Transportation Research Part C 89 (2018) 188–204

Contents lists available at ScienceDirect

Transportation Research Part C

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

Infrastructure-cooperative algorithm for effective intersection collision avoidance

Yuchuan Fu[a], Changle Li[a,*], Tom H. Luan[b], Yao Zhang[a], Guoqiang Mao[c]

[a] State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an, Shaanxi 710071 China
[b] School of Information Technology, Deakin University, Melbourne, VIC 3125, Australia
[c] School of Computing and Communications, University of Technology Sydney, Sydney, NSW 2007, Australia

ARTICLE INFO

Keywords:
Intersection collision avoidance
Vehicle state evolution model
Dynamic Bayesian Networks
Risk assessment

ABSTRACT

To guarantee the road safety by avoiding collisions at the intersections is one of the major tasks of intelligent transportation systems (ITSs), which contributes to the minimal fatalities and property loss in crashes. This paper proposes an effective algorithm for infrastructure-cooperative intersection accident pre-warning system with the aid of vehicular communications. The proposed algorithm realizes accurate and efficient collision avoidances through five steps, i.e., defining variable, reasoning the vehicles evolution state, verifying safe driving behavior, assessing risk, and making decision. The critical factors are theoretically analyzed, and a vehicle state evolution model based on the Dynamic Bayesian Networks (DBNs) is established. The efficient risk assessment method based on identifying the dangerous driving behavior at intersection and different collision avoidance strategies are proposed according to the actual situation. Finally, extensive simulations are carried out to verify the performance of the proposal, and simulation results show that the proposed algorithm can effectively detect risk and accurately migrate the collision.

1. Introduction

Traffic accident at the intersections is one of the biggest global killers in urban traffic. Intersections are the vital traffic components of traffic networks in which a large volume of vehicles from different directions come together and steer freely at a high speed, making a high possibility for traffic accidents (Lei and Cristofer, 2016; Marchesini and Weijermars, 2010). In 2015, of all police-reported traffic accidents in European Union (EU), accidents occurred at intersections took the total number of fatalities to 26,161 (European Road Safety Observatory (ERSO), 2016; Department for Transport, 2016). In the United States (US), more than 5 million accidents occurred at intersections or intersection related roadways in 2015, accounting for around 47.2% of all accidents, with an estimated economic cost of $114 billion (World Health Organization, 2012; National Highway Traffic Safety Administration, 2016).

For decades, traffic rules and intersection infrastructures (e.g. traffic lights, stop sign and roundabout) have been practically applied to ensure the safety of intersection traffic (Lei and Cristofer, 2016). However, traditional solutions are not working when drivers are at poor health states, encountering illumination changes or bad weather scenarios (e.g. heavy snow, fog and haze) (Yan et al., 2016; Francesco et al., 2015). A recent solution is to install collision warning devices in cars that monitor and predict the surrounding environment, which are mainly based on multi-sensors, to warn the corresponding driver if a potential collision is

* Corresponding author.
E-mail address: clli@mail.xidian.edu.cn (C. Li).

https://doi.org/10.1016/j.trc.2018.02.003
Received 18 July 2017; Received in revised form 27 November 2017; Accepted 4 February 2018
0968-090X/

detected. However, such equipment can be very expensive and only affordable by luxury car models, and thus impractical for large-scale commercial use (Francesco et al., 2015; Inman and Davis, 2011). More importantly, the vehicle-mounted sensors are typically of short sensing range and can be easily blocked by buildings or other vehicles; it may be too late for drivers of poor states to take actions based on the sensed information only.

To report and avoid potential risks in a wide range in a scalable yet cost-effective way, the infrastructure-based warning systems under the umbrella of ITSs have recently been proposed. In specific, the ITSs deploy communication devices at the roadside as well as intersections (e.g., on traffic light) and send periodic road information to upcoming vehicles using non-light-of-sight wireless communications. Furthermore, the real-time information exchange enables connection and cooperation between road users, infrastructure and control centers, forming cooperative ITS (C-ITS). Note that most of the traffic accidents happening at intersections result from drivers' misjudgment on the current states, perception failures and faulty operations. The inclement weather can also affect speed control, and brake performance, leading to severe traffic accidents. The ITSs, by incorporating the mobile computing and artificial intelligence to learn the driver's health condition (Yu et al., 2016) and adapting to road and weather conditions, allow upcoming vehicles in a wide range to learn potential hazard. With the aid of vehicle control technologies and vehicle automation, the drivers even the vehicles can adopt appropriate operations in time to avoid accidents (Campos et al., 2017).

With the advancement of the ITSs, extensive works have been carried out, including system design (Misener, 2010; Tan and Huang, 2006), intelligent traffic signal setting (Fayazi and Vahidi, 2016), cooperative intersection scheduling and management (Lio et al., 2017; Colombo and Vecchio, 2015), and collision avoidance algorithm (Xiang et al., 2014; Ba et al., 2017), etc. Among these works, we are attracted by the designing of collision warning/avoidance system. Particularly, the prediction and decision-making algorithms which applied at different components are the core parts of collision warning/avoidance systems (Kim et al., 2015; Brännström et al., 2013). Mathematical theories, mathematical optimization and artificial intelligence have been applied for algorithmic design (Lei and Cristofer, 2016; Xiang et al., 2014; Joseph et al., 2011). Despite previous important works, we notice that two significant problems are not fully addressed: the complex traffic environment and some unpredictable driving behavior.

The design of such algorithms and systems is challenging due to the following issues: (1) *complex road environment*, in that two or more roads cross each other and the road situation as well as sensory observations evolve over time; (2) *dynamic interactions among vehicles*, in which multiple activities have the potential for conflicts resulting in crashes; (3) *noised data*, in that incomplete data acquired from sensors usually exists different degrees of uncertainty due to ambient noise, sensors' systematic errors, and the reliability of data transmission; (4) *immediate actions*, in that decision must be made accurately and quickly. The challenges indicate that the algorithms and systems have high requirements on computational capabilities, communication capacity, reliability, latency. Therefore, it is necessary to develop a cost-effective yet adaptive technology that can simultaneously address all above challenges, which motivates our work.

This paper proposes an collision warning/avoidance algorithm for infrastructure-cooperative accident pre-warning system. We consider an accident scenario where two vehicles in different directions driving on a two-way stop-controlled intersection with traffic lights. In particular, some critical factors are analyzed firstly. We also propose prediction and risk assessment algorithms, and different strategies are implemented to avoid accidents according to the situation. The main contributions of the paper are threefold:

- *Analysis*: The critical factors, i.e. timing factor, communication and positioning factor, are detailed analyzed in this paper. Particularly, we analyse why they occur and how they can affect the performance of collision warning algorithm, which will provide reference for algorithm design.
- *Algorithm*: A prediction algorithm is realized by establishing the vehicle state evolution model which based on Dynamic Bayesian Networks (DBNs). It allows the prediction of the possible states of upcoming vehicles from current and previous states with uncertain contextual information. In addition, we take the human factors and road conditions into account, which makes the model more practical and applicable to real-world scenario.
- *Validation*: The evaluation of a risk situation is based on distinguishing safe behaviors and drivers' intention at the intersection. The risk assessment method can avoid the complex trajectories prediction, which will satisfy the requirements of rapid decision-making.

The remainder of this paper is organized as follows. The related works, including trajectory prediction algorithms and collision avoidance systems, are reviewed in Section 2. Section 3 depicts overall diagram and analyses the effect factors. Section 4 describes the process of realizing the collision avoidance in detail, which contains vehicle state evolution model, risk assessment and collision avoidance algorithm. Section 5 evaluates the performance of proposed algorithm using simulations, and Section 6 concludes the paper.

2. Related works

Driven by the growing user and application requirements, Collision Warning Systems (CWSs) (Córdoba et al., 2017), as an important component of the ITSs, plays an prominent role in traffic safety. Particularly, the collision warning/avoidance algorithm is the core of the CWSs, which has obtained extensive research.

Heretofore, the most popular algorithms for the collision detection and avoidance are based on trajectory prediction and risk assessment. It was observed by researchers in Katrakazas et al. (2015) that the existing methods for vehicle trajectory prediction can be classified into three levels: physics-based motion models, maneuver-based motion models and interaction-aware motion models. In Funke et al. (2017), a new control structure was proposed, which integrates path tracking, vehicle stabilization, and collision