Modeling Vehicle Safety in Vehicular Networks Using Markov Chain Model Based on Cooperative Awareness

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***Abstract*—Main concern of many safety applications in emergency situations is determining the safety of a vehicle respect to the other ones. Consecutive packet losses reduce the overall performance of a safety application which using vehicular networks as its source of awareness. Thus, determining the impact of consecutive packet losses on safety and awareness seems critical. However, speed, acceleration and the other dynamic properties of the vehicles play an important role in determining number of tolerable packet losses and safety assessment process. In this paper, we model the safety and awareness values according to consecutive packet losses using Markov chain model. Our model serves a novel and promising framework for analyzing a vehicle safety based on the current situation of the network and the vehicle dynamical properties. This model gives us the channel situation as well as the vehicle risk value. In the proposed model, the uncertainty of the driver perception about an upcoming event due to the lack of information is also taken into account. Using this model, one can investigate the impact of distance and velocity on safety efficiently.**

Keyword- Vehicular Networks, Safety Modeling; Markov Chain Model; Awareness;

I. INTRODUCTION

Vehicular networks in context of the Intelligent Transportation Systems (ITSs) have attracted plenty of attentions in the recent years. Supporting safety applications is the main driving force behind their development. Safety applications, like other safety control systems and decision making systems, need real time and accurate information in order to perform with high performance. In vehicular networks, messages play an important role in creating mutual awareness between the vehicles and delivering necessary information to the safety applications. The awareness helps the drivers to take appropriate actions (e.g. slow down or change lane) in timely manner [1].

In order to create the situational awareness, each vehicle broadcasts its position, direction, velocity and acceleration following a specified period [2][3] (e.g. each 0.1, 0.5, 1 second). This information is given to the safety application to assess the situation and produce appropriate warnings, alerts and other form of assistance to the drivers. Thus, each message loss causes a minimum degree of error on tracking process, however, Kalman filter can be used as a help to fill these gaps between exact positions and approximated values [4]. Determining how much a host vehicle is safe based on the current situation and successive packet losses embrace every safety application as a challenge.

Many researches like [3][5] use network performance metrics such as packet reception rate (PRR) to analysis the reliability of safety application. However, these metrics may have a weak performance in the situation assessment of current moment. Safety applications should work on most possible conditions so; they should consider the conditions which have the high packet loss probability for short period of time. Handling the errors and uncertainty of delivered data should be considered in situation assessment process. In order to evaluate the current situation based on packet reception rate and dynamic properties more appropriately, we have used the Markov chain modeling aiming at proposing a framework for safety evaluation of the safety applications, i.e. Forward Collision Warning (FCW) and Emergency Brake Warning (EBW).

Awareness Ranges (AR) introduced in this paper refers to the required awareness levels that prevent the accident. Meaning that, they determine whether human inception or the awareness created by communication or even both of them can handle an unsafe situation or not. These regions are application-specific and they change from an application to other one. First of all, we calculate the awareness regions for the host vehicle with respect to its leading vehicle. Then, we compute the safety of host vehicle based on the number of successive packet losses which are tolerable. To the best of our knowledge, this paper is the first study in field of safety modeling and assessment. Our analysis provides new quantitative guidelines and analytical inputs for the design of adaptive V2V safety protocols which should be capable of maintaining high reliability and efficiency in the face of large variations in vehicular traffic and V2V network conditions.

The rest of this paper is organized as follows. In Section 2, we point out the situational awareness importance. In Section

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3, the importance of packet at different situations is evaluated. Our proposed model is described in Section 4. Numerical study and simulation evaluation are presented in Section 5. Finally, we conclude this paper in Section 6.

II. AWARENESS

The driver's perceptions are the primary source which can recognize the events in surrounding environment and react to them properly. In fact, speed of human reaction to a specified event which depends on perception quality and uncertainty of the driver will increase the reaction time [6]. The perception quality itself is affected by many factors include human and environmental ones. Thus, the driver must be notified before in time regarding to human reaction constraints because the received alarms can reduce the driver perception time effectively. Based on the findings in [6][7], the perception-reaction time in presence of alarm is between 0.3 and 0.7 second and otherwise is between 1.1 and 1.8 second.

Creating situational awareness always has been a hard task. Many technologies are invented to realize this matter. Having the awareness, the operator or control system is able to make more accurate decision which can be used as a primary basis for subsequent decision makings [1]. Using sensors is one of the usual ways to create situational awareness. However, ranging sensors, image processing and other related leading technologies try to create situational awareness [8, 9]. Certain properties of wireless networks such as acceptable coverage range, customizable attributes and accuracy of delivered data make them suitable frameworks for the development of safety applications [2]. Information dissemination between communicating vehicles leads to enhancing situational awareness in VANET [3]. This information reflects dynamic properties of the sender vehicle. Note that, this information is sent as DSRC messages.

As was mentioned in the previous section, emergency and beacon are two types of DSRC messages which are triggered differently from each other. Beacon messages mostly are used for tracking purposes and also enhance the overall awareness. On the other hands, emergency message are used to cover unexpected events in a way that create awareness about the events which endanger safety. However, many factors degrade the reliability of safety applications [3] [10]. Cross layer approaches and adaptive rate methods have been proposed to address this issue [11]. In [3] [10] [12], new metrics for performance evaluation of the vehicular network have been introduced. Packet reception rate (PRR), Packet Delivery Rate (PDR) and Effective Range (ER) are three metrics which are mostly used for performance evaluation. However, these metrics cannot be used to evaluate the current situation and do not give us the level of awareness at the moment. In [13], new metrics have been introduced for analyzing the quality of cooperative awareness in presence of beacon messages. In there, message forwarding is used to improve the quality. In [11], new adaptive beaconing method for enhancing the overall awareness has been proposed. Nevertheless, in [11][13] the impact of awareness on situation assessment and decision making in emergency scenarios have not been considered.

III. TOLERANCE OF MESSAGE LOSS

The main objective of emergency messages is informing the vehicles involved in an accident before getting too late. A crashed vehicle starts to send emergency messages. When an emergency message receives at the receiver side, collision probability of current situation is calculated by the safety application. The collision probability is interoperated as alarms and warnings in order to decrease the driver reaction time. But the question is how many messages a vehicle can miss while the collision is avoided?

Based on vehicles relative distance, their velocity acceleration and the type of upcoming event, safety applications can only tolerate a specified latency in order to function effectively (i.e. preventing the rear end accident). Obviously, the tolerable delay is calculated by considering the reaction time of a driver in presence of alarms. Therefore, we convert this tolerable latency to message number aiming at determining how many message losses we can tolerate.
In some situations, no time has been left to message reception can be influential in preventing an accident. However, maybe there is some time for possible maneuvers which is not in the scope of this paper. Anyway, number of tolerable messages can also show us the risk of an event. As was mentioned before, this number depends on event type, so in this paper we consider emergency braking and collision as the target events. Based on this assumption, (1) and (2) are the motion equations for leading (host) vehicle.

$$X_L = -\frac{1}{2}d_L t^2 + v_L t + d \tag{1}$$

$$X_H = \begin{cases} \frac{1}{2}a_H t^2 + v_H t & for\ t \le t + t_r + t_{latency} \\ -\frac{1}{2}d_H t^2 + v_H t + D_r & for\ t > t + t_r + t_{latency} \end{cases} \tag{2}$$

Where in (1), d_L and v_L are deceleration rate and initial velocity respectively for leading vehicle and d is its relative distance from host vehicle. In Equation (2), a_H, v_H and d_H are acceleration, velocity and deceleration of host vehicle and D_r is displacement during $t_r + t_{latency}$ time. Reaction time, t_r , is considered for a case which alarm exists. Maximum latency tolerable by the leading vehicle is shown with $t_{latency}$ which will be calculated using $X_H(t) = X_L(t)$ equation. The number of messages depends on message interval given by λ and calculated by (3):

$$TML = \left\lfloor \frac{t_{latency}}{\lambda} \right\rfloor \tag{3}$$

The impact of messages in some situations is trivial but for awareness it is not the case. So, we introduce threshold n_{th} which is defined as number of sent messages during perception reaction time, and it is calculated by $n_{th} = \lfloor t_r/\lambda \rfloor$. This threshold shows that in which situations the impact of messages on safety is negligible. Fig. 1 depicts the threshold and the number of tolerable messages for different distances and relative velocities. The area under n_{th} surface refers to the messages affecting safety.

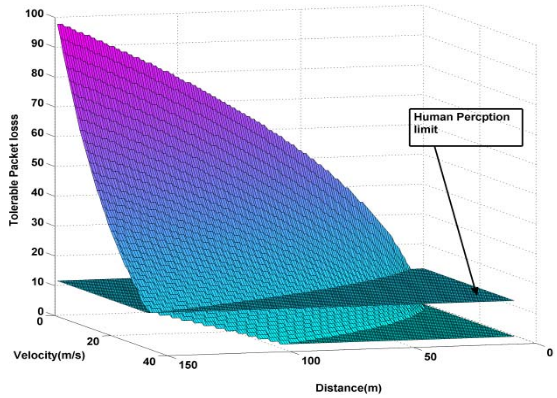

Figure 1. The number of tolerable messages losses with respect to the host vehicle velocity and relative distance to the leading vehicle λ = 0.1.

IV. Modeling Vehicle's Safety

The relative safety of two vehicles in the case which the front vehicle has crashed is modeled by Markov chain. Each message delivery and loss changes the rear vehicle's current state. Our model skips all predictable and inessential situations and just focuses on emergency situations. In this regard, Awareness Ranges (ARs) are introduced which help us to better understand relative situation of host vehicle respect to the other vehicles. ARs also show the urgency of the situation and the required level of awareness needs to avoid a particular accident.

A. Model Assumptions

Our model concept is presented based on the following assumptions in order to show the applications of model more clearly. Two vehicles V_H and V_L are host vehicle and leading vehicle respectively. Both of them are equipped with GPS and DSRC communication system. Vehicles only use communication for informing each other and also no ranging sensor has been used. The safety applications have a precise estimator for the tracking purposes. Built in sensors within a vehicle gives us velocity, acceleration and deceleration. Besides, vehicles are totally aware of situation of each other before the first packet loss. Finally, the rear vehicle is in AR of the front vehicle during first packet loss.

B. Awareness Ranges

Awareness Range (AR) is defined as the distance required to response to a particular event while considering a particular source for awareness. In this paper, two types of awareness ranges are defined respect to their source of awareness: Visual Awareness Range (VAR) and Communication Awareness Range (CoAR). VAR is the distance in which a driver can handle his/her vehicle without getting any alarms provided that an event occurs. The perception-reaction time of a driver for VAR is between 1.1 and 1.8 [6]. Obviously, if the weather condition is not well, then the distance which the drivers can percept an event is very close to the event, and VAR does not exist in practice. The effects of human factors on VAR are out of the scope of this paper. You can find an evaluation about effective parameters (e.g. Human Factors) in [7].

CoAR is the distances in which a driver can handle upcoming events if there is awareness created by communication network. The perception-reaction time of a driver for CoAR is from 0.5 to 0.7 second [6][7]. The host vehicle is allowed to be closer if the level of awareness is high enough. This means that, if the error of computed distances is greater than a specified threshold, the CoAR value is not reliable for decision making. Our model only works for the area between CoAR and VAR. This is due to the fact that we consider the other areas whether fully safe or totally unsafe. As Fig. 2 shows, the area between two vehicles is divided in a way that both zones are distinguished from each other.

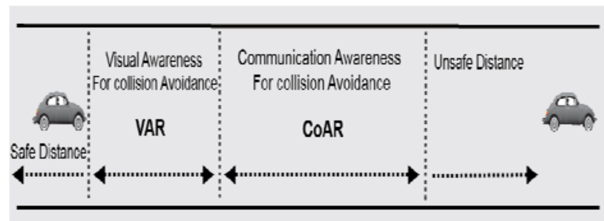

Figure 2. Awareness types, safe and unsafe reigns

These ranges are application-related and for different applications there would be different ranges based on their corresponding events (e.g. lane changing and lane change assistant). In this paper, according to on simplicity and similarity of applications, FCW and EBW have been taken into account. VAR for the both applications are the same. On the other hands, CoAR is different for the both applications so we use CoARB for EBW. ARs calculation requires kinematical information of involved vehicles. This information is captured by in-vehicle sensors and is sent via DSRC protocol. For two vehicles V_L and V_H with initial velocity v_L and v_H respectively, awareness ranges are calculated for worst case scenario as follow:

$$\mathrm{VAR} = \frac{\left(v_H + t_{r_{\mathrm{Visual}}}\right)^2}{2 d_H} \quad (4)$$

$$\mathrm{CoAR} = \frac{\left(v_H + t_{r_{\mathrm{Warning}}}\right)^2}{2 d_H} \quad (5)$$

Where $t_{rvisual}$ and $t_{rwarning}$ are reaction time for visual and warning cases. As shown in (4) and (5) reaction time is important part of the calculation. The effect of relative velocity on awareness ranges is depicted in Fig. 3.

C. Markov Chain Model

The safety of rear vehicle in respect to front vehicle is shown as a Markov chain model. In this model, each state refers to a specific number of successive messages losses. The model has two fixed states: safe and unsafe state. These two states determine initial and final states of proposed model. The start state refers to the safe situation with full awareness and no message losses, and the end state refers to accident situation.

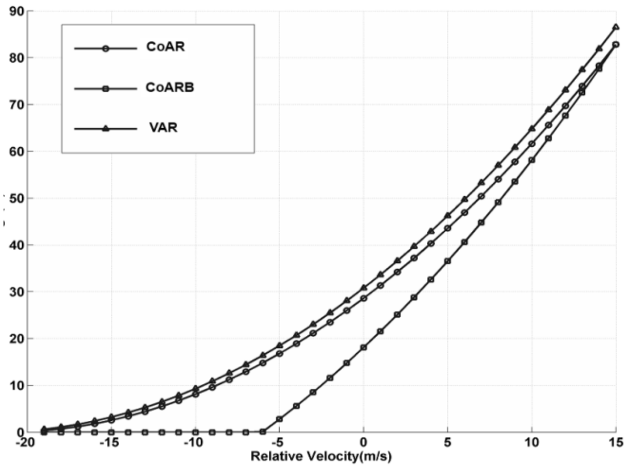

Figure 3. Awareness Ranges with respect to the relative velocity of participating vehicles.

Each middle state refers to the number of successive messages losses and its value is the state identifier. They are displayed by S_i where index i refers to number of successive messages losses. The transition between two consecutive states S_i and $S_i + 1$ happen when a message is lost. Number of middle states is determined by (3) and obviously the smaller λ results in more middle states. The transition probability P used in the model is the PRR. We also include the uncertainty of human perceptions or control system about the accident in the proposed model. Uncertainty for control system is due to the lack of information or data caused by sensors or trackers. However, the driver perceptions are related to human and environmental factors. In order to handle this uncertainty, the probability of accident, P_{acc}, is added to the model. The Markov model for a simple scenario with accident probability P_{acc} and emergency brake probability $P_{brake} = 1 - P_{acc}$ has been depicted in Fig. 4. As shown in Fig. 4, when a vehicle enters area between CoAR and CoARB, by delivery of each messages vehicle will be informed about upcoming incident. The host vehicle will be in the safe state if at least one message is received before entering the danger zone. The red and yellow states show the border of CoARB and CoAR respectively. This process for area between VAR and CoAR is different and if either accident or brake happens by delivery of each message, vehicle state transits to the safe state. During an accident, if the host vehicle is in the CoAR, the approximated risk matches with actual risk and consequently the host vehicle is in unsafe state. In other cases, if no accident happens or leading vehicle brakes, then host vehicle is in safe state provided that it is not in CoARB.

When host vehicle enters unsafe state, there is no way to exit. This is because of our consideration about unsafe state. By increase of the number of middle states, which depends on packet interval, borders between VAR, CoAR and CoARB will be clearer. Possible maneuvers are ignored due to simplicity.

We show the transition matrix of model by five states in (6) wherein states 3 and 4 are the borders of CoAR and CoARB in the uncertain section of the model. Afterwards, P_{acc} appears in their transition probabilities. This sample has been showed for sake of showing the transition matrix not a real-world scenario.

$$TM_{4,4} = \begin{pmatrix} P & 1-P & 0 & 0 & 0 \\ P & 0 & 1-P & 0 & 0 \\ P.(1-P_{acc}) & 0 & 0 & 1-P & P.(P_{acc}) \\ P.(1-P_{acc}) & 0 & 0 & 0 & P.(P_{acc})+1-P \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (6)$$

For the general cases the transition matrix is produced by (7):

$$TM_{n,m} = \begin{cases} P & for\ n = 0\ and\ R_V \geq m \leq R_{CA} \\ 1-P & for\ n+1, m\ and\ m \neq m_{max} \\ P.(P_{acc}) & for\ n = 0\ and\ R_{CA} \leq m < R_{CVB} \\ P.(1-P_{acc}) & for\ R_{CV} \leq m < R_{CVB}\ , m \\ 1 & for\ n_{max} = m_{max} \\ 0 & otherwise \end{cases} \quad (7)$$

Where R_V , R_{CA} and R_{CAB} are VAR, CoAR and CoARB respectively.

D. Safety Assessment

Quantifying the safety of the host vehicle in current situation relative to a particular event is major achievement of our model. For safety assessment of current situation, steady state probabilities should be calculated. Steady state probabilities for the model are calculated using balance equations. Intermediate states probability is $P_k = (1 - P)^k$ where k represents number of successive messages losses. The probabilities of the safe state P_{safe} and unsafe state P_{unsafe} which are calculated using balance equations are shown in (8) and (9) respectively:

$$P_{safe} = 1 - P_{unsafe} \quad (8)$$

$$P_{unsafe} = P_n.(P.(P_{acc}) + 1 - P) + P.(P_{acc})(\textstyle\sum_{i=m+1}^{n} P_i) \quad (9)$$

Where the first part of (8) refers to sum of state probability of the states before VAR and the second part refers to the area between CoAR and CoARB in which P_{acc} has effect on safety of host vehicle. In fact safety of the host vehicle when it is out of VAR is equal to sum of state probabilities of all states between VAR and CoAR so their probabilities must be added to P_{safe} because if the vehicle is informed in one of those states, it is safe. In (9), unsafe state probability only depends on the states between CoAR and CoARB. Now, we can calculate conditional probabilities $P(\text{safety}|\text{acc})$, $P(\text{col}|\text{acc})$, $P(\text{Safety}|\#\ \text{lost}, \text{col})$ and etc which can be used for situation assessment and decision making.

V. NUMERICAL RESULTS AND SIMULATION

In this section, we numerically investigate the probability of safety of host vehicle which is application of our interest. Our numerical results are obtained for three scenarios in which vehicles move straight in the same direction on a highway. Besides, the transmission of a vehicle range is 300 meters. In all scenarios, we have 2 vehicles in the middle lane V_H and V_L which are host vehicle and lead vehicle respectively. Both of these vehicles have the same deceleration i.e. for the dry road case is $8\frac{m}{s^2}$. The driver perception reaction time in presence of the communication awareness is set to 0.5 second and for the

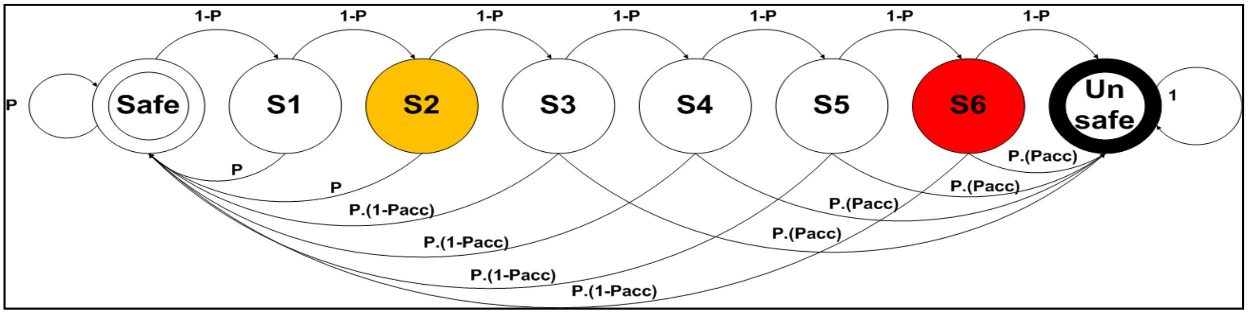

Figure 4. The Proposed Safety Markov Model in Presence of Uncertainty

visual awareness is 1.1 second. In scenario 1, V_L continues its path and no accident occurs, so $P_{acc} = 0$. Scenario 2 is the same as scenario 1 except that, V_L at time $t = 0$ crashes with probability $P_{acc} = 50\%$ and with probability $1 - P_{acc}$ brakes. In scenario 3, V_L crashes at $t = 0$ and driver in VH takes brake after t_r which depends on the type of awareness. We use formula presented in [14] to compute PRR in our numerical studies. We first set up a simulation with two simulators NS-2 and Veins [15] to validate PRR equations in [14]. We use those equations in our numerical results as the probability of successful delivery P. With these three scenarios, we investigate the impact of PRR, packet interval and vehicle's dynamic on the safety.

The safety of the host vehicle based on PRR is depicted in Fig. 5. As depicted in Fig. 5 with increasing the PRR, the safety increases. In scenario 3 this growth totally depends on PRR.

In Fig. 6, impact of message interval on safety of V_H has been depicted. In scenario 3 where the accident happens and VH is locates in the area between VAR and CoAR, safety is always zero because relative distance is not enough to avoid collision. Obviously, when velocity of the host vehicle increases, passed distance per second increases consequently, and just a small time remain for driver reaction. Distance affects the safety both PRR and delivering time window simultaneously. Fig. 7 shows these effects with a surface plot.

VI. Conclusion

In this paper, we modeled the safety of the receiver vehicle with Markov chain model approach. In this model, impact of the network and dynamic parameters were investigated. Besides, uncertainty of the driver perceptions about the upcoming events was considered in terms of P_{acc}. The awareness ranges were introduced to help us understand where exactly vehicular network has most effects on safety. We showed that, not only network performance metrics should be used as the only safety application performance metrics, but vehicles kinematic properties should be taken into accounts as well. Using the proposed model, we managed to compute the safety of the receiver vehicle more realistically. However, in order to have effective performance evaluation of safety applications, new metrics are supposed to be introduced to handle both uncertainty and risk of situations. As a future work, we work on defining these metrics aiming at improving the performance of the safety applications.

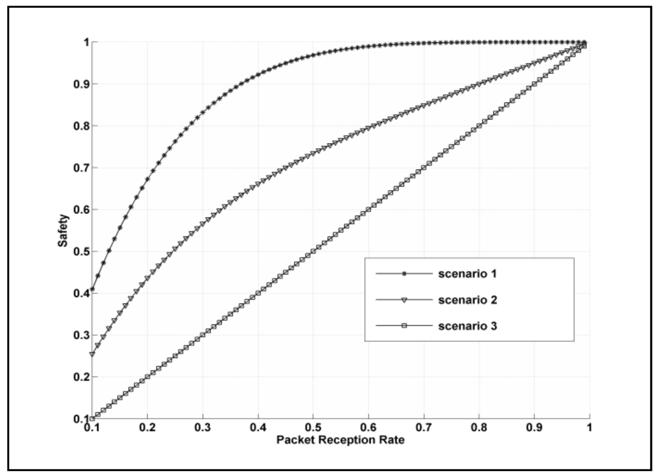

Figure 5. Safety of V_H for different PRR

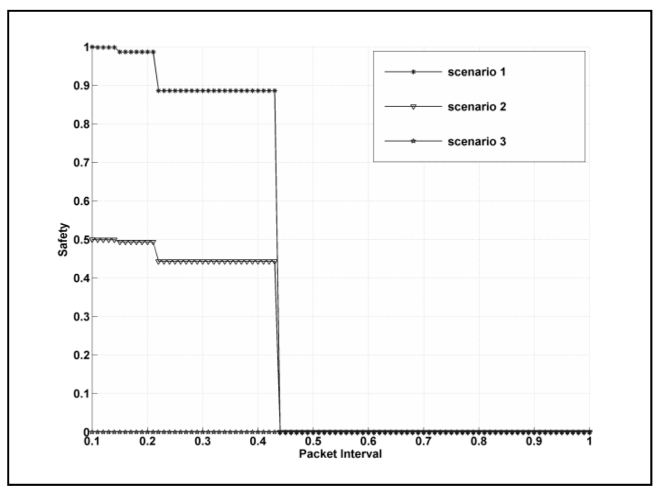

Figure 6. Safety of V_H for different message intervals λ

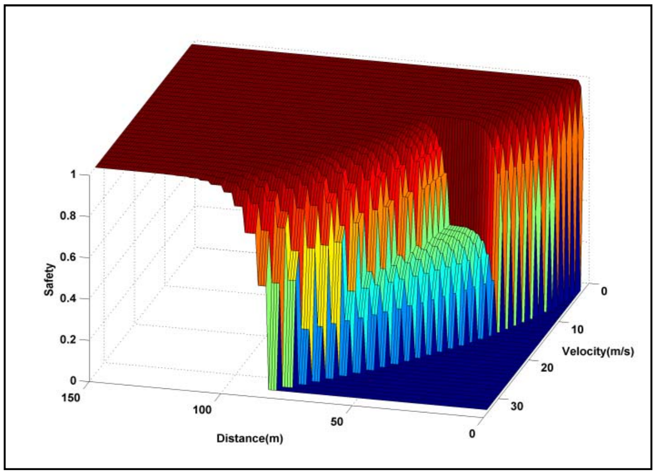

Figure 7. Safety of VH based on its velocity and its relative distance to V_L. $P_{acc} = 50\%$

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