A microsimulation approach for the impact assessment of a Vehicle-to-Infrastructure based Road Hazard Warning system

Kallirroi N. Porfyri^{1*}, Areti Kotsi¹, Evangelos Mitsakis¹

¹Centre for Research and Technology Hellas (CERTH) - Hellenic Institute of Transport (HIT) E-mail: kporfyri@certh.gr, akotsi@certh.gr, emit@certh.gr *Corresponding Author

Abstract

Cooperative Intelligent Transportation Systems (C-ITS) constitute technologies which enable vehicles to communicate with each other and with road infrastructure. Verification or testing is required for C-ITS applications, in order to assess their impact on traffic operation. In this work, a microscopic traffic simulation approach is used, to evaluate the impact of Vehicle-to-Infrastructure (V2I) technologies in the context of a road traffic accident. Specifically, the methodology is implemented to explicitly models vehicles collisions, Road Hazard Warning (RHW), Emergency Electronic Brake Light (EEBL) warnings and the resulting driver behavior. Moreover, a new gap control mechanism is adopted, to improve safety by advising vehicles in hazard lane to increase their headways with respect to their preceding vehicle, so that they can avoid a collision. Perfect communication links to all vehicles are assumed. The study findings indicate that the proposed V2I hazard warning strategy has a positive impact on traffic flow safety and efficiency.

Keywords: Cooperative Intelligent Transportation Systems, Road Hazard Warning, Emergency Electronic Brake Light, microscopic simulation, SUMO.

1. Introduction

Cooperative Intelligent Transportation Systems (C-ITS) constitute an array of connected vehicle technologies anticipated to improve driving experience through the provision of constant and real-time Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) services (Baskar, Schutter, Hellendoorn, & Papp, 2011; Fernandes & Nunes, 2012; Kim et al., 2012). The exchange of multiple data collected from field and/ or in-vehicle equipment assists in the deployment of services, which work in a cooperative way, aiming to improve network efficiency, sustainability, safety and environmental impacts mitigation. Concerning road/traffic safety, the focus is on the reduction of car accidents' risk and on the minimization of unavoidable accidents' resulting damage (Alam, Fernandes, Silva, Khan, & Ferreira, 2015).

Contrary to typical safety warning systems, which utilize information obtained from individual vehicles, V2V and V2I communications apply to a wider range addressing possible implications generated from hazard estimations based on close proximity measures (Milanes et al., 2012).

Technology examples enabling such interactions include Dedicated Short Range Communications (DSRC) based on the IEEE 802.11p standard, and 4G technology using Long Term Evolution (LTE) (Araniti, Campolo, Condoluci, Iera, & Molinaro, 2013; Karagiannis et al., 2011), while interworking between DSRC and cellular network technologies for more efficient Vehicle-to-Everything (V2X) communications has also been proposed (Abboud, Omar, & Zhuang, 2016).

Drivers' behavior with access to V2X technologies is expected to be affected and differentiated from that of conventional vehicles, due to the element of additional information provision. Anticipated benefits are investigated and estimated through simulations, as a more cost effective and less complicated approach compared to field tests. Simulations applicable to such systems cover the aspects of traffic, i.e. vehicle movements, and communication, i.e. message exchanging between vehicles and infrastructure. Under this framework, approaches utilizing the combination of different simulators, in order to address challenges related to components interactions, have been proposed (Queck, Schünemann, Radusch, & Meinel, 2008; Schunemann, Massow, & Radusch, 2008). However, the scope of this work is to examine alterations in driver behavior with V2I integration rather than an in-depth analysis of message communication techniques and requirements.

Taking into account the currently low market penetration rates of V2X communication technologies, microscopic traffic simulation is adopted as an approach enabling accurate modelling of individual vehicles, such as driver acceleration and lane-changing responses to incident and warning messages (Brackstone & McDonald, 1999). Any limitations resulting from assumptions related to zero drivers' mistakes responsible for collisions shall be tackled either by driver behavior modifications (Yang & Peng, 2010) or by computing Surrogate Safety Measures (SSMs) (Caliendo & Guida, 2012; Motro et al., 2016).

The assessment of the impacts of connected vehicle technology-based safety warning systems has been thoroughly studied in the literature. Ye et al. (Ye et al., 2018) develop and evaluate a V2V-based application, performing lane-level hazard prediction, and a corresponding driver's response model. Microscopic traffic simulation results indicate mobility and safety benefits associated to conflicts' decrease, even under low V2V penetration rates. Yeo et al. (Yeo, Shladover, Krishnan, & Skabardonis, 2010) investigate the impact of V2V hazard alert systems on freeway traffic by microscopically modelling equipped and non-equipped driver response to lane-blocking incidents. Simulation outputs show the contribution of V2V hazard alert systems to the mitigation of traffic congestion, as a result of speed reduction and optional lane change messages transmitted to drivers. A hybrid collision warning system for V2V environments, utilizing information collected from vehicle and loop detectors is proposed by Tak et al. (Tak, Woo, & Yeo, 2016). The effectiveness and applicability of the developed system, targeting in overcoming withdraws of typical V2X communication-based collision warning systems (ElBatt, Goel, Holland, Krishnan, & Parikh, 2006; Tak & Yeo, 2013; Wang, Cheng, Lin, Hong, & He, 2008), is tested through the simulation of a vehicle trip. Results lead to the conclusion that the hybrid collision warning system is capable of generating benefits for individual drivers similar to the ones of a V2V system.

In this work the application of a V2I communication-based Road Hazard Warning (RHW) system is supported through LTE technology, in an attempt to avoid any limitations originated from inherent DSRC characteristics. Advantages of LTE include higher market penetration rates, high network capacity, wide cellular coverage range, and technology maturity (Abboud et al., 2016; Araniti et al., 2013). Moreover, perfect communication links to all vehicles that can support communication are assumed.

2. Methodology

In this section the methodological approach adopted to study and evaluate the impact of V2X hazard alert systems in incident situations on road and passenger safety, as well as on traffic efficiency, is elaborated.

2.1 Traffic management strategy implementation

A Long Term Evolution (LTE) data communication network to route V2X data communications is assumed whereas Cooperative Awareness Messages (CAMs) ensure communications among C-ITS enabled vehicles by exchanging continuously data packets with information such as location, speed, identifier, etc. In general, acquired information is integrated to infrastructure through a central server, hereafter denoted as Traffic Control Server (TCS). Subsequently, the TCS generates proposed messages which are taken over by the infrastructure and transmitted to vehicles via V2I communications.

In this work, the road hazard is considered to be a sudden braking (abrupt stopping) of a driver resulting in serious crashes with the following vehicles. Since the location of vehicles can be tracked easily and accurately by the TCS through CAMs, the TCS is able to detect the crash; CAMs indicating abrupt deceleration or sudden stop of the transmission of messages could suggest to the TCS that a crash or a hazardous incident has taken place. When the TCS detects such a conflict, it distributes the corresponding messages to the vehicles in the considered network. The related messages, as well as the drivers' actual responses to a message activation, are described in Table 1.

Message	Description	Drivers' response	
Road Hazard Warning (RHW)	Aims to inform drivers in a timely manner of an upcoming hazardous event, as well as how far ahead the hazard is and which lanes are affected.	Drivers on the hazard lane attempt to change lane constantly with the purpose of avoiding a crash.	
Emergency Electronic Brake Light (EEBL) Warning	Aims to avoid rear-end collisions by warning the drivers that a vehicle in front is suddenly braking hard or	Drivers on the hazard lane smoothly increase their desired headways to avoid a collision (gap control	
	crashing.	mechanism).	

Table 1: Drivers' responses to the proposed messages

Speed Change Request	Aims to inform drivers to change	Drivers on the hazard lane and on the	
(SCR)	their speed in response to current	adjacent one receive a SCR message	
	traffic conditions (crash).	to adjust their desired speed.	

2.2 Traffic management logic for modelling Traffic Control Server and drivers' responses to incidents

This section presents the modelling of drivers' responses to warning messages and the crashing of vehicles using the microscopic traffic simulator SUMO (Simulator of Urban MObility) (Lopez et al., 2018). A major benefit of SUMO is that it is open source, which enables users to develop and integrate new car-following models. Moreover, the simulator includes the Traffic Control Interface tool, shortly known as TraCI, which is a Python API offering users the ability to interact with the running simulation, in order to control the vehicle's parameters, and by extension enabling in case the modelling of drivers' responses, as well as the vehicle collisions.

The default car-following model implemented in SUMO is a variant of the Krauss model, introduced by Stefan Krauss (Krauss, 1998), which is a collision-free model and is based on the same principle as the Gipps car following model (Gipps, 1981). SUMO's inherent default lane change model (i.e. the LC2013 model) also determines the lane changes of a vehicle, which is a sophisticated model that reflects lane change behaviors due to different reasons (e.g. strategic, tactical, mandatory, cooperative, etc.).

In general, the driver's response to the traffic conflict depends on the type of information that is provided by the TCS, as well as on the location of the C-ITS enabled vehicles regarding the road hazard and the other implicated vehicles of the considered network. Taking the above into consideration, we assume that the vehicles are grouped to drive in specific zones; thus, the behavior of a vehicle will be defined with respect to the zone or zones in which it belongs. When the TCS detects that an accident has occurred, it regularly sends RHWs to all vehicles of the predefined influence zones through broadcast communications. The RHW range over which vehicles receive the messages is defined at 500 meters. The communicating vehicles will then adjust their driver behavior by responding to the receiving messages, which correspond to the current traffic conditions. Before proceeding, it is pointed out that we assume perfect communication links to all C-ITS equipped vehicles and that there is no delay between the transmission of messages by the TCS.

In particular, vehicles which travel on the hazard lane and enter the dangerous zone (refer Figure 1) receive a RHW message to adjust their desired speed (SCR), as well as to try to change lane at every time step, if it is feasible; in our model, the vehicles will travel at a lower speed with respect to the speed limit of the freeway after the SCR. Vehicles that drive in the near crash zone (see Figure 1) receive an EEBL warning to inform drivers that a vehicle in front may crash or brake abruptly and therefore the drivers are advised to increase their headways appropriately via a newly developed open-gap function, in order to avoid a collision. Specifically, a gap control mechanism has been recently incorporated into SUMO, allowing the user to impose a smooth adaptation of the vehicle's desired headway. This mechanism aims to facilitate the creation gap between two specific subsequent vehicles and has been modelled to increase the

desired time headway of the following vehicle (car-following parameter tau), and also determine the minimum space headway that must be maintained between the two vehicles for a predefined duration. The parameters used in the open-gap function are presented in Table 2. Moreover, the TCS decides to which vehicles an EEBL warning will be send, based on the following equation:

$$EEBL_d = RT \times V \times SF \times \frac{V^2}{2d}$$
(1)

where, $EEBL_d$ is the distance from the point of initial collision up to which the EEBL warning will be transmitted. *RT* is the drivers' reaction time and is generally defined as the time that a driver needs to react to avoid an accident after the onset of a threat; the proposed value for reaction time is RT = 0.9 s, which is much lower than the usual reaction time of 2.5 s, but is expected for a person reacting to an auditory collision warning (Mohebbi, Gray, & Tan, 2009). *V* is the speed limit of the road, *SF* is a safety factor equal to 2 and *d* is the deceleration ability of vehicles that is set as $4.5 m/s^2$.

Parameter name	Parameter description	Parameter value	
newTimeHeadway [s]	The vehicle's desired time headway will be changed to the given new value with use of the given change rate.	4	
newSpaceHeadway [m]	The vehicle is commanded to keep the increased headway for the given duration once its target value is attained.	2	
duration [s]	The time period in which the time and space headways will be changed to the given new values.	-1^* *the largest possible time is set	
changeRate	The rate at which the new headways' effectiveness is gradually increased.	0.5	
maxDecel [<i>m/s</i> ²]	The maximal value for the deceleration employed to establish the desired new headways.	1.5	

Table 2: Drivers' responses to the proposed messages

As regards vehicles that travel in a lane different than the hazard one, they pertain to the safe zone (refer Figure 1). The TCS advises these vehicles to reduce their desired speed with respect to the speed limit of the freeway, whereas they are concurrently restricted from entering the hazard lane. After passing the conflict area, vehicles' speed and lane change operation are no longer under the control of the TCS. Finally, vehicles that have received no information from

the TCS are considered to belong in the standard zone (see Figure 1); the behavior of drivers in this state is entirely determined by the default car-following (Krauss) and lane change (LC2013) model implemented in SUMO. The overall traffic management scheme for the modelling of the TCS and the corresponding drivers' responses to messages are described as a flowchart, illustrated in Figure 2.



Figure 2: Flowchart of the proposed traffic management strategy

2.3 Surrogate Safety Measures for conflicts points

This section deals with the description of different traffic conflict indicators for highway safety analysis on a network afflicted by a collision. Specifically, potential SSMs that represent the temporal and spatial proximity characteristics of unsafe interactions and rear-crashes have been used in the simulation-based approach. One of these indicators is the Time to collision (TTC), the most commonly used and well-developed time-based measure. This indicator was initially introduced by Hayard (Hayward, 1972) as an effective measure for rating the severity of traffic conflicts and is defined as the mean time required for two consecutive vehicles to collide if they continue at their current velocity and in the same lane or the same path. In the vast literature, there are different threshold values for the minimum TTC (critical TTC value) required for drivers to safely react, ranging from $1.5 \ s$ to $4 \ s$ (Dijkstra et al., 2010; Eisele & Frawley, 2004; Essa & Sayed, 2015); the smaller TTC value indicates the higher probability of collision. In this study, a $1.5 \ s$ time to collision was adopted as a threshold, which was proposed by the surrogate safety assessment model (SSAM), developed by the Federal Highway Administration (FHWA), to identify a traffic conflict that could lead to a traffic crash (Gettman & Head, 2003; Gettman, Pu, Sayed, & Shelby, 2007). The TTC formulation is as follows:

$$TTC = \frac{D_{LF}}{V_F - V_L} \tag{2}$$

where, D_{LF} is the distance between the rear bumper of the leading vehicle and the front bumper of the following one (the vehicle under examination); V_F and V_L indicate the speed of the following vehicle and the speed of the leading vehicle, respectively. At this point, it is important to clarify that the TTC is defined for all the follow-lead situations for which the speed of the following vehicle is higher than the speed of the leading one.

A modified SSM derived from TTC is the Time Integrated Time-to-collision (TIT), developed by Minderhoud and Bovy (Minderhoud & Bovy, 2001), and is referred to as the entity of the TTC lower than the threshold. In general, the TIT provides a single value representation of the frequency of crashes and their severity in the area of interest and is also applied to evaluate the risks of traffic conflicts aggregately:

$$TIT = \sum_{i=1}^{N} \int_{0}^{T} max(TTC^{*} - TTC_{i}(t), 0)dt$$

$$\forall 0 \le TTC_{i}(t) \le TTC^{*}$$
(3)

in which N is the total number of vehicles, TTC^* is the specified threshold value of TTC that distinguishes safe from unsafe car-following situations, and $TTC_i(t)$ is the TTC of vehicle *i* at time *t*.

The concept of safe stopping distance between the leading and following vehicle has also been used, in order to assess the potential risk of collision. Among the most popular safe stopping distance-based indicators for safety estimation is the Deceleration Rate to Avoid Collision

(DRAC), which is defined as the minimum rate at which a vehicle must decelerate to avoid a possible traffic conflict. In the context of this study, potential conflict scenarios are considered when the DRAC exceeds a threshold braking value of $3.35 m/s^2$ (Archer, 2005). For rear-end interactions, the DRAC indicator can be expressed as:

$$DRAC = \frac{(V_F - V_L)^2}{2D_{LF}}$$
(4)

Besides the above SSMs, several other indicators are described in the literature (Karim, Saifizul, Yamanaka, Sharizli, & Ramli, 2013; Kuang, Qu, & Wang, 2015; Ozbay, Yang, Bartin, & Mudigonda, 2008) that are used for safety assessment of different traffic conflicts through micro-simulation models. However, as the type of vehicle conflict that is modeled in our scenario concerns a rear-end crash that occurs on a freeway stretch and since the aforementioned surrogate indicators are considered to be good measures of the severity of these types of traffic conflicts, TTC, TIT, and DRAC are used as SSMs in our experiment.

3. Simulation experiment

The network used for simulations is a two-lane freeway stretch without any on-ramps and offramps; the stretch has a total length of 5 km, with a speed limit of 110 km/h; the simulation time is 1 h whereas the simulation step is set to 0.1 s. Traffic is flowing at a capacity of 3000 vehicles per hour, constituting of 100% passengers cars. Experiments were conducted for different penetration rates of 0%, 25%, 50%, 75% and 100% C-ITS equipped vehicles to determine their effect on safety and efficiency of the network.

Usually, there are three types of driving: conservative driving, moderate driving and aggressive driving. Therefore, in this study to account for the variation in drivers' behavior and to reflect a more realistic scenario we assume that drivers' behavior follows a normal distribution, which means that most of the drivers have an average aggressiveness in driving (moderate driving behavior) and only a small percentage of drivers would be either very aggressive or conservative in driving. In this respect, the exact degree of aggressiveness for each driver was achieved by setting a normal distribution of sigma, decel, accel and speedFactor parameters in SUMO. Table 3 provides the driver model parameters' values used for our simulation experiment. In case that the entry is not a single number, it has the format normal(<mean>, <std>); [<min>,<max>], specifying a cut off Gaussian distribution.

Parameter name	Parameter description	Parameter value
sigma	The driver imperfection.	normal(0.2, 0.5); [0.0, 1.0]
tau [s]	The driver's desired time headway.	2.0

Table 3: Driver model parameters values

The maximal deceleration of vehicles.	normal(3.5, 1.0); [2.0, 4.5]
The maximal acceleration of vehicles.	normal(2.0, 1.0); [1.0, 3.5]
The maximal physically deceleration for the vehicles.	4.5
Lane-change aggressiveness (willingness to accept lower gaps).	1.3
The reaction time.	0.9
The vehicle's maximum speed.	30.5
The proportionality factor for the desired speed.	normal(1.1, 0.2); [0.8, 1.2]
	The maximal deceleration of vehicles. The maximal acceleration of vehicles. The maximal physically deceleration for the vehicles. Lane-change aggressiveness (willingness to accept lower gaps). The reaction time. The vehicle's maximum speed. The proportionality factor for the desired speed.

The road hazard that is considered in our experiment is the sudden crash of a vehicle. To simulate this, a vehicle destined for collision is introduced into the network; when this vehicle covers 4 km of the overall length of the freeway stretch, it is made to stop abruptly resulting in serious crashes with the following vehicles. After the onset of the traffic conflict, the resulting behavior of vehicles in the network depends on the predefined by the user values of specific simulation parameters. The parameters that can vary in our experiment are the aforementioned percentage of C-ITS equipped vehicles, as well as the percentage of SCR provided by the TCS. In particular, we assume that the TCS advises vehicles to reduce their desired speed by 15%, 25% and 50% with respect to the speed limit of the freeway. Therefore, this parameterization scheme resulted in a total of 17 different simulation scenarios.

The traffic safety and efficiency of the simulated scenario are evaluated based on the number of crashes that occur, the resulting average network speed and capacity, as well as the three SSMs, i.e. the TTC, the TIT and the DRAC. We assume that events with TTC lower than 1.5 s and DRAC lower than $3.35 m/s^2$ are safety critical conflicts. The TIT safety indicator is computed for a duration of 15 seconds after the first crash.

4. Numerical results

Table 4 displays key safety metrics for the 17 simulation experiments for several RHW parameterization schemes. Comparison between them reveals that the penetration rate of C-ITS enabled vehicles has a significant impact on the number of crashes, the TIT indicator as well as a positive effect on the capacity of the network. Specifically, the freeway capacity increases when the penetration rate of vehicles that are capable of communication is increased, due to the information that the vehicles receive to change lane markedly prior to the traffic conflict, whereas the number of crashes is significantly reduced with the increase of the penetration rate of C-ITS equipped vehicles. Moreover, a crash reduction is observed as the SCR ratio is

decreased. Simulation results also demonstrated that both the increase of equipped vehicles and the lower percentage of SCR result in the reduction of TIT.

ID	Penetration rate [%]	Percentage of SCR [%]	TIT	Number of Crashes	Flow [veh/h]
1	0.00	-	128.16	5	934
2		0.50	93.75	4	949
3	0.05	0.75	94.85	5	948
4	0.25	0.85	123.34	5	936
5		1.00	130.49	5	933
6		0.50	90.32	3	953
7	0 5 0	0.75	93.89	4	950
8	0.50	0.85	104.68	5	943
9		1.00	126.71	5	938
10		0.50	83.86	2	958
11	0.75	0.75	90.42	3	953
12	0.75	0.85	110.84	5	942
13		1.00	118.79	5	940
14		0.50	43.16	2	969
15	1.00	0.75	59.75	2	962
16	1.00	0.85	89.4	2	953
17		1.00	92.45	3	951

Table 4: Numerical results

The maximum DRAC and minimum TTC values of the parameterization schemes 1 (0% C-ITS equipped vehicles) and 14 (100% C-ITS equipped vehicles) are illustrated in Figure3; as it can be noticed, in the case of non-equipped vehicles 5 critical situations are indicated with values above the considered thresholds (red dash-dot lines with DRAC= $3.35 m/s^2$ and TTC=1.5 s), while in the case of C-ITS equipped vehicles a lower number of critical conflicts are identified (only 2 critical events). Furthermore, the possible critical events that are indicated below the specified thresholds are temporarily shifted and are also lower in number in the case of 100% C-ITS enabled vehicles due to the advice these vehicles receive from the TCS to change lane and increase their headways considerably prior to the crash. Figure 4 depicts the time series mean speed of the traffic flow for non-equipped and 100% C-ITS enabled vehicles; it can be observed that with the operation of RHW the vehicles are moving at higher speeds. Finally, in Figure 5 it can be noticed that the traffic queue observed in the hazard lane for non-equipped vehicles propagates further upstream compared to the case of 100% C-ITS equipped vehicles.



Figure 3: DRAC and TTC values over the considered time interval (at the beginning of the traffic conflict for (a) non-equipped and (b) 100% C-ITS equipped vehicles



Figure 4: Average network speed for non-equipped and 100% C-ITS equipped vehicles vehicles



(b) 100% C-ITS equipped vehicles

Figure 5: Space-time diagram of speed for (a) for non-equipped and (b) 100% C-ITS equipped <u>vehicles</u>

5. Conclusions

In this study, a microsimulation approach was proposed to analyse the effects of a hazard warning system on the behavior and safety of drivers, as well as on the overall traffic efficiency. The implemented methodology explicitly models vehicles collisions, RHW, EEBL warnings and the resulting driver behavior. Moreover, a recently developed gap control mechanism was adopted to improve safety by advising vehicles in the hazard lane to increase their headways appropriately with respect to their preceding vehicle, in order to avoid a collision. Safety was measured using robust SSMs, such as the TTC, the TIT and the DRAC indicators. The study findings demonstrate that the deployment of the proposed V2I hazard warning system has a

positive impact on traffic flow safety and efficiency with higher market penetration rates of C-ITS equipped vehicles, particularly if it combines with the reduction of the speed of the vehicles.

6. References-Bibliography

- Abboud, K., Omar, H. A., & Zhuang, W. (2016). Interworking of DSRC and Cellular Network Technologies for V2X Communications: A Survey. *IEEE Transactions on Vehicular Technology*, 65(12), 9457–9470. https://doi.org/10.1109/TVT.2016.2591558
- Alam, M., Fernandes, B., Silva, L., Khan, A., & Ferreira, J. (2015). Implementation and analysis of traffic safety protocols based on ETSI Standard. 2015 IEEE Vehicular Networking Conference (VNC), 143–150. https://doi.org/10.1109/VNC.2015.7385561
- Araniti, G., Campolo, C., Condoluci, M., Iera, A., & Molinaro, A. (2013). LTE for vehicular networking: a survey. *IEEE Communications Magazine*, 51(5), 148–157. https://doi.org/10.1109/MCOM.2013.6515060
- Archer, J. (2005). *Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling : a study of urban and suburban intersections*. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-143
- Baskar, L. D., Schutter, B. D., Hellendoorn, J., & Papp, Z. (2011). Traffic control and intelligent vehicle highway systems: a survey. *IET Intelligent Transport Systems*, 5(1), 38–52. https://doi.org/10.1049/iet-its.2009.0001
- Brackstone, M., & McDonald, M. (1999). Car-following: a historical review. Transportation Research Part F: Traffic Psychology and Behaviour, 2(4), 181–196. https://doi.org/10.1016/S1369-8478(00)00005-X
- Caliendo, C., & Guida, M. (2012). Microsimulation Approach for Predicting Crashes at Unsignalized Intersections Using Traffic Conflicts. *Journal of Transportation Engineering*, 138(12). Retrieved from https://trid.trb.org/view/1237041
- Dijkstra, A., Marchesini, P., Bijleveld, F., Kars, V., Drolenga, H., & van Maarseveen, M. (2010). Do Calculated Conflicts in Microsimulation Model Predict Number of Crashes? *TRANSPORTATION RESEARCH RECORD*, (2147), 105–112.
- Eisele, W. L., & Frawley, W. E. (2004). Estimating the Impacts of Access Management with Micro-simulation: Lessons Learned. Presented at the Sixth National Conference on Access ManagementTransportation Research BoardFederal Highway AdministrationMissouri Department of TransportationKansas Department of TransportationMidwest Transportation Consortium. Retrieved from https://trid.trb.org/view/806563
- ElBatt, T., Goel, S. K., Holland, G., Krishnan, H., & Parikh, J. (2006). Cooperative Collision Warning Using Dedicated Short Range Wireless Communications. *Proceedings of the* 3rd International Workshop on Vehicular Ad Hoc Networks, 1–9. https://doi.org/10.1145/1161064.1161066
- Essa, M., & Sayed, T. (2015). Simulated Traffic Conflicts: Do They Accurately Represent Field-Measured Conflicts? *Transportation Research Record*, 2514(1), 48–57. https://doi.org/10.3141/2514-06
- Fernandes, P., & Nunes, U. (2012). Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow. *IEEE*

Transactions on Intelligent Transportation Systems, *13*(1), 91–106. https://doi.org/10.1109/TITS.2011.2179936

Gettman, D., & Head, L. (2003). Surrogate Safety Measures From Traffic Simulation Models, Final Report (No. FHWA-RD-03-050). Retrieved from U.S. Department of Transportation website:

https://www.fhwa.dot.gov/publications/research/safety/08051/index.cfm

- Gettman, D., Pu, L., Sayed, T., & Shelby, S. (2007). Surrogate Safety Assessment Model and Validation: Final Report (No. FHWA-HRT-08-051). Retrieved from U.S. Department of Transportation website: https://www.fhwa.dot.gov/publications/research/safety/08051/index.cfm
- Gipps, P. G. (1981). A behavioural car-following model for computer simulation. *Transportation Research Part B: Methodological*, 15(2), 105–111. https://doi.org/10.1016/0191-2615(81)90037-0
- Hayward, J. C. (1972). NEAR-MISS DETERMINATION THROUGH USE OF A SCALE OF DANGER. *Highway Research Record*. Presented at the 51st Annual Meeting of the Highway Research Board. Retrieved from https://trid.trb.org/view/115323
- Karagiannis, G., Altintas, O., Ekici, E., Heijenk, G., Jarupan, B., Lin, K., & Weil, T. (2011). Vehicular Networking: A Survey and Tutorial on Requirements, Architectures, Challenges, Standards and Solutions. *IEEE Communications Surveys Tutorials*, 13(4), 584–616. https://doi.org/10.1109/SURV.2011.061411.00019
- Karim, M. R., Saifizul, A., Yamanaka, H., Sharizli, A., & Ramli, R. (2013). Minimum Safe Time Gap (MSTG) as a new Safety Indicator incorporating Vehicle and Driver Factors. 11.
- Kim, S., Gwon, G., Choi, S., Kang, S., Shin, M., Yoo, I., ... Seo, S. (2012). Multiple vehicle driving control for traffic flow efficiency. 2012 IEEE Intelligent Vehicles Symposium, 462–468. https://doi.org/10.1109/IVS.2012.6232187
- Krauss, S. (1998). *MICROSCOPIC MODELING OF TRAFFIC FLOW: INVESTIGATION OF COLLISION FREE VEHICLE DYNAMICS.* Retrieved from https://trid.trb.org/view.aspx?id=579157
- Kuang, Y., Qu, X., & Wang, S. (2015). A tree-structured crash surrogate measure for freeways. *Accident Analysis* & *Prevention*, 77, 137–148. https://doi.org/10.1016/j.aap.2015.02.007
- Lopez, P. A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y., Hilbrich, R., ... WieBner, E. (2018). Microscopic Traffic Simulation using SUMO. 2018 21st International Conference on Intelligent Transportation Systems (ITSC), 2575–2582. https://doi.org/10.1109/ITSC.2018.8569938
- Milanes, V., Villagra, J., Godoy, J., Simo, J., Perez, J., & Onieva, E. (2012). An Intelligent V2I-Based Traffic Management System. *IEEE Transactions on Intelligent Transportation Systems*, 13(1), 49–58. https://doi.org/10.1109/TITS.2011.2178839
- Minderhoud, M. M., & Bovy, P. H. L. (2001). Extended time-to-collision measures for road traffic safety assessment. Accident Analysis & Prevention, 33(1), 89–97. https://doi.org/10.1016/S0001-4575(00)00019-1
- Mohebbi, R., Gray, R., & Tan, H. Z. (2009). Driver reaction time to tactile and auditory rearend collision warnings while talking on a cell phone. *Human Factors*, *51*(1), 102–110. https://doi.org/10.1177/0018720809333517

- Motro, M., Chu, A., Choi, J., Lavieri, P. S., Pinjari, A. R., Bhat, C. R., ... Heath, R. W. (2016). Vehicular ad-hoc network simulations of overtaking maneuvers on two-lane rural highways. *Transportation Research Part C: Emerging Technologies*, 72, 60–76. https://doi.org/10.1016/j.trc.2016.09.006
- Ozbay, K., Yang, H., Bartin, B., & Mudigonda, S. (2008). Derivation and Validation of New Simulation-Based Surrogate Safety Measure. *Transportation Research Record*, 2083(1), 105–113. https://doi.org/10.3141/2083-12
- Queck, T., Schünemann, B., Radusch, I., & Meinel, C. (2008). Realistic Simulation of V2X Communication Scenarios. 2008 IEEE Asia-Pacific Services Computing Conference, 1623–1627. https://doi.org/10.1109/APSCC.2008.23
- Schunemann, B., Massow, K., & Radusch, I. (2008). A Novel Approach for Realistic Emulation of Vehicle-2-X Communication Applications. VTC Spring 2008 - IEEE Vehicular Technology Conference, 2709–2713. https://doi.org/10.1109/VETECS.2008.593
- Tak, S., Woo, S., & Yeo, H. (2016). Study on the framework of hybrid collision warning system using loop detectors and vehicle information. *Transportation Research Part C: Emerging Technologies*, 73, 202–218. https://doi.org/10.1016/j.trc.2016.10.014
- Tak, S., & Yeo, H. (2013). The Impact of Predictive Cruise Control on Traffic Flow and Energy Consumption. *Computing in Civil Engineering (2013)*, 403–410. https://doi.org/10.1061/9780784413029.051
- Wang, S., Cheng, Y., Lin, C., Hong, W., & He, T. (2008). A Vehicle Collision Warning System Employing Vehicle-To-Infrastructure Communications. 2008 IEEE Wireless Communications and Networking Conference, 3075–3080. https://doi.org/10.1109/WCNC.2008.537
- Yang, H.-H., & Peng, H. (2010). Development and evaluation of collision warning/collision avoidance algorithms using an errable driver model. *Vehicle System Dynamics*, 48(sup1), 525–535. https://doi.org/10.1080/00423114.2010.515745
- Ye, F., Wu, G., Boriboonsomsin, K., Barth, M. J., Rajab, S., & Bai, S. (2018). Development and Evaluation of Lane Hazard Prediction Application for Connected and Automated Vehicles (CAVs). 2018 21st International Conference on Intelligent Transportation Systems (ITSC), 2872–2877. https://doi.org/10.1109/ITSC.2018.8569340
- Yeo, H., Shladover, S. E., Krishnan, H., & Skabardonis, A. (2010). Microscopic Traffic Simulation of Vehicle-to-Vehicle Hazard Alerts on Freeway. *Transportation Research Record*, 2189(1), 68–77. https://doi.org/10.3141/2189-08