The 10th International Conference on Ambient Systems, Networks and Technologies (ANT)
April 29 – May 2, 2019, Leuven, Belgium

V2V and V2I Communications for Traffic Safety and CO_2 Emission Reduction: A Performance Evaluation

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Abstract

In this paper, we consider a special scenario where connected (V2V and V2I) vehicular technologies are used to alert motorists when they approach a hazardous zone, such as a low visibility area, and recommend proper speeds. We present the principles of the proposed safety driving system and compare the performance of V2V and V2I communications in terms of road safety effectiveness and network communication efficiency. This performance analysis is based on extensive computer simulation experiments by adapting the *iTetris* platform under various scenarios. We also explore, via simulations, whether CHAA systems, based on V2V and V2I communications can potentially contribute towards eco-driving by reducing Carbon Dioxide (CO_2) emissions. Our simulation results showed that our alerting system, based on V2I communication, yields better message reception rate and better safety efficiency compared to a V2V alert system. The results also show that the proposed CHAA system can contribute as well towards reduced CO_2 emissions by promoting speed harmonization.

1. Introduction

For the past years, various Connected Vehicle (CV) technologies have been developed under the umbrella of

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Intelligent Transportation Systems (ITS) to contribute towards safer roads through cooperative situational awareness and hazard avoidance. Two main types of communications have been proposed: Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications

In addition to their safety applications, V2V and V2I communications can potentially contribute towards reducing fuel consumption and emissions [1]. To this regard, various studies have shown that vehicle emissions adversely affect the environment. According to a study conducted by the European Environment Agency (EEA), the transport sector in the European Union contributes by 25% of the total Carbon Dioxide (CO_2) emissions [2]. This concern has prompted renewed interest in the decarbonization of the transport sector. In the context of smart-cities, many researchers are exploring the potential usage of connected vehicles to support eco-driving by reducing CO_2 gas emissions. This is often accomplished through cooperative efforts among vehicles (V2V) and between vehicles and road-side units RSUs (V2I) to harmonize vehicle speeds by maintaining traffic flow and reducing unnecessary stops and starts [3]. In fact, excessive gas emissions are often associated with hard braking, changing cruise speeds and the acceleration/decelerations, especially at signalized intersections [4].

In [5], Outay et.al proposed a safety driving system, based on cooperative hazard awareness and avoidance mechanism that uses V2V communication to alert drivers of the presence of hazardous driving conditions so that they can proactively adjust their speed. In this contribution, we extend this safety driving system to include the adoption of V2I communication to disseminate warning messages to the vehicles that are approaching a hazardous zone. We evaluate and compare the performance of V2V and V2I-based approaches in terms of coverage efficiency and road safety, using the iTETRIS open source simulation platform [6]. We also investigate if, in addition to their primarily safety role, a CHAA system can contribute towards reducing CO_2 emissions. The main contributions of this paper can be summarized as follows:

- Select a suitable modeling tool for simulating the impact of V2V and V2I communications on traffic safety and CO_2 emissions.
- Adapt some of the features of the selected simulation platform to meet the objectives of this research
- Extend our alerting system described in [7] to include V2I communications
- Evaluate the performance of the proposed CHAA system in terms of coverage efficiency, road safety and CO_2 emissions.

The rest of this paper is organized as follows: Section 2 provides a literature review of some earlier contributions related to the applications of V2V and V2I communications for traffic safety and CO_2 emissions reduction. In section 3, we describe our proposed V2V / V2I traffic safety system. Section 4 describes the simulation environment and experimental setup. In section 5, we present and discuss our simulation results. Finally, in section 6, we provide a summary of the main findings of this study and provide some suggestions for future research.

2. Literature review

In this section, we provide a brief summary of key earlier contributions related to the applications of connected (V2V and V2I) vehicle solutions to enhance road safety and reduce CO_2 emissions.

2.1. V2V & V2I communications for enhanced road safety

Sepulcre and Gozalvez [7] performed some field tests to evaluate three V2V cooperative safety applications under real-world conditions: overtaking assistance, lane change assistance and forward collision warning. In [8], the authors presented a performance study of the IEEE 802.11p standard in an urban V2I communication environment. Their simulation results showed that the average packet loss and end-to-end delay increase with vehicle speeds, while end-to-end delay increases with increasing source data rates. Boban and d'Orey [9] conducted some field tests to analyze the efficacy of V2V and V2I cooperative awareness systems in terms of packet delivery ratio, neighborhood awareness ratio, and ratio of neighbors above range. They found that cooperative awareness is strongly dependent on link quality and propagation conditions.

Azimi et al [10] investigated, via simulations, the use of V2V communication among autonomous vehicles to increase throughput and mitigate collision risks at road intersections. Their results showed good improvements in safe throughput across multiple traffic scenarios. Other noteworthy CV safety contribution includes the Red Light and Stop

Sign Violation Warning system [11]. The reader is also referred to [12] for a comprehensive summary of CV safety initiatives undertaken by the U.S. Department of Transportation (DOT).

2.2. V2V & V2I communications for reduced gas emissions

Various studies have explored the interplay between driving behavior and fuel consumption [13-15]. In a nutshell, many driving practices and maneuvers contribute towards increasing fuel consumption and gas emissions: frequent acceleration/deceleration, excessive speeds, slow movements on congested roads and unnecessary idling of the vehicle. As a result, most of the earlier CV eco-driving solutions focused on maintaining uniform speeds among the vehicles to avoid unnecessary accelerations and decelerations [16] or implementing intelligent adaptive traffic signal control systems [17]. These studies have mainly focused on signalized arterials (rather than freeways) where the interplay between traffic signal controls, volatile traffic patterns, and vehicle queuing due to congestion at intersections contribute towards traffic flow interruption and delays [4]. Accordingly, various arterial eco-driving strategies have been proposed to obtain near real-time vehicle positions and traffic signal timings at downstream locations and then implement optimization algorithms to recommend suitable speeds for the timely arrivals of vehicles at green lights [4] or to reroute vehicles to the most ecological route by avoiding congested roads and minimizing travel time and CO_2 emissions [2]. These contributions mainly differ in the choice of the optimization algorithm which is the heart of the speed recommender and eco-routing systems.

Chen et al [4] observed that eco-driving strategies on freeways tend to be straightforward given the continuous and uninterrupted nature of traffic flow. However, we argue that this is not always the case as the freeway might exhibits danger zones due for instance to low visibility driving conditions or road construction work zones.

Our work departs from the aforementioned contributions in two main aspects. First, we do not focus on eco-driving strategies for signalized arterials. Second, we do not intend to introduce new speed planning algorithms or additional network overhead to favor eco-friendly driving. Instead, we wanted to explore if our proposed V2V / V2I cooperative mechanisms, originally developed for road safety, could be leveraged to reduce CO_2 emissions.

In this paper, we elaborate on the previous cooperative hazard awareness and avoidance study [7] by (1) including V2I communication performance analysis (apart from V2V), (2) providing additional V2V safety results and (3) investigating the impact of our CHAA systems on CO_2 emissions.

3. Proposed CV traffic safety system

Our approach is based on an alert system that can proactively warn vehicles before they enter a hazardous zone so that they can slow down, maintain safer distances and avoid cascaded collisions. The hazardous zone detection and alert dissemination can be accomplished by a Road Side Unit (RSU) or by a sensor-equipped vehicle with the On Board Equipment (OBE). The dissemination of V2V alert messages was based on DSRC/IEEE 802.11p (for the MAC layer) and on geographic routing (for the network layer). Each vehicle is equipped with a GPS receiver and an IEEE 802.11p wireless communication module. For our use cases, and without any loss of generality, the hazardous zone is defined as a low-visibility area created by some foggy weather conditions.

3.1. V2V alert system description

When a vehicle encounters a hazardous zone (e.g. through its onboard fog-detection sensor), it automatically brakes, and geo-broadcasts a message within its broadcast range, at regular time-intervals. Upon receiving the alert message, any vehicle in the broadcast zone processes the message and relays it to its neighbors. All vehicles in the alert zone, that are heading towards the hazardous zone, will slowdown and will retransmit the alert message to neighbors. Those that are not heading towards the hazard zone will simply relay the alert message.

An alert message consists of three fields: "*alert type*" (e.g. FOG), "*alert recommendation*" (REDUCED SPEED, e.g. 40Km/h) and "*vehicle position*" (as reported by the GPS device). As shown in figure 1, the alert zone defines the effective coverage zone of the alert message on both directions of the road.
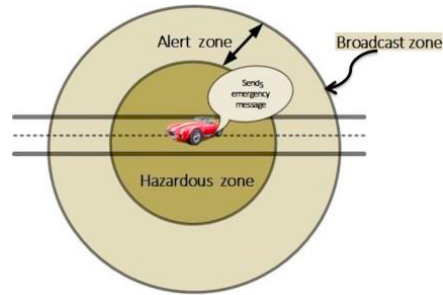
Fig.1. V2V alert zones

3.2. V2I Alert system description

When the RSUs installed along the highway detect (or are informed of) a hazard situation, those located close to the hazard zone (i.e. within the broadcast zone) will broadcast an alert message to all vehicles within their coverage range at regular time-intervals. Each vehicle in the alert zone that receives the alert message processes the message and slows down. The alert message consists of three fields: "*alert type*" (e.g. FOG), "*alert recommendation*" (REDUCED SPEED, e.g. 40Km/h) and "*RSU position*". No V2V communication takes place under this scenario.

4. Simulation environment and experimental setup

To evaluate the performance of our proposed approach, we consider the scenario shown in figure 2. We consider a 10Km highway road segment (two lanes in each direction) with a 1Km hazardous zone in the middle and an alert zone of 2Km in each direction. The road is covered by RSUs that are 4Km apart from each other. We set the speed limit on the highway to 33 m/sec and we consider three types of vehicles:

- Standard passenger cars (70%) with a maximum speed limit of 40 m/sec
- Slow cars (20%) with a maximum speed limit of 30 m/sec
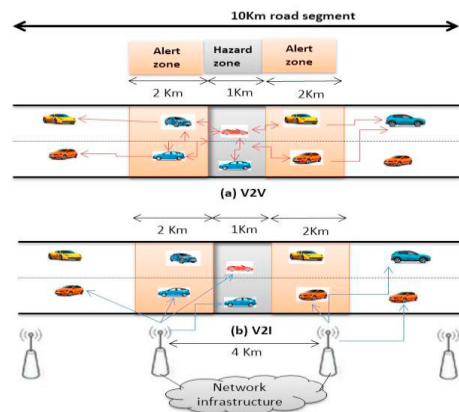- Trucks (10%) with a maximum speed limit of 25 m/sec

Fig.2. Simulated scenario a) V2V mode b) V2I mode

4.1. Simulation setup, settings and scenarios

We have developed our cooperative traffic safety applications for iTetris in C++. The source code is available in [18]. We have used SUMO's "set speed" and "slow down" behaviors to simulate vehicle braking to the maximum deceleration (according to the vehicle type) and vehicle slowdown (deceleration within 5 seconds), respectively. In

our V2V application, the vehicle will brake abruptly and send an alert if it detects a hazard zone without a prior alert. Alternatively, the vehicle will slow down within 5 seconds when it receives an alert message.

We have identified several bugs related to the geo-broadcast routing feature in iTETRIS and consequently we provided a patch with the source code of our application [19].

4.1.1. Simulation scenarios

We have considered four scenarios:

- *Baseline scenario*: We launch the simulation with SUMO alone, without NS-3 or iCS. In this case, the vehicles do not react to the danger situations. This allows us to obtain baseline statistics related to the dynamics of the vehicles such as Time-to-Collision (TTC), journey durations and CO_2 emissions.
- *Deactivated alert scenario*: When a vehicle enters the hazard zone (low-visibility foggy area in our case), it will brake but will not send any alert messages.
- *V2V cooperative alert scenario*: When a vehicle enters the hazard zone, shown in figure 1, it will brake abruptly to reach a reduced speed of 20m/sec and then geo-broadcasts an alert message at regular intervals of 5 sec. The alert message is propagated in the opposite direction of traffic.
- *V2I alert scenario*: When a vehicle receives an alert message from one of the RSUs, it will brake abruptly to reach the reduced speed of 20m/sec, but it will not relay the alert message to other vehicles. The RSU will broadcast the alert message to all vehicles within its 2Km range and at regular intervals of 1 sec.

4.1.2. Simulation parameters

The simulation parameters are illustrated in table 1. We run the simulations for 500 sec, during which vehicles arrive at the highway on both directions during the first 100 seconds with different densities: 500, 1000, 1500, 2500 and 4500 vehicles/hour. We have run each scenario 30 times by varying the seed values in SUMO and then averaged the performance results.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Simulation area	10Km with 2xe lanes	Reduced speed	20 m/sec
Simulation time	500 seconds	Vehicle densities	500, 1000, 2500, and 4500 vehicles/hour
Alert zone	2 KM	Propagation loss	46.5777 dB
fog alert interval	5 sec	Tx power	20dBm
Hazardous zone radius	0.5 KM	Tx/ Rx gain	7.0 dBi
Slowdown duration	5 sec	RSU positions	3 Km and 7 Km
Initial vehicle speed	40, 30, 25 m/sec (standard car, slow car, truck)	Emission class	P_7_7 class (passenger cars) HDV_3_3 class (trucks)

4.2. Performance metrics

We have considered four performance metrics related to coverage efficiency, safety and CO_2 emissions:

- *Reception rate*: it is a measure of coverage efficiency and communications reliability, defined as the ratio of the number of vehicles that successfully received an alert before entering the hazardous zone to the number of total vehicles that entered the hazardous zone (whether alerted before or not).
- *Road safety*: From SUMO's traces, we derived values for the TTC. When the TTC is lower than a threshold value $\varepsilon=3$ sec, we consider that there is a risk of collision. Accordingly, we derived two metrics:
  - *Cumulative TTC < 3 sec*: This is the time (in seconds) spent by all vehicles in a risky unsecured situation. The lower this cumulative TTC period, the safer are the vehicles.
  - *Fraction of time with TTC < 3 sec*: This is the fraction of time spent by all vehicles in a risky unsecured situation. It is computed by normalizing the above cumulative TTC period by the total simulation time. The lower this value, the safer is the road.
- *CO_2 emissions*: This is the amount of CO_2 (in grams) emitted as per the HBEFA reference model.

5. Simulation results and discussions

5.1. Coverage efficiency

Figure 3 shows the packet reception rate corresponding to our V2V and V2I safety applications under different vehicle density scenarios.
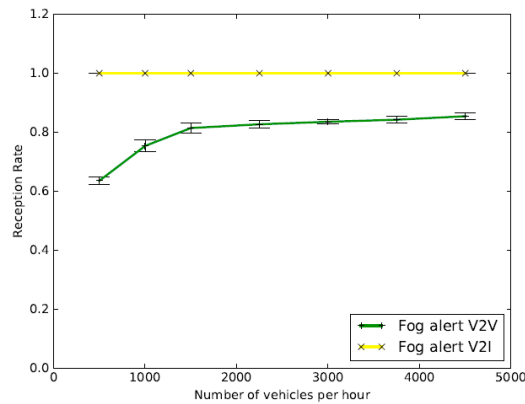

Fig.3. Alert Message reception rate versus traffic density

As may be seen, the V2V reception rate increases steadily from 60% towards 80%. This can be explained by the fact that at low traffic densities, the network is not connected enough to communicate the alert message to all the vehicles in the vicinity, whereas at high densities, the network gets more connected to disseminate the warning message to a larger number of vehicles. We also observe that the V2I alert system achieves better reception rates compared to the V2V case. This can be explained by the fact that in the V2I case, the RSU transmits the warning message up to one hop vehicle within its range. Vehicular mobility is also a lesser concern in the V2I case as the RSUs constitute fixed nodes.

5.2. Traffic safety

Figure 4 shows that our proposed V2V cooperative collision warning application introduces slight safety enhancements as reflected by lower TTC values. The safety contribution is more significant in the V2I early warning scenario for densities starting from 1500 vehicles/hour. This is normal as the V2I reception rate is higher than that of V2V, which results in higher awareness of the hazardous zone and less collisions. We also observe that the baseline scenario reflects similar safety performance to that of the "without Alert" scenario across various vehicular densities. This suggests that in the latter case, the safety gain is attributed to general spontaneous slowdown rather than the slowdown that precedes the arrival to the hazardous zone.
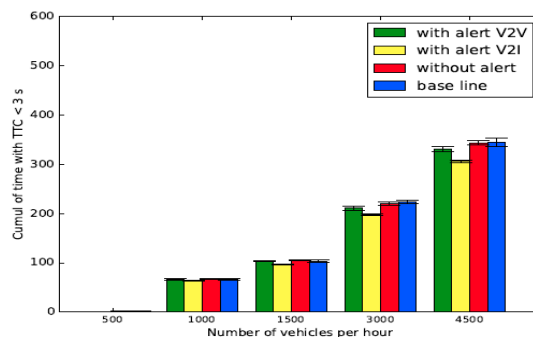

Fig. 4. Cumulative TTC < 3s for different densities

Road safety results are better seen when we look at the normalized TTC results shown in figure 5. The V2I early warning approach provides the best safety results, which is followed by the V2V cooperative collision approach, the "Without Alert" case and finally the "Baseline" scenario. These results confirm that the proposed CV safety applications based on V2I and V2V communications contribute towards enhancing drivers' situational awareness about potential hazards through the dissemination of early warning messages so that vehicles can slowdown and avoid cascaded collisions.
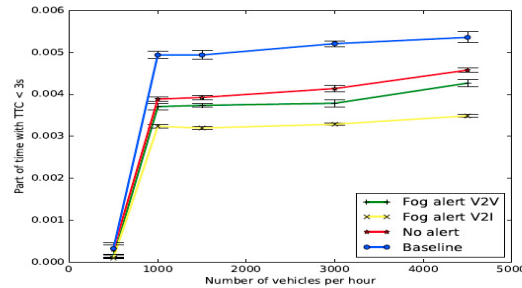

Fig.5. Fraction of time with TTC < 3s for different densities.

5.3. CO2 emissions

Figure 6 illustrates the impact of the proposed CV safety applications on CO_2 emissions (in grams) for three scenarios: standard vehicles, slow vehicles, and trucks.

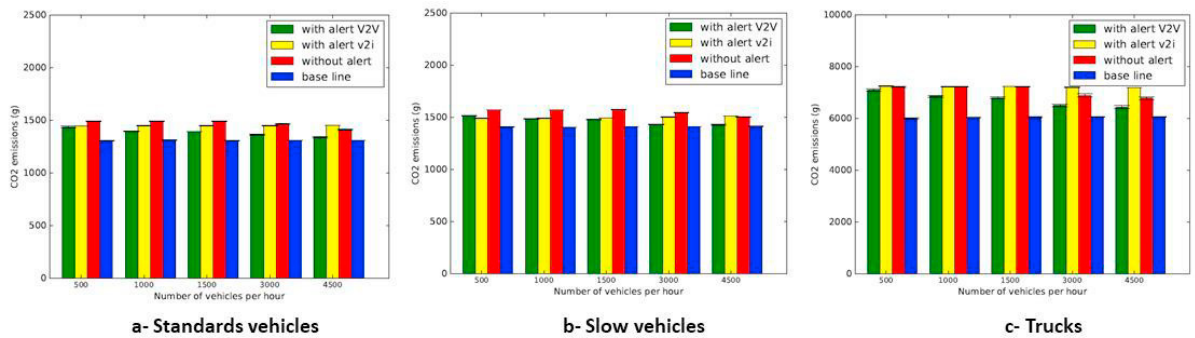a- Standards vehicles b- Slow vehicles c- Trucks

Fig.6. CO_2 emissions results

Several observations can be made regarding these results. First, we note that the V2V and V2I alert systems contribute towards reducing CO_2 emissions by around 5% for vehicular densities up to 3000 vehicles/hour for the three types of vehicles. This can be explained by the fact that our two CV safety applications favor speed harmonization when vehicles enter a hazardous zone, which contributes towards reducing unnecessary accelerations/decelerations and sudden stops, thus reducing fuel emissions. We also note that the V2V alert system yields better performance in terms of CO_2 emissions compared to the V2I alert system, across all types of vehicles. For the baseline scenario where there is no danger, the amount of CO_2 emitted is the lowest since vehicles are moving without any danger situation and without slowing down or braking.

6. Conclusion

In this contribution, we presented two CV traffic safety applications based on V2V and V2I communications to disseminate alerts when vehicles approach a hazardous zone. We demonstrated the efficacy of the proposed approach via extensive simulation results that showed that the proposed V2V/V2I alert systems contribute towards reducing the risk of collisions. Although the primary objective of our proposed connected vehicle systems was to enhance road

safety through a cooperative hazard awareness and avoidance mechanism, we showed that the system contributes as well to reducing CO_2 emissions due to smoother speed variations. We are currently exploring the usage of a hybrid V2X alert system that combines both V2V and V2I communications. We also plan to test the proposed approach in the field in the context of a real-world experimental study.

Acknowledgments

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