Transportation Research Part C 50 (2015) 51–67

Contents lists available at ScienceDirect

Transportation Research Part C

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

Development and evaluation of an enhanced surrogate safety assessment framework

Jaehyun (Jason) So [a,*], George Dedes [b,1], Byungkyu Brian Park [c,2], Siavash HosseinyAlamdary [d,3], Dorota Grejner-Brzezinsk [d,3]

[a] *Department of Civil, Geo, Environmental Engineering, Technische Universität München, München 80333, Germany*
[b] *DGNSS Solutions, LLC, Columbus, OH 43212, United States*
[c] *Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA 22904-4742, United States*
[d] *Department of Civil, Environmental and Geodetic Engineering, Ohio State University, Columbus, OH 43210, United States*

ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form 29 September 2014
Accepted 8 October 2014
Available online 6 November 2014

Keywords:
Surrogate safety assessment
Connected Vehicle
Global Positioning System (GPS)
Inertial Navigation Unit (INU)
Driver warnings
Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I).

ABSTRACT

This study adopted an integrated simulation approach for generating more realistic vehicle trajectories, ultimately for enhancing the surrogate safety assessment methodology under the Connected Vehicle (CV) environment. This integrated simulation divides into two main parts, real time-based simulation approach and post-processing approach. The real-time simulation environment consists of the microscopic traffic simulator to generate various traffic situations, driver warning simulator, GPS/INU simulator, and V2V/V2I communication delays probability model. The post-processing approach includes vehicle dynamics model to incorporate vehicle dynamics to the vehicle trajectories and Surrogate Safety Assessment Model (SSAM) to identify traffic conflicts. This integrated simulation approach was adopted to assess the safety impact of Connected Vehicle (CV)-based traffic applications by considering potential positioning errors and communication delays which are likely to occur in reality. The evaluation results showed that the V2V/V2I communication delays degraded the effectiveness of driver warnings by 3–13% while the driver warnings under ideal conditions (i.e., error-free vehicle positions and no V2V/V2I communication delays) reduced conflicts by 27–42%. In addition, the most accurate GPS/INU device (i.e., Real-Time Kinematic (RTK) GPS) was the best for use with vehicle safety applications as the RTK case was the closest to the ground truth-based warning scenario. Meanwhile, the device with the lowest accuracy (i.e., autonomous GPS) was not very suitable for deployment in the safety application as this case showed even worse results than the base case (i.e., no driver warnings). This integrated simulation approach used for these experiments is a practical and reliable alternative for assessing the safety impact of CV-based traffic applications since it considers the potential positioning errors and communication delays which are likely to affect the performance of CV-based traffic applications in reality and uses vehicle dynamics-incorporated vehicle trajectories which are more realistic than the sore traffic simulator vehicle trajectories.

---

* Corresponding author. Tel.: +49 174 450 7282.

E-mail addresses: jaehyun.so@tum.de (J. So), gdedes@dgnsssolutions.com (G. Dedes), bpark@virginia.edu (B.B. Park), hosseinyalamdary.1@osu.edu (S. HosseinyAlamdary), grejner-brzezinska.1@osu.edu (D. Grejner-Brzezinsk).

[1] Tel.: +1 614 937 1993.

[2] Tel.: +1 434 924 6347.

[3] Tel.: +1 614 292 8787.

http://dx.doi.org/10.1016/j.trc.2014.10.004
0968-090X/© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

In the past few decades, many safety applications have been studied and developed by taking advantage of Global Positioning System (GPS) (NRC, 1995) and the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technology. In Particular, in the United States, since the Connected Vehicle research program (US_DOT, 2013) was initiated, various studies have been conducted to develop safety applications, namely, the Cooperative Intersection Collision Avoidance System (CICAS) (Maile and Delgrossi, 2009), the Forward Collision Warning system (FCW) (Hsu et al., 2009), the Cooperative Adaptive Cruise Control (CACC) (Bu et al., 2010), and the lane change and lane departure warning system (LCW) (LeBlanc et al., 2006). Although there are many possibilities for the devices used in providing the vehicle status information and in identifying potential dangers, GPS and V2V/V2I communications are core systems considered in the Connected Vehicle technology-based transportation safety applications (Faezipour et al., 2012; MDOT_and_CAR, 2012). Moreover, these systems provide the basic vehicle maneuvering information including current position, heading angle, acceleration, speed, and also the information of the other vehicles over short and long distances. This capability is especially beneficial for certain safety applications such as intersection collision warning system and ramp merging collision warning system in which the embedded sensors including the radar/LiDAR[4] systems could not provide accurate distance due to skewed angle. Therefore, Automobile manufactures initiated to develop the fusion detection system; Cadillac announced that various safety applications including forward collision alert system and cross traffic alert system will be deployed by mid-decade by relying on a fusion of radar, ultrasonic sensors, cameras, GPS, and vehicle communications (Cadillac, 2012).

However, in the Transportation engineering domain, existing safety assessment studies based on the vehicle safety applications have been conducted simply based on the assumption of a perfect vehicle positioning data and no communication delays, although it is unlikely in reality due to the imperfect nature of radio signals and the surrounding obstructions (e.g., buildings and mountains). Although some research efforts based on the field-experiments using equipped vehicles (i.e., equipped with GPS or wireless communications devices) have been made in the Mechanical and Electrical engineering domains (Ibanez-Guzman et al., 2010; Rezaei et al., 2010; Sengupta et al., 2007; Sepulcre et al., 2013), the experiments were conducted with a few vehicles under the controlled and relatively simple traffic situations. On the contrary, while the most benefit of using the traffic simulation models is that various traffic situations (i.e., at freeway ramp/mainline, signalized intersections, etc.) which are likely to occur in the field can be tested, there is no appropriate traffic simulation environment that can utilize the performance of the vehicle positioning and wireless communications technologies with the off-the-shelf driver warning systems. Under these circumstances, the conceptual design consisting of the positioning, communications, and vehicle dynamics simulators was proposed by the previous studies (Dedes et al., 2011a,b), the detailed interface between these multiple simulators has not been developed and implemented.

Currently, as the state-of-the-art, more advanced positioning systems such as a Differential Global Positioning System (DGPS) (Parkinson et al., 1996) and Real-Time Kinematic (RTK) are being developed. In addition, an Inertial Navigation Unit (INU) (Dedes et al., 2012), which measures accelerations, and orientation rates of a moving object using motion sensors and rotation sensors, was recently introduced and used as a GPS supporting device for the blackout of GPS. Despite the advances in positioning systems, positioning errors are still prevalent. While the accuracy in the existing positioning system (i.e., 1.5–4 m (Kee et al., 1991)) may not significantly affect the general traffic applications such as travel time estimation and route guidance system, they are crucial to the traffic safety related applications that require an accuracy level pinpointing vehicle positions at the lane level. Even a relatively small error (e.g., a few meters in positioning error) would significantly affect the performance of vehicle warning systems, such as CICAS, FCW, CACC, and LCW, due to false alarms. In other words, given that the skewed surrogate values based on the positioning errors can increase the likelihood of false alarms, it could lead to not only dangerous conditions but also a decrease in the driver's compliance in response to the warning messages. Obviously, this does not help the traffic safety on the US highways (Ben-Yaacov et al., 2002; Lee et al., 2002).

Likewise, given that the basic safety data including vehicle positioning are transmitted to adjacent vehicles and/or infrastructures based on the Connected Vehicle (CV) technology environment (Ibrahim et al., 2013), the quality of communication can be another factor affecting safety. Several studies have investigated the performance of a vehicular wireless network such as Wireless Access in Vehicular Environments (WAVE)/Dedicated Short-Range Communications (DSRC) standard (SAE-I, 2009; Uzcátegui and Acosta-Marum, 2009), through field tests or the communication simulator and traffic simulator-integrated environment (Kandarpa et al., 2009; Miloslavov et al., 2011). However, communication performance is generally affected by various external factors such as the distance between devices (i.e., transmitters and receivers), the amount of data transmitted, and the surrounding environment (e.g., buildings, tunnels, and any other physical obstacles) (Lee, 2011; Zhou et al., 2009). Such communication delays are crucial as recent vehicle safety applications have been implemented by utilizing the V2V/V2I communications.

In addition, since this study considers the microscopic traffic simulation approach assessing traffic safety using surrogate safety measures such as Time-To-Collision (TTC) and Deceleration-Rate-Difference (DRD), using the vehicle dynamics-based trajectories is another factor that enhances a credibility of the traffic simulator-based surrogate safety assessment. This is because the microscopic traffic simulation models such as VISSIM (PTV, 2011), AIMSUN (Cheu et al., 2003), and PARAMICS

---

[4] Compound word of 'light' and 'radar'.