Automatic Emergency Braking

Realistic Analysis of Car Dynamics and Network Performance

Michele Segata and Renato Lo Cigno

***Abstract*—Safety applications are among the key drivers in VANET research, and their true performance can be assessed only if the application and the communication network are jointly considered. This work presents a simulation study of an emergency braking application accomplished by embedding mobility, cars' dynamic, and drivers' behavior models into a detailed networking simulator (ns-3). The overall system allows capturing the interactions of the communications with the car's automated braking mechanism and the driver's behavior. At the same time yields very detailed information on the communication level. Besides the integrated tool, the paper presents a novel and simple message aggregation mechanism to empower message re-propagation while controlling the network congestion during the peak load due to the emergency braking. Next it discusses the effectiveness of such applications as a function of the market penetration rate, showing that even cars that are not equipped with communication devices benefit from the smoother and earlier reaction of the cars that can communicate. Fading phenomena and sensitivity to the radio transmitted power are analyzed, while fine grained dynamics of cars' collisions as taking into account different masses and different elastic coefficients are introduced to evaluate the severity of impacts.**

***Index Terms*—VANET, vehicular networks, emergency braking control, automated braking system, ns-3 simulation, rebroadcast schemes.**

I. Introduction

THE potential of V2V communications to improve safety and increase infrastructure efficiency is enormous and well recognized. Yet, in spite of this, development and deployment are lagging behind. There are many reasons for this situation, ranging from legal issues to lack of clear economic incentives for both car-makers and road management entities. One clear reason is also the objective difficulty of moving from theoretic analysis to realistic implementations, but also the lack of studies that put together communications and car dynamics, making a clear link between the communication level and the advantages for safety or efficiency.

Car platooning [2], [3] is definitely the application striking imagination the most, and probably also the most challenging one from a global system perspective. This explains why large projects concentrate on demonstrating car platooning[1].

Car platooning is very complex, but simpler safety applications, like Emergency Braking (EB), are easier to implement, yet extremely useful. With EB, a vehicle executing an emergency braking broadcasts warning messages informing vehicles behind, even those where drivers cannot actually see the braking vehicle. Recall that bad brake usage by drivers lies at the root of most car accidents and the correlated casualties[2].

In spite, or maybe because, of the application's simplicity, there are still many issues that have not been completely explored, specially relating the application dynamics and the VANET communications.

In this work we consider a version of EB that uses warning messages to feed an Adaptive Cruise Control (ACC) to perform automated braking if the driver does not intervene. Throughout the paper we refer to such application as Emergency Electronic Braking (EEB). We focus on the joint analysis of EEB, its supporting protocols and the underlying VANET, coupled with detailed models of vehicles dynamics and human drivers for legacy cars that are not equipped with EEB: An approach that to the best of our knowledge is utterly missing in the literature, where research either mainly focuses on network performance or on car dynamics separately. The adopted technique is simulative. An integrated simulation tool is developed and made available to the community for further use. It jointly models the packet network, with all its details and channel impairments, and the dynamics of moving vehicles including their mass, inertia and even different Coefficients of (energy) Restitution (CoR) upon cars' impact.

This paper extends the work we presented in [1] as a preliminary contribution, adding results on important aspects like the influence of fading or the role of different CoRs on the deceleration the car passengers are subject to.

The contribution focuses on a highway scenario, where a flow of cars is forced (e.g., by an accident) to come to a complete stop. A very detailed vehicle, driver and Automated Braking Mechanism (ABM) model is developed, and it is coupled with a realistic packet-level 802.11p VANET and propagation model, looking for the most appropriate level of modeling abstraction to tackle the complete problem via simulations. We define our

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[1]See for instance the recent and on-going EU SARTRE project http://www.sartre-project.eu/, or the early demonstrations of PATH http://www.path.berkeley.edu/ in California.

[2]This statement is supported by data published by the US National Highway Traffic Safety Administration (NHTSA) http://www-fars.nhtsa.dot.gov/. Data published by NHTSA clearly shows that drivers' distraction or lack of driving capabilities, including drugs and alcohol, are the dominant cause of accidents and casualties.

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automatic braking system as ABM instead of using ACC for correctness, since we consider a safety system performing only automated braking when needed, and not car following.

The paper is organized as follows. Sect. II reviews the state of the art and works that influenced and inspired us; Sect. III describes the simulation scenario and the developed models; Sect. IV discusses the network-level performance; Sect. V presents the safety improvements obtained as a function of the market penetration rate; Sect. VI and Sect. VII explore the effects of the transmission power and fading respectively. Sect. VIII finally shows how the tool can model also the details of single collisions, while Sect. IX closes the paper with a discussion of the contribution and the work ahead.

II. Related Work

Information diffusion in Vehicular Ad-hoc Networks has always been, and it still remains, a major research challenge, due to the high mobility and the environment affecting the performance of wireless communications. One of the biggest issues is how to spread safety information as farther as possible without congesting the network. Several solutions have been proposed, from gossiping-based protocols, to clustering algorithms, to schemes which can adapt to traffic or wireless channel conditions [4]–[7].

These approaches usually reach significant levels of performance in terms of network results. Rather often, however, application requirements and/or vehicles dynamics are not considered. For example, the protocol developed by Ibrahim and Weigle [5], is able to ensure an update rate in the order of 300-$400\,\mathrm{ms}$. Such update frequency is really high from a network point of view, and it is well suited for the diffusion of information such as traffic conditions, but it might be not enough for safety application. As an example, the U.S. D.O.T. indicates a rate of $10\,\mathrm{Hz}$ for many applications [8]. Moreover, rebroadcast protocols such as the ones presented in [4], can keep channel utilization under control and spread the information far from the origin really quickly, but questions like "*When should we re-propagate an information?*" or "*What is the re-propagation range needed for a particular application?*" have never been taken into account.

On the other hand, purely application-oriented analysis exist, where application-provided benefits are shown but without considering the impact on the network [9], [10].

Only recently, the importance of application-level requirements in the design of VANET network protocols has been highlighted [11]–[16]. Surprisingly, as stated in Haas and Hu [13], the protocols proposed in the literature are analyzed with simulators using crash-free mobility models, so there is no way to evaluate their impact on safety.

Some work which jointly addresses safety benefits and network protocols is present in the literature but it lacks details [17], i.e., the vehicular model is simple and a deep analysis of network parameters, e.g., channel load, is missing. Some research papers about emergency situations are listed in the survey by Willke et. al. [18], but again, they are aware of dynamics and human behaviors but network details such as employed PHY/MAC are not taken into account [19]. Similarly to our approach, the work by Biswas et. al. [14] performs a study of the Cooperative Collision Avoidance application: the benefits in terms of reduced crashes are shown but the network analysis limits to delay and packet error rate. Finally, in [15] and in [16] the authors develop a method to determine the communication requirements of simultaneous application. While [15] focuses only on network metrics, [16] focuses on a higher layer, trying to take into account dependencies between the applications: the potential benefits in terms of crash reduction is, however, not analyzed in details.

These are the motivations behind our joint application/network analysis, using an integrated network and a mobility simulator modified to account for accidents and to couple the dynamics of the vehicles with those of the VANET, providing realistic results, even if only in a synthetic environment.

III. Simulation Models and Tools

A discussion of existing simulation tools with their pros and cons is beyond the scope of this paper. We have developed the mobility and dynamic models integrated within the ns-3 (v 3.9) network simulator[3]. The base for the vehicles' dynamics are the IDM (Intelligent Driver Model) and MOBIL microscopic mobility models [20], [21] proposed in [22]. These tools offer a good starting point, but they lack three fundamental features: *A)* a bi-directional coupling between the network simulator and the IDM/MOBIL simulator to empower modeling ABM and EEB, so that the mobility of the nodes affects the network and vice versa; *B)* realistic models of driving dynamics going beyond the IDM, which assumes a "perfect" driver-plus-vehicle behavior, even if this means violating physical/technical limitations as, for instance, having decelerations larger than $1\,\mathrm{g}$ ($\simeq 10\,\mathrm{m/s^2}$) with standard vehicles; and *C)* realistic impact models taking into account the fundamental properties of vehicles, including different mass and the capacity of the vehicle's body of partially absorb the impact energy, a feature modeled by mechanical engineers through the CoR [23].

Feature *A)* is fundamental, since it is the one critical step that couples the dynamics of vehicles with the communication level: i.e., how cars and drivers react to the information transmitted among vehicles (in time and space), and how packets are offered by EEB to the VANET. This represents a major "improvement" compared to tools where the mobility model follows a pre-defined (stochastic) pattern, which is not influenced by the outcome of the communication pattern. Features *B* and *C* add realism to simulations. Indeed, without realistic human behaviors and actual vehicles technical/physical limits, car accidents simply do not appear in simulations, so that the study of safety applications is impossible. The additional physical details, not yet available in [1], enable also to study the accelerations imposed on car passengers.

We present here the key features of the evaluation models and scenarios. Further details, the code, and its usage manuals are available from our repository[4].

IDM is crash-free by construction; indeed, as pointed out by Haas and Hu [13], previous works do not consider collisions,

[3] http://www.nsnam.org

[4] http://vnt.disi.unitn.it

and we actually could not find open source simulators with this feature, preventing any study on the effectiveness of different communication strategies on ABM applications. IDM results in arbitrarily large decelerations (we commonly observed decelerations larger than $10\,\mathrm{m/s}^2$, which are not reachable by common production cars [24], [25]). To overcome this impairment, we introduced a maximum deceleration $b_i^{\max}$ as a physical limit for each vehicle i, using values obtained from braking tests on dry surface [24]. The actual deceleration of any vehicle is thus:

$$a_i(t) = \max(-b_i^{\max}, a_i^{\text{IDM}}(t)) \tag{1}$$

where $a_i^{\text{IDM}}(t)$ is the value of acceleration obtained from the IDM formula for the vehicle. We call this model "Limited-IDM" (L-IDM), i.e., a more realistic model which accounts for fundamental physical limits. This modification results in crashes during emergency braking, as normally observed in highways. For managing the collision, we refer to the formulas detailed in [23], i.e., we take into account the speeds before collision v_1 and v_2, the coefficient of restitution (CoR) e and the masses m_1 and m_2 to compute the speeds after the impact u_1 and u_2, where vehicle 1 is the follower and vehicle 2 is the leader. In particular:

$$u_1 = v_1 - \frac{(1+e)m_2}{m_1+m_2}\Delta v \quad ; \quad u_2 = v_2 + \frac{(1+e)m_1}{m_1+m_2}\Delta v \tag{2}$$

where $\Delta v = v_1 - v_2$. For the first experiments, we set $e = 0$. Sect. VIII shows the impact of e on accident severity.

Each vehicle is equipped with an accelerometer, which estimates the acceleration of the vehicle every $100\,\mathrm{ms}$ in order to stamp this value on beacons and to take ABM and EEB decisions. This is more realistic than simply taking the perfect acceleration computed with the L-IDM formula. We further use the accelerometer to measure the peaks of acceleration caused by crashes: even if we have not attempted it in this paper, one can imagine to evaluate the damage to cars and passengers starting from the acceleration of the involved vehicles, but this requires to model also the energy absorbing features of vehicles' body (only partially modeled by the CoR), of possible derailments due to panicked behavior, etc.

Another enhancement is the use of an independent per-car clock, used to avoid the occurrence of events at the same exact time, which is unrealistic and causes the simulation to generate synchronization phenomena. Moreover, ns-3 does not consider processing delays: to emulate them every send and receive event is delayed by a random time smaller than $10\,\mu\mathrm{s}$.

A fundamental component which is added to the simulator is the ABM, which processes the data received from other vehicles to keep safety distance and brake if the driver does not react in time to a dangerous situation. The ABM works first of all by considering the approaching rate: if it is negative (i.e., leading vehicle is traveling faster than its follower), then the vehicles are increasing their gap and the ABM remains disabled leaving the car control to L-IDM. If instead the approaching rate is positive, the ABM computes the safety gap to determine if a vehicle is too close to its leader. The safety gap depends on the speed of the vehicle and it is computed as

$$s_{\text{safe}} = T_{\text{ABM}} \cdot v_i + \varepsilon_{\text{ABM}} \tag{3}$$

where T_{ABM} is the time headway for the ABM, v_i is the current vehicle's speed and ε_{ABM} is a small quantity to account for errors. T_{ABM} is set to $1\,\mathrm{s}$, which, as mentioned in Treiber et al. [26], is an average time measured on German freeways which is considered safe. ε_{ABM} is set to $1\,\mathrm{m}$.

The actual gap between the car and leading vehicle can be greater or lower than the safety gap. If it is lower, then the follower must brake in order to move away from the leader. The applied deceleration can be computed from the leader's acceleration minus a small quantity. If, instead, the actual gap is greater than the safety gap, the ABM computes a deceleration using the formula:

$$a^{\text{ABM}} = \frac{v_{i+1}^2 - v_i^2}{2 \cdot (s_{\text{actual}} - s_{\text{safe}})} \tag{4}$$

which computes the acceleration needed to bring the speed of the following vehicle (v_i) to the speed of its leader (v_{i+1}) in a space equal to the difference between the actual gap (s_{actual}) and the safety gap (s_{safe}).

The ABM is designed to work only with messages received directly from the vehicle in front, to guarantee that the deceleration correctly follows the goal of avoiding a direct crash[5]. In the presence of cars not equipped with communication devices, however, this can be a limitation, and will in any case hamper any benefit derived from propagating EEB messages far from the originator. Indeed, EEB messages coming from vehicles far ahead can be used as warnings, idling the gas and resulting in a deceleration induced by the air resistance[6]. The deceleration is a function of the speed and vehicle mass M_v:

$$b_{\text{air}} = \frac{F_{\text{drag}}(v)}{M_v}. \tag{5}$$

If no EEB messages are received for two seconds, the vehicle returns to obey the L-IDM formula.

The drag force is defined by

$$F_{\text{drag}} = \frac{1}{2}\rho v^2 C_D A \tag{6}$$

which is known as the *drag equation* [28] and gives the force which a body with a section A and a drag coefficient C_D is subject to if it runs at a speed v in a fluid of density ρ. We set $\rho = 1.20\,\mathrm{kg/m}^3$ (air at $20\,^\circ\mathrm{C}$) while the $C_D \cdot A$ product is randomly set for each vehicle using values for common production cars found on a site which collects this kind of measurements[7]. In the first experiments, the mass M_v is fixed at $1\,500\,\mathrm{kg}$ for the sake of simplicity. Afterwards, when demonstrating the impact of the CoR, we use a randomly distributed mass. Once more, further details as mixing heavy vehicles are easy to add, but there is the risk that they simply add noise to the experiments.

[5]This is why we decided to differentiate it from an ACC, which operates in a different way. We already implemented a real ACC model into another simulation framework for platooning [27] and we plan to port such model into the ns-3 based simulator.

[6]This is another improvement added by L-IDM; we disregard other phenomena as rolling resistance and the motor braking effect, since at high speed the air drag is dominant. This "second order" details can be added at any time, but their effect is probably much smaller than the statistical significance of results.

[7]http://rc.opelgt.org/indexcw.php

The reaction to warnings is simply an immediate gas throttling: a simplification of a complex human and ABM behavior which could be enhanced by giving a weight to the warning according, for example, to the distance from the message originator.

A. Network Protocols

Apart from the mobility modifications, we implemented VANET level protocols to diffuse information among vehicles. First of all beaconing, which broadcasts messages at a frequency of $1\,\mathrm{Hz}$: messages contain information about the sending vehicle, such as speed, acceleration, position, etc. The same message structure is used for both beacons and EEB messages, following the indications of the U.S. Department of Transportation [8, Tab. 4.3]. Moreover, a header is defined to meet other application requirements, for example sender identification. The size of the header is $101\,\mathrm{B}$. Its structure is defined in [1]. Table I summarizes the main fields.

Field	Size (B)	Field	Size (B)
Type	1	Packet id	4
Originator id	4	TTL	1
Sender id	4	Count	1
Certificate [5]	58	Digital Signature [5]	28

Tab. I
DESCRIPTION OF THE FIELDS OF BEACON MESSAGES

In practice the EEB protocol sends beacon messages with a $10\,\mathrm{Hz}$ frequency as indicated by U.S. D.O.T. [8]. Switching between beaconing and EEB protocol happens when the deceleration of the vehicle is greater than $1\,\mathrm{m/s^2}$. Moreover, packets coming from vehicles behind are ignored.

To analyze the application's benefits and the impact of message re-propagation on network load, we implement a rebroadcast protocol taken from the literature, as depicted by the listing in Alg. 1. We call it EEB with Rebroadcast (EEBR) and it is based on the *weighted p-persistence* broadcast suppression mechanism [4]. The rebroadcast decision is taken with a probability p which depends on the distance from the sender. If a message is seen for the first time (identified with the 'Packet id' field), it is passed to the application for processing and, if needed, rebroadcast; otherwise it is ignored. If TTL $= 0$, it is not rebroadcast even if it is seen for the first time. The parameters are the same as in [4]. Notice that this is not a state-of-the-art protocol for vehicular rebroadcast. We chose this because it is simple and well known: a smarter protocol would not provide qualitatively better results given what we want to show in this article.

The rebroadcast of single messages is highly inefficient due to the 802.11p MAC protocol, whose overhead for channel contention is very large. For this reason, we implement an *aggregation and rebroadcast* protocol, which blends the advantage of efficient message dissemination with a lower usage of network resources. The protocol is described by the listing in Alg. 2 and builds on the same idea of stochastic rebroadcast of EEBR, but provides for application level message aggregation; for this reason we call it EEB with Aggregation (EEBA).

```
list KnownPackets

on InitProgram()
KnownPackets ← ∅

on ReceiveEEBPacket(eebl):
if KnownPackets.Contains(eebl) then
    return
else
    KnownPackets.Insert(eebl)
    ProcessPacket(eebl)
    if eebl.ttl ≠ 0 then
        p ← ComputeRebroadcastProbability(eebl)
        if Random() < p then
            eebl.ttl ← eebl.ttl − 1
            Broadcast(eebl)
        end if
    end if
end if
```

Algorithm 1: EEBR protocol.

The rebroadcast decision is taken with the same criterion of EEBR, but, instead of sending a message immediately, it is inserted into a queue to be sent in the same 802.11p frame as the (potential) local EEB message, generated with the $10\,\mathrm{Hz}$ frequency. Since the queue is managed by the application, if another copy of the message is received it means that the 'Packet id' message has already been rebroadcast by someone else close by, and it is removed from this queue, reducing the number of useless rebroadcasts. This is not possible with EEBR due to the fact that, once a packet has been scheduled for rebroadcast, it cannot be removed from the MAC queue even if it has not been transmitted yet. All EEB messages to be rebroadcast are inserted in the same queue. Every $100\,\mathrm{ms}$, the queue is emptied and a single frame (if the maximum frame size allows it) containing all messages is sent.

B. Simulated Scenario

The scenario we select for experiments is basic but fundamental: a highway where, due to an accident or any other impairment, some cars brake until they arrive to a complete stop, forcing all the following cars (the platoon) to come to a complete stop too. The leader (or the leaders, in the multi-lane scenario) brakes with a constant deceleration of $4\,\mathrm{m/s^2}$. Driving styles and vehicles characteristics are chosen at random within reasonable boundaries. For example, we model the aggressiveness of the driver using different values for desired speed, time headway (the T parameter of the IDM formula) and politeness (the p parameter of MOBIL), and we characterize vehicles through different maximum deceleration and different drag area (see (6)). The parameters are described in Sect. III-C. Results refer to the four application and behavior models defined:

L-IDM: VANET technologies are not employed;
EEB: beaconing and plain EEB protocol without rebroadcast;
EEBR: beaconing and EEBR protocol;
EEBA: beaconing and EEBA protocol.

Beacons are never rebroadcast and L-IDM can be freely mixed with any other model to test situations where VANET technologies have a limited penetration.

```
list KnownPackets, SendQueue

on InitProgram():
KnownPackets ← ∅; SendQueue ← ∅
ScheduleEvent(SendPackets, 100ms)

on ReceiveAggregatedEEBPacket(aggregatedeebl):
for all eebl in aggregatedeebl do
    ReceiveEEBPacket(eebl)
end for

ReceiveEEBPacket(eebl):
if KnownPackets.Contains(eebl) then
    if SendQueue.Contains(eebl) then
        SendQueue.Remove(eebl)
    end if
    return
else
    KnownPackets.Insert(eebl)
    ProcessPacket(eebl)
    if eebl.ttl ≠ 0 then
        p ← ComputeRebroadcastProbability(eebl)
        if Random() < p then
            eebl.ttl ← eebl.ttl − 1
            SendQueue.Insert(eebl)
        end if
    end if
end if

on SendPackets():
if SendQueue.Size() ≠ 0 then
    if SendQueue.Size() = 1 then
        packet ← SendQueue.Get(0)
    else
        packet ← CreateAggregatedPacket(SendQueue)
    end if
    Broadcast(packet)
    SendQueue.Empty()
end if
ScheduleEvent(SendPackets, 100ms)
```

Algorithm 2: EEBA protocol.

Simulation experiments are repeated 20 times or more with a different seed until a satisfactory confidence interval, with a $95\,\%$ confidence level is reached. We investigate scenarios with 1, 2, 3, 4 and 5 lanes with average desired speeds of 50, 70, 90, 110, 130 and $150\,\mathrm{km/h}$, but we report here only the most interesting results for lack of space. The results encompass the fraction of cars involved in collisions, the average maximum decelerations, and the deceleration profiles of the different models, the network load and the fraction of lost messages.

The system is first analyzed in the ideal case where all cars are equipped with VANET technologies. Then, a market penetration rate (MPR) analysis is conducted. MPR indicates the fraction of vehicles that are equipped with VANET technologies and ABM. The aim is to determine what are the benefits when not all vehicles are equipped, and if benefits at low MPRs justify the effort of deployment. Finally, we also investigate the impact of fading and transmission power.

C. Simulation Parameters

Tab. II lists the values for IDM/MOBIL and network parameters used in the simulations. The cars' maximum deceleration is uniformly distributed in $[5.9, 8.4]\,\mathrm{m/s^2}$ [24]. The desired speed v^{des} of drivers falls uniformly within $\pm\,15\,\%$ of the nominal speed $\bar{v}$ of the simulation. The L-IDM maximum acceleration a is $1.7\,\mathrm{m/s^2}$, while the desired deceleration b is $4\,\mathrm{m/s^2}$, large but suitable for situations of emergency braking and still comfortable for passengers. Time headway T ranges randomly between $0.1\,\mathrm{s}$ (very aggressive driver) and $1.1\,\mathrm{s}$ (safe driver). Finally, the jam distance s_o and the acceleration exponent δ are taken from the original IDM paper [20].

The second part of Tab. II lists MOBIL parameters. The politeness factor p ranges between 0 (totally impolite) and 0.5 (very polite). We set the b_{safe} parameter so that $7\,\mathrm{m/s^2}$ is the maximum deceleration a driver can cause to incoming vehicles by changing lane. The minimum gap s_{min} is set to $2\,\mathrm{m}$, the lane changing threshold δ_{thr} to $0.3\,\mathrm{m/s^2}$ and the bias for right lane δ_{bias} to $0.2\,\mathrm{m/s^2}$, so the changing threshold right to left $\delta_{R\to L}$ and left to right $\delta_{L\to R}$ are 0.5 and $0.1\,\mathrm{m/s^2}$ respectively.

Parameter	Value	Unit
b_{max}	$[5.9, 8.4]$	$\mathrm{m/s^2}$
v^{des}	$\bar{v}\cdot[0.85, 1.15]$	$\mathrm{m/s}$
a	1.7	$\mathrm{m/s^2}$
b	4	$\mathrm{m/s^2}$
T	$[0.1, 1.1]$	s
s_0	2	m
δ	4	
p	$[0, 0.5]$	#
b_{safe}	7	$\mathrm{m/s^2}$
s_{min}	2	m
δ_{thr}	0.3	$\mathrm{m/s^2}$
δ_{bias}	0.2	$\mathrm{m/s^2}$
IEEE standard	802.11p CCH	
AC (beacons)	AC_BK	
AC (EEB)	AC_VO	
Data rate	6	$\mathrm{Mbit/s}$
Bandwidth	10	MHz
Tx power	20	dBm
Propagation loss	Three log distance	
d_0, d_1, d_2	1, 200 and 500	m
n_0, n_1, n_2	1.9, 3.8 and 3.8	#
L_0	46.67	dB

Tab. II
IDM/MOBIL AND NETWORK PARAMETERS USED IN SIMULATIONS.

The third part of Tab. II lists the wireless network (802.11p) parameters. We use two different ACs for beacons and EEB messages: AC_BK and AC_VO respectively. The data rate is $6\,\mathrm{Mbit/s}$ (as suggested in Jiang et. al. [29]) and the transmission power is $20\,\mathrm{dBm}$ unless otherwise stated when we study the impact of the transmission power.

The basic propagation model is the ns-3 "three log distance" with default parameters ($d_0, d_1, d_2, n_0, n_1, n_2, L_0$ in Tab. II). We deliberately base the initial study on this simple model for the sake of results' interpretation. Then, in Sect. VII we explore the impact of fading using the Nakagami fading model.

IV. Fundamental Networking Results

Beacons and EEB messages are all transmitted in broadcast, as 802.11p safety-related messages. The goal is the evaluation of the impact the EEB application has on the network as a function of the protocol used: plain EEB, EEBR or EEBA.

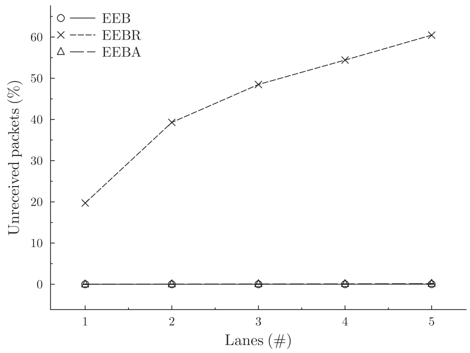


Fig. 1. l_{uf} as a function of the number of lanes for plain EEB, EEBR and EEBA. The confidence intervals have been omitted for the sake of readability, since they were really small.

Trivial computations indicate that for low car densities or a small number of lanes the network load is marginal. This is confirmed by results, so we concentrate on scenarios where all cars are equipped with EEB and there are multiple lanes (up to five) on the highway.

Albeit it may seem strange, the simple definition of *network performance* is not trivial in these scenarios. The "communication channel" is distributed in space and time, and it evolves as the platoon of cars compacts due to braking and slowing down. The network load is difficult to define due to the complexity of the communication channel. The collision rate is hard to measure in reality and in a realistic simulator like ns-3, which, on a per-station basis, computes the decoding probability.

We measure the network performance based on two metrics. The first one is the *channel load at each station* $\rho_i(t)$, defined as the fraction of time, for each second t, that a station s_i observes the channel busy, including the time s_i itself uses to transmit. The meaning and measure of this metric is straightforward, which is one of the reasons why we chose it.

The second metric is the percentage of messages l_{uf} that are completely lost for the system, i.e., *not a single station received them*. l_{uf} is again time-varying and typically zero during normal operation. However, we are interested in l_{uf} during the "most stressful" period for network load. In the absence of a formal definition of this period, we heuristically choose to define it as the time starting when leaders begin to brake and ending when the deceleration of all vehicles is less than $1\,\mathrm{m/s^2}$ and their speed is lower than $30\,\mathrm{km/h}$. Notice that it is not necessary that $\rho_i(t) = 1$ for l_{uf} to be larger than zero. Together $\rho_i(t)$ and l_{uf} define reasonably well the status of the communication channel and the network "stress" due to the emergency event.

The analysis we performed has shown fairly heavy maximum network loads for EEBR and EEBA (peaking over $50\,\%$ for EEBR). The network load as defined by $\rho_i(t)$ does not however tell all the story about network performance, because it is averaged over $1\,\mathrm{s}$ intervals and because it is well known that CSMA/CA protocols can lead to high data loss rates even for moderate network loads. Fig. 1 reports l_{uf} as a function of the number of lanes. This is probably the main measure to evaluate the possibility that the application will not react correctly due to lack of information. Albeit neither the plain EEB nor EEBA have an information loss rate strictly equal to zero, l_{uf} remains extremely low. EEBR on the contrary leads to a very high fraction of messages that are not received by any station, so that they are completely lost for the application and may jeopardize its performance.

The maximum load and the message loss rate l_{uf} give only a snapshot of the network dynamics, which is not enough to understand the "big picture" of how the VANET evolves as the car platoon brakes. Fig. 2 reports a color plot of the load $\rho_i(t)$ of the network as a function of time (vertical axis) and space (horizontal axis) measured from the first car of the platoon, so as to capture the dynamics of the network as the platoon brakes and finally stops. We regret to have to resort to colors, which may hamper clarity in printed versions, but it has proven impossible to plot the results satisfactorily with a 3-D plot. The color in the plots represent the channel load $\rho_i(t)$ mediated over the cars present in road sectors of $50\,\mathrm{m}$.

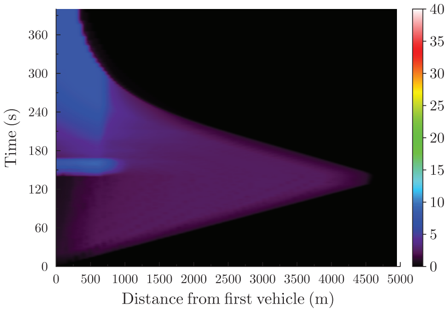
Black areas identify the portions of the highway without cars due to the simulation scenario. The void area on the lower right corner of the plots is due to the fact that cars enter the simulated stretch of highway following the cars that will simulate the emergency braking. Around the time instant $130\,\mathrm{s}$ all cars are on the $5\,\mathrm{km}$ stretch of highway and the emergency braking begins. Black area on the upper right corner of the plots is due to the platoon compacting in space as the cars come to a complete stop. Beaconing gives rise to dark blue colors equivalent to 3-5 % of channel occupation when cars are moving (and hence quite far one another) and a light blue color equivalent to about $10\,\%$ of channel occupation when they are still (and very close). With plain EEB, the increment in load due to the emergency braking is visible but very low. EEBR instead leads to channel congestion (more than $35\,\%$ load) for more than $30\,\mathrm{s}$ and a stretch of highway more than $1\,\mathrm{km}$; EEBA maintains the network load much lower and the messages spread more uniformly in space, indicating that the communication pattern is more efficient.

In the preliminary version presented in [1], we also analyzed the case when there is traffic in the reverse direction on the other carriageway, and some drivers slow down to watch, generating interfering traffic as the EEB starts sending messages. The results, albeit interesting, do not change the fundamental conclusions drawn here, so we avoid reporting them again.

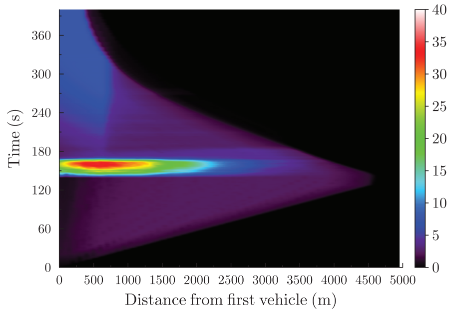
V. Impact on Safety

Sect. IV evaluated the network performance of EEB, EEBR, and EEBA protocols when all cars are equipped with the system, which is the most stressful situation for the network, but the most favorable to the application: as a matter of fact, in the simulations no accidents at all occur for any protocol. This might not be true in reality, where network overloading might harm the application. More challenging for the application is the case when only a fraction of cars is equipped with EEB.

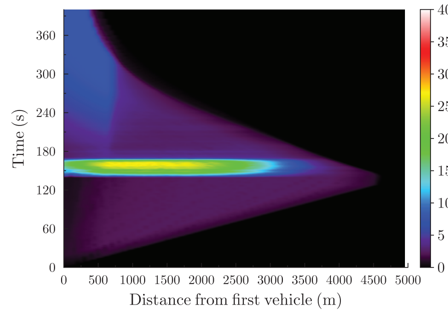
The scenario envisaged is the progressive introduction of the EEB system on cars, so that only a percentage of them is able to communicate and react to communications: the others follow the L-IDM model as defined in Sect. III. Fig. 3 reports the fraction of cars involved in crashes as a function of the Market Penetration Rate (MPR) of EEB systems from $0\,\%$ to $50\,\%$ in the basic scenario of a single lane. Plot 3(a) refers to an average



(a) plain EEB

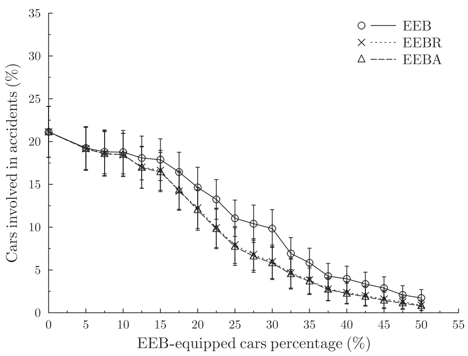


(b) EEBR

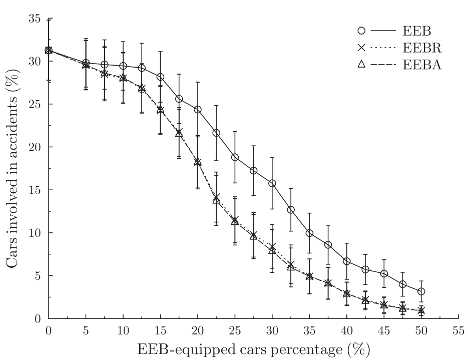


(c) EEBA

Fig. 2. Average load as a function of the time and the distance from the platoon head for the 5-lane scenario, average speed $130\,\mathrm{km/h}$.

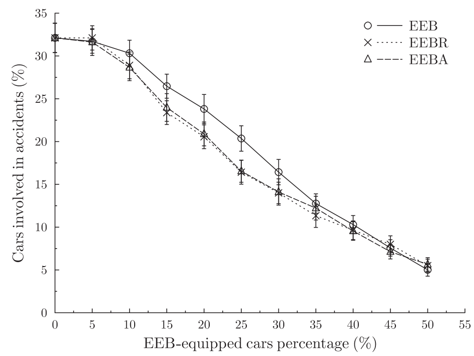


(a) $130\,\mathrm{km/h}$ reference speed

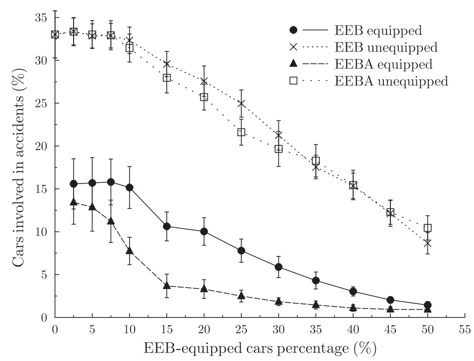


(b) $150\,\mathrm{km/h}$ reference speed

Fig. 3. Percentage of cars involved in accidents vs. MPR for single-lane tests for the different protocols and average speeds 130 and $150\,\mathrm{km/h}$.



(a) Percentage of cars involved in accidents vs. MPR

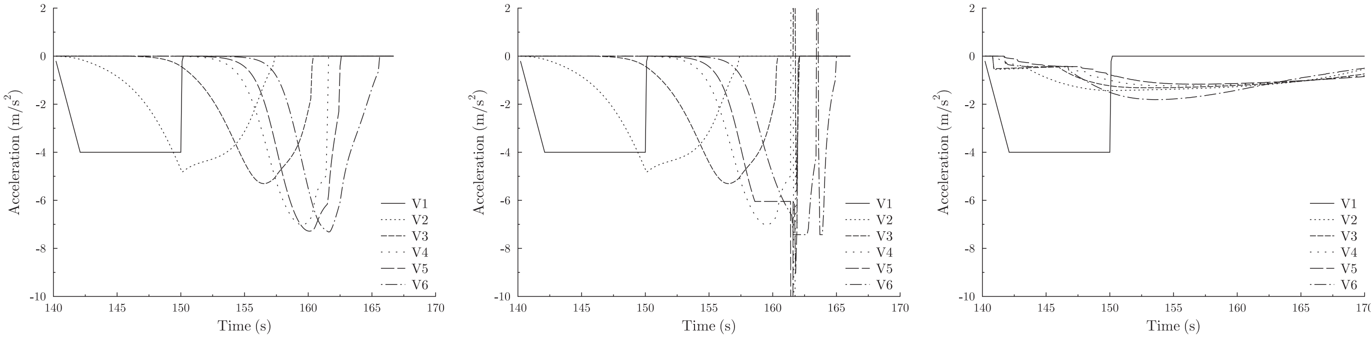


(b) Split-down of equipped and unequipped cars involved in accidents vs. MPR

Fig. 4. Safety benefits for the 5-lane test, reference speed $130\,\mathrm{km/h}$.

initial speed of $130\,\mathrm{km/h}$, while Plot 3(b) refers to $150\,\mathrm{km/h}$. Error bars report the $95\,\%$ confidence interval. Simulations for slower initial speeds yields qualitatively similar results, with an obvious reduction in accidents. Even small penetration rates (10-20 %) give measurable and statistically meaningful accident reduction. The advantage of message rebroadcasting is evident: the percentage of cars involved in accidents with plain EEB is consistently larger then with EEBR and EEBA protocols: only for very high MPRs the performance of plain EEB converges to the others. The adoption of intelligent rebroadcasting is thus very important specially during the initial commercialization of these systems: with a low MPR the chance of having an equipped car right ahead is marginal, so that the accident reduction is due to early warning received from cars not directly in front, which leads to idling the gas, thus slowly reducing the speed and enabling more efficient braking when the car in front will eventually brake itself. This effect is amplified by the fact that drivers of unequipped cars will react to this slow deceleration generating a wave of early speed reduction instead of the abrupt braking typical of emergency situations.

Results for the single-lane scenario are very promising, yet the performance when there are more lanes and the network is more loaded are those of major interest. Fig. 4(a) analyzes the results for 5 lanes. As a general comment, we observe that the system performance remains extremely positive even with low MPRs. We observe that the L-IDM model forecasts an increment of accidents as the number of lanes increases (these results are confirmed by the 2, 3 and 4 lanes experiments, not reported for lack of space). At the same time EEB systems give an increased benefit for low MPRs as the number of lanes increases, because the chance that cars communicate is increased by the higher density. EEBR and EEBA protocols



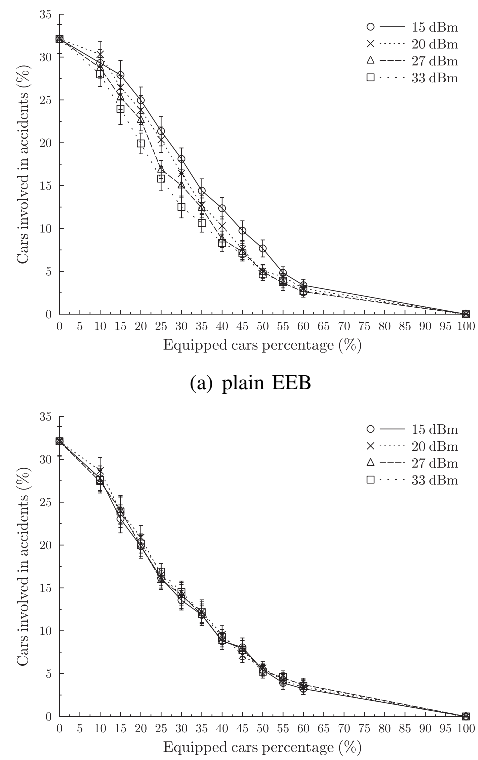
(a) IDM (b) L-IDM (c) EEBA

Fig. 5. Acceleration traces for three simulations, showing the first six vehicles in the first right lane, for $130\,\mathrm{km/h}$ reference speed and 5 lanes.

still give an advantage at the application level, though the gain is smaller, once more due to the higher density of cars.

A question that often arises is the impact of the presence of EEB-equipped vehicles on the other lot. Fig. 4(b) attempts to provide an answer: also non-equipped cars benefit from the introduction of EEB enabled vehicles, even at medium-low MPRs. The figure refers to a five-lane scenario, but results for smaller number of lanes are similar. The impact of the rebroadcast protocol (EEBA compared to plain EEB) on non-equipped cars is marginal, but the reduction in accident probability is unquestionable for MPR as low as 15-20 %. The explanation is that the earlier and smoother deceleration of EEB-equipped vehicles allow other drivers (the L-IDM model indeed) to react earlier with still a larger safety margin in front. Equipped vehicles have a much larger benefit, and, for this category, message rebroadcast with EEBA has a huge impact, halving the collision rate up to a 40-45 % MPR. We were not able to distinguish (in simulation) between cars causing the accidents and cars involved without guilt, but we conjecture that equipped cars are (almost) never the cause of accidents.

Reducing accidents is the main goal of EEB applications, but investigating how they influence the deceleration curves also yields meaningful insight. Fig. 5 analyzes the deceleration of the first 6 vehicles in the rightmost lane of a 5-lane scenario with reference speed $130\,\mathrm{km/h}$. Plot (a) refers to the pure IDM model, plot (b) to L-IDM (without EEB) and plot (c) to EEBA. Vehicle V1 is at the head of the platoon, while V2–V6 are the followers. All plots show the first vehicle braking at a constant deceleration of $4\,\mathrm{m/s^2}$ and the followers behaving differently according to the model employed. In Fig. 5(a), IDM causes a strong deceleration (often not achievable by commercial vehicles) for V4, V5 and V6 (7-8 $\mathrm{m/s^2}$), resulting in no crashes. With L-IDM (Fig. 5(b)), instead, vehicles have a random maximum deceleration to account for physical limits. V5 has a breaking capability of no more than $6\,\mathrm{m/s^2}$ of deceleration and, due to this, it collides with V4, causing a sudden acceleration (V4) and deceleration (V5). This shows how the simulator reproduces natural crashes by introducing a basic physics law, and that it can be used to measure the severity of an accident if proper physical parameters are used, as we will show in Sect. VIII. Finally, Fig. 5(c) shows the extremely smooth (and anticipated) decelerations provided by the ABM with EEBA, which, besides avoiding accidents, also makes such situations much more comfortable for all passengers.



(a) plain EEB

(b) EEBA

Fig. 6. Percentage of cars involved in accidents vs. MPR for different values of transmission power, 5-lane scenarios, average speed $130\,\mathrm{km/h}$.

VI. Transmission Range Sensitivity

The choice of the “best” transmission power for VANET applications has been discussed a lot: high transmission power means longer one hop transmission range, but also increased interference and channel load. The optimum transmission power can also be a function of the application, since different applications may have different requirements. EEB can have different requirements than, say, “potential collision warning” in an urban crossroad, where the communication is normally without line-of-sight.

We consider the 5-lane scenario (the most stressful for the channel), $130\,\mathrm{km/h}$ reference speed and power values of 10, 15, 20, 23, 27, 30, 33 and $37\,\mathrm{dBm}$ (0.01-5 W), though we do not report results for all of them for the sake of clarity.

37 dBm is a level not included in the standard. The power values we consider translates into a communication radius ranging roughly from 50 m to more than 1 km.

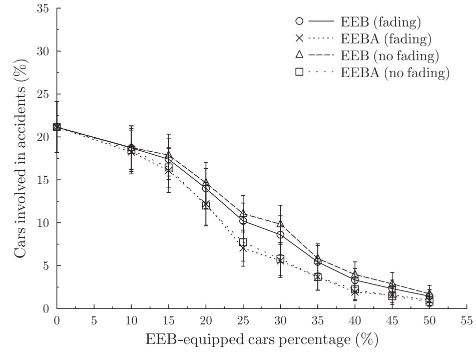
First of all we analyze the impact on collision-avoidance capabilities. Fig. 6 shows the percentage of cars involved in accidents as a function of MPR, for different values of transmission power (i.e., 15, 20, 27 and 33 dBm) for EEB and EEBA protocols (EEBR behaves like EEBA as far as the application is concerned). When no rebroadcast is employed (plot 6(a)), the transmission power plays a fundamental role: the higher the transmission range, the lower the probability of a rear-end collision; results for 10 dBm (not shown) indicate that the application functionality is at risk and 37 dBm do not offer meaningful gains compared to 37 dBm. The result holds for any value of MPR.

With EEBA (and EEBR) instead, the transmission power does not provide statistically significant differences in terms of accidents reduction. This means that, even with a short transmission range, EEBA is able to correctly spread the information among the cars in the platoon. Fig. 6(b) emphasizes the independence of EEBA to the transmission power, thus it seems possible to use low transmission power, reducing the interference and network load (see the following analysis), with all the benefit of an EEB application. We stress once more that this is an application-dependent result, and other applications may have different requirements. For EEBA this result holds also for much lower car densities, which we have tested, but are not reported here for the sake of brevity.

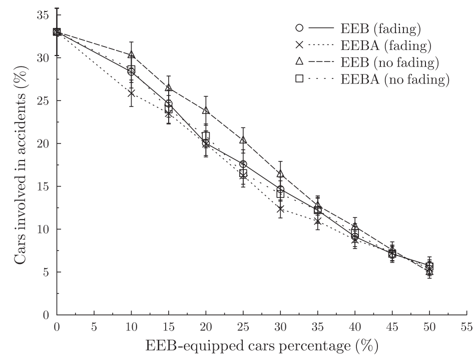
The 20 dBm power was already considered in Sect. IV and V, thus we focus on 33 dBm to analyze the impact on the network.

As the transmission power increases, the dominant factor becomes the network load. Indeed, as Fig. 7 depicts, a transmission power of 33 dBm causes, for EEBR, the complete congestion of the network along the entire stretch of the platoon, which is nearly 5 km. As a consequence of this overload the application works badly, even if this is reflected only by different deceleration profiles and not by the crash rate.

EEBA does not completely saturate the channel, but instead the load increases, compared to the 15 dBm case (not shown here), from 25 to 40 % for a power increment of 62.5 times.

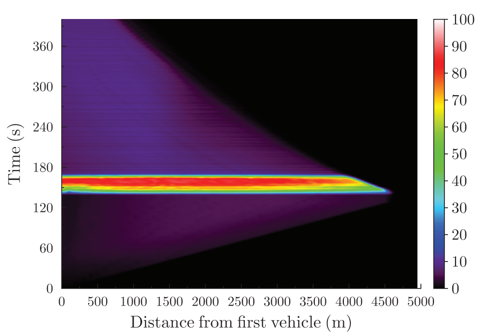


(a) single-lane scenario

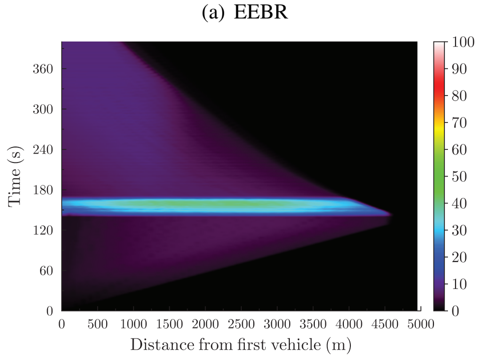


(b) five-lane scenario

Fig. 8. Percentage of cars involved in accidents vs. MPR for the experiment with Nakagami fading, reference speed 130 km/h.



(a) EEBR



(b) EEBA

Fig. 7. Average loads as a function of the distance from the platoon head for 33 dBm transmission power, 5 lanes, reference speed 130 km/h.

VII. Fading Effects

Can fading jeopardize the application? To answer the question, we employ the Nakagami fading model [30], which is embedded in ns-3, using $m = 3$ as shape parameter, as commonly used in VANET simulations [31], [32]. We consider the 130 km/h, single and 5-lane scenarios, a transmission power of 20 dBm, and limited MPR (0-50 %), since these are most demanding conditions for the application when fading alters the regularity of the message propagation.

Fig. 8 shows the percentage of cars involved in accidents, as a function of the market penetration rate. Comparing the plot with Fig. 4(a), there are no evident differences, i.e., the fading does not cause an increment in the number of crashes. In some cases (e.g., 10, 25 and 30 %), there is even a reduction of accidents, albeit minimal. This can be due to the randomness of the simulation or to the fact that interference can also be constructive, leading to amplifications, and in some cases warning messages could be received even farther than with a simple path-loss channel.

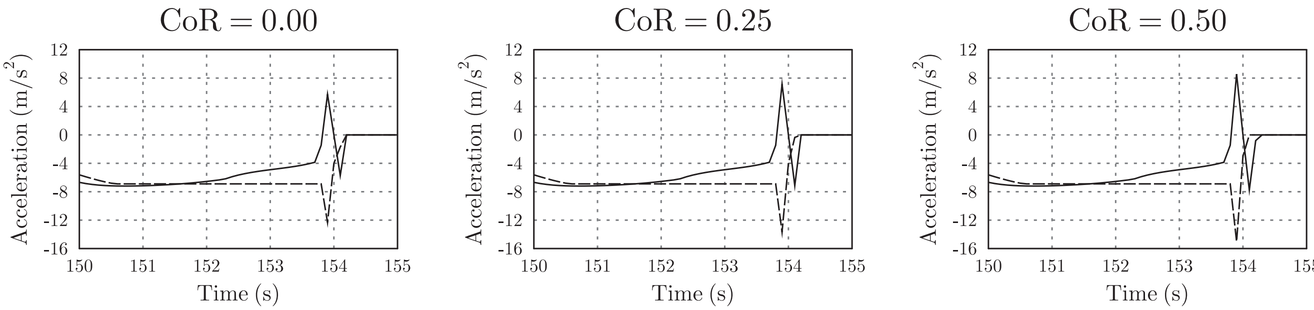


Fig. 9. Deceleration/acceleration profiles of a rear-end collision in the simulation, for different CoR values. The solid line represents the front vehicle, while the dashed line represents the follower.

VIII. Crash Severity Considerations

An EEB system at low MPR might provide only a slight reduction of the number of crashes, but might actually decrease the relative speed at collision and consequently the resulting damage. The damage to cars and people can only be evaluated by experts in the field, and we are not. Thus we evaluate the severity of a collision by measuring the acceleration that cars are subject to during a collision.

Up to now, we considered perfectly inelastic crashes (i.e., CoR $= 0$) and a mass $M_v = 1\,500\,\mathrm{kg}$ for each vehicle. These are clearly unrealistic assumptions. Vehicles do not have all the same mass and, most important, the coefficient of restitution varies with vehicles construction, maintenance [33], [34] and impact speed. Setting CoR $= 0$ implies that the impact energy is completely absorbed by the components of the car, so the car being hit is not "pushed" by the other: they remain "glued" together. Disregarding such fundamental parameters may completely invalidate realism of results. As already described, we include in the dynamic model of cars and impacts the CoR and we explore here if this parameter affect in a measurable way the car acceleration (and thus the force to which passengers are subject to) during the impact.

To this purpose, we ran a set of simulations choosing masses at random (taking weights from 850 (supermini car) to $2\,000\,\mathrm{kg}$ (big SUV) and setting different CoRs for different simulations, i.e., ranging from 0 to 0.5. Fig. 9 shows the acceleration profiles of two colliding vehicles, for CoR values of 0, 0.25 and 0.5. As clearly shown in the picture, different values of CoR causes different impact severity, as depicted by the different acceleration/deceleration vehicles are subject to. When the CoR is set to 0, more kinetic energy is dissipated because of the perfectly inelastic collision. As the CoR increases, so does the impact severity, as shown by the stronger maximum acceleration/deceleration.

The peaks of the impulses are single points because the time resolution of the simulator is $100\,\mathrm{ms}$. However, as shown in [35], the duration of a rear-end collision impulse ranges roughly between 65 to $130\,\mathrm{ms}$, so our time resolution is good enough for the level of realism we want to consider. There are also some differences between the accelerations shown in [35] and the ones we obtained. This is perfectly normal, since the authors of [35] are taking into account high speed collisions.

These are only early results, but demonstrate that a proper simulation environment can be used for realistic studies of safety applications over VANETs, including the evaluation of potential casualties reduction and the damages to vehicles.

IX. Conclusions

An automatic braking system is a mandatory component for adaptive cruise control and cooperative driving in general. Its efficiency with medium to low market penetration rates is key for the path leading to safer roads and a more efficient and intelligent use of vehicular transportation systems.

To the best of our knowledge this is the first time that a safety application is studied with this level of realism and detail, albeit still via simulations. In particular, the time-space analysis of the channel load is novel, as it is enabled by the joint simulation approach, as contrasted to simpler approaches partially decoupling the VANET from the vehicles dynamics, and it gives insight in the dynamics of the joint network and application evolution.

The results in this work are extremely promising. They stress the need for proper application-level message aggregation strategies to avoid clogging the network in case of high vehicular density. The aggregation technique we present strikes for its extreme simplicity and effectiveness, being able to reach an excellent compromise between network utilization and provided safety.

Furthermore, the market penetration rate analysis indicates that benefits are obtained for penetration rates as low as 5-$10\,\%$, and, most notably, that also cars not equipped with cruise control and communication devices benefit from the presence of cars whose reaction is smoother and anticipated with respect to the standard human reaction.

Work ahead includes the refinement of the channel model following the proposal and guidelines given in [36], the further development of the vehicular dynamics models, and the exploration of scenarios more complex than a stretch of highway, albeit the large scale emergency braking support we analyze is mostly needed in these cases, especially with low visibility conditions.

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