# A Communication Protocol for Vehicle Collision Warning System

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***Abstract*— With the development of wireless technologies such as DSRC [?], vehicles on a highway can communicate with each other to share safety-related information. With the help of these communication services, vehicle collision warning is made possible. This paper proposes a communication protocol for vehicle collision warning system on a highway. With the vehicle status information shared in the ad hoc mobile network consisting of vehicles, the protocol is able to predict potential collision in different emergency scenarios by applying corresponding invariants. A forward collision warning mechanism is designed to propagate the warning in a platoon of vehicles with minimum number of messages while at the same time covering all endangered vehicles. A simulation on SPIN shows the correctness and effectiveness of the protocol.**

## I. INTRODUCTION

Each year, large amount of vehicle crashes happen. For example, statistics provided by NHTSA showed that 5,811,000 vehicle crashes were reported by police across US in 2008 with 37,261 people killed and 2,346,000 people injured [?]. Studies [?] show that if vehicle drivers are provided with early warnings, a large number of crashes can be avoided compared with the number when no warnings are provided. Because of perception limitations of human beings, vehicle drivers do not always have a way to knowing the approaching dangers. These perception limitations include: limited line of sight which is a big problem in curve roads, response delay which means a driver needs 0.7s to 1.5s to react to an emergency event, and wrong judgement in an emergency situation which may make drivers take improper actions.

To make vehicle driving safer and more efficient, the U.S. Department of Transportation's (USDOT) proposed the ITS (Intelligent Transportation System) program which focuses on intelligent vehicles, intelligent infrastructure and an intelligent transportation system [?]. Several systems, such as Cooperative Intersection Collision Avoidance Systems, Integrated Vehicle-Based Safety Systems, have been proposed as an aim to improve transporation safety. So far, a number of collision warning systems have been developed to prevent crashes on highways or in intersections. Collision warning systems integrate several-purposed apparatus such as radar, infrared ray, radio, etc. to get a whole view of the vehicle status, like speed, acceleration, etc. and the driving environments. By taking advantage of different apparatus, collision warning system doesn't suffer from vision limitation, long response delay and other perception limits that hinder drivers, and can react to emergency situations in a quicker and safer way. Based on the collected information, the system will compute whether a vehicle is in potential danger.

In this paper, we propose a protocol for vehicle collision warning systems. It is capable of predicting potential collisions based on the status information shared among vehicles. The information sharing is enabled through the ad hoc mobile networks formed by vehicles. Several invriants are introduced in different scenarios to predict potential collisions and reduce unnecessary warning messages. A forward collision warning mechanism is designed to propagate warning messages in the scenario where a lead vehicle is crashed.

The rest of the paper is organized as: problems confronting our research is described in section 2; section 3 discusses related work that has been done; section 4 contains the detailed description of the proposed protocol; section 5 outlines the simulation and results; the last section shows the conclusion and future work expected.

## II. PROBLEM DESCRIPTION

Vehicle Collision Warning Systems (VCWS) are typically composed of apparatus devices, computing resources and communication network. Apparatus devices, such as radar, infrared ray, speed sensor, GPS devices, etc. are used to get a holistic view of the vehicle status and its surrounding environment, whereas the computing resources enable messages processing and the necessary computation. The most complicated part of VCWS is usually the communication network and the communication protocols operating on it. The communication network for VCWS has some major differences from traditional Wireless Sensor Networks (WSN):

- Mobility. Computing nodes in a VCWS's communication network include vehicles which may move fast, whereas in traditional WSN, the nodes are static or move at lower speeds. Thus, communication protocols for VCWS must take into account the high speed of nodes when considering broadcast frequency and range.
- Topology and routing. Due to unpredictable movement of vehicles, a VCMS's communication network may not have a stable topology. For example, a platoon of vehicles will always have vehicles moving out and new vehicles joining in, and vehicles within the communication range of a roadside infrastructure will change dynamically. Hence, the communication topology is only a

temporary assembly of vehicles and infrastructure nodes and lasts for a short time. Due to this dynamic nature of the nework, it is inefficient and impractical to establish and maintain routes for message propagation.
- Transmission delay. One of the aims of a VCWS is to improve transportation security, e.g. reducing vehicle collisions. If warning messages are delivered to vehicles in a timely manner, they can notify drivers of potential dangers, giving them sufficient time to take actions in advance. This impose more stringent requirements on the transmission delays of safety-critical messages.
- Redundant messages. Since VCMS mainly use broadcasting for message transmission, message redundancy is a significant issue. Concurrent message transmissions by vehicles in a platoon will increase the probability of message corruption and decrease the successful message transmission rate due to competition for the shared channel.

Given these challenges, the communication protocol for VCWS should be designed carefully to adapt to the specific transportation environment. Research on communication protocol focuses on two main areas: message forwarding mechanism and MAC layer. For the MAC layer part, unlike traditional WSN where IEEE 802.11 standard is used, VCWS requires a more adaptive MAC layer because of the differences listed above. To satisfy latency requirements of vehicular security applications like VCWS, Dedicated Short Range Communications (DSRC) has been proposed. DSRC provides high data transfer rates and supports low-latency communication in both roadside to vehicle and vehicle to vehicle communications [?]. The PHY and MAC layers of DSRC are adapted from IEEE 802.11 standard. The differences between them are given in [?]. We won't discuss about MAC layer and DSRC in detail in this paper. However, our paper focuses on the message forwarding mechanism which includes: message generation and message forwarding. There are some questions we need to answer before designing the message forwarding mechanism:

- Emergency detection. How is an emergency situation detected? When to generate warning messages? When to stop propagating messages?
- Broadcast mechanism: passive or active. In passive approach, vehicles periodically broadcast their status such as speed, acceleration, etc. and the receiving vehicle is responsible to detect potential danger itself [?]. In active approach, a vehicle broadcasts its status included in the warning messages only when it acts abnormally.
- Single-hop or multi-hop forwarding. When warning message is generated, how it is forwarded, single-hop or multi-hop, detemines its coverage. The protocol should ensure that relevant vehicles are notified of the potential danger.
- How to reduce redundant messages. What techniques are needed to reduce redundant messages as much as possible?

## III. Related Work

So far, several message forwarding mechanisms have been proposed in application area like highway and intersection. [?], [?], [?], [?], [?], and [?] propose VCWSs on the highway, while the VCWSs in [?], [?], and [?] works on intersection. We will consider applications on the highway and discuss their message forwarding mechanism.

In [?], Biswas *et al.* proposed a direction-aware broadcast forwarding protocol within a platoon of vehicles. Its goal is to propagate the warning messages to all vehicles in the platoon. To do this, rather than using naive broadcast, in which all vehicles periodically broadcast the warning message that they have received from front, I-BIA (Intelligent Broadcast with Implicit Acknowledge) is adopted. I-BIA introduces implicit acknowledge to reduce unnecessary messages. If a forwarding vehicle receives a message from vehicles behind with the same event, it stops broadcasting the warning message. Besides, a vehicle ignores messages if it finds out that the same message has been propagated beyond it. The message propagation stops only when the warning message arrives at the last vehicle of the platoon. Similarly, [?] also introduced implicit acknowledge in its direction-aware message forwarding mechanism. The difference is that, [?] used message timestamp to stop propagation.

ElBatt *et al.* used passive broadcast in the Forwarding Collsion Warning (FCW) application [?]. In FCW, each vehicle periodically broadcast its current status. Which messages a vehicle is interested in depends on the scenarios. In Collision Compuation scenario, a vehicle is interested in only messages from the vehicle direclty in front of it in the same lane (Forward Vehicle, FV); in Lane Change Assistance scenario, a vehicle is interested only in messages from adjacent vehicles (AV) in adjacent lanes; in Electronic Emergency Brake Light scenario, a vehicle is interested only in messages from the vehicle directly in front of FV in the same lane.

Yang *et al.* proposed a communication protocol comprised of three components: message differentiation mechanism, congestion control policies, and emergency warning dissemination methods [?]. Three classes of messages are defined to guarantee that security-related messages have more priority to access the channel: EWMs (Emergency Warning Messages), Forwarded EWMs, and non-time-sensitive messages. When an abnormal vehicle (AV) generates new EWMs, it become *Initial AV* which broadcast EWMs with decreasing rate. When acknowledgement is received from vehicle behind or a specific timer timeouts, the AV becomes *Non-Flagger Vehicle* and stays here if acknowledgement is received within a specific time period. If not, the *Non-Flagger Vehicle* becomes *Flagger AV* and broadcasts EWMs with minimum rate. Besides EWMs, Forwarded EWMs are used by vehicles to forward the EWMs up to a certain range. The message dissemination stops when no new reacting AV appears.

Unlike protocols above, [?] and [?] adopts a mixture of broadcast and multicast and nodes grouping. In [?], an abnormal vehicle first broadcasts the warning message and then uses the TRAck DEtection (TRADE) protocol for message re-transmission. In TRADE, vehicle categorizes neighboring vehicles into different groups using the GPS information and picks a few from each group to retransmit the message. As a supplement to TRADE, Distance Defer Transmission (DDT) protocol is applied to compute the defer time for vehicles before re-transmission. In [**?**], the abnormal vehicle starts sending warning messages only when it senses new neighboring vehicles. Each vehicle keeps track of its neighboring vehicles (set N) and vehicles from which it has received warning messages (set S). When N > S, a vehicle will resend the message after a specific delay to vehicles in N\S.

Although several methods have been used to propagate warning message and reduce redundant messages, some deficiencies of protocols discussed above are identified. First, there is no explicit way to decide whether some message forwarding is necessary. For example, in a platoon of vehicles, vehicles endangered by the abnormal vehicle can be only those subsequent to it in a limited range. So there is no need to forward the message until the last vehicle in the platoon. Second, rather than taking actions after an emergency event happens, we can do better if we can predict potential collision and take actions in advance. Third, most protocols don't differentiate application scenarios. The message forwarding mechanism for different scenarios such as changing lane, sudden acceleration and deceleration, crashed vehicles, etc. can be different. Instead of applying the same mechanism, using different forwarding methods for different scenarios can boost system performance. Fourth, vehicles roles in message forwarding are mostly differentiated by "front" and "behind". We can categorized vehicles into different roles based on their front or behind position, but also their lanes. By doing this, we can reduce redundant messages in the way that vehicles don't randomly forward messages because of their specific role in the forwarding mechanism.

## IV. Vehicle Collision Warning Protocol

The communication protocol proposed in this paper introduces different safety invariants and message forwarding methods for different scenarios. The scenarios considered here include: Sudden Acceleration, Sudden Deceleration, Changing Lanes and Crashed Vehicle. Safety invariants are used to determined whether a vehicle is endangered by the emergency event based on the concept of Shortest Safety Distance.

### A. Shortest Safety Distance

On a highway, there exists a Shortest Safety Distance (SSD) for two successive vheicles in the same lane to avoid collision when the subsequent vehicle brakes as a response to emergency events. In Figure 1, vehicle 1 and vehicle 2 are moving in the same direction in the same lane. When the driver of vehicle 2 steps on the brake as a reaction to some events, if the inter-vehicle distance $d_{12}$ is large enough for vehicle 2 to stop before colliding with vehicle 1, then we call $d_{12}$ a safe distance. And the minimum inter-vehicle distance

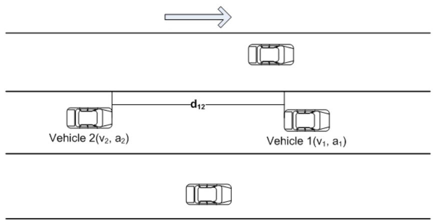

Fig. 1. Shortest Safety Distance

to avoid collision is the Shortest Safety Distance. Apparently, SSD varies with the status of the two successive vehicles.

Assume both vehicles are doing Uniformly Accelerated/Retarded Motion. $v_1$ and $a_1$ are the speed and acceleration of vehicle 1, $v_2$ and $a_2$ are the speed and deceleration of vehicle 2. if vehicle 2 collides with vheicle 1, then we have:

$$v_1 t + \frac{1}{2}a_1 t^2 + d_{12} = v_2 t + \frac{1}{2}a_2 t^2 \quad (1)$$

There may be no solution, one solution or two solutions for t in this equation. If it has no solution, the two vehicles never collide; if it has solutions, one or two, then we pick the *valid* one - "positive and smaller". By comparing the solution, say $t_0$, with the time needed for vehicle 2 to stop, that is $v_2/a_2$, we can decide whether potential collision exists. If $t_0 > v_2/a_2$, then vehicle 2 stops before colliding with vehicle 1; else, they will collide before vehicle 2 stops.

Based on Shortest Safety Distance, we can design safety invariants for different scenarios that happen on a higway to detect potential collision and carry out corresponding actions.

### B. Assumptions

- Environment. The environment we consider here is a straight highway which has 3 lanes. We also assume our system is installed on each vehicle. Broadcast is used for message transmission. We use a unifrom message format containing status information of trigger vehicle and message source vehicle. Trigger vehicle is the vehicle triggers an emergency event (generates and broadcast the first warning messages), whicle message source vehicle is the source vehicle of the current message.
- Sensor devices. Each vehicle is equipped with sensors and GPS devices to detect its status, including speed, acceleration or deceletation, the lane it is in, GPS location etc. Also, we assume that the combination of these devices can detect abnormal actions such as sudden acceleration or deceleration, changing lane, etc. Moreover, we assume each vehicle is available to figure out the positional relationships with other vehicles and its distance to the vehicle immediately in front in the same lane or adjacent lane. Positional relationships include before, immediately before, behind, immediately behind, the same lane and different lanes.
- Average Emergency Deceleration. When emergency event happens, the deceleration of vehicles varies because of different vehicle types, drivers and situations.

Without losing generality, in our invariants, we adopt an average deceleration $a_{ave}$ for vehicles having emergency brakes. This average value can be attained by statistical analysis of vehicles and driver's behavior.

- Response Time. As we know, it takes some time for a human to react to emergency events. We use $t_{res}$ to represent the total time needed for message transmission, invariant computation and driver's reaction delay before he steps on the brake.
- Uniformly Accelerated/Retarded Motion. The moment a vehicle receives the status of another vehicle, the system assumes that the vehicle is doing Uniformly Accelerated/Retarded Motion with the same acceleration or deceleration. The acceleration/deceleration rate can be 0, which means the vehicle is doing Uniform Motion with the same speed.

### C. Changing Lanes Scenario

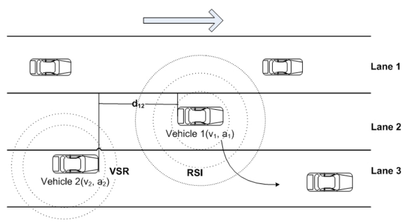


Fig. 2. Changing Lanes Scenario

Figure 2 shows the Changing Lanes Scenario, where Vehicle1 is going to join Lane3 from Lane2. Vehicle1 needs to ensure that SSD exists between itself and Vehicle2 in case that Vehicle2 has to apply emergency brakes with deceleration $a_{ave}$. Assume that Vehicle1 doesn't change speed during lane change process. If Vehicle1 collides with Vehicle2 at some time after it joins Lane3, say t time later from the time it starts changing, then we have:

$$v_1 t + \frac{1}{2}a_1 t^2 + d_{12} = v_2 t_{res} + \frac{1}{2}a_2 t_{res}^2 + v_2 t' + \frac{1}{2}a_{ave} t'^2 \quad (2)$$

Here, t= $t_{res}$+t'. $t_{res}$ is the response time needed before Vehicle2 brakes. During this time, Vehicle2 moves without changing status. After $t_{res}$, Vehicle 2 starts decelerating with $a_{ave}$ until it collides with Vehicle1. If the equation has no valid solution for t', then Vehicle1 and Vehicle2 won't collide; if it has a valid solution $t'_0$, we compare it with the time needed for Vehicle2 to stop, that is $t_2$=($v_2$+$a_2$ $t_{res}$)/$a_{ave}$. If $t'_0 > t_2$, they won't collide and it is safe for Vehicle1 to change lane; otherwise, it's unsafe to change lane. So the safety invariant for this scenario, Lane Change Safety Invariant (LCSI), is either no valid solution for the equation, or $t'_0 > t_2$.

To guarantee safe lane changing, we introduce the following protocol. When a vehicle is going to change lane, a message RSI (Require Status Information) with the vehicle's position information is broadcast. If a vehicle receives RSI from a vehicle immediately before it in the adjacent lane, it replies VSR (Vehicle Status Requested) with its status. If the sender of VSI doesn't receive VSR during a specific time period, or it finds that LCSI is not violated, then it's safe to change lane. Otherwise, the driver will be notified of the potential collsion after changing.

### D. Sudden Acceleration and Deceleration

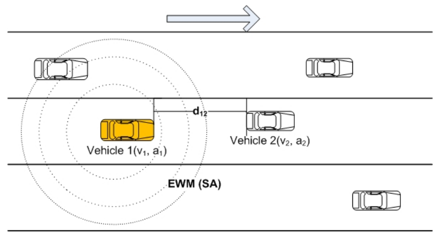


Fig. 3. Sudden Acceleration Scenario

Figure 3 shows the Sudden Acceleration (SA) Scenario. In this scenario, Vehicle1 suddenly accelerates (defined as the acceleration exceeding a threshhold value) and a message EWM-SA (Emergency Warning Message with type SA) containing the vehicle status is broadcast. If the receiving vehicle (Vehicle2 in this case) finds out that the message is from the vehicle immediately behind it in the same lane, it needs to make sure SSD exists between them when the following vehicle has emergency brakes due to some emergency events. Assume Vehicle1 and Vehicle 2 collides when Vehicle 1 brakes with deceleration $a_{ave}$, we have:

$$v_2 t + \frac{1}{2}a_2 t^2 + d_{12} = v_1 t_{res} + \frac{1}{2}a_1 t_{res}^2 + v_1 t' + \frac{1}{2}a_{ave} t'^2 \quad (3)$$

t= $t_{res}$+t'. $t_{res}$ is the response time needed before Vehicle1 brakes. The invariant for SA scenario, SASI (Sudden Acceleration Safety Invariant), is: either the equation has no solution for t', or the valid solution $t'_0 >$ ($v_1$+$a_1$ $t_{res}$)/$a_{ave}$, the time needed for Vehicle1 to stop. If SASI holds, the two vehicles won't collide. Otherwise, potential collision exists and the driver of Vehicle2 will be notified to take actions such as acceleration. However, even if no potential collision exists, the driver can still be reminded of the SA of the subsequent vehicle, but no further actions are needed. Figure 4 shows

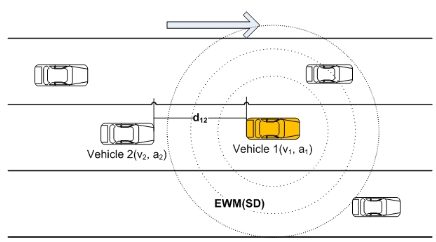


Fig. 4. Sudden Deceleration Scenario

the Sudden Deceleration (SD) Scenario, in which Vehicle1 suddenly decelerates (defined as the deceleration exceeding a threshhold value). Vehicle1 sends out message EWM-SD(Emergency Warning Message with type SD) with its status to notify the vehicle immediately behind it (Vehicle2 in this case) in the same lane. Now it is Vehicle2's job to ensure that SSD exists between itself and Vehicle1 if it has emergency brakes. The equation will be:

$$v_1t+\frac{1}{2}a_1t^2+d_{12}=v_2t_{res}+\frac{1}{2}a_2t_{res}^2+v_2t'+\frac{1}{2}a_{ave}t'^2 \quad (4)$$

t= $t_{res}$+t'. Similarly, the SDSI (Sudden Acceleration Safety Invariant) for SD scenario is: either the equation has no solution for t', or the valid solution$t'_0 > (v_2$+$a_2$ $t_{res})/a_{ave}$. If Vehicle2 finds out SDSI doesn't hold, then both drivers of Vehicle1 and Vehicle2 are notified to take actions to avoid potential collision.

### *E. Crashed Vehicle Scenario*

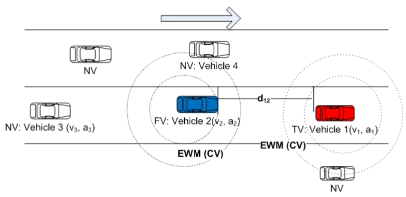


Fig. 5. Crashed Vehicle Scenario - SLF

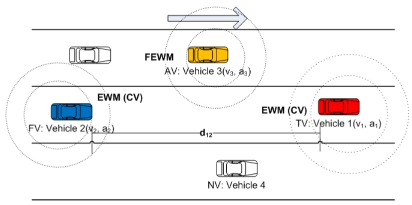


Fig. 6. Crashed Vehicle Scenario - DLF

Figure 5 and 6 show Crashed Vehicle (CV) Scenario where a vehicle has an accident and stops in the central lane of the highway. This crashed vehicle (in red color) broadcasts the first EWM-CV (Emergency Warning Message with type CV). Unlike Sudden Acceleration and Deceleration scenarios, where warning messages are forwarded single-hop, the message forwarding of CV scenario adopts multi-hop forwarding in order to prevent chain accidents. In Figure 5, when Vehicle2 receives EWM-CV from Vehicle1, if it finds out that potential collision exists between itself and Vehicle1, it helps forward EWM-CV to subsequent vehicles. Here, we again introduces invariants to detect potential collisions between vehicles. When Vehicle2 receives EWM-CV from Vehicle1, it should ensure that SSD exists between them when Vehicle2 has emergency brakes. If Vehicle2 collides with Vehicle1 after it applies emergency brakes, we have:

$$v_1t+\frac{1}{2}a_1t^2+d_{12}=v_2t_{res}+\frac{1}{2}a_2t_{res}^2+v_2t'+\frac{1}{2}a_{ave}t'^2 \quad (5)$$

Here, t= $t_{res}$+t' and both $v_1$ and $a_1$ equal to 0 because Vehicle1 stops there. Then the invariant for this scenario, Crashed Vehicle Safety Invariant (CVSI), is: either the equation has no solution for t', or its valid solution, say $t'_0$, is larger than the time needed for Vehicle2 to stop, which is ($v_2$+$a_2t_{res}$)/$a_{ave}$. If CVSI doesn't hold, then potential collision exists and Vehicle2 should forward the message to following vehicles. Vehicle3 will compute CVSI when receiving forwarded EWM-CV to detect potential collision between itself and Vehicle2. The trigger vehicle and message source vehicle of the message EWM-CV broadcast by Vehicle1 are Vehicle1 itself. The trigger vehicle of the forwarded EWM-CV broadcast by Vehicle2 is Vehicle1, while the message source vehicle is Vehicle2, not Vehicle1.

In the message forwarding mechanism, four vehicle roles are define: Trigger Vehicle (TV), Following Vehicle (FV), Adjacent Vehicle (AV) and Normal Vehicle (NV). Trigger Vehicle is the crashed vehicle which generates and broadcasts the first EWM-CV, Following Vehicle is a vehicle in the same lane as the TV and helps forward EWM-CV, Adjacent Vehicle is a vehicle behind the TV in the adjacent lane and helps forward EWM-CV, and Normal Vehicle is a vehicle which doesn't help forward any EWM-CV. Initially, except the TV, eash vehicle is NV at first. A vehicle playes only one role at any time. The role of a vehicle can change based on its status and its. There are two message forwarding methods: Same Lane Forwarding (SLF) and Different Lane Forwarding (DLF). Both methods are direcetion-aware and forward message in the opposite direction of vehicle movement. In SLF, messages are forwarded in the TV's lane without help from vehicles in the adjacent lane. In DLF, help from vehicles in adjacent lanes is needed. SLF is suitable in dense traffic, while DLF is preferred in sparse traffic.

Figure 5 shows SLF. Vehicle 2 and 3 are in the same lane as Vehicle1 and they are in the broadcast range of Vehicle1. Although both Vehicle 2 and 3 receive EWM-CV from Vehicle1, messages are forwarded hop-by-hop based on the CVSI. For example, Vehicle2 forwards CVSI only when the CVSI doesn't hold between itself and Vehicle1. If the CVSI holds, it won't forward EWM-CV because the vehicle can stop before colliding with Vehicle1. Vehicle3 will judge the necessity of forwarding only when it receives forwarded EWM-CV from Vehicle2 based on CVSI between itself and Vehicle2. So we have two layers of notification during message forwarding: whenever EWM-CV is first received from vehicles in the same lane, the driver is notified of the accidents, but whether to forward the messages depends on the invariant CVSI.

In DLF, shown in Figure 6, Vehicle2 is out of the broadcast range of the Vehicle1 and Vehicle3 in the adjacent lane helps forward the warning message. The DLF works like this: when a vehicle (say A) receives EWM-CV from a TV in front in the adjacent lane, it waits for a specific time (enough for the TV to get a response from vehicles behind in the same lane) before sending message OTH (Offer To Help) to the TV. If the TV accepts the help because no response has been received, it broadcasts FEWM (Forwarding Emergency Warning Messages) with A as the target. If A doesn't receive any FEWM targeted at it in a specific time period, it sends NAA (No Available Anymore) to the TV to cancel the help; if it does, then it becomes AV and broadcasts FEWM periodically until it passes by the TV.

When the TV receives warning message, either EWM-CV or FEWM with the same Trigger Vehicle from behind, it stops broadcasting and setups a timer. If no EWM-CV or FEWM are received before the timer timeouts, it resumes broadcasting. For FV and AV, if they receive EWM-CV with the same TV or pass by the TV, they send NAA to the TV and stop forwarding messages and become NV. For a vehicle other than the TV, the priorities of messages are: EWM-CV or FEWM with the TV in the same lane > FEWM with the TV in the adjacent lane. For example, if a AV receives message EWM-CV from a vehicle in the same lane, then it knows that there must be a crashed vehicle in its lane. If the CVSI doesn't hold, then this AV needs to forward the warning message triggered by the TV in the same lane. Thus the AV will stop helping the TV in the adjacent and become a FV for the TV in the same lane. Message merge operation is enabled when several TVs in the same lane exists.

In summary, the communication protocol combines several scenarios on a highway and proposes the concept of Shortest Safety Distance to detect potential collision between vehicles. Different invariants are then given to apply in different scenarios. Especially, the invariant CVSI is used to decide whether message forwarding is necessary in Crashed Vehicle Scenario. In the messge forwarding mechanism of Crashed Vehicle Scenario, two message forwarding methods, Same Lane Forwarding and Different Lane Forwarding, are introduced to deal with different traffic conditions. Four vehicle roles, TV, FV, AV and NV, and role transfromations are designed as a way to reduce redundant messages as much as possible, while at the same time guarantees all endangered vehicles are notified.

## V. Simulation and Results

The proposed protocol is simulated on SPIN [?], a model checker for distributed software systems. The simulation focuses on the correctness of the message forwarding mechanism for Crashed Vehicle Scenario, i.e., Same Lane Forwarding (SLF) and Different Lane Forwarding (DLF). Since the goal is to check the logic correctness of the communication protocol, we don't simulate the underlying MAC layer, but simply construct a broadcast environment for message transmission based on the channel operations provided in SPIN.

The protocol is run in a 3-lane highway environment and a grid map with 3 columns and 8 rows is used to simulate a digital map that we expect GPS devices can provide. Each column represents one lane. A vehicle occupies a grid and so the map can represent at most 24 vehicles. Using this map, vehicles can figure out their neighbors and check positional relationship. The status of a vehicle includes: vehicle id, acceleration/deceleration, speed, GPS coordinates, distance to the vehicle immediately in front of the same lane. Each vehicle has a status queue. The statuses in the queue are pre-designed in fixed interval based on the initial speed and acceleration of the vehicle. The movement of the vehicle is then simulated by updating the vehicle status periodically. Two functions are provided for each vehicle to check position and compute invariants.

Since SPIN doesn't support broadcast operation, we design a Broadcast process based on message channels to simulate the broadcast environment. Whenever a vehicle wants to broadcast a message, it forwards the message to Broadcast Process, who delivers the message to all vehicles. A central Controller process is designed to control the timing of the system because SPIN doesn't define any explicit timing. Actions like broadcast, updating status, etc. can be fired only when the Controller grants them. So when a vehicle wants to send messages or update its status, it sends a request containing the expected time to fire the action. The Controller collects these requests and grant the time to the one with the ealiest expected time by updating the system clock and notifying the corresponding vehicle. The Controller also deal with timeout actions of timers setup by vehicle processes. With this Controller, we carefully simulate vehicle movements on the highway and the communication among them.

Two groups of simulation are carried out to simulate SLF and DLF based on different inputs, which are the status queues of the vehicles. In both, a crashed vehicle in the central lane, two other vehicles in the same lane, and two vehicles in lanes ajacent to the central are designed. The four vehicles are subsequent to the crashed vehicle in the moving direction. Intially, the crashed vehicle acts as TV and the others acts as NVs. In SLF, the four vehicles are in the broadcast range of the TV, while in DLF, only the two vehicles in adjacent lanes are in the broadcast range of the TV and the two vehicles in the same lane as the TV are in the broadcast range of the vehicles in adjacent lanes.

Four properties of the proposed protocol are verified:

First, deadlock. This property is meant to check whether the proposed protocol will cause any deadlock in the communication network formed by the vehicles and the the internal operation of each vehicle. The verification results show that no deadlock is caused and the protocol runs smoothly.

Second, Broadcast Consistency. One of the goals of the protocol is to guarantee that as long as a crashed vehicle exits, endangered vehicles should be notified and Broadcast Consistency is a precondition to this goal. Broadcast Consistency is defined as: whenever there is a crashed vehicle on the highway, there must be warning messages propagated. Here, we assume that broadcast radios work perfectly even when the vehicle is crashed. To make Broadcast Consistency holds, vehicles must cooperate with each other harmoniously, such as when to start or stop sending messages, what to do when timer timeouts, etc. Each vehicle is assigned with a boolean variable. If the vehicle is currently broadcasting, the variable is set to true(1), otherwise, it is false(0). So

Broadcast Consistency holds when the sum of these variables has a value no less than one. The verification results suggest that this property invariantly holds.

Third, Effectiveness. In SLF, the two following vehicles' statuses are designed as: if the warning messages are received within a time period, the vehicles can avoid the collision. Effectiveness is to check whether the vehicle can receives warning message in time and take actions before it is too late to avoid the collision. The verification results suggest that this property holds sometimes, but not invariantly. The inconsistency among these results is mainly cause by different message transmission delay. However, to some extent, the effectiveness of the proposed protocol is proved and the protocol does guarantee that endangered vehicles are warned, although not in time to avoid the danger.

Fourth, message forwarding methods. This property checks whether the message forwarding process in SLF and DLF works in the right way. By enabling vehicles to give output information whenever they forward messages, we can observe the message forwarding process. The results show that the process works as we expected.

From the simulation and verification results, we conclude that the proposed protocol provides continuous warning environment and satisfy the requirments of Vehicle Collision Warning Systems, such as Broadcast Consistency, warning coverage, etc. We expect to compare its capabilities to reduce redundant messages with other existing protocols in our following work.

## VI. Conclusions

This paper proposed a communication protocol for Vehicle Collision Warning Systems on a highway. It combines several emergency scenarios that happen frequently on a highway. The concept of Shortest Safety Distance is presented and several invariants, LCSI, SASI, SDSI and CVSI, are designed based on it to detect potential collisions in different scenarios. The simulation and verification based on SPIN shows that the protocol satisfy the requirements of a collsion warning system. However, the simulation we have done is not complete. Other aspects of the protocol such as redundant messages, stringent message transmission delay, etc. are going to be considered. Besides, future work is needed to design the proper MAC layer for the protocol and a full simulation on NS-2 is expected to give a full view of the proposed protocol.

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