Highway Chain Collision Avoidance using Inter-Vehicular Communications♦

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Abstract — Statistics show that about 23% of all vehicle crashes per year are rear-end collisions. In most cases, these accidents are due to the sudden decrease in the speed of the front vehicle and insufficient time for the rear vehicles to decrease their speed. This is usually the consequence of limited view span of the driver and thus failure to react at the proper time. The issue exacerbates in today's high-speed highways in which several fast-moving vehicles move consecutively in one line. In such situations sudden decrease in the speed of one vehicle may result in a chain collision. Due to limited coverage and functionality, current vehicle safety systems like sensor and radars fail to extend the view span of the drivers as desired. Therefore, recently taking advantage of vehicular short communications is attracting lots of interest among car manufactures and academic bodies. In this paper, we use the test-bed of the CVT-Project (Connected Vehicle Technology Project) to investigate the amount of success of inter-vehicle communications (based on IEEE 1609/WAVE standard) in chain collision avoidance. We first implement a multi-hop safety message dissemination algorithm through which approaching vehicles can be informed about sudden speed reductions (e.g., collisions) in a timely manner. In comparison to drivers' perception which is simply based on brake-light of the front vehicle, the above-mentioned message dissemination buys some time for the drivers to react timely. Our results suggest that inter-vehicle communication technology contributes significantly in decreasing the probability of chain collision occurrence. Furthermore the number of vehicles involved in the accident is decreased noticeably. We also show that the severity of accident is reduced significantly by even 50% technology penetration.

Keywords:V2V Communiacation; Penetration Rate; Packet Reception Rate; Chain Collision Avoidance; Road Safety

I. INTRODUCTION

The rapid evolution of wireless data communication technologies witnessed recently creates an opportunity to deploy these technologies in vehicular safety applications. Taking advantage of dedicated short-range communications (DSRC) [1] for vehicles communication is a recent development contributing in collision reduction. DSRC is a proposed variant of standard IEEE 802.11a designed to work in bandwidth of 5.9 GHz, and it is optimized for operating in high speed vehicular environments. Although the DSRC standard is suitable for higher ranges, it has been shown in [2] that DSRC provides an effective communication between two vehicles in a range of 250m. Furthermore, it has been shown in [3] that the chance to successfully receive a DSRC message is approximately 90% over distance of 300m and it drops off significantly with longer distances. Despite of these restrictions, this technology has been used in many different projects over past decades.

DSRC is an enabling technology that allows vehicles to communicate with each other. The vehicle to vehicle (V2V) communications have been considered as the basic scheme to transmit information between vehicles in dangerous situations in which vehicles must stop as soon as possible. There are many safety applications supporting DSRC in vehicular ad-hoc networks (VANETs) such as collision avoidance warning, lane-changing assistant, intersection collision warning, etc. approximately, more than 23% of all vehicle crashes per a year are rear-end collisions. In most cases, these types of accidents are due to the sudden decrease in the speed of the front vehicle and insufficient time for the rear vehicles to decrease their speed. This is usually the consequence of limited view span of the driver and failure to react at the proper time. The issue exacerbates where several vehicles move consecutively in one line of a highway. In such situations sudden decrease in the speed of one vehicle may result in a chain collision.

In the Fig. 1, the effect of inter-vehicle communications on collision avoidance has been shown in a 3-vehciles scenario. In this scenario, all vehicles cruise at an identical speed of 32m/s and have the same deceleration of $4m/s^2$. The time for all drivers to percept and react to their front vehicle brake light are also identical (1.5s). Also, assuming an arbitrary movement direction, first vehicle represents the leading one, second vehicle pursuits the first vehicle, and third vehicle pursuits the second one all in a row. Vehicles equipped with DSRC device brake as soon as they receive Emergency Warning Message (EWM). Each vehicle follows its front vehicle with an inter-vehicle distance of 32m. Assume that, at time zero, first driver see the obstacle and stops the vehicle. In this case, in absence

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of inter-vehicular communication, the second vehicle strikes the first vehicle. Also, after a short while the third vehicle strikes the second one as well. However, by utilizing inter-vehicular communication, vehicles are informed about a potential danger by receiving EWMs which make them brake instantly. As it has been demonstrated in the Fig. 1, the vehicles could successfully prevent the collision.

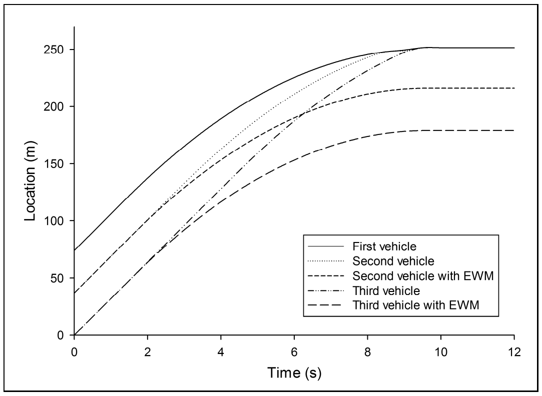

Figure 1. Impact of inter-vehicle communications on collision avoidance

In this paper, we tests viability and usefulness of inter-vehicular communication to avoid chain collisions with real-world data. ACECR[1] – Sharif branch in collaboration with IDRO[2] has initiated a project known as CVT-Project [7] aiming at using vehicular networks to enhance the safety of vehicles in the country's highways. One of the defined applications in the CVT-Project is Collision Warning application wherein safety messages created by crashed vehicle is disseminated within the network and make the vehicles aware about the occurred collision. This application has been tested in real-world scenarios over a V2V communication. Harvested data of this application serves as a data source required in the study of this paper. We show that even when penetration rate of DSRC equipped vehicles goes down (e.g. below 40%), the average probability of chain collision occurrence is lower than unequipped scenarios. The severity of accidents in the chain is also studied for different penetration rates, which is a very important factor in safety assessment of highways.

The remainder of this paper is as follows. In the section II, related works in the field of Chain Collision Avoidance (CCA) and proposed protocols are reviewed. In the section III, the CVT-Project plus collision warning application are described. In the section IV, the numerical formulations used in conducted simulation are explained. The section V presents the simulation results. Finally, this paper is concluded in section VI.

II. Related Works

Over the last decades plenty of studied have been conducted in order to investigate performance of wireless networks. However, many of these studies have been done for infrastructure-based networks. Evidently, inter-vehicular communications carried out in a V2V network are significantly different from those of infrastructure-based networks. On the other hands, some of previous researches are targeted to MANETs. However, the results of these studies cannot be generalized to the inter-vehicular communication because vehicular networks are specified by their rapidly changing topologies due to the fast movement of vehicles and also the nodes' mobility is restricted by predefined roads which are completely deferent from MANETs. Thus, performance evaluation of inter-vehicle communications required more investigations and examinations.

In [8], using received information from surrounding vehicles, probabilities of accident occurrence are calculated by software known as Collision Avoidance Software (CAS). According to their study, in order to describe the time of collision avoidance, the time needed to avoid a collision is divided into three different phases: stop or slow down time, communication time and collision analysis time. Also, they have introduced three timing zones based on aforementioned timing phases: pre-warning time, preferred time to avoid collision (PTAC) and critical time to avoid collision (CTAC). Pre-warning zone is defined as from when two vehicles start communicating through DSRC to PTAC; PTAC is the time when a driver is warned and she/he can brake moderately to avoid a collision; CTAC is the time when a driver is warned and s/he must brake intensely to avoid a collision. However, this timing zone defined between two vehicles can be used for every two vehicles which are in the transmission range of each other in the chain.

Utilizing inter-vehicular communication to prevent chain collision was initially proposed by [4] in which avoidance strategies were modeled and simulated by NS simulator using V2V communication. The authors of [3] have evaluated effects of inter-vehicular communication using protocols named Naïve Broadcast (NB) and Intelligent Broadcast with Implicit Acknowledgement (I-BIA) functioning as relay policies. Reception of alerting message to the rear vehicles is guaranteed in both protocols. Although the previous studies have shown the impact of V2V communication on CCA as well, they have not taken into account (at least not effectively) some factors that affect DSRC system performance and reliability such as IEEE 802.11 backoff counter process, hidden terminals, concurrent transmissions, diffusion ratio of communication systems in a chain, etc.

As it was mentioned earlier, one of the important issues that should be considered as a key factor to evaluate the effects of V2V communication on chain collision mitigation is the percentage of vehicles that equipped with DSRC technology in the chain (Penetration Rate). Reference [9] has conducted a study about penetration rate which, we believe, is a necessary factor to reduce percentage of collision in a chain. Also, they have investigated the effect of inter-vehicular communication on CCA by utilizing different distributions for inter-vehicle spacing in a chain. In there, it has been shown that when penetration rate is approximately greater or equal than 25%, the difference between the various distributions is negligible. However, they have mainly focused on distribution of inter-vehicle spacing wherein effect of network communications have been ignored for sake of simplicity.

[1] Academic Center for Education, Culture and Research
[2] Industrial Development and Renovation Organization of Iran

In addition, there are some studies which have evaluated CCA application exclusively. For example, in [10], the effect of different relaying mechanisms on the general functionality of CCA application has been examined. They have analyzed the effect of two relaying algorithms proposed by [4] compared to no relay policy for different metrics such as percentage of accidents, successful delivery rate, average end-to-end delay, etc. However, optimality of the algorithms and their overheads have not been probed. Similarly, in [11], performance of CCA application has been evaluated using general merit factor of the system. General merit factor is the quantitative improvement of the system which is the number of avoided collisions by utilizing CCA divided by the total number of collided vehicles in the system without CCA. Penetration rate of DSRC devices have not been taken into account.

III. CVT-Project

Currently various operational or pilot scale projects using DSRC in different countries are in progress. In this regard, ACECR-Sharif Branch in cooperation with IDRO has devoted extensive efforts in *Design and Implementation of Vehicular Intelligent Transportation System Project* (name as CVT-Project) [6] aiming at increasing driving safety, traffic management improvement and reducing vehicles fuel consumption in Iran. Having this project implemented, required communicational infrastructure is established in order to receive and transmit safety messages in vehicles moving in urban crossings and suburban roads plus offering other value-added services. This project following the primary researches, producing software applications and conducting experimental and field tests, is in the pilot phase. By conducting the pilot phase, required measures have been taken to prepare road map of application development and also to use the CVT-Project results for operational purposes. Also, By successful accomplishment of defined applications in the pilot, stakeholders' cooperation has been gained in order to prepare a road map for vehicular communication technology development in the country.

For the goal of this paper, we capture the required data from Collision Warning application. In the following we describe the test-bed and the settings of this application.

Multi-hop algorithm responsible for disseminating the collision warning packets is IVG (Inter-Vehicle Geocast) [12]. In IVG, every node within the transmission range of sender puts off its sending as much as a specific time know as *defer time*. This time is inversely proportional to the distance from sender. In this algorithm, each vehicle sets a timer for each receiving packet. If the same packet receives from the same transmission range before timer expiration, the timer is cancelled and the vehicle refrains from re-forwarding the packet. This is due to the fact that if another vehicle re-forwards the packet, it locates behind the vehicle and there is no need to flood the network with redundant packets. Otherwise, the packet is re-broadcast. Let *defertime(x)* denotes value of this timer. The defer time of vehicle (x) receiving a packet from other vehicle(s) is inversely proportional to the distance from them in favour of farthest node to be designate as forwarder [12]. Equation (1) shows the defer time calculated by node (x).

$$defertime(x) = MaxDeferTime \times \frac{R^{\varepsilon} - D_{sx}{}^{\varepsilon}}{R^{\varepsilon}} \qquad (1)$$

Where R is the transmission range and D_{sx} is the distance between nodes (s) and (x). Variable ε controls the value of obtained defer time. We have set ε=2 which produce a uniform distribution over interval [0, *MaxDeferTime*].

Whenever a vehicle crashes, it creates a notification packet and broadcasts it. This vehicle pastes its longitude, latitude and course (direction of movement) using the GPS device connected to the OBU device. There is also a field known as hop which is set to zero by accident-stricken node. This field specifies how many hops a packet has travelled. It also pastes a time stamp when the packet has been created. Every packet has an ID which identifies the accident uniquely. Finally, there are three fields for longitude, latitude and course of forwarder which are filled by intermediate (forwarder) vehicles. Crashed vehicle periodically broadcast the accident packet at interval of 0.5 second. The Fig. 2 shows the pseudo code of the implemented IVG algorithm with some subtle implantation-related modifications.

```
when vehicle (x) receives an accident notification p
 if p is relevant
 then calculates DisSender (x) and DisAccident (x)
   if DisAccident (x) >= 600
     then
        if it is the first packet
        then set BaseHop to p.hop
        endif
        else
            if timer has been set
             then
                if BaseHop=p.hop+1
                then cancel the timer
                endif
              endif
            else
              if BaseHop=p.hop
              then set the timer according to (1)
              endif
             endelse
          endelse
      endif
   endif
when the timer expires it update the packet
       and re-forwards it
```

Figure 2. pseudo code of the implemented IVG algorithm

According to recommendation of traffic experts in the CVT-Project, informing the driver beyond 600 meters distance from accident is not necessary. Thus, we covered this concern in the implementation. Transmission range of an OBU device is 300 meters, and MaxDeferTime is set to 400. A 4-vehcile scenario was tested over 10 km of highway between Tehran and Karaj. The results of the test showed timely informing the derivers and suitable performance of implemented algorithm. The Fig. 3 shows test-bed roadway where is highway between Tehran and Karaj.

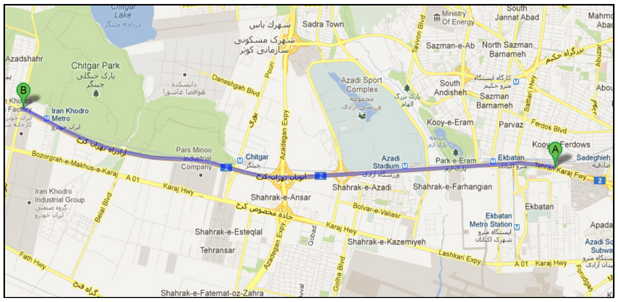

Figure 3. Test-bed roadway (Tehran-Karaj highway)

IV. NUMERICAL STUDY

We divide the time for collision avoidance into three distinct zones as follow: communication time which comprises of the time required for transmitting the message plus broadcast latency [8], collision analysis time which is defined for analyzing and calculating the chance of collision by means of the data describing the movement of vehicles plus the time required for activating the effective way of warning driver, collision avoidance time is defined as time required for the vehicle to reach the complete stop. Speed drop for the vehicle can be divided into the other components such as time required for driver's perception and reaction time and speed deceleration time of the vehicle. In this paper, some parameters related to the driver's behavior also are taken into account as well. These parameters, indicating the driver's perception and reaction time, depend on several issues such as brake action time, age of driver and so on.

In order to measure the distance the vehicle moves during the slowdown time several factors are supposed to be considered. These factors depends on the mechanical features of a vehicle such as motor regulation, braking system, environmental conditions like weather, moisture, temperature, road slope and some human behaviors such as driver perception and reaction time. In order to calculate the aforementioned distance, we should compute the distance that the vehicle moves from the time the alarm message is received until the vehicle stops, represented by D_s. In this paper, we include physical movement formulation in our Monte Carlo simulation. This distance is modeled by [8] and [13] for constant velocity. After including the effect of acceleration to the numerical formulation, the following equations are obtained:

$$D_s = D_b(R_d, rc) + D_{pr}(p, r) + loc \qquad (2)$$

Where D_b denotes the distance passed from braking until the vehicle's stop calculated as shown in (3), R_d represents deceleration rate according to road condition, rc indicates road condition, D_{pr} represents the distance passed during driver's perception and reaction time calculated as demonstrated in (4), p denotes time needed for driver's observation and perception, r indicates driver's reaction time, loc shows vehicle's displacement during the process of sending packet from crashed vehicle and reception in the receiver which is calculated as shown in (5).

$$\begin{aligned} D_b &= \frac{1}{2} R_d t^2 + v_b t \\ v_b &= a_0(p+r) + v_{pr} \\ t &= t - (t_{cp} + p + r) \end{aligned} \qquad (3)$$

In (3), v_b represents velocity of the vehicle at the time of braking, a_0 indicates initial acceleration, v_{pr} shows the vehicle's velocity right at the time of CAS warned the driver, t_{cp} shows the time event that CAS warned the driver and t denotes the current time.

$$\begin{aligned} D_{pr} &= \frac{1}{2} a_0 (p+r)^2 + v_{pr}(p+r) \\ v_{pr} &= a_0 t_{cp} + v_0 \end{aligned} \qquad (4)$$

Equation (3) and (4) represent the distance that a vehicle passes from time event which CAS warned the driver until the driver can successfully stop the vehicle. Essentially, it is the distance passed by the vehicle during collision avoidance phase. Also, location of the vehicle before collision avoidance phase calculated in (5).

$$loc = \frac{1}{2} a_0 t_{cp} + v_0 t_{cp} + l_0 \qquad (5)$$

Where l_0 indicates initial location of the vehicle in the start of simulation.

V. SIMULATION

In this section, performance of CCA is investigated by simulating Monte Carlo developed in visual studio IDE. We assume that vehicles are partially equipped with GPS device and DSRC technology. Also, the vehicles are contemplated as a chain consisting of all vehicles on the highway. In order to provide conditions closer to the real-world situations and to be closer to a random pattern, inter-vehicle spacing is generated using Poisson distribution. Initial velocities have normal distribution. The vehicle accelerations are chosen using a random function. The network parameters such as one-hop and multi-hop delay are set using the data gathered in collision warning application of the CVT-Project through the conducted field tests. Using the real-world data for delay parameters backs up the model in a way that much better imitates the real-world scenarios. The parameters used for modeling the vehicle movements have been shown in Table 1.

TABLE I. SIMULATION SETTINGS

Vehicle Parameters	
Parameter	***Value***
Chain size	50 vehicles
Vehicle velocity	Normal Distribution [80-120] Km/h
Inter-vehicle spacing	Exponential Distribution λ= [10-100] V/Km
Vehicle length	4 m
Deceleration Rate	According to road condition [3.74,8] m/s^2
Road conditions	Dry,Wet
Driver's perception and reaction time	[0.75-1.5] s
Brake response time	0.2 s

Overall Monte Carlo simulation has been conducted for collision probability in conditions wherein chain of unequipped, fully equipped or partially equipped vehicles is tested against potential hazards. Furthermore, the study is manipulated according to metric of *average percentage of accidents*. This metric demonstrates the system improvement by utilizing V2V communication between vehicles.

In the Fig. 4, the impact of penetration rate on average percentage of accidents has been shown for various chain sizes. As depicted in the Fig. 4 the average of accident decreases by growing the number of equipped vehicles. This phenomenon occurs due to the added capabilities stemming from radio devices and their effects on decreasing average reaction time. Results of the Fig. 5 show that how much penetration rate can reduce the percentage of accidents in different inter-vehicle distance. By increasing density, the average inter-vehicle spaces decrease; so based on velocity and acceleration of each vehicle this space is not enough for them to stop the vehicle. Obviously, as mentioned before using inter-vehicle communication can reduce the average stopping distance. In the Fig. 6, the average percentage of accidents for various chain size and density has been exhibited. According to the Fig. 6, only equipped vehicles are influenced by chain size in which the probability of accident raises when the chain size grows. In unequipped cases only in low densities the chain size has impact on percentage of accidents which is due to inter-vehicle space and lower probability of accident available in them.

As was mentioned before, result of the real-world implementation of inter-vehicle communications has been used in our simulation. Receivers of alarm packets re-forward them based on IVG algorithm. IVG has one important application-specific parameter which is called *MaxDeferTime* which determines the maximum tolerable delay by the application. As depicted in the Fig. 7, the effect of this parameter on average percentage of accidents is negligible which is because of the PDF of inter-vehicle spacing. The PDF is considered exponential and based on it the probability of existence of at least one vehicle in the border of communication range of sender is almost 1. This means that the overall transmission delay of alarm packets to reach the end of a chain is below 1 second. In the Fig. 8, the PDF of number of vehicles involved in an accident has been shown for two cases: fully equipped and unequipped chain of vehicles. As demonstrated in the Fig. 8, by utilizing inter-vehicular communication, the number of vehicles involved in a chain accident reduces. This is because of the awareness created by inter-vehicular communication through which more vehicles in a chain can take a proper action even before their front vehicle starts to brake. In [4], the rear vehicle velocity at the time of accident has been considered as a metric for calculating accident severity. In this paper, we consider the relative velocity of involved vehicles in an accident as a metric for analyzing severity. Fig. 9 shows the relative velocity for different densities and penetration rates. As it is evident from the chart of the Fig. 9, as the percentage of number of equipped vehicles increases, the relative velocity of a vehicle at the time of accident decreases. This shows how equipping the vehicles with DSRC can lead to velocity reduction. Note that, higher density results in more relative velocity at accident time.

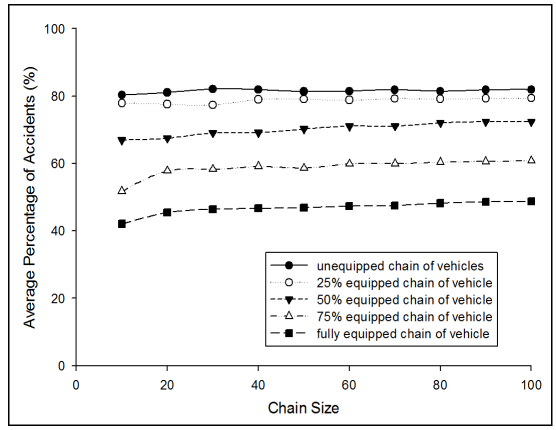

Figure 4. Impact of penetration rate on average percentage of accident for different chain size

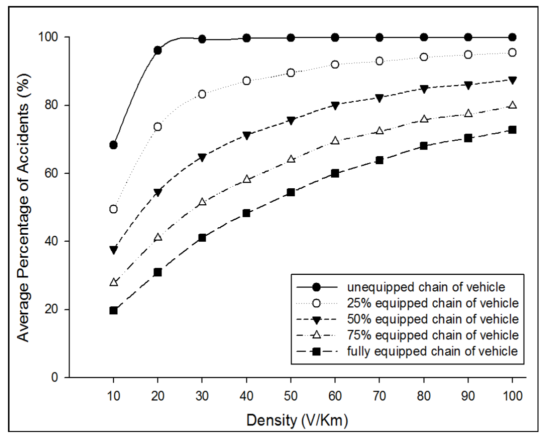

Figure 5. Impact of penetration rate on average percentage of accident for different densities

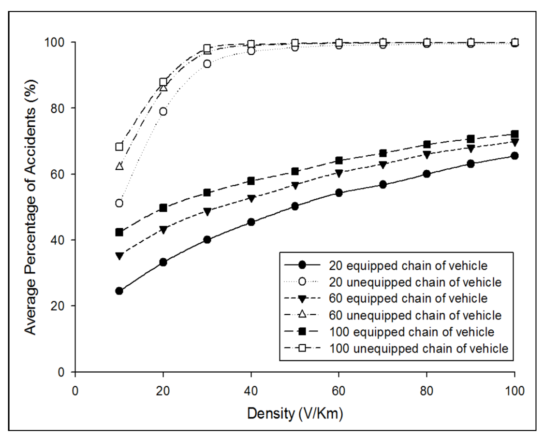

Figure 6. The impact of inter-vehicle communication on average percentage of accidents

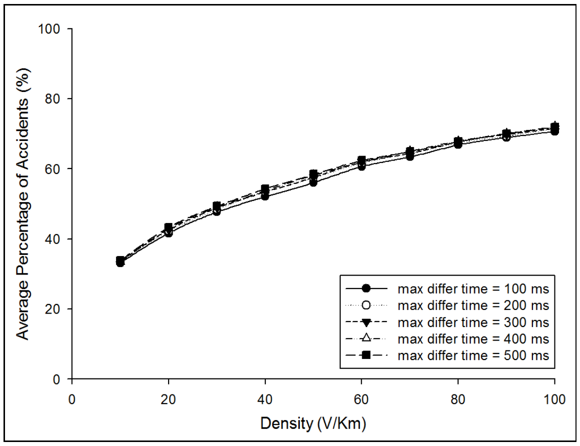

Figure 7. The impact of max differ time on average percentage of accidents

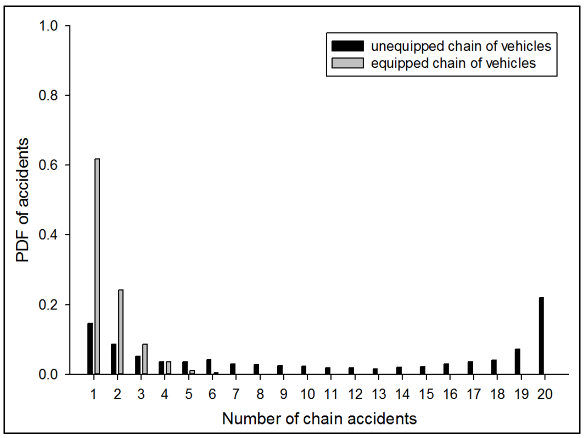

Figure 8. The probability density function of number of vehicles involved in an accident

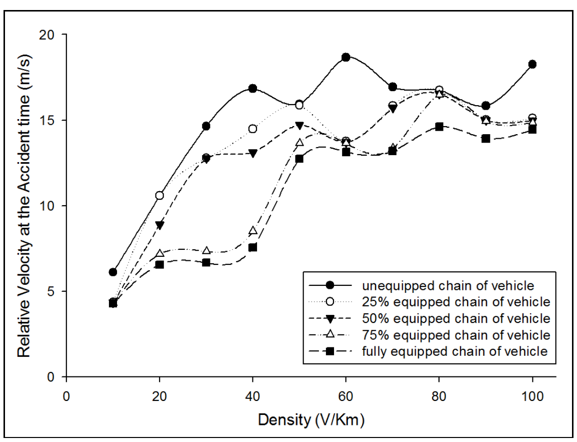

Figure 9. The probability density function of number of vehicles involved in an accident

VI. CONCLUSION

In this paper, by taking advantage of Monte Carlo simulation, we attempted to inspect inter-vehicular factors influencing chain collision in vehicular networks. In order to make the simulator to better imitate real-world behavior of vehicles, we chose density distribution functions in which inter-vehicular events much better are realized. Regarding to this issue, for inter-vehicular distances in simulated collisions, polynomial distribution was used. Also, vehicle velocity, in accordance with the free flow of traffic, was considered as having a normal distribution. In addition, the network parameters such as one-hop and multi-hop delay were set using the data gathered in collision warning application of the CVT-Project [7] through the conducted field tests. We investigated some traffic flow parameters such as inter-vehicular distances and chain size by Monte Carlo simulation. Afterwards, we examined chain collisions for some parameters like vehicle density at the of accident and probability density function of chain collisions. Results of simulation with probability density function of chain collisions showed that the severity of accident can be reduced drastically just even by equipping 50% of the vehicles with inter-vehicular communication technology.

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