

# **A MICROSIMULATION APPROACH TO QUANTIFY THE SAFETY BENEFITS OF CONNECTED VEHICLES: A ROAD HAZARD WARNINGS APPLICATION**

## **Gopindra Sivakumar Nair**

The University of Texas at Austin  
Department of Civil, Architectural and Environmental Engineering  
301 E. Dean Keeton St. Stop C1761  
Austin TX 78712, USA  
Tel: 1-512-200-5884, Fax: 1-512-475-8744, Email: [gopindra@utexas.edu](mailto:gopindra@utexas.edu)

## **Mohammed E. Eltayeb**

The University of Texas at Austin  
Center for Transportation Research  
1616 Guadalupe, Suite 4.202, Stop D9300  
Austin, TX 78701, USA  
Tel: 1-512-232-8393, Fax: 1-512-232-3153, Email: [meltayeb@utexas.edu](mailto:meltayeb@utexas.edu)

## **Robert W. Heath Jr.**

The University of Texas at Austin  
Wireless Networking and Communications Group  
2501 Speedway Stop C08061  
Austin, TX 78712-1687  
Tel: 1-512-686-8225, Fax: 1-512-471-6512, Email: [rheath@utexas.edu](mailto:rheath@utexas.edu)

## **Chandra R. Bhat**

The University of Texas at Austin  
Department of Civil, Architectural and Environmental Engineering  
301 E. Dean Keeton St. Stop C1761  
Austin TX 78712, USA  
Tel: 1-512-471-4535, Fax: 1-512-475-8744, Email: [bhat@mail.utexas.edu](mailto:bhat@mail.utexas.edu)  
and  
The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

## **Natalia Ruiz Juri (corresponding author)**

Center for Transportation Research, Network Modeling Center  
1616 Guadalupe, Suite 4.202, Stop D9300  
Austin, TX 78701, USA  
Tel: 1-512-232-3099, Fax: 1-512-232-3153, Email: [nruizjuri@mail.utexas.edu](mailto:nruizjuri@mail.utexas.edu)

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## **ABSTRACT**

The deployment of connected vehicles is highly anticipated, and likely to become a reality in the near future. There is an enormous potential for connected technologies to improve safety, which can only be realized if communication capabilities are paired with smart strategies to manage traffic, complementing vehicle sensors and navigation technologies. Microsimulation can provide invaluable insights into the design and implementation of such strategies. This paper proposes an approach to model and quantify the safety benefits of connectivity enabled through Long Term Evolution (LTE) technology. The methodology extends an existing microsimulation tool and implements it to the analysis of a freeway accident. The enhanced simulation model allows for vehicle collisions, and captures the reaction of drivers to road hazard warnings. Safety is measured using a robust surrogate safety metric, the Time Integrated Time to Collision, and the number of secondary crashes. Numerical experiments are used to test the impact of various communication and traffic-related parameters. We also consider a novel strategy to improve safety by slowing down vehicles in lanes adjacent to the hazard lane, which facilitates merging. Experimental results suggest that the proposed strategy has a positive impact on safety. However, the performance of strategies was observed to vary across scenarios, suggesting that adaptive strategies coordinated by a centralized warning system may provide significant benefits. The framework proposed in this work may be extended to the analysis of such systems, and to the study of other scenarios where communications may have significant impacts on safety.

## INTRODUCTION

Vehicle-to-vehicle (V2V) and vehicle-to- infrastructure (V2I) communication, often referred to as vehicle-to-everything (V2X) technologies, are an emerging trend in the transportation industry. Several leading automakers are already taking steps to include communicating capabilities in their future models (1). Further, the National Highway Traffic Safety Administration has recently published a proposed rule that would make it mandatory for future vehicles to be capable of communication (2). Therefore, it is reasonable to assume that in the near future a large proportion of vehicles on the road will be communicating with one another and/or the infrastructure.

V2X communication is expected to bring about major improvements in traffic safety (3) and traffic throughput (4,5). A recent report by the NHTSA (3) suggests that communication technologies have the potential to reduce the number of crashes by 81%. However, such estimates are based on the assumption of a perfect communication system that is able to prevent all crashes between unimpaired drivers. There are many technologies which could be used for V2X communications. Examples include Dedicated Short Range Communications (DSRC) based on IEEE 802.11p standard, WI-FI, Universal Mobile Telecommunications Service (UMTS), 4G technology using Long Term Evolution (LTE), and recently millimeter wave, a candidate for 5G technology (6-9). The actual safety improvements attained through any of such technologies will depend on the corresponding market penetration, and on the characteristics of the traffic management and control strategies that they enable.

The behavior of vehicles with V2X will be vastly different from that of ordinary vehicles because of the extra information available to them. Since the widespread use of V2X has not yet materialized, we must rely on Microscopic Traffic Simulators (MTS) to gain insights on how a connected system would function. However, assessing safety using MTS is quite challenging. Most MTSs assume that drivers do not make mistakes that lead to collisions. The literature proposes two approaches to addressing such limitations: modifying driver behavior to allow collisions (10) or computing metrics based on simulation outputs that are correlated to the overall safety of the system (11). Such measures are called Surrogate Safety Measures.

In this paper, we use both techniques to develop a methodology to assess the impact of V2X in the context of a freeway accident. Crashes are modeled explicitly to appropriately model the impact of secondary collisions, which further reduce the distance available to get to a full stop.

In an accident scenario, the extended range of communications provided by V2X can support warning and management strategies that are not possible using offline collision avoidance technologies such as radar-based collision warning systems. The series of V2X interactions that take place following a traffic incident constitute a Road Hazard Warning (RHW) system. This work analyzes the impacts of the characteristics of such system on safety. The methodology used in this work may be extended to study additional scenarios.

## BACKGROUND

Several aspects of a transportation system in a V2X environment have been studied in detail in the transportation and the communication literature. The communication literature is primarily focused on the performance of the communication infrastructure in a V2X environment (12-14). Vehicular Ad-Hoc Network (VANET) simulators model vehicle behavior along with communications between them. The reader is directed to Ahmed et al. (15) for a detailed study on VANET simulators. However, since we are interested in modeling the altered vehicle behavior as a result of V2X and not the specific techniques used in communication of the message, we do not use VANETs

The impact of V2X technologies in the performance of the transportation system has been studied in detail in the literature. Among others, Talebpour et al. simulate the implementation of a speed harmonization algorithm using a VANET simulator and measure traffic parameters such as flow rate and CO<sub>2</sub> emissions along with communication parameters such as communication delay (5). Okamura et al. (11) study the impact of vehicle platooning and Adaptive Cruise Control on traffic safety and flow. Tientrakool et al. study how vehicles with communication capabilities can improve highway efficiency (4).

The safety impacts of V2X technologies have been assessed using driving simulators and MTSs. For shorter range technologies such as forward collision warning, the impact on safety is predicted using driving simulators (16,17) or by analyzing vehicle trajectory information (18). Since we are interested in studying network level impacts of safety applications, we use MTSs. However, since most MTSs are designed to represent accident free scenarios involving vehicles without communication capabilities, we modify an existing MTS to produce the required vehicle behavior. In experimental studies Surrogate Safety Measures (SSMs), which measure the incidence of near crash situations, are used to quantify safety (11,19,20).

### **Modeling Assistive Technologies**

In MTSs, each vehicle in the network is assigned a route, and a Car Following Model (CFM) governs the movement of vehicles along their route. Traditionally, CFMs emulate human drivers without any assistive technologies. Several studies on V2X and safety propose a new CFM to capture alternative driver behavior. Tientrakool et al. use this approach (11).

Yeo et al. model a V2X based RHW system for a sudden lane closure (21). The authors consider two information scenarios. In the first case, drivers are only warned about a road hazard ahead, while in the second case they also receive information about the lane affected by the hazard. The study shows that the RHW system reduced traffic delays, particularly when lane specific warnings were provided. Unlike this study, which considers the effect of RHW on traffic flow over a relative longer duration, we study the impact of RHW on traffic safety during the first few seconds that following the occurrence of the road hazard.

The transportation literature has also explored the impact of simple sensing technologies, such as Forward Collision Warning (FCW) or Emergency Electronic Brake Light warning (EEBL), on safety. Such technologies depend only on radars, and are expected to be available by the time V2X is deployed. An EEBL is issued to a driver when any vehicle in the queue in front experiences an emergency braking episode. In such scenario drivers become aware of hard braking ahead even when their view of the braking vehicle is obstructed. Szczurek et al. (22) suggests that vehicles that receive EEBL try to leave more headway with the vehicle in front and propose an algorithm to determine which vehicles behind the braking vehicle should issue this warning.

### **Quantifying Safety**

Quantifying vehicle safety on roads, whether real or simulated, has never been straightforward. A commonly used measure of safety is the ratio of the frequency of crashes to vehicle flow. However, since traffic crashes are extremely rare occurrences and may not be reported, computing this metric reliably is difficult. Even if reliable information of the number of crashes were available, the number of crashes only provides a measure of the most extreme unsafe traffic incidents. It may be argued that a road where vehicles frequently make dangerous maneuvers is more dangerous than a road on which a crash has occurred once. In other words, it is preferable to have a metric that incorporates both the severity and frequency of traffic conflicts.

These considerations have led to the development of Surrogate Safety Measures (SSM) as a measure of traffic safety (23). SSMs attempt to quantify safety not just based on the number of crashes, but also the number of “near crash” scenarios or conflicts. A parameter frequently used for computing SSMs is the Time to Collision (TTC). TTC is the time in which two vehicles will collide if both vehicles continue with their same velocity. An encounter between vehicles is considered a conflict if the TTC falls below a certain threshold at any point during the encounter. The severity of a conflict is determined by the minimum value of TTC (minTTC) observed during an encounter. Since observing TTCs in the field is cumbersome, the use of TTCs for safety analysis has gained more traction in MTSs. Most CFMs are designed to model a perfect human driver and therefore vehicles following a CFM will never crash. For example, the CFM suggested by Krauss et al. (24) assumes that vehicles will never collide with each other, while Wiedemann (25) implements an automatic emergency braking mechanism if vehicles get dangerously close. The absence of collisions using CFMs has motivated the extensive use of SSMs in MTS for the evaluation of safety (26). MTSs have the added advantage that they can provide much more detailed vehicle trajectory information from which richer SSMs can be computed.

Rather than comparing minTTC distributions for assessing safety, a more consolidated measure of TTC was suggested by Minderhoud and Bovy (27) called the Time Integrated TTC (TIT). TIT provides a single value representation of the frequency and severity of all the traffic conflicts in an area of request.

$$TIT = \sum_{i=1}^N \int_0^T \max(TTC^* - TTC_i(t), 0) dt \quad (1)$$

where,  $TTC^*$  is the threshold value of  $TTC$  below which the vehicle encounter is a conflict,  $N$  is the total number of vehicles,  $TTC_i(t)$  is the  $TTC$  of vehicle  $i$  at time  $t$ . Thus TIT is a measure of the negative deviation of  $TTC$  from the threshold  $TTC$  (which is considered to be safe) aggregated over time and vehicles. Several other SSMs are described in the literature (28-31) and Laureshyn et al. (23) suggest that there is no one SSM that is suitable for all types of traffic conflicts. In this paper, we model a scenario where a road hazard occurs on a freeway stretch. The type of vehicle conflict that is of concern in this scenario is the rear end conflict. Since  $TTC$  is a good measure of the severity of rear end conflicts, we use TIT as the SSM in our experiments.

### Long Term Evolution (LTE) for V2X

Dedicated Short Range Communications (DSRC) using IEEE 802.11p is considered the de-facto standard for vehicle-to-everything (V2X) communications. There has been recent interest, however, in the adopting 4G technology using the Long Term Evolution (LTE) standard to support vehicular applications (32-35). LTE has a higher market penetration when compared to DSRC (6) and can potentially resolve many of the challenges of DSRC which include the limited communication range, hidden terminal problem, low data rate, unbounded delay in dense traffic, and shadowing effects caused by neighboring vehicles and obstacles in intersection (9,36). LTE base stations are located at higher positions, and thus, can help in leveraging the non-line of sight issues. Moreover, the lower operating frequency of LTE translates into lower path-loss when compared to DSRC. For these reasons, we adopt LTE technology for V2X in this paper.

In this paper, we assume that all vehicles communicate periodic status (CAM) messages with an LTE network. We also assume perfect communication links to all vehicles that can support communication.

## METHODOLOGY

This section describes the methodological approach used to study the impact of V2X enabled road hazard warnings on traffic safety and performance. The next two sections describe the assumptions on information communication and drivers' behavior, and how these are implemented for the purpose of this research respectively.

### Modeling Assumptions and Proposed Traffic Management Strategies

We assume that the V2X communications are made possible by LTE network. All the vehicles that can communicate are continuously transmitting their location and velocity information using CAM. This information is processed by a central server that we shall refer to as the Traffic Control Server (TCS). It is assumed that, based on the CAM messages, the TCS can precisely identify the location of vehicles. The road hazard we are considering is the sudden crashing of a truck. The TCS detects this crash by processing the CAM information transmitted by the truck. CAM messages indicating sudden deceleration or the abrupt stopping of CAM messages could suggest to the TCS that a crash or a hazardous incident has occurred.

When TCS detects a crash (or similar hazardous incidents), it sends out information regarding the crash to vehicles in the network. We assume that the TCS can send out 3 different types of messages, which will trigger specific driver responses. The warnings and their corresponding responses are described in Table 1.

**TABLE 1 Proposed Messages and Corresponding Driver Responses**

Message	Description	Response
Road Hazard Warning (RHW)	Location information informing drivers how far ahead the hazard is and which lanes are affected.	Drivers on the hazard lane continuously try to change lanes.
Emergency Electronic Brake Light Warning (EEBL)	Alerts the vehicle of the possibility of sudden deceleration or crashing of the vehicle in front.	Increased headway equal to the stopping distance with leading vehicle
Speed Change Request Message (SCR)	Updated speed limit information.	All drivers that receive the message adjust their desired speed.

The EEBL warning is sent only once when the crashing of the first truck (road hazard) occurs. It is assumed that if this warning is not received, the headway a vehicle leaves with the vehicle in front is an approximate difference in stopping distance between the vehicle and its leading vehicle. The SCR is used to implement a strategy consisting on lowering the speed of vehicles adjacent to the hazard lane. We hypothesize that this will make it easier for drivers on the hazard lane to switch to the safer lane.

### Implementation Details

We build our model over the MTS- Simulation of Urban Mobility (SUMO) (37). The response of drivers to warnings and the crashing of vehicles constitute behavior that is not usually modelled in MTSs. Two features of SUMO facilitate modeling the modified driver behavior: its rich Traffic Control Interface (TraCI), which provides a user near complete control over the mobility of

vehicles during simulation runtime, and its open source nature that allows anyone to add new CFMs. The assumptions described in the previous section are modeled by defining several vehicle states during which drivers' behavior is altered. The next two sections describe the modeling of vehicle states and the TCS respectively.

### *Modelling of Vehicle States*

The behavior of a vehicle is dependent on what information it has received from the TCS and the location of the vehicle with respect to the road hazard and other vehicles. Based on these two factors we can consider the vehicle to belong to certain states. Thus, the behavior of a vehicle will be determined by the states it is in. The vehicle behavior and modeling of the different states are as follows.

**Standard State** A vehicle that has received no information from the TCS is assumed to be in the standard state. This state models the normal behavior of drivers. The mobility of a vehicle in this state is completely determined by the Krauss CFM (the default CFM) in SUMO, and its lane changes are determined by the Lane Change Model (LCM) LC2013 (38).

**Near Crash State** The minimum headway every vehicle leaves with the vehicle in front is determined by the parameter *minGap*. The CFMs are designed in such that vehicles always maintain a headway of at least the *minGap*. If a vehicle gets closer than the *minGap*, SUMO teleports that vehicle out of the network. In order to model vehicle collisions this work stops teleportation using TraCI. At every time step TraCI is used to scan the headway of all vehicles and identify cars for which the observed headway would lead to a gap lower than *minGap* in the following time step. The *minGap* parameter for such vehicles, which are considered to be in a near-crash state, is changed to zero. The latter allows them get arbitrarily close to the leading vehicle without being teleported. A vehicle in near-crash state may avoid collision by changing lanes or successfully stopping before crashing.

**Crash State** This state is used for vehicles that have crashed. Such vehicles have zero speed and *minGap*, and a disabled LCM.

**Safe State** This state models the behavior of a driver who is aware of a road hazard ahead and is travelling in a lane other than the hazard lane. Vehicles in this state are restricted from entering the hazard lane and have a maximum equal to the SCR if present.

**Danger State** This state is used to model vehicles that receive a road hazard warning while travelling in the hazard lane. Vehicles in this state actively try to change lanes away from the hazard lane. This is modeled by checking if the vehicle can change lane at every time step.

**EEBL State** The purpose of EEBL is to inform drivers that a vehicle ahead of them may crash or brake suddenly; such warning allows travelers to adjust their headways appropriately and avoid a collision.

We model vehicles that have received the EEBL warning by changing their CFM. The CFM, by changing the desired headway to the stopping distance with the vehicle in front.

Note that many of the above states are not mutually exclusive. For example, a vehicle can simultaneously be in Near Crash state, Danger state and EEBL state, in which case the driver would comply with the specified behavior for all states.

### *Modeling the Traffic Control Server*

When the TCS detects that a crash has occurred, it sends out periodic road hazard warnings to all vehicles in a predefined distance from the detected hazard. The communicating vehicles that receive this information will assume the Danger state or Safe state depending on the lane they are in. We assume that the TCS is responsible for sending EEBL also (this need not be the case, as EEBL can be implemented using offline technologies such as radar). The following parameters determine how the TCS will function.

1. RHW Range (RHWR): This defines a buffer around the road hazard over which vehicles receive a warning.
2. Latency: This represents the average delay between the transmission of a message by TCS and its reception by the vehicle. This delay may be because of the limitations of the communicating technology or the periodicity in sending CAM.
3. Reaction Time: Although this is a parameter that affects vehicle behavior, the TCS takes this into account when sending the EEBL warning. After a vehicle receives any message from TCS, its behavior will change corresponding to the message only after the reaction time has passed since the reception of the message. In all the experiments we conducted, the reaction time was set to 0.9 seconds. This is much lower than the reaction time of 2.5 seconds usually used in traffic design (39), but is expected for a person reacting to an auditory collision warning (40).
4. Speed Change Request Ratio (SCRR): This parameter is the ratio of the speed requested using SCR to the speed limit of the freeway. In our model, although all vehicles will heed to a SCR, the speed they maintain may not be the same as the speed suggested by SCR. If the vehicle had been travelling at a speed 5% more than the speed limit, it will travel at a speed 5% more than the speed suggested by SCR also.

The TCS decides which vehicles to send an EEBL warning based on Equation (2).

$$EEBL_r = RT \times v + SF \times \frac{v^2}{2d} \quad (2)$$

where,  $EEBL_r$  is the distance behind the initial road hazard up to which EEBL will be sent,  $RT$  is the reaction time,  $v$  is speed limit of the road,  $d$  [4.5m/s<sup>2</sup>] is the minimum deceleration capacity of vehicles in the network and  $SF$  [2] is a safety factor. Unlike the RHW which is sent repeatedly to vehicles, EEBL is sent only once when the crash first occurs.  $EEBL_r$  is computed such that all vehicles which can stop before colliding with the crash chain produced by the hazard receives EEBL.

## **EXPERIMENTAL DESIGN**

A five kilometer stretch of a unidirectional two-lane freeway road is simulated. The speed limit of the freeway is set to 70 mi/hr. The traffic flow constituted 5% trucks and 95% cars at a rate of 3000 vehicles per hour. Vehicle type parameters were set to values similar to those suggested by (41). Randomness was introduced in the maximum speed that can be attained by a vehicle, given the speed limit, by setting a bounded normal distribution for the *speedfactor* parameter of each vehicle type. We also defined two vehicle types for cars with slightly different parameters and these were randomly assigned to cars in the simulation.



The road hazard in our simulation is the sudden crash of a vehicle. This is representative of any hazard that is a result of the sudden blockage of a lane, such as the falling of a tree or crossing of animals. To simulate this, a truck meant for crashing is introduced into the road. When this truck covers 4000 m or four fifths of the total length of the road, it is made to come to a sudden halt and its state is changed from Standard to Crash.

After the road hazard appears, the resulting behavior of vehicles in the network is dependent on the user supplied values for several simulation parameters. The parameters that can be varied in our simulation are the four TCS parameters described in the previous section, the percentage of vehicles in the vehicle which are capable of communication (% Com) and traffic volume. The user can also input a random seed which fully determines the traffic pattern that enters the simulation.

We evaluate the safety of a simulated scenario based on the number of crashes that occur and the TIT. The TIT was computed using a TTC threshold value of 2.5 seconds. It was observed that all secondary crashes occur only within the first 10 seconds of the first crash. Therefore, in every simulation, the TIT was computed for a duration of 15 seconds after the first crash. For a crashed vehicle, the TTC used for the calculation of TIT is assumed to be zero. Since there were large variations in the number of crashes that occur because of the randomness in traffic flow, for each set of simulation parameters, which will be henceforth referred to as RHW configuration, we perform 25 simulations with 25 different random seeds. The same 25 random seeds were used for all RHW configurations, which allows evaluating RHW configurations by comparing average performance metrics across all iterations, or individual simulation results.

## NUMERICAL RESULTS

Table 2 presents safety metrics aggregated over 25 experiments for several RHW configurations. The behavior of the selected performance metrics in response to the variation of model parameters follows the expected trends. Comparison between configurations 1, 2, 3 and 4 reveals that market penetration of V2X vehicles has a linear impact on the percentage of crash reductions when RHW is provided. Also, the safety improvement in the case were RHW is provided is much higher than when only EEBL is provided (configuration 4 versus 8). There is a drop in crash reductions from 18.06% to 13.89% as communication latency is increased from 0.1 seconds to 0.3 seconds (configuration 4 versus 5). The reduction is much less between communication latencies of 0.3 seconds and 0.5 seconds (configuration 5 versus 6). This suggests that the effect of message latency on traffic safety follows a polynomial or exponential trend.

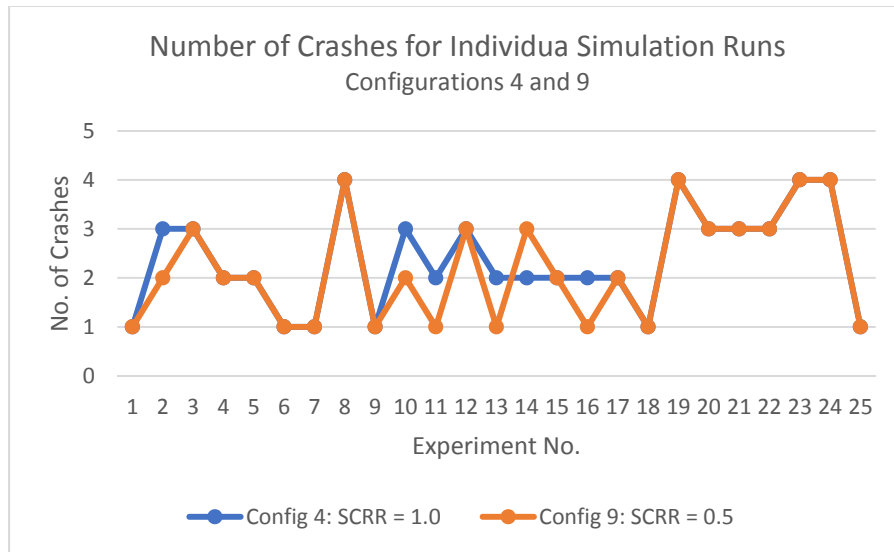
**TABLE 2 Numerical Results**

Config. ID	Parameters				TIT	Mean Crashes	% Crash Reduction
	% Comm	Latency (s)	RHWR (m)	SCRR			
1*	0.00	-	-	-	101.36	2.88	-
2	0.50	0.10	500	1.00	92.62	2.60	9.72%
3	0.75	0.10	500	1.00	88.88	2.48	13.89%
4	1.00	0.10	500	1.00	85.91	2.36	18.06%
5	1.00	0.30	500	1.00	90.08	2.48	13.89%
6	1.00	0.50	500	1.00	90.98	2.52	12.50%
7	0.50	0.10	0	1.00	98.59	2.80	2.78%

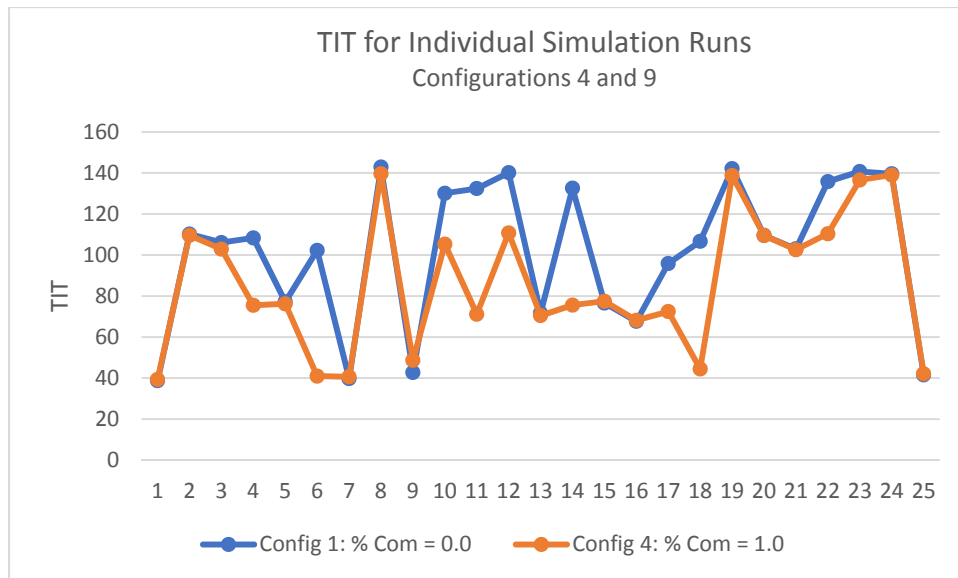
8	1.00	0.10	0	1.00	95.74	2.68	6.94%
9	1.00	0.10	500	0.50	80.81	2.20	23.61%
10	1.00	0.10	500	0.75	83.54	2.28	20.83%
11	1.00	0.10	500	0.85	84.78	2.32	19.44%

\* Base case assuming no communication among vehicles

Even though the same random seeds were used across RHW configurations, the relative safety impact of different configurations differed across some scenarios. For example, a comparison of the relative performance of strategies 9 and 4 shows that in experiment 14 configuration 4 outperforms configuration 9, which contradicts the overall trend (Figure 1). Further examination of the vehicle trajectories reveals that a vehicle which is about to crash is unable to change lanes under configuration 9 because a vehicle in the adjacent lane slows down when receiving the speed change request. A similar situation is observed when comparing configurations 1 and 4. In experiment 9 a vehicle at risk of collision is unable to move to the safer lane because a faster vehicle behind it performs such maneuver earlier, increasing the perceived risk of the lane change. Although the vehicle manages to avoid crashing, its headway with the vehicle in front becomes lower than the *minGap* and enters the Near Crash state, and the lower safety level is captured by the TIT values as illustrated in Figure 2.



**FIGURE 1 Comparison of number of crashes across individual simulations for different values of SCRR.**



**FIGURE 2 Comparison of TIT across individual simulations for different market penetration levels.**

The above scenarios suggest that even though some of the tested RHW configurations perform, on average, better than others, the best configuration for a given scenario depends on the relative positions and speeds of all vehicles in the hazard area. A RHW system which can dynamically select a configuration based on the traffic pattern would perform better than a RHW system with a fixed configuration. The implementation of such an RHW system would be made possible only if the CAM from vehicles are collected and processed in a centralized manner.

## CONCLUSIONS

Technology availability and recent proposals by legislators suggest that a widespread deployment of V2X technology is imminent. Such technologies are expected to deliver substantial safety improvements. However, communication system-specific factors (e.g. communication latency, traffic management strategies) and factors external to the system (e.g. market penetration) may have a significant impact on the ultimate impact of V2X.

In this paper, we propose a microsimulation approach to assess the safety impacts of V2X technologies, and implement it to the study of a Road Hazard Warning system. The methodology explicitly models collisions, RHW, EEBL, and the resulting driver behavior. Additionally, we proposed a novel approach to improve safety by slowing down vehicles on the lane adjacent to the hazard lane, and used our model to study its performance. The proposed methodology is implemented in SUMO, an open source simulation package. A sudden crash on a freeway section is used to test the impact of the model parameters available in our methodology.

Our results suggest that the market penetration of V2X technology has a linear effect on traffic safety, while the effect of communication latency is polynomial or exponential. The combined use of RHW and EEBL significantly outperforms using EEBL alone. Slowing down vehicles in the lane adjacent to the hazard lane improves safety. We also observed that the relative performance of various RHW configurations is case specific. This means, there may not be a single configuration that works best in all scenarios. An adaptive system that dynamically switches among RHW configurations based on the traffic pattern may deliver a more robust performance.

Such a system requires a more centralized V2X system, which may be a relevant finding to inform the ongoing debate on whether to use Direct Short Range Communication (DSRC) or cellular networks as the standard for V2X communication. A centralized V2X system may be more easily implementable using cellular communication technology than DSRC.

The model we have proposed may be enhanced by implementing more advanced and arguably more realistic CFMs. The latter may also lead to a more refined representation of the lateral movement of vehicles during lane changes. This study analyzed an extreme road hazard warning scenario, and the conclusions may not be general to all V2X based safety applications or traffic scenarios.

However, the proposed framework is expected to support further research on the design and implementation of V2X strategies. Having a set of models which can predict the safety impacts of V2X application is critical to support a successful deployment of V2X technologies.

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