DSS: Smart In-Vehicle Decision Support System for driving at signalized intersections with V2I communication

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ABSTRACT

In this paper, we present a Smart In-Vehicle Decision Support System (SIV-DSS) to help making better stop/go decisions in the indecision zone as a vehicle is approaching a signalized intersection. Supported by the Vehicle-to-Infrastructure (V2I) communications, the system integrates and utilizes the information from both vehicle and intersection. The effective decision support models of SIV-DSS are realized with the probabilistic sequential decision making process with the capability of combining a variety of advantages gained from a set of decision rules, where each decision rule is responsible to specific situations for making right decisions even without complete information. The decision rules are either extracted from the existing parametric models of the indecision zone problem, or designed as novel ones based on physical models utilizing the integrated information containing the key inputs from vehicle motion, vehicle-driver characteristics, intersection geometry and topology, signal phase and timings, and the definitions of red-light running (RLR). In SIV-DSS, the generality is reached through physical models utilizing a large number of accurate physical parameters, and the heterogeneity is treated by including a few behavioral parameters in driver characteristics. The performance of SIV-DSS is evaluated with systematic simulation experiments. The results show that the system can not only ensure traffic safety by greatly reducing the RLR probability, but also improve mobility by significantly reducing unnecessary stops at the intersection. Finally, we briefly discuss some relevant aspects and implications for SIV-DSS in practical implementations.

1. Introduction

The driving behavior of vehicles with regard to crossing a signalized intersection during the signal transition period has major impacts on safety and efficiency of transportation. The decision of a driver at the intersection is a binary decision process, i.e., the driver can either *stop* the vehicle before the stop line or let the vehicle *go* through the intersection. If a driver makes a decision to go while the situation is a "should-stop", the vehicle ends up to a red-light running (RLR) or even more severe to a collision. In USA, 771 people were killed and an estimated 137,000 of people were injured in the accidents involving RLR in 2015, according to Insurance Institute for Highway Safety (IIHS) (2016). If a driver makes a decision to stop while the situation is a "should-go", the vehicle encounters more traffic delay, which not only wastes time and increases fuel consumption as well as emissions, but also more likely causes a rear-end collision. According to National Highway Traffic Safety Administration (NHTSA) (Choi, 2010), about 40% of the total accidents are intersection-related crashes. Similar results have been also shown by big data analysis (Xie and Wang, 2015).

Among all possible factors resulting in the intersection-related crashes, the indecision zone at the intersection is one of the major

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causes. In literature (Gazis et al., 1960; Zegeer and Deen, 1978), the *indecision zone* is defined at the onset of yellow light into two types. Type-I (Gazis et al., 1960) is called the Dilemma Zone (DZ) if the vehicle can neither make a comfortable stop nor pass the intersection without running the red light. Type-II describes the optional zone where both stopping and going can be performed (Zegeer and Deen, 1978), and the decision making by drivers can be inconsistent. In the indecision zone, making inappropriate or hesitant decisions could be prone since a driver has to make his decision during a short signal changing period from green to red and the decision information space is complicated (Sheffi and Mahmassani, 1981; Sharma et al., 2011), especially as traditionally some inputs are not available to drivers.

Previous research has studied different aspects corresponding to the inherent model and mechanism of the indecision zone (Liu et al., 1996). About the driver-vehicle characteristics (Fu et al., 2016; Gates et al., 2007; Maurya and Bokare, 2012; Mehar et al., 2013; Rakha et al., 2007), research has been performed on the Perception-Reaction Time (PRT), the acceleration and deceleration characteristics. Two important parameters, the stopping distance and the clearing distance (Gazis et al., 1960; Liu et al., 1996; Lu et al., 2015), have been proposed to determine the indecision zone. Decision making at the onset of yellow light has been estimated using different methods based on a set of predictor variables. Existing estimation methods include logistic regression (Elhenawy et al., 2015; Gates et al., 2007; Park et al., 2015), and the other methods based on the critical time (Sheffi and Mahmassani, 1981) and the comfortable acceleration (Sharma et al., 2011). About the signal timings, study has been focused on the impacts of yellow interval duration (Bonneson and Zimmerman, 2004; Liu et al., 1996). On the RLR law, there are two commonly-used versions, i.e., *permissive yellow* and *restrictive yellow* (Federal Highway Administration (FHWA), 2009; Urbanik et al., 2015), and recently, the all-red extension used in the DZ protection (Gates and Noyce, 2016; Park et al., 2015) might be seen as an *unlimited* version.

Different protection methods have been proposed for handling the indecision zone and safety problem at a signalized intersection (Gates and Noyce, 2016; Li et al., 2015; Park et al., 2015; Zegeer and Deen, 1978). A common method is to hold the green light until the number of vehicles in the zone is lower than a threshold (Li et al., 2015; Zegeer and Deen, 1978; Zha et al., 2016). Many methods also use advanced warning signs (AWS) or flashers to provide more information to drivers (Park et al., 2015; Wang and Sharma, 2017). In the Ref. (Park et al., 2015), the AWS was designed to couple with the advisory speed limit to help drivers making better decisions at the onset of yellow light. To discourage RLR, red light camera enforcement was evaluated in a number of studies demonstrating significant safety benefit in reducing risk of right-angle crashes, though it might have a mixed effect on the risk of rear-end crashes (Huang et al., 2006; Lee et al., 2018). Recently, a few methods used all-red extension (Gates and Noyce, 2016; Park et al., 2015) to provide the ultimate protection to a vehicle in RLR until the vehicle passes the intersection safely.

More recently, a few in-vehicle systems (Bar-Gera et al., 2013; Chang et al., 2013; Li et al., 2014) have been proposed. In the current era of the Internet of Things (IoT), a typical in-vehicle system is able to connect with the intersection through Vehicle-to-Infrastructure (V2I) communications, such as the 4G Long-Term Evolution (LTE) and Dedicated Short Range Communications (DSRC). For example, in the Avoiding DZ and Warning system (ADZW) (Chang et al., 2013), the inputs from roadways, drivers, and vehicles have been used to develop the algorithms for the DZ estimation, prediction, and warning selection at the onset of yellow light. In the Ref. (Bar-Gera et al., 2013), the in-vehicle system could warn drivers when the vehicle need to stop, where the warning system was designed according to the distance to the stop line and the remaining green time. In the LBS-based DZ Warning System (DZWS) (Li et al., 2014), the information including vehicle position and speed, yellow interval, intersection width, communication delay and PRT, has been used to estimate the dilemma zone and alarm drivers at the onset of yellow light. For in-vehicle systems, vocal and visual warnings (Bella and Silvestri, 2017; Chang et al., 2013; Li et al., 2014; Yan et al., 2015) can be provided for different situations.

In this paper, we present a novel Smart In-Vehicle Decision Support System (SIV-DSS) to help drivers making right stop/go decisions as the vehicle is approaching a signalized intersection. Our effective decision support models (DSM) are realized via the probabilistic sequential decision making process (PS-DMP) (Xie et al., 2014) which combines the advantages obtained from a set of decision rules. With the theory of bounded rationality (Brandstatter et al., 2006; Gigerenzer and Gaissmaier, 2011), each decision rule is (fast and) frugal, which works well on different situations. We extract decision rules from the state-of-the-art models and mechanisms pertinent to the indecision zone problem. We also extend them and design new decision rules to utilize and handle the key inputs from vehicle motion, vehicle-driver characteristics, signal timings, intersection geometry and topology, and the definitions of RLR. Thus, SIV-DSS is able to explore in a much larger variable space of physical and behavior parameters than the previous methods, to support individualized decisions for different drivers and robust indecision zone protection at different intersections. The performance of the proposed system is evaluated with systematic simulation experiments. The results indicate that for vehicles approaching an intersection, our integrated in-vehicle decision support system can not only enhance the safety through significantly reducing RLR probability, but also improve the efficiency through reducing unnecessary stops.

2. Problem description

Fig. 1 illustrates a generic situation when a vehicle moves on a road approaching toward a signalized intersection, where some information is known about the intersection and associated infrastructure. The intersection geometry and topology (i.e. MAP) contains the location information of the stop line and the clear line for each entry movement, etc. The intersection width W is the distance between the stop line and the clear line. On the Signal Phase and Timing (SPaT) of the traffic light, let t be the remaining green time, T_{CD} be the green countdown time, Y represent the yellow change interval, and R represent the red clearance interval. The road information contains the speed limit V, the grade G, and other road conditions on the approach road. Each vehicle follows a specific definition of red-light running (RLR) according to the local law, as crossing the intersection. On the vehicle, let v be the moving speed, x denote the distance of the vehicle from the stop line, and L be the length of the vehicle. Each vehicle can