Modeling the Impact of inter-vehicle communications on Chain Collision Avoidance

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ABSTRACT

We investigate the impact of utilizing inter-vehicle communication on the chain accident in which several vehicles collide on highways. We aim at studying the effect of vehicles characteristics as well as driver behavior on the probability of accidents. We use a Markov chain for modeling the problem using which we obtain the tail probability of accidents in terms of above-mentioned characteristics. Since in practice the vehicular communications may be popularized gradually, the effect of technology penetration rate is also taken into account in the proposed model. The proposed model also takes advantages of real-world data which is collected from CVT-project test-bed. The result of Monte Carlo simulations reveals that the proposed model has an acceptable accuracy. Using the proposed model, one can evaluate the influence of different road traffic parameters (i.e., vehicle density, velocities, and decelerations) and network parameters (i.e., delay, penetration rate) on the probability of chain collisions.

Keywords: V2V Communication, Stochastic Model, Chain Collision Avoidance

1. INTRODUCTION

Road traffic accidents take many lives each year, exceeding any deadly disease or natural disasters in the world. The World Health Organization (WHO) ranked road traffic injuries as the

11th and 9th leading causes of death in 2002 and 2004 respectively [1]. WHO also predicted that road traffic injuries will be the fifth leading cause of death by 2030 [1]. According to WHO statistics, road traffic death rate has been estimated about 35.8 people per 100,000 populations in 2007 in Iran. Number of casualties incurred in highway accidents has decreased as a result of utilizing several safety devices such as airbags and ABS. However, such innovative devices have no effect in avoiding the occurrence of accidents. With emerging new technologies, different approaches have been proposed to reduce road accidents. The development and application of Dedicated Short-Range Communications (DSRC) for vehicular communication is a recent development that because of in-time exchange of warning messages can help to reduce vehicle accidents significantly.

A DSRC device works in bandwidth of 5.9 GHz which is also based on the IEEE 802.11p standard [2]. Although the DSRC standard is suitable for higher ranges, it has been shown in [3] that DSRC provides an effective communication between two vehicles in a range of 250m in a vehicles following scenario. Furthermore, it has been shown in [4] that the chance to successfully receive a DSRC message is approximately 90% over distance of 300m and drops off significantly with longer distances. Nevertheless, despite of its 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 in a way that advance emergency warning can be given to the drivers to mitigate potential accidents. Ideally the DSRC device could detect potential hazards such as intersection collision or rear-end collision before the driver can perceive them. Approximately more than 23% of all vehicle crashes per year are rear-end collisions [5]. In most cases, these types of accidents are due to 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. This issue becomes more serious where several vehicles move consecutively in a line of a highway. In such situations, sudden decrease in the speed of one vehicle may result in a chain collision.

The advantages of utilizing inter-vehicular communication to prevent chain collision have been discussed in several literatures [6, 7, 8]. In this paper, we intend to model and investigate viability and usefulness of inter-vehicular communication to avoid chain collisions by taking advantage real-world data samples. Markov modeling approach has been used to model the chain collisions. The penetration rate of DSRC technology and its impact on the tail probability of accidents are also considered in the model. The proposed model is also validated by Monte Carlo simulations. Academic Center for Education, Culture and Technology (ACECR) – Sharif branch has initiated and implemented a project in Iran known as CVT (Connected Vehicle Technology) [9]. In this project, several projects have been defined in both V2V (Vehicle-to-Vehicle) and V2I

(Vehicle-to-Infrastructure). Among the V2V application Collision Warning application serves as data source for the work of this project. The multi-hop algorithms used for Collision Warning is IVG algorithm [10] with a little implementation modifications. Indeed, the dissemination delay needs has been captured from test-bed conducted experiments. Also, in order to have conditions closer to real-world situations, network parameters in this paper are chosen according to those of CVT-Project.

The remainder of this paper is as follows. In section 2 related works in the field of Chain Collision Avoidance (CCA) and proposed protocols are reviewed. Some description about the CVT-Project represented in section 3. The proposed model for chain collision and numerical formulations are explained in section 4. Then section 5 presents simulation results and finally. This paper is concluded in section 6.

2. RELATED WORKS

There are many studies that have simulated and tested Vehicular Ad-Hoc Networks (VANETs) worldwide. As stated by [11], by using information received from surrounding vehicles chances of accident occurrence are calculated by software known as Collision Avoidance Software (CAS). According to their study, in order to describe the time for collision avoidance, the time needed to avoid collision are divided into to three distinct phases: stop or slow down time, communication time and collision activation time. Also, they introduced three timing zones based on aforementioned timing phases: pre-warning, 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 s/he can start to brake moderately to avoid a collision; CTAC is the time when a driver is warned and s/he must brake hard to avoid a collision. However, this timing zone defined between two vehicles, will be generalized between every two vehicles which are in the transmission range of each other in the chain.

Utilizing inter-vehicular communication to prevent chain collision was proposed by [6] in which avoidance strategies were simulated by NS simulator via using V2V communication. They have evaluated effects of inter-vehicular communication by taking into account the protocols named Naïve Broadcast (NB) and Intelligent Broadcast with Implicit Acknowledgement (I-BIA). It is worth to note that in both protocols, the first stricken-accident vehicle sends alerting messages. Other vehicles transmit the same messages in conditions where they receive alerting message from their front vehicles. Reception of the alerting message to the rear vehicles is guaranteed in both protocols. They have assumed that all vehicles in a chain are equipped with DSRC device. In a similar work by [7], a different solution has been proposed to avoid such chain collisions based on vehicle clustering concepts. In this method, vehicles are divided into different clusters according to their movement information. They also have designed a risk-aware MAC protocol to increase the responsiveness of their proposed CCA scheme. They have verified the effectiveness of their proposed solution for mitigating collision risks of the vehicles arising from accidental hazards through mathematical analyses and also computer simulations. Although, both of the previous studies have shown the effect of V2V communication on CCA, they suffer from inattention to the 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 and etc in a chain. In [8], a stochastic model has been developed for chain collisions using homogeneous Markov chain. They have analyzed accident probabilities for different conditions. Conducted model of [8] has been validated using a Monte Carlo simulation. However, in their proposed model the penetration rate of DSRC technology has not been taken into account in a way that its effects on average number of collision has been ignored.

As was mentioned earlier, one of the important issues that should be considered as a key factor to evaluate effect of V2V communication on chain collision mitigation is the percentage of vehicles that equipped with DSRC device in the chain (Penetration Rate). A different research in [12], study about the penetration rate which is necessary to drastically reduce percentage of collision in the chain. Also they have analyzed the effect of inter-vehicular communication in CCA by utilizing different distributions for inter-vehicle spacing in the chain and has been shown when penetration rate is approximately greater or equal than 25%, the difference between the different distributions is negligible. However, they mainly focused on distribution of inter-vehicle spacing and effect of network communications ignored due to simplicity.

3. CVT-PROJECT

There Currently various operational or pilot scale projects using inter-vehicular communications technology in different countries are in progress. In this regard, ACECR-Sharif Branch (Academic Center for Education, Culture and Research) in cooperation with IDRO (Industrial Development and Renovation Organization of Iran) has devoted extensive efforts in *Design and Implementation of Vehicular Intelligent Transportation System Project* aiming at increasing driving safety, traffic management improvement and reducing vehicles fuel consumption in Iran. This project following the primary researches, producing software applications and conducting experimental and field tests, has been ready for the pilot phase.

Primary goal of Design and Implementation of Vehicular Intelligent Transportation System Project which has been named as CVT (Connected Vehicle Technology) [6] is taking advantage of DSRC (Dedicated short-range communications) technology in vehicular environments. The defined applications in the project divided into two categories: V2V (Vehicle-to-Vehicle) and

V2I (Vehicle-to-Infrastructure). Collision warning is one of the most important V2V applications and for the goal of this paper we capture our data real-world test of this application.

In the real-world test-bed, 4-vehicle scenario was tested over 10 km of highway between Tehran and Karaj where is shown in Fig 1. According to recommendation of traffic experts in the CVT project, the drivers in 600 meters distance from accident must be informed. Thus, we cover this concern in the program by design and implementing a multi-hop algorithm e.g. transmission range of an OBU device is 300 meters. The collected data from tested scenario was included single-hop and multi-hop end-to-end delays which is used in our both simulation and model results.

4. PROPOSED MODEL

The probability of occurrence of at least *n* collision in a chain can help us to investigate the key factors which have impact in chain accidents. In this regard, a chain of vehicles is considered as shown in Fig. 2 wherein each vehicle in the chain has constant velocity and deceleration.

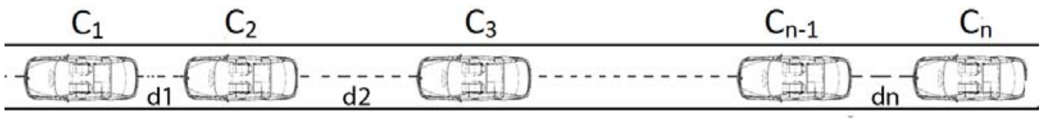

Figure 2. Scenario under consideration

There are N vehicles in a chain and each vehicle C_i has velocity V_i and deceleration rate d_r. Vehicles are exponentially distributed in the chain with parameter *lambda* which refers to the mean value of inter-vehicle distances d_i. Based on our assumptions, vehicles are partially equipped with DSRC devices which affects the driver's perception-reaction (*pr*) time. According to type of the vehicle, the brake time is also shifted by corresponding reaction time. When the first vehicle (chain's head) crashes at time zero, EWMs (Emergency Warning Message) are sent and each vehicle C_i starts to brake at time by receiving EWMs.

4.1. Markov Model

Obviously, the collision probability of each vehicle depends on the state of its preceding vehicle in the chain. Therefore, based on the dynamic properties of vehicles in the chain, it is probable that at least one or more vehicles collide with each other consecutively. To calculate the probability of at least x crashed vehicle in a chain that called tail probability of x accidents and is shown with $P_t(x,n)$ in which n refers to the chain length, we propose a scheme based on the Markov modeling approach. Our Markov model has N states in which each state S_i refers to at least i collided vehicles in the chain and also all transitions start from S_0, Fig. 3 shows an

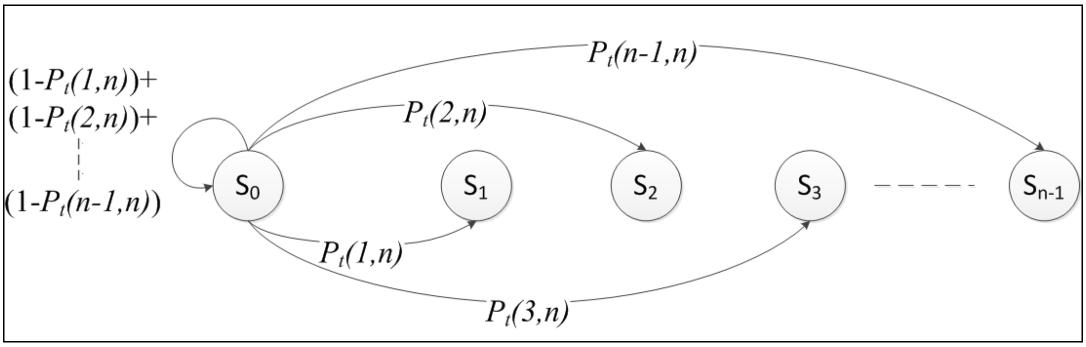

Figure 3. Markov Chain model; S_i represent the state with at least *i* collided vehicle

overview of proposed model. For the sake of clarity, Eq.1 shows how to calculate the tail probability of 1 collided vehicle for a 5-vehicle chain length.

$$\begin{aligned} P_t(1,5) &= P_1 + P_2(1-P_1) + P_3(1-P_2)(1-P_1) \\ &\quad + P_4(1-P_3)(1-P_2)(1-P_1) + P_5(1-P_4)(1-P_3)(1-P_2)(1-P_1) \end{aligned} \qquad (1)$$

Where P_i refers to the collision probability of vehicle C_i in the chain which will be discussed in the following. In fact, in calculation of Eq. 1, only at least number of accidents is important and the position of involved vehicles is ignored. Therefore, in calculating the tail probability of 2 collided vehicles in a 5-vehicle chain length, all possible combinations to choose 2 of 5 vehicles should be considered. Given this assumption, to compute the tail probability of 2 collided vehicles in a chain, the tail probability of 1 collided vehicle should also been taken into account. In this regards, transition between two consecutive states S_i and S_{i+1} where $i >= 1$ is not possible and transition probabilities and state probabilities are same. The transition probabilities for at least 1 to 3 collided vehicles in N vehicles length chain are shown in Eqs. (2, 3, 4) respectively.

$$P_t(1,N) = \sum_{i=1}^{N-1}\left[P_i \times \prod_{j=1}^{i-1}(1-P_j) \right] \qquad (2)$$

$$P_t(2,N) = \sum_{i=1}^{N-2}\left[P_i \times \left(\prod_{j=1}^{i-1}(1-P_j) \right) \times \left(\sum_{z=i+1}^{N-1}\left[P_z \prod_{k=z+1}^{z-1}(1-P_k) \right] \right) \right] \qquad (3)$$

$$P_t(3,N) = \sum_{i=1}^{N-3}\left[P_i \times \left(\prod_{j=1}^{i-1}(1-P_j) \right) \times \left(\sum_{z=i+1}^{N-2}\left[P_z \times \left(\prod_{k=z+1}^{z-1}(1-P_k) \right) \times \left(\sum_{t=z+1}^{N-1}\left[P_t \prod_{r=t+1}^{t-1}(1-P_r) \right] \right) \right] \right) \right] \qquad (4)$$

As shown in Eqs.2, 3 and 4, Eq.2 included in Eq.3 and Eq.3 also included in Eq.4 which mean they have cascading nature. This trend continues and the tail probability of n crashed vehicles is calculated using the tail probability of *n-1* crashed vehicles, and so on. Therefore, we came up with a general recursive function for calculating the tail probability of *nc* collisions in a chain which is shown in Eq. 5.

$$P(a,nc,N)=\begin{cases}\sum_{i=a}^{N-nc}\left[P_i\times\left(\prod_{j=a}^{i-1}(1-P_j)\right)\times P(i+1,nc-1,N)\right], nc\neq 0\\ 1, nc=0\end{cases} \quad (5)$$

Where *a* refers to the first vehicle of the chain and *N* refers to the chain size. As depicted in Eq. 5, in order to calculate the tail probability of *nc* accidents in a chain we should have the tail probability of *nc-1* accidents in a chain first.

4.2. Probability of Collision

The main parameter of Eq. 5 is the probability of collision for a specified vehicle which is shown by P_i. In [8], the authors have modeled the collision probability based on some assumptions like the distribution of inter-vehicle distances, collision types and etc. However, penetration rate of the DSRC technology is not considered and all vehicles are considered equipped. Moreover, the used constant transmissions delay in the proposed model which does not follow the real-world data. The collision probability in our proposed model is taken all these parameters into account. To consider the impact of penetration rate, we adopt the same collision probability as modeled in [8] due to our same assumption about the distribution of inter-vehicle spaces. The difference between equipped and unequipped vehicles modeled as effects of alarm and brake light on *pr* time of vehicle's driver. So, the braking time of equipped vehicles equals the *pr* time which is cause by reception of the warning messages. However, for the unequipped vehicles, it depends on when the brake lights of front vehicle is turned on, so, the *pr* time must be added to the braking time of in-front vehicle. Therefore, to calculate the effect of penetration rate in the collision probability we only need to change the approach of calculating the breaking time for each vehicle represented by δ_i. In the fully equipped vehicles, each vehicle starts to brake after a specified *pr* time which is calculated by sum of human perception and communication delay. We change the brake time of [8] model as like that of Eq. 6.

$$\delta_i=(P_p\times pr_i)+((1-P_p)\times(pr_i+\delta_{i-1})) \quad (6)$$

Where in Eq. 6, P_p refers to the percentage of the technology penetration, δ_{i-1} refers to braking time of the front vehicle C_i and pr_i shows the perception-reaction time of vehicle C_i. In fact, the brake time is calculated as mean of perception-reaction time for the equipped and unequipped cases.

5. SIMULATION

In this section, we describe the methods to validate the proposed model. Monte Carlo simulations have been conducted and the results compare with our solutions to validate the proposed model. The applied values in the simulations have been mentioned in the following.

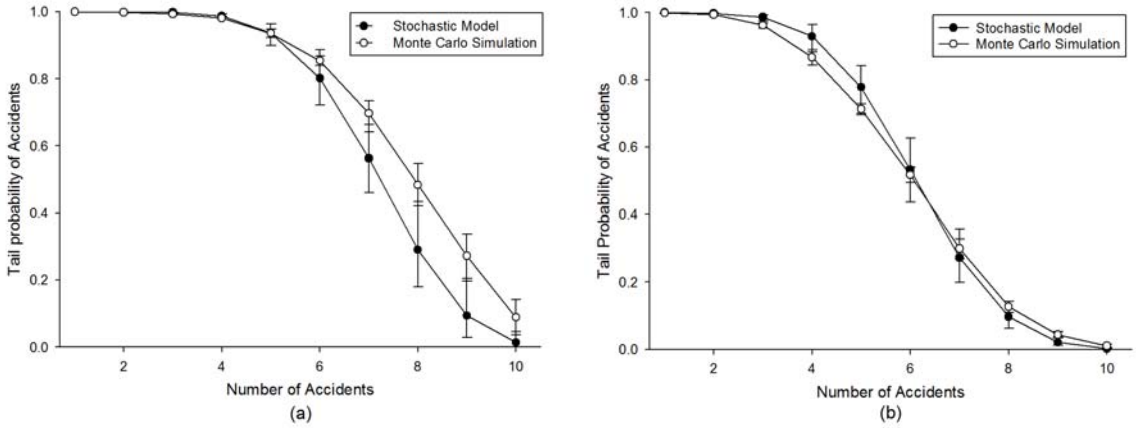

Figure 4. Model validation; (a) 40% equipped vehicle (b) 70% equipped vehicle

The number of vehicles in a tested chain is 10 which are exponentially distributed along the chain. The λ parameter of the exponential distribution is selected from the value between 10 and 100 V/Km. The velocity of vehicles follows normal distribution with mean 100 Km/h and standard deviation 20 Km/h. Each vehicle's length is also considered 4 meters and its deceleration is chosen uniformly from the range 3.74 to 8 m/s2. Driver's perception and reaction time is distributed uniformly between 5 and 1.5 second. As mentioned before, we take advantages of collected data from test-bed applications in CVT-project. Therefore, in order to have more realistic results instead of using random variable, single-hop and multi-hop communication delay is used in both Monte Carlo simulations and proposed model. In Fig. 4, the results of the proposed model are shown and compared with the results of the aforementioned Monte Carlo simulations. The error bars show the 95% confidence interval of the results. As depicted in Fig. 4, both the stochastic model plotted using the Eq. 5 and the simulation results follow the same trend and also their confidence intervals overlap in most case. Thus, the model effectively emulates the real-world behavior of chain collisions. Moreover, the effects of penetration rate are also shown in Fig. 4. The collision probability for 40 veh/km density and penetration 40% is shown in Fig. 4(a) and Fig. 4(b) shows the collision probability in the same density for 70% penetration rate.

In the following, we use our validated model to study the effects of different factors in chain accident. The impact of different penetration rates on tail probability of accidents is shown in Fig. 5. As depicted in Fig. 5, with increasing penetration rate of the DSRC technology, the probability of accidents will not decrease with same degree. However, the probability of accident

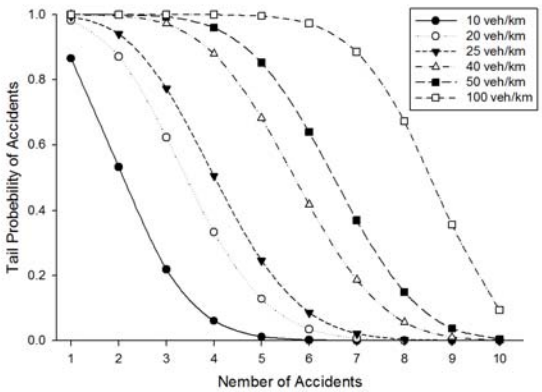

Figure 6. Impact of Density on Tail Probability of Accidents

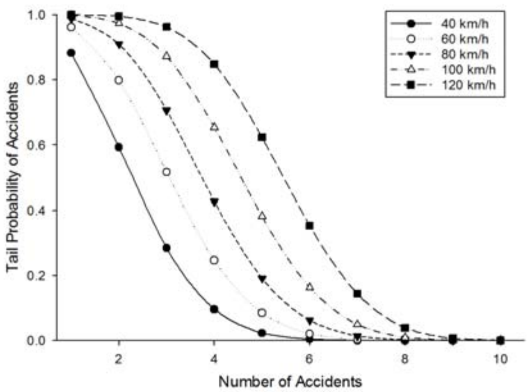

Figure 7. Impact of mean value of velocity on Tail Probability of Accidents

is decreased but the rate of decreasing is not very impressive, especially below 60%. Also in fig 6, the tail probability of accidents for densities with 100% penetration rate is shown. As demonstrated in Fig. 6, when the density rises then the effects of inter-vehicle space is dominated the penetration rate effects. In Fig. 7, we investigate the impact of mean velocity of the involved vehicles in a chain on probability of collision. As depicted in Fig. 7, the mean velocity is one of the most important factors in accidents. The results obtained from 100% penetration rate and 30 V/Km density.

6. CONCLUSION

In this paper, we have proposed and derived a stochastic model aiming at obtaining the tail probability of collisions in a chain of vehicles. Furthermore, the effect of technology penetration rate is also taken into account in the proposed model. Our model sufficiently predicts the trend of exact data obtained from exhaustive Monte Carlo simulations.

This work aims at investigating the success rate of inter-vehicle technology under the framework of CVT project. We found that if the penetration rate excesses 50 percent then, it has impact on preventing the accidents with the high number of vehicles involved. However, as shown in the results section, the dynamic characteristics of the vehicle (e.g. velocity and etc.) have a huge impact on the probability of accidents. Thus, V2V communication parameters which affect communication delay must be chosen by considering dynamic conditions of the chain.

7. ACKNOWLEDGMENT

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