A Study of Safety Applications in Vehicular Networks

Christophe J. Merlin and Wendi B. Heinzelman
Department of Electrical and Computer Engineering,
University of Rochester, Rochester, NY

Abstract—**Car crashes claim the lives of more than 100,000 people every year in the US alone. Forming ad-hoc networks among vehicles traveling on a highway can be very helpful to avoid such deadly accidents and pile-ups. In this paper, we define two classes of applications for such networks: safety-related applications and internet connectivity. We also propose a new model for highway traffic and events that can be used to automatically generate movement files readable by the NS-2.28 simulator. Through simulations of such vehicular networks using flooding and IEEE 802.11 for safety-related applications, we attempt to answer the fundamental question: are highway vehicular networks feasible and efficient for safety purposes?**

***Index Terms*—Vehicular Networks, Inter-Vehicle Communication (IVC), IEEE 802.11, Ad-Hoc Networks, Traffic Generator, Mobility Model.**

I. Introduction

In 2002, car accidents were the leading cause of mortality for people between the ages of 15 and 44 in the US [10]. A traveler is more likely to die in a car than on an airplane (exception made of small aircrafts), riding a train, or in a terrorist attack. Although generally less prone to creating accidents, highways see scores of deaths every day because high speeds tragically increase impacts. Vehicle traffic ranges from scarce to gridlock on highways and in inner cities. Providing car drivers with notifications that traffic has stopped ahead would greatly improve the chances of avoiding deadly pile-ups, especially in foggy conditions. Alerting drivers to other conditions, such as slippery roads, and providing emergency services call-up would also improve safety.

The goal of this paper is to study the feasibility and efficiency of ad-hoc networks established between automotive vehicles on a highway using a combination of light protocols. Previous work attempted to reproduce [5] or simulate [6] vehicular networks using UMTS Terrestrial Radio Access Time Division Duplex (UTRA TDD). While interesting, UTRA TDD does not enjoy IEEE 802.11's popularity today. Peer-to-peer approaches [3] provide the right intuition that ad-hoc networks can be adapted to vehicular networks but fail to convince of the pertinence of interest-driven clustering, and they fall short of presenting quantified evidence that such networks can fill their purpose.

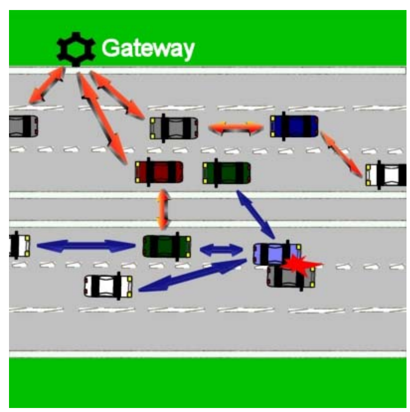

Figure 1: Vehicular Communications Example

Two classes of applications have to be defined, corresponding to the light-colored arrows (internet-based applications) and dark-colored arrows (safety-based applications).

Our approach focuses on creating ad-hoc networks due to the advantages such networks provide: lack of a need for a fixed infrastructure, self-organization capabilities, and resilience to mobility. However, because such networks may not scale well and vehicles are traveling at very high relative velocities, safety applications may not be properly implemented in such networks (e.g., not all nodes may be notified in time of important safety-related events). Our work determines whether or not accident notification on highways is in fact feasible.

The first part of our work is a discussion about inter-vehicle communications (IVC). Although we

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C. J. Merlin is with the University of Rochester, Rochester, NY 14627 USA (phone: 585-275-8078; fax: 585-273-4919; e-mail: merlin@ece.rochester.edu).

W. B. Heinzelman is with the University of Rochester, Rochester, NY 14627 USA.

Class	1	2		
Appli-cation	All (ASaN)	ANA	Internet Connectivity and VRC	CuLSA
Priority	Highest	High	Normal	Low

Table1: Priority assignments as a function of the application.

will focus on safety-related applications in this paper, we assume that some internet base stations will be disseminated along the road, and that vehicles will enjoy a connection to the internet in these covered areas (see Figure 1). However, in these areas and elsewhere, vehicles should be able to form an ad-hoc network for safety purposes. We also present a C++ generator that models traffic on a highway and creates *.tcl* files used for NS simulations. Lastly, we validate the use of vehicular networks for safety-related applications by simulating highway scenarios in NS with various vehicle densities and showing that safety notification packets can be received by vehicles in enough time to allow them to react to the notification.

II. Classes of Applications

The most pressing applications for vehicular networks pertain to safety features and should be offered on all vehicles. However, as the efficiency and success of vehicular networks depends heavily on the number of vehicles equipped with ad-hoc connectivity, in order to be commercially viable, users should be offered internet connection services in conjunction with the basic safety-related features. Thus, it appears that two classes of applications can be defined.

A. Class ①: Assistance for Safe Navigation (ASaN)

Although the least common of the two classes of applications, class ① manages critical aspects of traffic safety. Several services can be offered, among them are the following:

- Collision avoidance applications through accident, sudden braking, or road maintenance notifications,
- Hazardous driving condition detection (for black ice, hydroplaning, etc.),
- Emergency services call after an accident, and
- Detection of a rogue driver going the wrong way.

When an accident occurs on side A of a road and is detected (through an airbag deployment, for instance), a notification packet should be broadcasted to all vehicles on the highway. It is critical that incoming traffic on side A be notified rapidly that a vehicle was involved in an accident. While vehicles traveling on the opposite side (B) of the road have little use for such packets, they can help increase the connectivity in the network and thus should be involved in the dissemination of these notification packets. Such events are considered the exception, however, with the predominant use of vehicular networks being for applications in class ②.

B. Class ②: Traffic Regulation and Internet Connectivity (TRIC)

The second class of applications we introduce in this paper includes the following:

- Advanced Navigation Assistance (ANA) such as passing assistance [5], car pool formation, real time congestion notification, expected weather driving conditions, etc.,
- Internet connection services for added travel comfort and improved productivity,
- Vehicular Relay Chat (VRC) between users of the same highway, and
- Custom Local Shopping Advertisement [5] (CuLSA), which lets local businesses inform travelers of local shops, malls, etc. Local gas stations could also advertise their location to attract cars that may not see them from the highway.

C. Properties of Class ① and Class ② Data Traffic

The applications defined in class ① and ② are different in nature; the former is inherently data-centric while the latter is user-centric. Furthermore, applications in class ① have very tight delay and packet delivery ratio requirements, whereas applications in class ② have less stringent quality of service needs. Finally, applications in class ① also require that all vehicles be equipped with GPS capabilities offering a resolution such that a node can identify on which side of the road it is traveling (a requisite already met since GPS's accuracy is under 3m), and that notification packets can be sent with precise positioning information.

Given the criticality of class ① packets, their priority is much greater than that of class ②. Thus, packets associated with class ① applications should have the highest priority, with the priority of the other applications as shown in Table 1.

III. Modeling highway Traffic

Highways are usually bidirectional and can be modeled as several straight lanes for relatively short distances, as shown in Figure 2. Vehicles on highways typically travel at very high relative speeds (from 0 to 260km.h^{-1}), and the density of vehicles with IVC capabilities on the road can vary greatly.

We consider per lane vehicle density to be a fundamental parameter of highway scenarios, as it influences the number

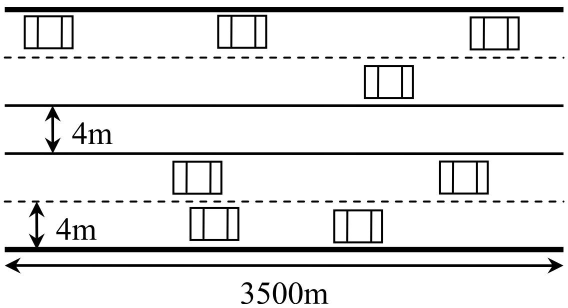

Figure 2: Highway scenario: a model
Highways are modeled as two groups of straight lanes of size *numLanes* x 4m by 3500m, separated by 4m.

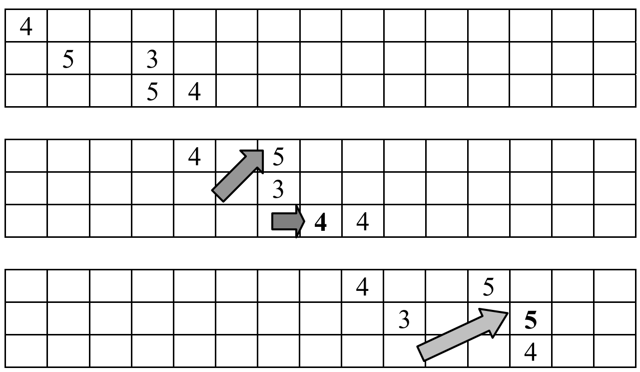

Figure 3: Traffic Behaviors of highway traffic model. Integers represent the velocities of the vehicles.
Cars traveling on the highway look for alternate paths when there is an obstacle ahead. If a car cannot find an alternate route, it slows down and reaccelerates when the traffic allows.

of receiving and transmitting nodes, the network connectivity, and the velocities of the vehicles—it is commonly observed that on congested highways vehicles travel at reduced speeds.

We also argue that given their extended length, only a limited number of IEEE 802.11 gateways could be disseminated along highways, forcing vehicles away from hot spot coverage to rely exclusively on ad-hoc networks for internet connectivity. This aspect of vehicular networks, while not studied in this paper, adds a constraint on the routing protocol that should be used for offering data-centric and user-centric capabilities.

In the following sections, we describe our traffic and event generation model. The code for this model can be downloaded from [11].

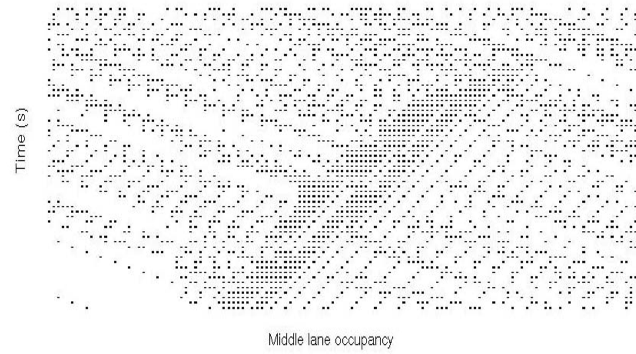

Figure 4: Backward movement on a 5-lane highway
On each lane of the highway (here: middle lane), the traffic jam goes backward over the 60s of our simulated traffic.

A. Highway Traffic Generator

Highways are represented by arrays of 7m x 4m *sites*, which can be occupied by *cars*. The site size was chosen to represent the size of a vehicle and the space between successive vehicles [6]. Each car is given an integer initial velocity between 3 and 5 sites.s^{-1}. These values translate into velocities of 21 to 35m.s^{-1} (or 75.6 to 126km.h^{-1}). A *highway* consists of one or more lanes of 500 sites, with every site being either occupied by a *car*, or empty. Initially, *cars* are assigned randomly to spaces with a uniform distribution. Maximum initial velocities are more likely to be assigned to *cars* driving on the leftmost lane; the opposite is also true of *cars* on the rightmost lane.

Cars traveling on the highway abide by the following rules:

- A spot on the right or on the left is free if and only if it is not occupied by another *car* and no *car* is coming from behind at a higher or equal velocity;
- If a *car* has a clear road ahead, it stays in the same lane at the same speed;
- Else (there is another *car* ahead traveling at a slower speed), it looks on its left side for a free spot. If it finds one, it moves to the left side to pass the obstacle;
- Else, it looks on its right side and if it finds a space, it moves to the right to pass the obstacle;
- Else (it cannot move to another lane), it slows down to the free space behind the slower vehicle and adapts its velocity to that of the slower vehicle;
- If a *car* has slowed down to a velocity below its initial speed, it reaccelerates ($v_{new} = v_{old} + 1$) when it finds a free spot;
- When a *car* comes to a complete stop, it waits for one second before it restarts when a spot becomes free ahead.

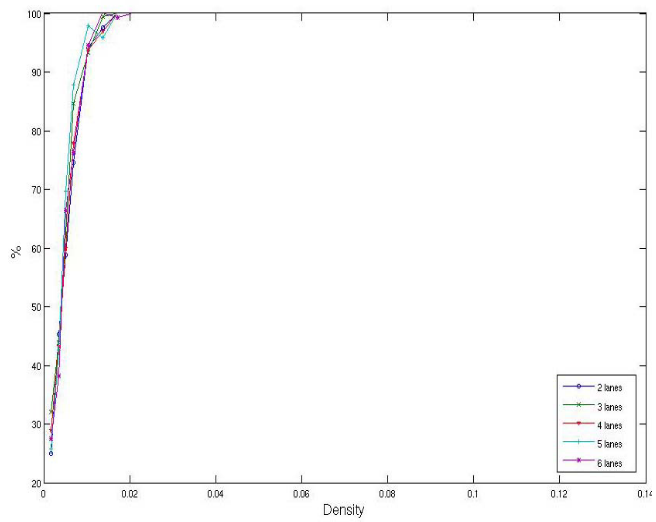

Figure 5: Max PDR vs. Density for 2-to-6 lane bidirectional highways. All nodes receive at least one notification packet for a density of at least 0.017.

Our traffic generator updates *car* velocities and positions using these rules every second.

Figure 3 shows the typical behavior of vehicles driving on a 3-lane highway. Following these rules, *cars* in very dense traffic adopt the same minimum velocity, as observed in reality. Also similar to real highways, we observe the known phenomenon of backward movement in congested traffic; in Figure 4, each line represents the positions of vehicles —black dots— on the middle lane of a 5-lane highway at every second of the simulation. After 10s (10^{th} line), a vehicle comes to a complete stop, causing a traffic jam. It then restarts after 4s, trailed by following vehicles. Vehicles involved in an accident have current velocities of 0. When incoming vehicles arrive at the scene of the accident, they either come to a stop or change lanes to avoid it.

B. Automatic Creation of .tcl Files

The core of the traffic generator is a C++ program that manages an array of *cars*. Other features include producing movement, nodes, and main simulation files that the NS simulator can read. The *.tcl* movement file contains the geographical coordinates and speed updated every second for each node. It is created and filled during the simulation by the C++ software. All *setdest* commands are derived from the speeds and coordinates of the aforementioned array. The *.tcl* nodes file keeps track of all nodes and is in charge of deactivating nodes when they arrive at the end of the highway to avoid edge effects. The main simulation file sets the background for an NS simulation.

IV. Simulation Scenarios

We model a highway of length 3.5km with various numbers of lanes and traffic densities. The length of the highway was chosen so that enough NS simulations could be obtained in a relatively short time so as to guarantee statistical validity. The size of the highway also ensures that the events generated remain locally relevant (1.75km in each direction), which is on par with having a lifetime value on all packets. In order to avoid border effects, nodes that arrive at the end of the highway are deactivated.

Our results show the average of 50 different scenarios unless otherwise specified. All simulations were run over 30s. Accidents occur after 10s of simulation and involve 2 vehicles in our scenarios. A node experiencing an accident floods notification packets to the rest of the nodes in the network. The transmission range is set to 250m.

A. Notification Packets after an Accident: Network Flooding

In our scenarios, several *events* are generated to represent safety-related incidents, and nodes involved in these incidences flood notification packets to the rest of the network. For example, when two vehicles experience an accident, each vehicle sends five notification packets during a short time interval. The period of time between two packets should be chosen such that no unnecessary contention is added at the time of the accident (otherwise causing packets to be dropped), but short enough for the notification to still be useful. Several packets are sent in order to increase the redundancy of the information for added safety.

For simplicity, we liken highway car accidents to a crash test against a wall at $60km.h^{-1}$ (we assume the driver tried to avoid the accident by pushing the brakes). The vehicle deforms and stops within 1m, or 125ms. This case, while exceptional, allows for 2 notification packets to be sent when packets are generated every 100ms. Thus, we send 5 packets (1 every 100ms) between the time t of the accident and t + 500ms.

Class ① packets are expected to be of fixed small size, while class ② packets have varying, often larger sizes. We believe that 500 bytes represents an acceptable size for class ① packets, leaving plenty of room for additional fields that may be needed in the future.

Our model allows various *events* to be reported to all the *cars* in the network. Accident notifications, tested in our simulations, slippery road conditions, and road maintenance warnings all require a fine time stamp, and geographical coordinates, which can be obtained via GPS. Vehicles traveling on the opposite side of the road to where an event

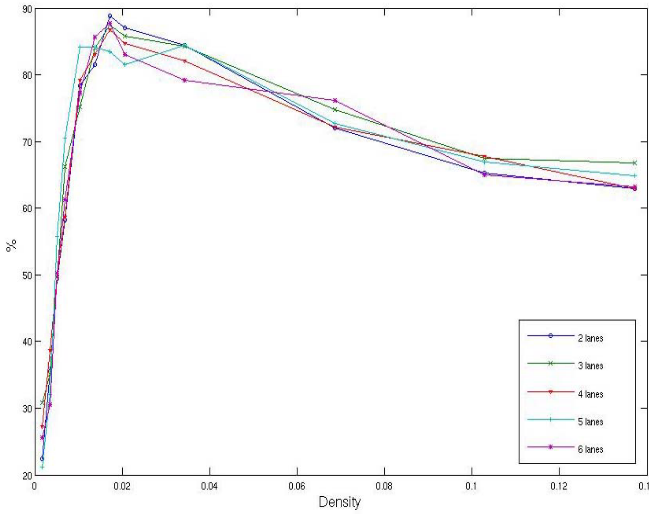

Figure 6: Average PDR vs. Density for 2-to-6 lane bidirectional highways. The number of lanes on the highway does not affect the behavior of the average PDR. The average number of delivered packets peaks at a density between 0.017 and 0.021.

occurred are expected to forward received packets, in order to increase network connectivity.

All packets' destination addresses are set to *BROADCAST*, and the packets are flooded through the network. Packets that were previously received by a node are discarded to avoid the broadcast storm problem. The MAC protocol is IEEE 802.11, which is beneficial for integrating vehicular networks with laptops, PDAs, or cell phones.

B. Simulation Metrics

We chose the following metrics to evaluate the effectiveness of ad-hoc vehicular networks: Packet Delivery Ratio, number of dropped packets, delay, and distance to the closest incoming car. Vehicles on side B of the road do not contribute to any of the results, other than by relaying packets. We define the packet delivery ratio as the percentage of vehicles behind the accident —but not involved in it— that receive a notification packet. Packets not received by any nodes are considered dropped.

We also measure two delays: the first one is the minimum delay separating the moment when the first packet is sent and when the first moving car receives it; the second is the delay from when a packet is sent to the time when the farthest vehicle receives it. This measure should give an upper bracket of the transmission time to the whole network. The absolute delay and distance to the closest car still in motion will help determine if the network could help avoid accidents.

Note that an interesting characteristic of vehicular networks is that, unlike most other types of ad hoc networks, power consumption is not a hard constraint and thus will be ignored in this work.

V. Simulation Results

We present results for a bidirectional highway with between 2 and 6 lanes in each direction in Figures 5 and 6, and 3 lanes in each direction for all other graphs.

A. Packet Delivery Ratio

The maximum PDR indicates the percentage of vehicles that have an interest in the notification that receive at least one notification packet. The average PDR gives an indication on the delivery of all 10 packets, and thus provides insight on the network's performance.

1) Maximum PDR

Figure 5 shows the maximum PDR with respect to the traffic density for bidirectional highways with between 2 and 6 lanes in each direction. A density of 0.02 on a 2-lane highway corresponds to a per-lane density of 0.01, which means there is 1 *car* every 100m. Figure 5 shows that the number of lanes does not significantly affect the maximum PDR. For a density greater than or equal to 0.021 on each side, all vehicles behind the accident scene receive at least one packet. Lower densities do not allow for the network to be fully connected.

2) Average PDR

Figure 6 presents the average PDR as a function of density for highways of between 2 and 6 lanes. The PDR increases with density until it reaches a peak value. The network connectivity does not depend on the topology of the highway, but only on the global density. The following paragraph gives more insights.

In Figure 6, the average PDR of the 10 packets sent increases for densities between 0 and 0.018. The number of vehicles on the highway does not allow for the network to be completely connected for these densities. Packets are sent and received correctly only if the nodes form a connected network. The average size of this network increases with higher densities until it includes all vehicles on the highway. The average PDR then decreases with an increase in density. This behavior is due to a higher number of dropped packets. The percentage of vehicles receiving packets remains generally the same but fewer packets get through at all (and are counted as dropped) because of an increase in the number of collisions. Thus, the "ideal" density is around 0.018, which translates into per lane densities of 0.9, 0.6, and 0.5 vehicles per 100m for 2-lane, 3-lane, and 4-lane highways, respectively; at this density, the average PDR approaches 85% for 10 packets.

A first observation relevant to these results is that the topology of the highway, as specified by the number of

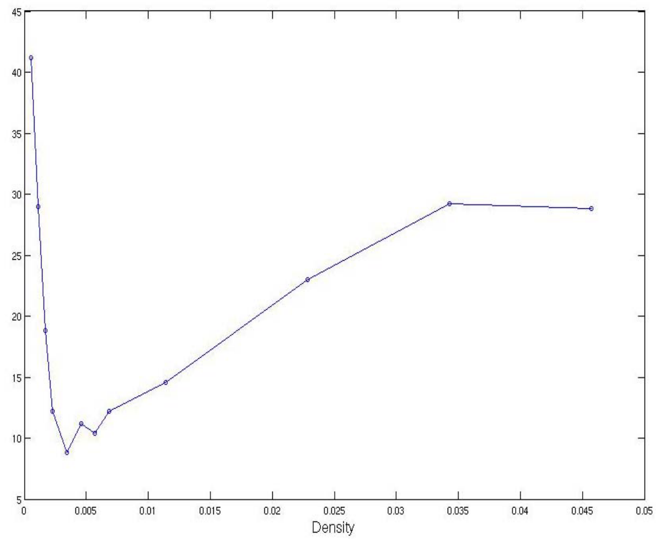

Figure 7: Average Number of Dropped Packets vs. per lane density on a 3-lane highway

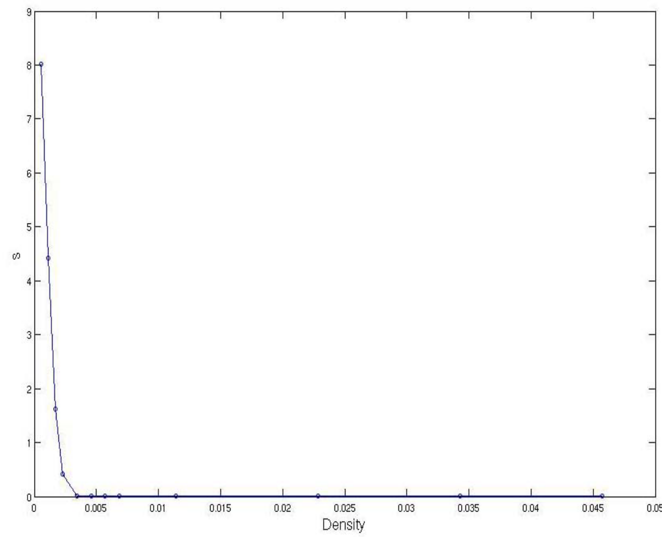

Figure 8: Minimum delay from accident vs. per lane density for a 3-lane highway.

lanes, does not affect the behavior of the vehicular network for a given global density. Another interesting result is that a density of 0.01 (or 0.5 cars per 100m on a 2-lane highway) guarantees enough connectivity for at least 90% of the nodes to receive one notification packet or more, with a modest *best effort* UDP protocol. While this result is very encouraging, the average PDR shows limitations in the resilience of the network. It suggests that there may be a limited number of class ① packets that can flood the network in the same interval of time. It also suggests that class ① packets must receive a high priority to prevent losing critical notifications at the benefit of unimportant transmissions.

Because we showed that the topology of the highway does not change the results when they are expressed as a function of the density, for clarity purposes in the following segments, we present our findings for 3-lane highways only as a function of per-lane density. This does not change our conclusions.

B. Percentage of Dropped Packets

Figure 7 shows the percentage of dropped packets with respect to traffic density for a 3-lane highway. One perhaps surprising result is that the lowest number of packets being dropped does not occur at the density that produces the highest average PDR. In fact, for low densities, packets are broadcasted to the boundaries of the connected network, and fail to go farther, sometimes (very low densities) not even one hop away. For connected networks however, as the density of nodes increases, more packets are dropped because of collisions caused by a higher contention. Dropped UDP packets are not retransmitted since UDP is a *best effort* protocol. When the originating node sends a packet, it is critical that the transmission is successful with at least one neighboring node. Otherwise, the packet is lost. These results also show, in conjunction with the average PDR, that the harsher limiting factor is not the percentage of dropped packets but the network connectivity. Of course several solutions can be devised to overcome these limits, such as more advanced transmission power management, or packet caching for further retransmissions. We observe a trade-off between network connectivity (linked to the transmission range), and the number of dropped packets induced by varying levels of contention.

C. Delays to the Vehicles in the Connected Network

1) Absolute Minimum Delay to the Closest Vehicle

The absolute minimum delay is the time gap separating an accident from the moment an incoming vehicle receives a notification. This measure is critical to validate the use of vehicular networks for safety applications. As seen in Figure 8, for a vehicle density of 0.0035 and higher, notifications are received in 5.2ms, or 19cm at 130km.h^{-1}. Clearly, vehicular networks allow for a prompt notification of drivers arriving at the scene of an accident for mostly or fully connected networks (1 or 0.6 car per 100m for 2-lane or 3-lane highways). In other cases, packets are either dropped or transmitted within 5.2ms, and thus do not provide any guarantee that incoming cars will be notified. In fact, this situation is a lot less bleak than it seems. For traffic scarcer than 1 car every 100m, drivers have time to assess the nature of the accident, as 100m (given in figure 10) represent 2.7s

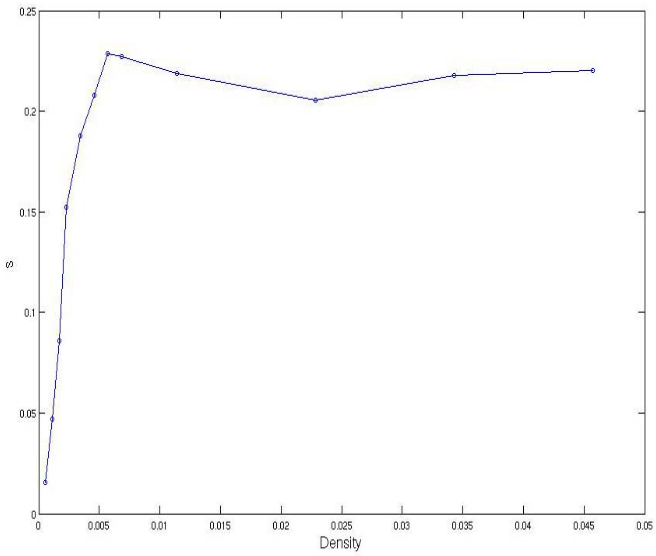

Figure 9: Minimum delay to the farthest node vs. per lane density on a 3-lane highway.

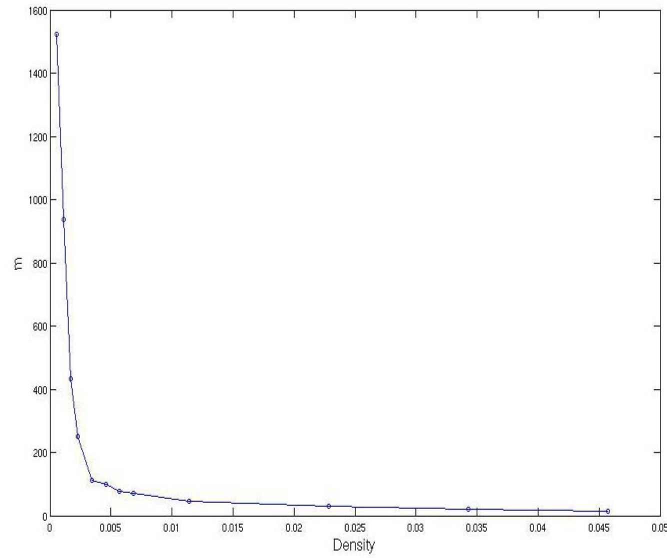

Figure 10: Distance to closest moving car vs. per lane density on a 3-lane highway.

at 130km.h^{-1}.

2) Absolute Minimum Delay to the Farthest Vehicle

Figure 9 shows the minimum delay between the moment when an accident happens and the instant the farthest node receives it. For a non-fully connected network, the delay increases with the density: on average, the size of the network increases; consequently, it takes more time to reach nodes located at the confines of the network. However, Figure 9 shows that when the network is fully connected, the minimum delay to the farthest vehicle remains almost constant as the density increases, with a maximum value of 240ms. This corresponds to 9m at 130km.h^{-1}, a distance much smaller than that of the accident to the farthest vehicle (about 1km). This part confirms that connected networks will successfully warn of dangers ahead of the traffic, and help avoid deadly accidents, and gives an interval of time during which all nodes will receive at least one notification.

D. Distance to the Closest Moving Vehicle

Figure 10 plots the distance to the closest moving vehicle at the time the first packet is received as a function of the traffic density. When all the packets are dropped (not received by any node), this value is set to the length of the highway (3500m). For a connected network, the distance ranges from 15m to 75m, or 415ms to 2.1s at 130km.h^{-1}. These results show that for cars very close to the scene of the accident (less than 30m away), a simple warning to the driver will not suffice in avoiding another accident; instead, the vehicle's brakes have to be triggered automatically. A typical human reaction time on a road is 1s, while that of the vehicular network can be brought to one fifth of a second[†]: the difference between a deadly accident and a close call.

Side B / Side A	Lower density	Higher density
Unconnected network	Packets are less likely to reach nodes on side A, but this case is not critical (see V. C. 1))	Gives a much greater chance to reach other node on side A
Connected network	No significant change expected as the network is already connected	May increase the delay to vehicles farther down side A, although certainly not in a penalizing way

Table 2: Cases not covered by this paper
A is the side of the highway experiencing an accident, B is the opposite side.

All simulations were conducted on highways that present the same statistics on both sides. This may not always be representative of reality, especially for highways connecting an inner city to its suburb. We refer the reader to table 2 for a qualitative discussion of these other scenarios.

[†] We grossly evaluate the reaction time of the network as the sum of the delays experienced to detect the occurrence of the accident, transmit and receive, and to process information at the receiving node

VI. Related Work

Previous traffic models have considered similar rules to those developed in our model. Nagel et al.'s model [4] used the idea of slowing down if another lane is not available, as well as speeding up once a lane change can be made. Similarly, [7] adopted the concept of lane changing. However, our model does not support randomly altering a vehicle's initial velocity (the velocity at which it would go on a deserted highway), as is done in [7]; consequently, it can be considered a simplified model. Our model also adds *events*, such as accidents and braking, to traffic scenarios.

A large amount of research concentrates on using UTRA TDD for IVC. UTRA TDD features code division multiple access (CDMA) with time division. [8] shows that vehicular networks can successfully make reservations for communication, despite high relative velocities. In [9], Rohling et al. compare UTRA TDD and IEEE 802.11b in highway and urban scenarios and show that the former outperforms the latter. Chisalita et al. [3] propose a clustering approach to IVC based on vehicles' interests. In [6], Artimy et al. found that density, relative velocities, and the number of lanes critically affect network connectivity. Our work adds to this knowledge by showing the viability of safety-related uses for vehicular ad-hoc networks.

VII. Conclusion and Future Work

We have provided a general framework for inter-vehicular networks and their performance evaluation. Our simulations show that even for low densities (1 or 0.6 car every 100m on each lane for 2-lane or 3-lane highways —corresponding to 1 car every 3 to 4s), vehicular networks can notify drivers of incoming dangers or prompt embedded systems to autonomously react in time to avoid accidents. These results, valid even in our minimalist implementation using UDP and flooding with IEEE 802.11, should persuade car manufacturers that vehicular networks are feasible and practical, even in the near future.

Future work includes improving the traffic model we devised and combining class ① and ② applications. MAC and routing protocols can also be customized to fit the unique features of vehicular networks. Additional work will also consider security issues, although we believe that IVC presents the same challenges and goals as other networks.

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