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EEBL SAFETY APPLICATION PERFORMANCE EVALUATION IN V2V NETWORKS

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Abstract

The reasearch community is working in the automotive field with the aim to design VANET applications whom will revolutionize the road traffic mobility in terms of number of lifes saved and accidents avoided.
This technology, as suggested by the U.S National Highway Traffic Safety Administration, Department of Transportation, tries to overcome the limits of radar systems and the situations in which drivers could be interested in having a wider perspective, not only about vehicles in its proximity.
This work focuses on EEBL safety application performance evaluation in single lane motorway scenario, where a leader of a fleet roughly brakes down until a complete stop.
The mobility model runs thanks to the traffic simulator *Simulation of Urban Mobility SUMO*, in which *Intelligent Driver Model IDM* has been set as the default driving profile, as to include also a strictly human delay component. SUMO has been modified for the purpose of introducing accidents during simulations.
The network structure instead is provided by the open-source *Omnet++* network simulator. The EEBL application exploits these network resources to deliver a particular EEBL message whenever the host vehicle performs decelerations over a certain treshold. The application has been designed to be integrated with an *Automatic Emergency Braking AEB* behaviour, as soon as a V2V communication capable car receives such information.
The test have been run varying the portion of the equipped vehicles, representing the *Penetration Rate PR* of the technology, on the total fleet and the *Time-to-Lock TtL* latency elapsed from the recpetion of the EEBL emergency message and the activation of the braking system.
The performed tests provide a scenario in which with the increasing of PR, for the first six cars involved, the number of vehicles involved in accidents are reduced as well as the maximum average deceleration braking intensity. Regarding TtL parameter, is possible to say that it doesn't influence the general outcomes significantly.
These results suggest that even without a considerable technology spread, EEBL can contribute to an important safety improvement in emergency road situations. This aspect is mainly due to the fact that benefits of this technology can be earned by other surrounding unequipped vehicles.

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Chapter 1

Introduction

Since the birth of civilization, mankind has always looked for a way to move safely and quickly. We started covering huge distance simply walking or running, then we learnt to ride horses and other animals, until to reach in the 19th century one of the biggest invention of the humankind: the car.
When in the 20th century Henry Ford conceived the assembly line production, the automobile became a mass asset and depopulate first in America and then in Europe and Italy, thanks to some pioneer including Giovanni Agnelli.
In 2016, the total number of vehicle registered in the United States was almost 270 milions [1], while in Italy in 2016 there were just less than 45 milion of registered vehicles [2], equivalent to about 70 vehicles every 100 inhabitants.
These numbers clearly represent high quality of live in developed country and more and more industrialized societies, but all these vehicles result in an inescapable sad other side of the coin: daily road death.
The Global Status Report on Road Safety made by the *World Health Organization (WHO)*, reports 1.25 milion of road traffic deaths in 2015 worldwide [3].
Moreover, *National Highway Traffic Safety Administration (NHTSA)* of the United States *Department of Transportation (DOT)* states that the annual price of those crashes is estimated to be equal to 871 billion of dollars in economic loss and societal harm in 2010.
These numbers show how it's important to search a way to prevent and stem accidents to occur. The benefits will outcome not only in number of lifes saved, which is by far the most important aspect to consider, but also in money spared and time taken from the daily hours spent in traffic jam due to traffic accidents.
To achieve this purpose, governments and car-maker industry are cooperating each other in order to accomplish a considerable level of traffic safety improvements. So far, great enhancements have already been made such as *Electronic Stabilty Control (ESC)*, *Anti-Lock Braking System (ABS)* and others, and for the immediate future we are talking about autonomous driving cars where vehicles without a driver's station (pedal board, steering wheel, etc...) will carry passengers in a completely autonomous and safety-oriented manner(level 5). The state-of-the-art is now represented by level 3, depitcing the situation in which in the right conditions, the car can manage most aspects of driving, including monitoring the environment. The system prompts the driver to intervene when it encounters

a scenario it can't navigate.
The majority of this technology is based on vehicle-resident sensors and their performances are subject to certain situations. Indeed, depending on weather conditions, lighting and shadowing transitions and also misalignment of the radar, these on-board devices can change and decrease their perception range and field-of-view reducing their overall reliability.
For this reason, in December 2016 the NHTSA, DOT published a *Notice of Proposed Rulemaking (NPRM)* [4] presenting a comprehensive proposal for mandating *Dedicating Short-Range Communications (DSRC)* based *Vehicle-to-Vehicle (V2V)* communications.
V2V proposes to create a framework thanks to which cars are able to "talk each other" forming wireless ad-hoc network, also known as *Vehicular Ad-hoc Network (VANET)*.
VANET is a peculiar case of *Mobile Ad-hoc Network (MANET)* where nodes cannot move randomly but their mobility is restricted to roads.

On top of VANET, several safety applications will born with the aim to mitigate and reduce the number of motor vehicle crashes, thereby reducing the losses and costs to society that would have resulted from these crashes. The agency believes that this new kind of technology will cover traffic dangerous situations not addressable by current camera-based systems, providing timely safety information directly to the drivers.
The main mechanism on which the whole V2V architecture is based is rather simple: each car continuously broadcast to nearby vehicles, and consequently receive from them, a *Basic Safety Message (BSM)* containing host vehicle information such as position, speed, acceleration and others. According to the informations collected, each car is now able to take decisions in order to be prepared to cope with an impending emergency traffic situation, for example. In this way all vehicles have always a precise idea about their immediate surrounding and about current neighbors conditions.
Figure 1.1 shows an example of V2V scenario.

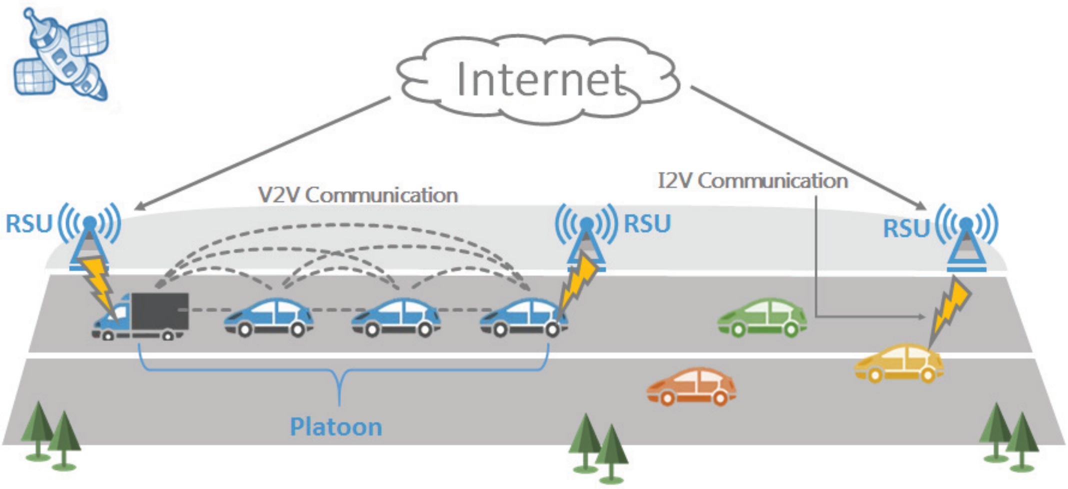


Figure 1.1: V2V scenario illustration

In addition, the agency assumes a number of prevented crashes ranging from about 423 to 595 thousand, and a number of saved life of about 1 thousand during the first thirty yeras of deployment. The monetary benefits in the same period will result in an amount varying from 53 to 71 billion of dollars [4].
As well as safety applications, vehicular networks can offer a wide variety of services like internet access and multimedia for entertainment. Each application has its own technical issue and specific requirements depending on several aspects.

The aim of this work is to study and evaluate the performance of the *Emergency Electronic Brake Lights (EEBL)* safety application in highway conditions, recording the number of crashes prevented and the variation of the acceleration profile during braking maneuvers. The scenario has been reproduced by means of network and traffic simulators, allowing us to set environmental conditions and to vary the portion of the fleet equipped with DSRC module, characterizing the first years of the technology adoption.
The work is organized as follow: Chapter I provides an overview of V2V technology and the need of safety introduction. Chapter II describes the underlying technologies and their standards, giving an introduction of the most promising applications. Chapter III presents the simulator tools utilized to buildup the scenario. Chapter IV discusses in details the scenario created for running the simulations defining parameters and driver braking profiles. In Chapter V the obtained results are presented. Chapter V and VI contain conclusions and future works possibilities.

Chapter 2

Communication Technologies

In 2016 the NHTSA publicated a notice of proposed rulemaking NPRM in which DSRC technology and its practical introduction have been presented in details to the car-maker industry and public acceptance. The document is avilable here [4].
The proposal explain how, thanks to a DSRC on-board unit, a vehicle becomes able to send and receive particular Basic Safety Message including some important informations about absolute (and relative) position, speed and acceleration among others. The informations will be transmitted within the 5.850 to 5.925 GHz frequency range.
The first two layers of this communication protocol are addressesd by the *802.11p* that is an enhanced version of the *802.11* (covering physical and mac layer of the *OSI* protocol stack [5]) allowing V2V and *Vehicle-to-Roadside (V2R)* communication. *IEEE* also developed *P1609* higher layers stack [6] focusing on security, authentication and privacy (P1609.2), networking services (P1609.3) and multi-channel operations (P1609.4).
These two standards toghether form the whole architecture of a *Wireless Access in Vehicle Environments*, the so called *WAVE* protocol.
The agency believes that putting the technology in place will increase an initial price of a new vehicle varying from 135 to 300 $, including security management system, additional fuel due to the higher weight and communicational cost. Moreover the document expresses that "cost estimates were not expected to change significantly by the inclusion of V2V-based safety applications, since the applications themselves are software and their costs are negligible." [4].
This prosposal would try to convince the interested parties about that an initial investment of around 300 $, will result in a not negligible amount of money saved in the next future in terms of overall road mobility impact and number of crashes prevented. More precisely, taking into account only two of the most important safety application, they estimated that this technology will reduce the costs resulting from motor vehicle crashes by 53 to 71 billion $ in 2051.
In order to achieve its maximum effectiveness V2V technology has been though to be fused with vehicle-resident safety system, like camera, sensors, RADAR and LIDAR to enhance the functionality of both types of systems. Together, the two systems can provide even greater benefits than either system alone. In addition, V2V can be also seen as a complementary source of information taken from not immediately close surrounding, providing

timely warning respect to only on-board sensor equipped scenario.
Safety requirements must rely on a standardized way to easily and responsive communicate vehicle mobility and traffic informations; the standard SAEJ2735 addresses these requirements defining the content and the characteristic of the reference BSM.
The fact that this NRPM accurately outlines the lower layers of the architecture, presenting only some guidelines for the most promising safety applications, invites the reaserach community to create and customize several applications according to their specific needs.

2.1 802.11

802.11 is an IEEE standard [7] that specifies wireless interface between client and base station or directly among wireless clients. Usually in a wireless network all cards are able to switch between two operational modes such as the *infrastructure* mode, wireless nodes and an access point, and *ad hoc* mode, where instead only clients devices are present.
This standard designates the PHYSICAL and MAC layers defining layer 1 characteristic such as transmission speed and modulation mechanism, and layer 2 features like frame format, multiple channel access operations and collision management.

2.1.1 Physical Layer and Modulation mechanism

The pysical layer of 802.11 schema communicates in the 900 MHz and 2.4, 3.6, 5, and 60 GHz frequency bands. At this level of the stack, when spread spectrum techniques are performed the power of the transmitted signal is spread on larger frequency keeping constant the power of the signal itself. This operation for which a narrow band wave-form is transofrmed in an equivalent larger band signal results in a reduction of the power spectal density, making the transmitted information confusable with noise.

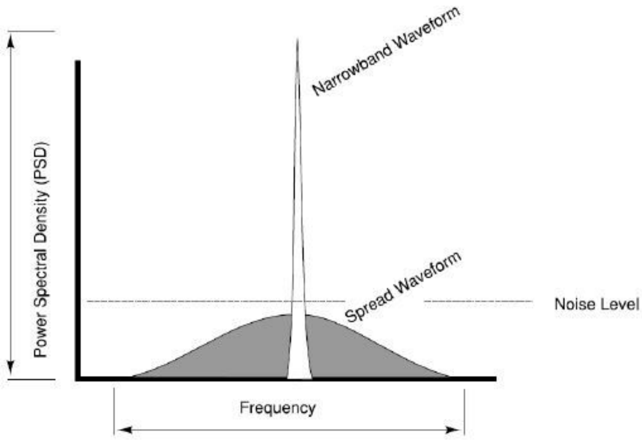


Figure 2.1: Spread Spectrum Technique

Supposing that $A(f)$ represents the power spectral density of signal A (Narrowband

Waveform in fig 2.1) and $B(f)$ (Spread Waveform in fig 2.1) is the power spectral density of the signal B received after the spreading operation, it holds

$$\int A(f)df = \int B(f)df.$$

Indeed, spread spectrum techniques are performed to mainly address the following aspects:

- Make the signal indistinguishable from noise. The possibility to detect and isolate it after the elaboration is reasonable only if the spreading operation is known a priori.
- Produce a signal more robust to jamming.
- Create a signal more robust to fading.

Direct Sequence Spread Spectrum (DSSS)

This particular spread mechanism enlarge the frequency of the signal by multiplicating the signal itself with a *cheap sequence*, represented by *PN bit stream* in fig 2.2. Each info bit is multiplyed by a *code sequence* that is formed by several cheaps of values +1 and -1 (or 0); in the particular case of fig 2.2, a code sequence is composed by 4 cheaps, so a cheap has a duration of one-fourth respect the original bit. In this way only the period of the signal is modified while the shape not.

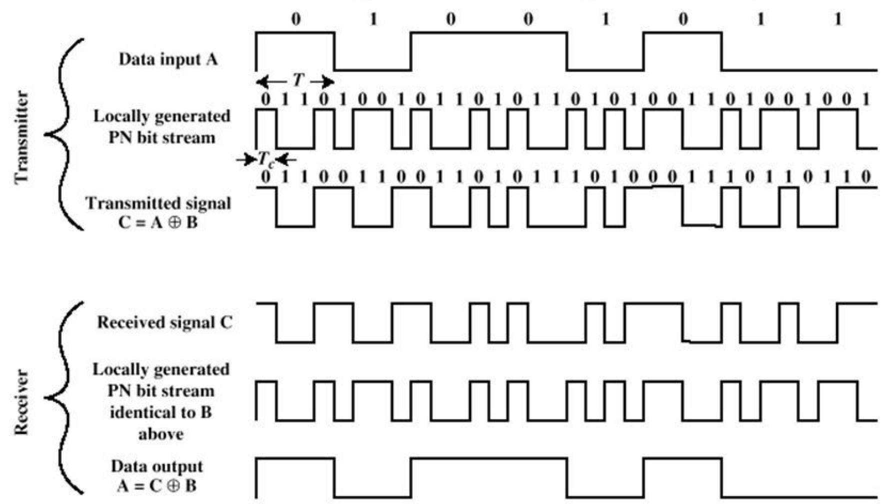


Figure 2.2: Direct Sequence Spread Spectrum DSSS

Once the signal C is received on the other side of the channel, the receiver performs exactly the same operation consisting in remultiplying the signal by the cheap sequence,

obtaining exactly the transmitted signal A plus some noise. Since noise introduced by the channel hasn't been yet spread by the transmitter, as soon the receiver operates the multiplication, the noise power spectral density is reduced and thanks to a simple filtering operation is possible to isolate the orginal information with a very small component of interference.
One important consideration of this modulation schema is that the sender and the receiver have to be synchronized, meaning that they both must be aware of the cheap sequence.
The entity of such a spread spectrum technique can be evaluated looking at its *Process Gain (PG)*, namely the ratio between W and B, respectively the band of the received signal and the band of the transmitted one. The higher PG, the more the signal has been spread in frequency, the higher the benefits.
The *Spreading Factor (SF)* instead represents the amount of cheaps used per each bit of the original signal, in other word the length of the code sequence.
DSSS is exploited by *Code Division Multiple Access (CDMA)* schema, where each user has its own code sequence, all of them belonging to the same family of orthognoal code. A large SF results in lots of users supported with the cost to decrease the transmission speed provided to each of them.
Moreover, DSSS allows to introduce robustiness to multipath and multiple fading, a peculiarity utilized by rake receivers whom are able to recognize among different signals and associate different delays to each of them for recombining all the shifted version received, as explained here [8].

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM sends in parallel several narrowbands channels at low symbol rate with *orthogonal carriers frequency.*
Thanks to this, the interference between adjacent frequency carriers is drastically reduced, because while all the sub-carriers are overlapped in frequency, their peaks are orthogonal each other, as depicted in figure 2.3.

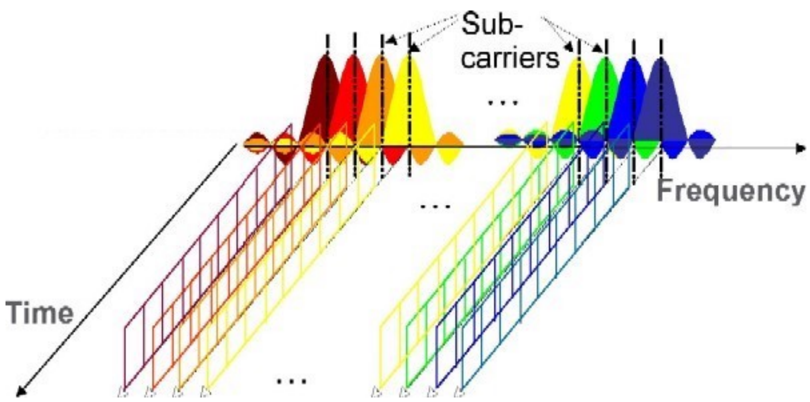


Figure 2.3: Orthogonal Frequency Division Multiplexing OFDM

Given two sub-carrier signals defined in time as

$$\varphi_1(t) = e^{\mathrm{j}2\pi \mathrm{f}_1 \mathrm{t}} \qquad \varphi_2(t) = e^{\mathrm{j}2\pi \mathrm{f}_2 \mathrm{t}}$$

they are said to be orthogonal if

$$\int \varphi_1(t)\varphi_2(t)dt = 0.$$

This multiplexing technique is also adopted in 4G broadband cellular network. More explanations on OFDM are accessible here [9].

2.1.2 Mac Layer and Channel Access Technique

For all the 802.11 versions, MAC layer covers numerous aspects such as resource allocation for channel access, data segmentation and assemblage, MAC addressing, frame format and error control.
Figure 2.4 reports 802.11 MAC frame format with all its fields.

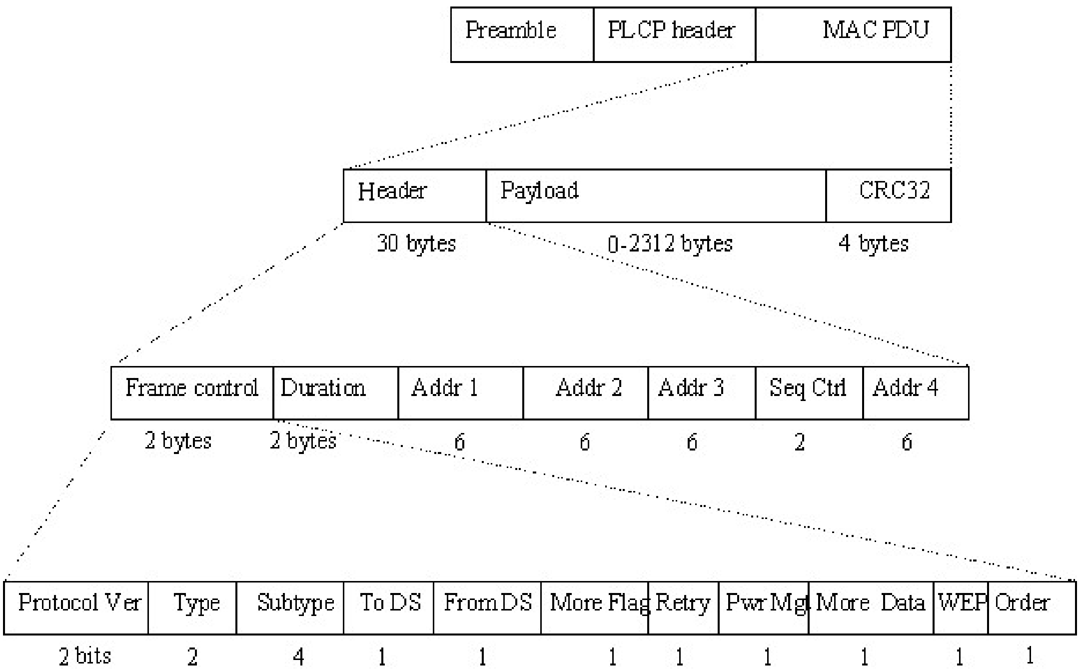


Figure 2.4: 802.11 MAC frame

The data transfer at this level can be considered an asynchrounous operation for *delay-tolerant* traffic, meaning that each node in the network makes its own decision to access the channel independetly on how all the other nodes are using their resources. Its clear that this control mechanism without a centralized entity will result in a framework with *Quality-of-Service (QoS)* not supported.

This *Distributed Coordination Function (DCF)* access scheme is based on *Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA)* since antennas listen the mean of communication and transmit only if this is assessed free. Since antennas are half-duplex they cannot hear the channel while sending, so this implementation is said to be Collision Avoidance because any time that a node detects the channel as busy, it starts a random recontend procedure (*BackOff procedure (BO)*) with the aim to minimize packet-collision probability (more than one packet sent on the channel in the same time instant).
Before providing an example of channel reservation attempt, we present the main time slots involved in the operation.

A time slot is defined as the sum of the *turnaround time* and the *power detection time*, respectively the time needed to switch between transmitting and receveing mode and the time required to integrate the power level over a specific period and compare it with noise power to decide if the channel is free or not. In 802.11b a time slot lasts for 20 μs.
The *InterFrame Space (IFS)* are intervals among frame transmission; the length of these times are used to establish the different priorities to access the channel. The main IFS are the following:

- **SIFS** stands for *Short IFS* and represents the shortest frame, used when two nodes are communicating each other. It is set to half of 1 slot: in this way a "dialog" can never be interrupted.

- **PIFS** represents the *Point Coordination IFS*; this time-frame is used by an Access Point for transmitting *Beacon* in order to keep nodes periodically synchronized. As a result, only the *Access Point (AP)* can access the channel between SIFS and DIFS. A PIFS is usually set equals to one SIFS and one time slot.

- **DIFS** is the *Distributed IFS* and is used by stations to verify the channel state before an attempt of transmission. The length of a DIFS is equal to a PIFS plus one time slot (SIFS plus two time slot).
  After DIFS is elapsed a station can start the BO procedure and try to access the channel.

- **EIFS** is a particular case of *Extended IFS* utilized whenever an error occurs at physical layer and MAC layer doesn't know how to behave as consequence of a not correctly packet reception. This longest interframe space suits for the case in which a device has to wait doing nothing. Its value is not fixed but it can reach values up to 100 ms.

Figure 2.5 depicts a succesfull transmission operation in which the sender senses the channel and detects it as idle; if this condition is still satisifed after a DIFS waiting-time period, the transmitter "grants" the possibility to send data. On the other side, the receiver computes the checksum to check if errors are present, then waits for SIFS time unit and sends back the *Acknowledge (ACK)*.
If the transmission succesfully occurs, as in this demonstrative case, the frame is delivered with an header contaning the *Network Allocation Vector (NAV)* used by all the other

listening-nodes to be informed about the channel unavailability period (defer access). NAV interval is computed as the sum of *MAC Protocol Data Unit (MPDU)* duration and a SIFS interframe and an ACK.

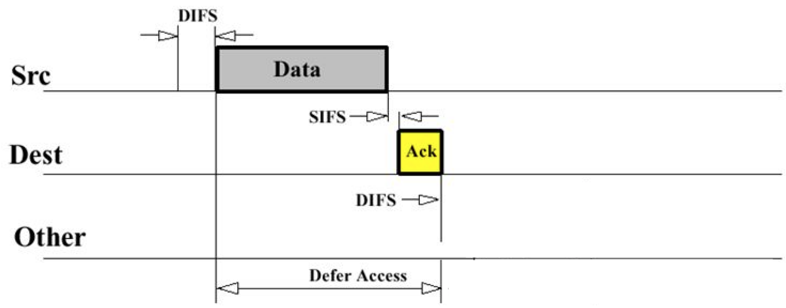


Figure 2.5: Succesfull data transmission in DCF access mode

On the other hand, anytime that the channel is checked busy, a recontention for the channel is performed also known as BO procedure. As long as for channel-busy event, also unseccusfully frame transmission and the intention to keep going the transmission for the subsequent frame cases trigger the BO procedure.
The BO procedure is esemplified in the listed below.

1. A station senses the channel. If this latter is busy, the station waits (according to NAV) until it becomes idle.

2. As soon as the channel is idle, the station waits DIFS and computes the *BO interval*.

3. The station update its BO counter and decrease it each time unit.

4. When BO count becomes 0 the station is immediately able to transmit a packet.

BO interval is basically a time defined as a time slot multiplied by a random number, where this random number is extracted from a unifrom distribution bounded by 0 and *Contention Window (CW)*.
The criteria here is to start with a predefined value of CW, computed as $2^{\mathrm{BE_{min}}} - 1$ (where *Binary Backoff* $BE_{min} = 5$ in /b standard), and increase the value of BE anytime an unsuccessfull transmission attempt is registered; according to this algorithm the CW is doubled each time that B0 reaches the value 0 and the channel is sensed busy, decreasing the probability that two CWs are equal and expire at the same time. Obviuously, the larger BE, the larger CW, the smaller the collision probability.
The BO procedure is done also to desynchronize contending stations and introduce fairness among them.
Another version of DCF with *Hand-Shacking* exists in order to solve the *hidden terminal problem* when large packet have to be sent in the network or a consistent number of terminal want to access the channel. In this case, specific interframes called *Request to Send*

(RTS) and *Clear to Send (CTS)* are used to reserve the channel access.

In case of necessity for a centralized control and the introduction of a QoS supported mechanism, the *Point Coordination Function (PCF)* has been implemeneted. Here, the channel access tries to occur in a *Contention-Free (CF)* period. More precisely, stations declare themselves and their relative MAC addresses to an AP working as central controller: then the AP creates a static *polling list* thanks to which it will be able to poll all the stations according to its list. In this way, stations can freely transmit only in response to a poll performed by the AP.
When PCF contention-free and DCF contention period coexist in a structure announced by a Beacon, this frame is called *superframe*. Anytime a superframe ends, the AP has to recontend for the channel and if this is detected busy, the transmission of the beacon is delayed, resulting in a not always constant superframe duration.
As introduced before, general 802.11 schema itself doesn't provide reliable mechanism to establish different levels of priority for introducing QoS, mainly because:

- **Unpredictable Beacon Delay**: since beacon transmission can be delayed during the contention period, the duration and the beginning of the PCF is not always invariable. For real-time traffic which needs a maximum delay guarantee, that system doesn't fit.
- **Unknown Transmission Duration**: Whenever the AP polls a station it doesn't know in advance if the station has packets to send (and how many), how long packets are and bit-rate of each station.
- **Huge Overhead**: Since the AP works with a static polling list, can happen that the list contains users with nothing to send, and the AP wastes time anyway looping through all the stations.

2.1.3 802.11e and QoS

In 2005 IEEE working group defined an enhancement to 802.11 standard with the aim to support QoS in wi-fi networks. 802.11/e includes changes only at MAC layer level [10].
This standard is able to remove some *anomaly effect* [11] due to the packet fairness approach of the 802.11 family standards.
Indeed, this platform works according to *temporal fairness* providing 8 different classes of service.
The *Enhanced Distributed Channel Access (EDCA)* represents an equivalent version of DCF/PCF presented in 2.1.2.
The composition of EDCA contention period and *HCF Controlled Channel Access (HCCA)* free contention period form the *Hybrid Coordination Function (HCF)* similar to previous AP controller.

The ECDA is described by the possibility for a station to send information along the channel seen as a *Transmission Opportunity (TXOP)*, meaning that each node can transmit as much data as it can in a given amount of time delimited by starting time and

maximum duration (burst transmission).
In EDCA TXOPs are allocated via contention according to 4 *Access Categories (AC)*.
At MAC layer every card is equipped with 4 queues storing packets according to their type of traffic, associated with relative AC priorities.
The four AC defined are:

- **AC_BK** *Background Access Category*
- **AC_BE** *Best Effort Access Category*
- **AC_VI** *Video Access Category*
- **AC_VO** *Voice Access Category*

where for higher priority categories (Voice, Video, Best Effort and Background in decreasing order), shorter values of BO and *Arbitration InterFrame Space (AIFS)* are specified inside the Beacon frame.
Anytime a frame goes onto MAC layer, a QoS field is added to its structure for identifying and translates different traffic type into different AC. The QoS field is 2bytes long and it includes *traffic ID*, power save information, ACK policy (cumulative-ACK like-version annexed) and TXOP limit, this latter which directly depends on the payload data nature.
If two packets of the same station belonging to separate AC queues want to access the channel concurrently, only the one with higher priority will deliver its packet. This simple mechanism solve only local node collision problem.

AC	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$
AC_BK	CW_{min}	CW_{max}
AC_BE	CW_{min}	CW_{max}
AC_VI	$(CW_{min}+1)/2-1$	CW_{min}
AC_VO	$(CW_{min}+1)/4-1$	$(CW_{min}+1)/2-1$

Table 2.1: AC-CW association

This is the reason because table 2.1 reports different CW values associated to different AC priorities, for desynchronize BO procedure made by different stations.

On the contrary, HCCA is a centralzed access method coordinated by a controller. It is able to control the channel thanks to the *Hybrid Coordination (HC)* mode, providing deterministic channel access in a polling fashion.
Its most important features are the possibility to operates in both CFP an CP modes, aka *Controlled Access Period (CAP)*, and to allocate TXOP using QoS dependendancy CF-Poll frames.
HC behaves like a three states system:

- **when in CP** can send CF-Poll frame only after a PIFS idle time and then enter in CAP mode.
- **when in CFP** is the only entity entiteled to grant a station assigning to it TXOPs.
- it can **always** allocate TXOP to itself but only after a PIFS idle period.

In the same way, stations follow a similar procedure:

- **when in CP** can gain TXOP as a consequence of a receprion of a CF-Poll sent by HC running in CAP mode, or using the standard contention mechanism like in EDCA.
- **when in CFP** do not attempt to access the channel since the only manner to send is to wait to being polled by HC.

This particular framework also supports traffic signalling allowing to serve only non-empty queues and to negotiate in advance some resourced to be reserved by the controller.
The problem of unpredictability beacon delay is still not totally solved, while instead two relevant improvements to the 802.11 previous drawbacks are introduced:

- thanks to its time basis approach, 802.11e has an idea about the TXOP maximum transmission duration, since each station can never exeeds its TXOP transmission limit,
- looking at the QoS frame field the schedulers are able to skip empty queues significantly reducing the overall delay.

2.1.4 802.11p

IEEE developed 802.11p version [12] for Vehicular communications; this standard runs on the frequencies around 5 GHz specifically reserved for *Intelligent Transport System (ITS)*.
802.11p addresses PHY and MAC layer of the WAVE protocol stack, that has the main task to provides specifications for communication environments where connectivity last for a very short time and, thus, data trasfers have to occur within short time intervals.
802.11p PHY layer is compliant with 802.11a, since they both use OFDM modulation technique at layer 1.
The data rate achevable is in the order of 3 Mbs using BPSK modulation until 27 Mbs exploiting 64 QAM modulation schema.
The communication range can change depending on the surrounding enviroinment (vehicular density) tuning the transmission power of the antenna.
The physical structure is composed by 7 channels, each of them with a bandwidth of 10 MHz, covering the frequency range from 5.85 to 5.925 GHz.
As is possible to see from figure 2.6, the channel-band starts with a *guard band* of 5 MHz.
The 7 channels are further subdivided in two sets of 3 *Service Channel (SCH)* separated in the middle by one *Control Channel (CCH)*, used respectively for general kind of services and to the transmission of safety relevant data.

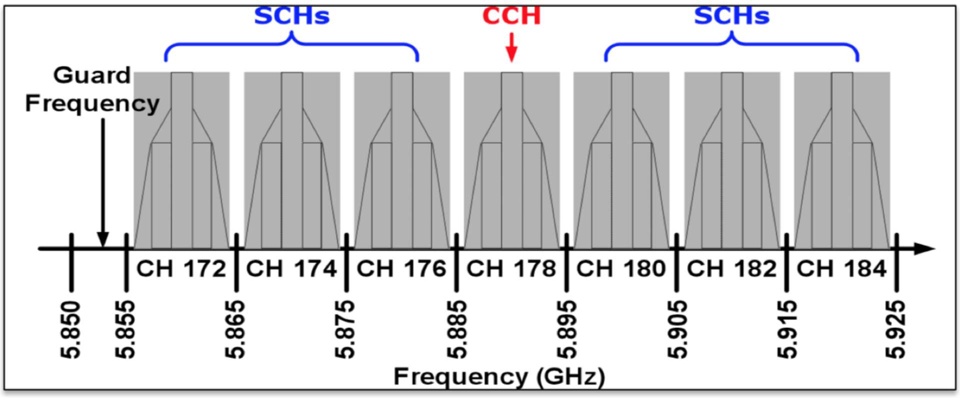


Figure 2.6: 802.11p frequency allocation

Also 802.11p MAC layer is very similar to 802.11 already explained; as a matter of fact it is based on CSMA/CA and include some features of 802.11e.
Peers of the same network work in ad-hoc manner, sending advertisement each other in order to partecipate into the system, creating a *Wave Basic Service Set (WBSS)*.
The architecture, as said, recalls EDCA used in 802.11e to support QoS.
An important part of this approach is the so called channel coordination, having as principal scope the management and supervisory of SCH and CCH allocation. As done for the previous implementations, a CCH and a SCH are put together (sperated and delimited by guard intervals) to form a *synchronization interval* (like a superframe) of 100 ms. These guard intervals are conceived to account for synchronization errors and also to allow to stations not *Global Positioning System (GPS)* equipped to stay aligned with the time reference *Universal Time Coordination (UTC)*).
Summarizing, CCH is used for

- broadcast safety communication,
- announce services on a specific SCH.

While instead SCH are used for

- specific applications (such as tolling, internet access, etc..),
- execute different application services in parallel,
- require WBSS initial setup.

Unfortunately, this method present as drawback a non negligible delay whenever a station working in SCH mode has to urgently delivered a safety message. In this particular situation the node must wait to enter in CCH to send or listen for this event, cleary resulting in a waste of precious time. Moreover, the higher the number of nodes in the network (congested scenario), the higher will be the packet collision probability.
Again, specific parameters like AIFS, CW_{min}, CW_{max} and TXOP have been assigned to each different AC. We report both CCH and SCH parameters value in table 2.2 and 2.3.

AC	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$	AIFS	TXOP limit
AC_BK	CW_{min}	CW_{max}	9	0
AC_BE	$(CW_{min}+1)/2-1$	CW_{min}	6	0
AC_VI	$(CW_{min}+1)/4-1$	$(CW_{min}+1)/2-1$	3	0
AC_VO	$(CW_{min}+1)/4-1$	$(CW_{min}+1)/2-1$	2	0

Table 2.2: EDCA parameter set used for CCH

AC	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$	AIFS	TXOP limit
AC_BK	CW_{min}	CW_{max}	7	0
AC_BE	CW_{min}	CW_{max}	3	0
AC_VI	$(CW_{min}+1)/2-1$	CW_{min}	2	0
AC_VO	$(CW_{min}+1)/4-1$	$(CW_{min}+1)/2-1$	2	0

Table 2.3: EDCA parameter set used for SCH

2.2 WAVE P1609

IEEE 1609 Working Group released WAVE, that namely is an architecture and a complementary, standardized set of services and interfaces that collectively enable secure V2V and *Vehicle-to-Infrastructure (V2I)* wireless communications in order to achieve safety, mobility and commercial advantages. Together these standards are designed to provide the foundation for a broad range of applications in the transportation environment, including vehicle safety, automated tolling, enhanced navigation, traffic management and many others [13].
At its lower layer, WAVE implemenets the 802.11p amendment. The whole WAVE protocl stack is depicted in figure 2.7.

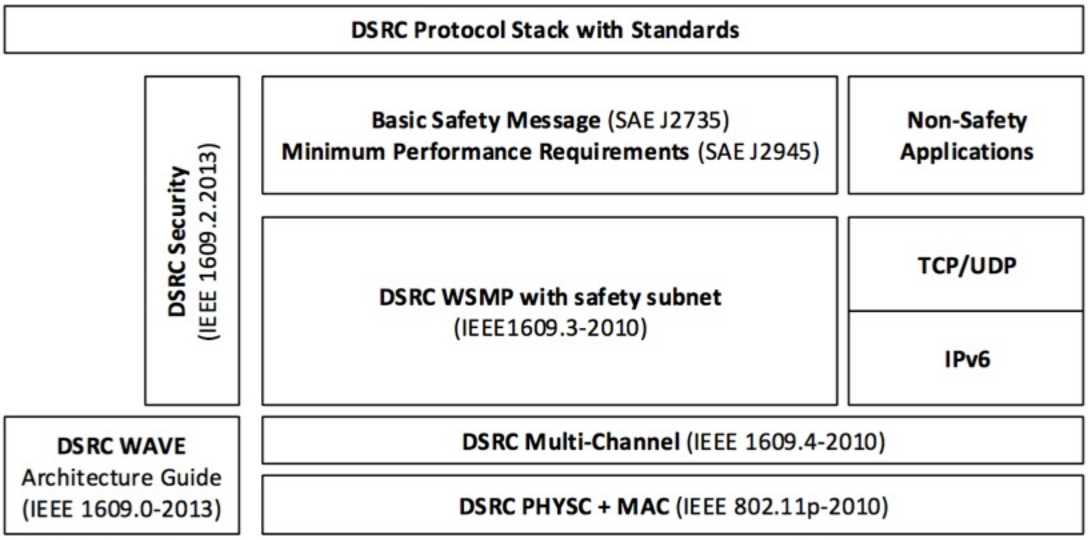


Figure 2.7: WAVE protocol stack

The reason beacuse a specific stack has been designed for this particular type of technology is that 1609 addresses both V2V and V2I mainly focusing on ad-hoc communiactions. We briefly introduce the 1609 modules present in figure above.

- **1609.0**: this module provides a guide to the general architecture of WAVE standard. All the 1609 standards are presented here.
- **1609.2**: it covers the Security Services for Applications and Management Messages aspect. This module affects all the other services present in the stack, securing authentication and integrity of message management. 1609.2 exploits the usage of both private and public infrastructure symmetric key. A practical example rise from the *Elliptic Curve Cryprography (ECC)* algorithm [14].
- **1609.3**: *Wave Short Message Protocol (WSMP)* shapes this standard describing Networking Services. Network and Transport OSI layers are represented here, as well as IP, UDP and TCP Internet protocols. This module is the core of the WAVE architecture providing addressing and data delivering; according to the frame size, it can forward traffic onto the WSMP in case that the frame size is under a certain threshold: all the other traffic flows instead goes on IP/TCP protocol. In this way the system is able to quick and reliable exchange specific short informations. Obviouously, it fits in high dynamic condition scenario.
  Moreover, WSMP is usefull for higher and lower layers due to the fact that it include mobility information such as position, speed, acceleration and direction among others. This module results particularly advisable for developing light and fast applications for vehicles.
- **1609.4**: this is the module that manages multi-channel operation, access prioratization, management services and channel switching and routing. It can be considered as an extension to the provided 802.11p MAC layer.

2.3 SAE J2735

Once the whole WAVE architecture has been put in place, a way to consent vehicles to understand each other is strictly required to ensure interoperability.
The task of *Society of Automotive Engineers (SAE) J2735* is exactly to define and standardize the content and the structure of the messages exchanged at application layer, without the need to standardize applications. The final goal of SAE J2735 is to provide a standard message set that can be universally approved and recognized.
We've already seen that WAVE protocol is designed to operates efficently over the DSRC thanks to the short size of the continuosly broadcasted information exchange. To do so, a *dense encoding* is used to define this standard, using three-way approach:

- **Data Element**: is the smallest and simplest division of information to be standardized.

- **Data Frame**: represents the next step, merging data elements.

- **Message**: this is the most complex information structure delivered in the system. A message is the payload that travels down towards 1609 and 802.11p lower layers.

These data concepts are described by *Abstract Syntax Notation (ASN)* and XML syntax and than encoded by *Basic Encoding Rule (BER)* to reduce overhead in the transmissions [15].
J2735 doesn't need a common header and none of it has been defined. The only mandatory part in every J2735 message must be the *DSRCmsgID*, reported as the first element of every message.

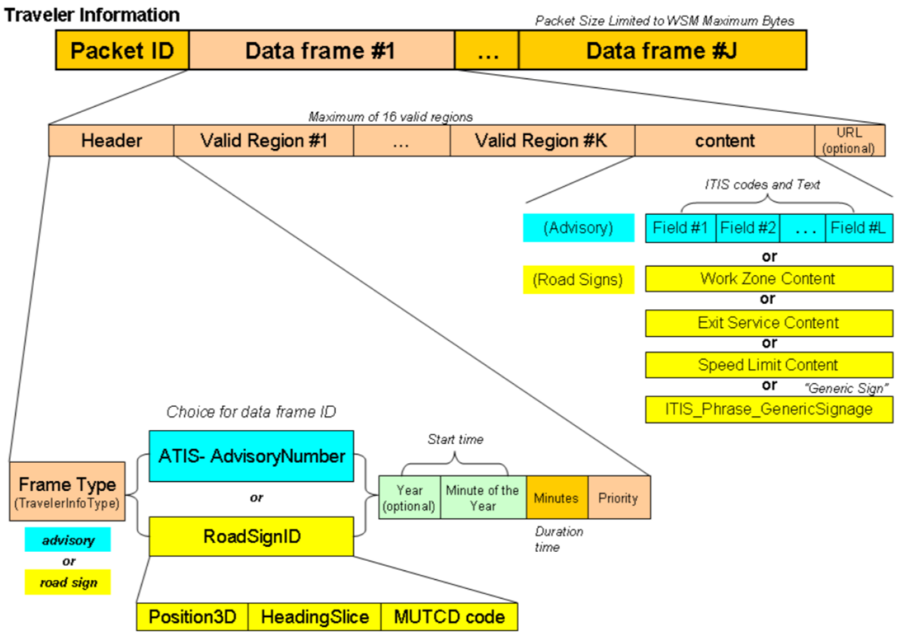


Figure 2.8: Packet format

We present below a list of some messages defined by SAE J2735, addressing specific traffic cases.

- **Basic Safety Message (BSM)**: is the most broadcasted and data-furnished type of message exchanged on this type of networks. It contains the safety data regarding vehicle and it is contiunuously sent over-the-air to surrounding vehicles to keep vehicles always aware of the neighborhood evolution. The U.S. standards defines the transmission rate to 10 Hz.
  BSM practically contains the majority of data required by safety applications.
  Table 2.4 shows the two parts composing this message:

Part I		
msgID	DSRCmsgID	1B
msgCnt	MsgCount	1B
id	TemporaryID	4B
secMark	DSecond	2B
pos	PositionLocal3D	
— lat	Latitude	4B
— long	Longitude	4B
— elev	Elevation	2B
— accuracy	PositionalAccuracy	4B
motion	Motion	
— speed	TransmissionAndSpeed	2B
— heading	Heading	2B
— angle	SteeringWheelAngle	1B
— accelSet	AccelerationSet4Way	7B
control	Control	
brakes	BrakeSystemStatus	2B
basic	VehicleBasic	
size	VehicleSize	3B
Part II (optional)		
eventFlag		
pathHistory		
pathPrediction		
RTCMPackage		
others		

Table 2.4: BSM message structure

1. **Part I**: this is the mandatory part and has to be present in all BSM messages. The entirely Part I, except for the DSRCmsgID field, is called *BSMblob* which is an octet blob used to convey a vehicle's position and motion and other critical data to be sent in the BSM. This blob set of data comprises the informations that must be updated most frequently and can be used also in other messages.
2. **Part II**: these fields are optional and can be customized according to the specific applications needs. Part II can included periodically (less frequent and/or for a given amount of time) or triggered by an event or request.

For a matter of clarity, the two words beacon and BSM will be used interchangeably for the same meaning, from now onward.

- **Common Safety Request (CSR)**: thanks to this message, a vehicle is able to directly ask to another vehicle an explicit information required by a particular safety application running on the sender side. The responding node can include this information inside Part II of BSM broadcast message.

- **Emergency Vehicle Alert (EVA)**: this message is used to warn surrounding vehicles about an emergency situation. It is usually used by Emergency Vehicle Operation (911). EVA appends to a normal message information such as the number of vehicle involved in the incidents and the gravity of the situation. It can be used both by private and public vehicles.

- **Intersection Collision Avoidance (ICA)**: ICA deals for providing data to the vehicles to recreate information about the status of the intersection and the characteristic of the vehicles present.

The only precise guide that SAE J2735 standard gives for message managemetn is the information about messages priority; whenever a packet has to be passed to lower layers, these must know how to treat the packet to schedule its transmission. As a consequence, two types of priority can be identified:

- **User Priority**: the IEEE WAVE Standards 1609.3 and 1609.4 define three bits for the priority of a message, which can therefore take values from 0 to 7, where 7 represents the highest possible priority. These levels of message precedency are needed to determine how a MAC sub-layer frames has to compete with other MAC frames in order to access the wireless channel.
  The default User priority of a message is equals to zero.

- **Access Category**: these types of priority are instead associated with the MAC layer defined by IEEE 802.11 standard and they range from 0 to 3 where 3 is the highest possible one.

Is clear that a way to match these two types of message priority is needed for having consistency in the whole protocol stack.
Table 2.5 displays the User Prority and Access Categoty associations.

Access Category	Priority
AC3	7
	6
AC2	5
	4
AC1	3
	0
AC0	2
	1

Table 2.5: Access Category - User priority matches

The message priority is a function only of the message type and the message content. It represents the combination of message urgency and importance. Indeed, SAE J2735 defines the criteria to select and assign priority to messages according to the two following definition of urgency and importance:

- **Urgency**: many applications are predicted upon allowable communications latency. The range of that latency defines the urgency of the message; if the message requires quick transfer from sender to listener, it has a higher associated urgency.

- **Importance**: the first level of priority is associated with societal and/or safety impact, and prioritizes safety above all other applications and/or communications. The greater the potential for saving life or preventing injury, the higher the importance the message and message sets receive.

2.4 Applications

So far, V2V technology has been practically traduced into some promising safety applications, that fusing with already asserted on-board techonolgies will try to revolutionize the road traffic mobility.
If these applications will receive important and positive feedback at the beginning of their introduction, they could also be adopted for any future self-driving projects. Indeed, the U.S. rule proposal states that: it is irrefutable that V2V, V2I, and V2P communications will be absolutely critical to the successful development of self-driving vehicles that can avoid collisions, navigate responsibly, and achieve a transport objective efficiently and in a timely manner.
Below a brief introduction of some of that is given.

- **Forward Collision Warning (FCW)** This system is intended to warn drivers about a possible incoming front-end collision with the vehicle ahead in traffic in the same lane and direction of travel.

It addresses the 3 most common crash cases depicted when a leading vehicle stops, decelerates or moves from its previous position. As a matter of fact, these three scenario alone, represent the majority of rear-end collision.
While this system is able to work beyond line-of-sight and radar sensors, it doesn't attempt to control the host vehicle in order to avoid an impending collision.
FCW suffers of some system intrinsic imprecisions due to alert timing reception, vehicle instantaneous speed and road environmental conditions like radius of curvature.

- **Emergency Electronic Braking Light (EEBL)** This application has been though to integrate or replace the warns provided by the brake lamps of decelerating car ahead in traffic, whenever bad weather conditions or a big vehicle obstruct the line-of-sight.
  Indeed, without any kind of V2V communication a following vehicle cannot be aware about the braking intensity of vehicles in front just looking at their brake lights; moreover, in case of heavy rain or fog or a truck between two cars, is possible that incoming cars see the red lights with considerable delay resulting in pile-up collisions.
  EEBL bypasses these inconvenients by forcing the host vehicle to broadcast a self-generated message containing the information of the strong braking, as soon as a given deceleration threshold is overcome. [4] suggests this deceleration value to be greater than 0.4 g.
  Figure 2.9 describes an example situation in which a truck impedes following vehicle to see braking lights of vehicle in front of it.

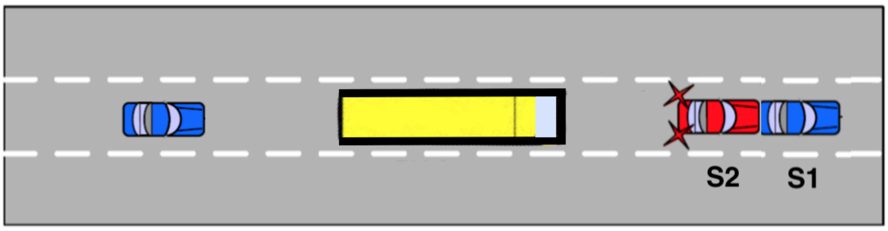


Figure 2.9: EEBL example scenario

As well as hard-braking event information, the EEBL message can contain other more specific data about sender such as position, speed and deceleration. Thanks to these informations and a timely message reception, the host vehicle can counteract the impending dangerous situation by means of some automatic vehicle mechanism (*Automatic Emergency Braking (AEB)*) or promptly warns the driver.

- **Left Turn Assist (LTA)** LTA is one of the most problematic application to implement, since it is based on the activation of the turn left signal performed by the driver, but this is activated only in the 75% of turn-left cases. [4].
  In fact, this safety application willing to inform a driver whenever a turn left attemp

may not be considered safe, due to traffic conditions.
More test are needed in order to better evaluate LTA, since on one hand is difficult try to predict left turn without light indicator and on the other hand, this prognostication approach can easily lead to false warning annoying drivers.

- **Intersection Movement Assist (IMA)** This safety application is intended to warn drivers anytime it is not safe to enter in an intersection due to the high collision probability. This application could be able to address the majority of crossroad dangerous situations. However, it can generate false warning as a consequence of several road shapes.

- **Blind Spot Warning/Lane Change Warning (BSW/LCW)** The BSW/LCW safety application advise the driver during a lane change attempt if the blind spot zone into which the vehicle intends to move is, or will be soon, occupied by an other vehicle travelling in the same direction. Furthermore, this application advise the driver when a vehicle in the adjacent lane is positioned in a blind spot zone even if a lane change is not being attempted. These advises elevate into warnings if the host driver activates the turn left signal indicator.

Chapter 3

Mobility Models and Simulators

In these last years MANET technology is being interpreted more and more like VANET, where its nodes are featured by high mobility and forced to move on predefined roads.
As a consequence, with the improvement of the technology, the term VANET is becoming synonimouos of Intelligent Transport System, and a way to study in depth this new branch is strictly necessary, for example for the implementation and further evaluation of safety road applications. As said, VANET is intrinsically characterized by the mobility of its vehicles-nodes, which frequentely travel at high speed and in large scale scenario. This peculiarity leads to a main disadvantage: deploying, implementing and testing VANET projects in real world environment can be time-consuming and economically too risky and prohibitive, in particular during the first approacching tests.
So simulation is actually the only feasible solution when these special type of applications have to be tested. Simulation of VANETs networks in particular, requires two different components: a traffic (or mobility) simulator and a network simulator.

- **Mobility Simulator**: to analyse vehicular ad hoc network characteristics and protocol performances, traffic simulators are needed to generate position and movement information of each single vehicle in VANETs environment.

- **Network Simulator**: to model and analyse the functionality of VANETs, a network simulator is required to support protocols and manage the exchange of messages between vehicles. A suitable network simulator should possess some features including a comprehensive mode, efficient routing protocols and communication standards (like IEEE 802.11[p] and IEEE 1609 specifications).

Figure 3.1 shows different available simulator tools.

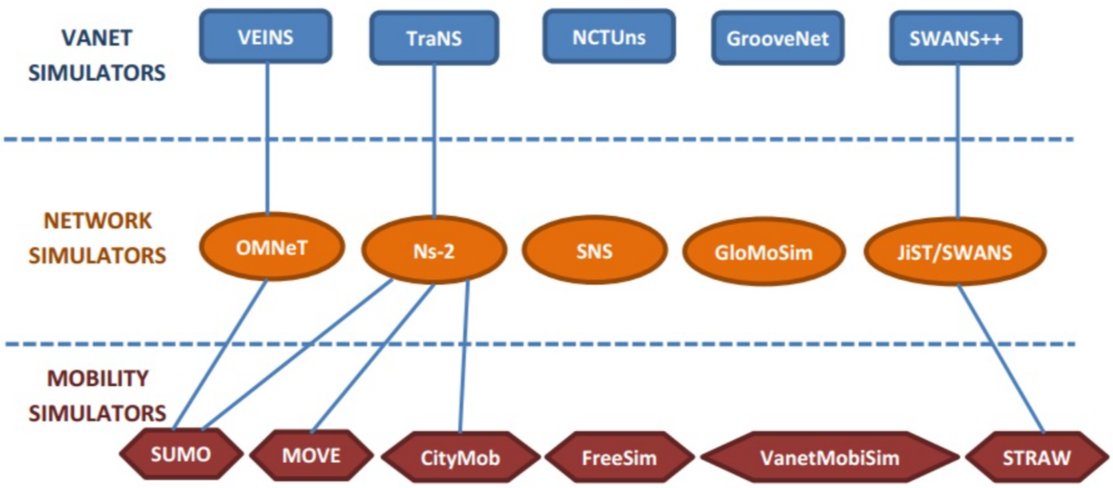


Figure 3.1: Classification of VANET simulators

In this thesis we've been chosen two open source tools to ricreate the scenario: SUMO that is a microscopic road traffic simulator and OMNeT++ a free and flexible network simulator.

3.1 SUMO

Simulation of Urban MObility (SUMO) [16] is an open source, highly portable and microscopic traffic simulator mainly developed from 2001 by employees of the Institute of Transportation Systems at the German Aerospace Center; it is licensed under the *Eclipse Public License (EPL)*.
Microscopic traffic is a specific type of mobility modelling approach for which each single vehicle-driver is defined by several parameters (like positioning, velocity and direction), in contrast with the macroscopic one, where instead mathematical traffic models are used to formulate relationship among traffic flows characteristic like density, flow, mean speed etc. [17] [18].
SUMO is purely microscopic as long as each vehicle running in the simulation obeys explicitly to its own parameters defined in a specific file.
To realize the potentiality of this space-continuous and time-discrete simulator, is enough to have a look here [19] about the number of variables associated to each car and the possibility to set/retrieve their value at each instant of the simulation.
Simulations are deterministic by default but there are various options for introducing randomness.
In addition, the tool *NETEDIT* easily allows to create your own personal map and on the other hand, SUMO provides the possibility to import an existing urban configuration and customize it, if necessary.
The simulator SUMO is written in C++ portable libraries and everything is easly defned

by xml files, such as *net.xml* and *rou.xml* inside the configuration file which load the map and routes crossed by different type of vehicles respectively.
This package includes among others, the *Krauss* car following models set as the standard behaviour that is collision-free. As a matter of fact, a realistic management of vehicle collision (car-interaction maneuver) is not addressed by this framework.
This simulation environment is provided to the final developer by a user-friendly gui interface. At the time of writing the latest release is the 0.32.0, but for our project we use the 0.29.0 stable version.
Last but not least, it is supported by a vibrant and strong community.

3.2 Omnet++

OMNeT++ [20] is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators.
It has generic arhitecture so it can address many differents problem:

- modeling of wired and wireless communication networks
- protocol modelling
- modeling of queueing networks
- modeling of multiprocessors and other distributed hardware systems
- validating of hardware architectures
- evaluating performance aspects of complex software systems
- in general, modelling and simulation of any system where the discrete event approach is suitable, and can be conveniently mapped into entities communicating by exchanging messages.

It is considered as a very good and powerfull tools in the simulation and research scope, because of its flexibility.
Another key strength is the modularity that this framework offers; as a matter of fact, the basic component of any kind of feasible architecture is called module (simple module) and combining several of them implementing different algorithms, is possible to create big and complex *models* (compound modules) as depicted in figure 3.2. These models can be further joined toghether via gates. This iteration has no theoretical end, allowing developers to conceive unlimited projects.
Informations among modules are passed via *messages* whom can even carry whole data structures.

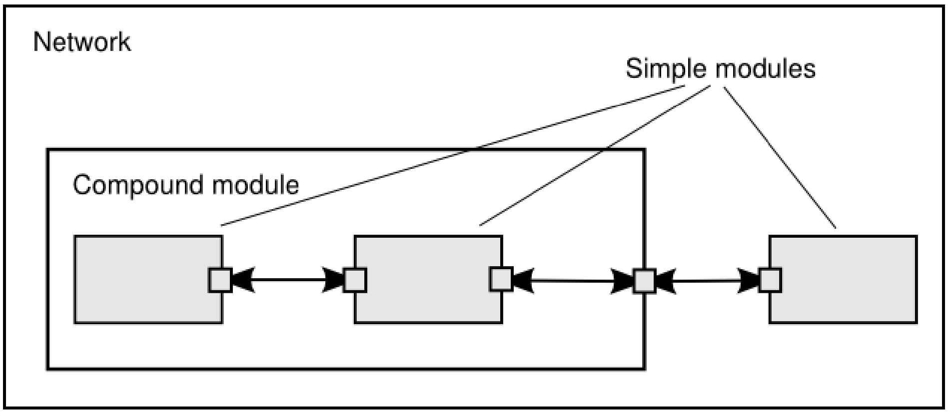


Figure 3.2: Example of simple Omnet project architecture

Omnet++ is a *Discrete Event Simulation (DES)* framework, meaning that state change events occur only at a discrete time instances and they take zero time to completely execute.
All the objects and the structures introduced so far are described by users in *NEtwork Description (NED)* language. NED files let users to declare the network topology and connect from simple to more complex modules to each other.
These NED files are among the most important files and their main features are:

- **Hierarchical**: each single module can be decomposed in more and simpler submodules.
- **Component-Based**: simple modules and compound modules are inherently reusable.
- **Interfaces**: module and channel interfaces can be used as a placeholder.
- **Inheritance**: modules and channels can be subclassed.
- **Packages**: the whole structure is packaged to reduce the risk of name clashes between different models.
- **Inner types**: channel types and module types used locally by a compound module can be defined within the compound module.

Another important file is the one named *omnetpp.ini* in which parameters needed to start the simulation are defined and load into the initial configuration, when not specified inside NED files.
The simulation system provides several components to the final user; indeed, the simulation can be run directly by the system kernel, flagging the option *Cmdenv* in the running configuration parameters, otherwise two graphics environment are supplied, respectively *Tkenv* and *Qtenv*. All these elements are written in C++.
During the drafting of the project the current Omnet++ version was 5.1 but we utilized the version 5 for compatibility reasons.

3.3 Veins & TraCI

Veichular in Network Simulation (VEINS) is an open source framework for running vehicular network simulations. It is based on two well-established simulators: OMNeT++, an event-based network simulator, and SUMO, a road traffic simulator. It extends these to offer a comprehensive suite of models for IVC simulation [21].
This library contains a particular extension with the task of making in communication the two aforementioned simulators, where SUMO acts as server that the Omnet++ client regularly queries about device mobility in order to update its network topology accordingly. This simple client-server architecture without-question relies on the *TCP/IP* protocol suite.
The *Traffic Control Interface (TraCI)* allow the developers to online retrieve and edit vehicle parameters like for example for changing a particular route as a consequence of an event occurred in the proximity or for modifying some vehicle driving profile.
The two protocol stacks IEEE 1609.4 and 802.11p presented in 2.1, as well as QoS channel access schema and background intereference noise, are part of the package, furnishing a complete and realiable platform for testing applications. The fact that Veins is open-source, leaves the door open to create your own personal command that your implementation needs to know for taking decision for eventually shaping the traffic flow. We've strongly employed this characteristic for modelling our application.
More precisely, we've customized the TraCIMobility class with an ad-hoc traffic flow pattern and then create our personal safety application on top of it.

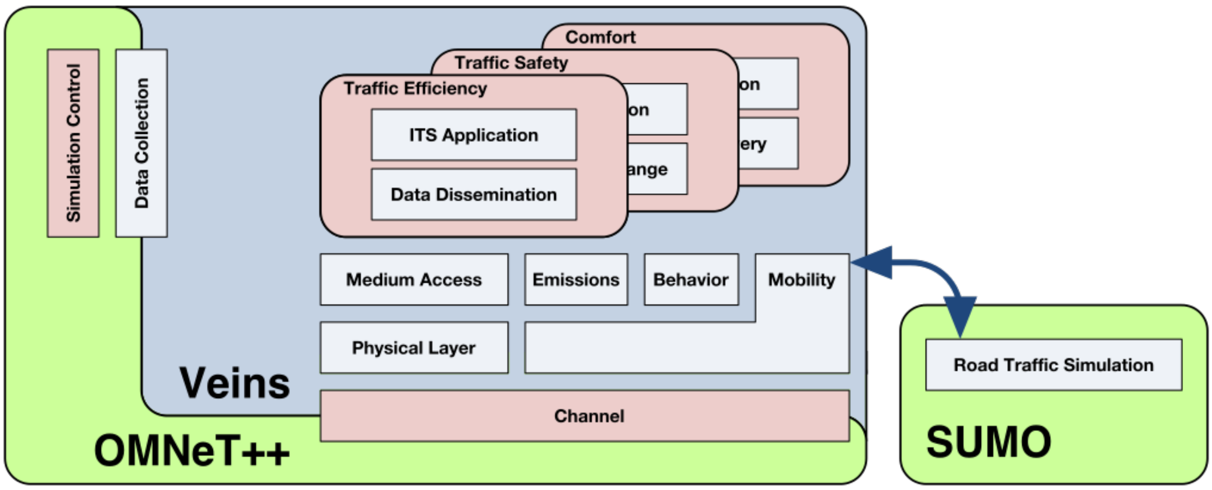


Figure 3.3: VEINS framework

Chapter 4

Scenario

The work aims to inspect the benefits of an EEBL V2V safety application taking into account several technological, environmental and human conditions.
As first, we decided to test the framework on a highway road because the nature of the application itself, that provides good performs in high speed situations. Then the presence of V2V technology has been varied as number of vehicles equipped with DSRC on-board module, to underline how this technology and its possible application can affect the traffic flow in this peculiar case given different *Penetration Rate (PR)* in the first-five years from the U.S. rulemaking proposal. Furthermore, a strictly human component has been inserted into the mobility model with the task to emulate the delay and unpredictability of the human component to a sudden and impending emergency event.
The scenario set to run the simulations relies on a piece of Autostrada del Brennero (A22 motorway) near the city of Trento, lead by the local motorway operator and by *FIAT Research Center (CRF)*, showed in figure 4.1. The test site is one of the seven European cities involved in the DRIVE C2X project [22].
The map has been imported exploiting the framework OpenStreetMap, which is able to convert the map into a customizable xml file; in this case the obtained map-file has not been edited for working with a scenario as close as possible to reality.
The road is provided with 2 lanes per direction and already equipped with ICT infrastructure for mobility [23].
According to Autostrada del Brennero [24] several traffic conditions can occur, that are translated into different levels of vehicles denisty and speed, respectively reported in table 4.1.

Traffic Density	Vehicles per hour	Speed [m/s]
Low	1580	32
Medium	2163	30
High	3305	25

Table 4.1: Traffic vehicle characterization

In order to create a scenario for testing an application such as EEBL, a leader followed by a fleet of cars has been forced to travel on a predefined path crossing a trait of the motorway. At a certain point along the road the first car of the fleet suddenly performs an emergency braking maneuver with an intensity of $7\,\mathrm{m/s^2}$ until it completely stops, due for example to a accident occured on the highway.
The following vehicles able to receive the EEBL warning message will take advantage from the timely advise of the dangerous impending situation with the aim to prevent or mitigate a possible pile-up crash from occurring.
For sake of simplicity only single lane test have been performed; modelling applications addressing multi lane scenario is out of the scope of this project.

4.1 Penetration Rate

As previously introduced, the road traffic has been conceived to represent possible ratios between DSRC-module supplied vehicles and not yet equipped ones, during the first transient years of technology spread.
According to the U.S. DOT rule-making proposal [4], the carmakers will start to implement these new technological requirements two years after the final rule adoption. Moreover, for the first three years from the rule entrance the percentage of the equipped vehicles introduced in the market will be 50%, 75% and 100% respectevely in the first, second and third year. Supposing the rule will entry into force in 2019, than the first three phase-in period will last from 2021 to 2023, where from that year onward all the new purchased light vehicles will be supplied with vehicle-to-vehicle communication techonolgy.
'Light vehicles', in the context of this rulemaking, refers to passenger cars, multipurpose passenger vehicles, trucks, and buses with a gross vehicle weight rating of 10,000 pounds (4,536 kilograms) or less".[4].

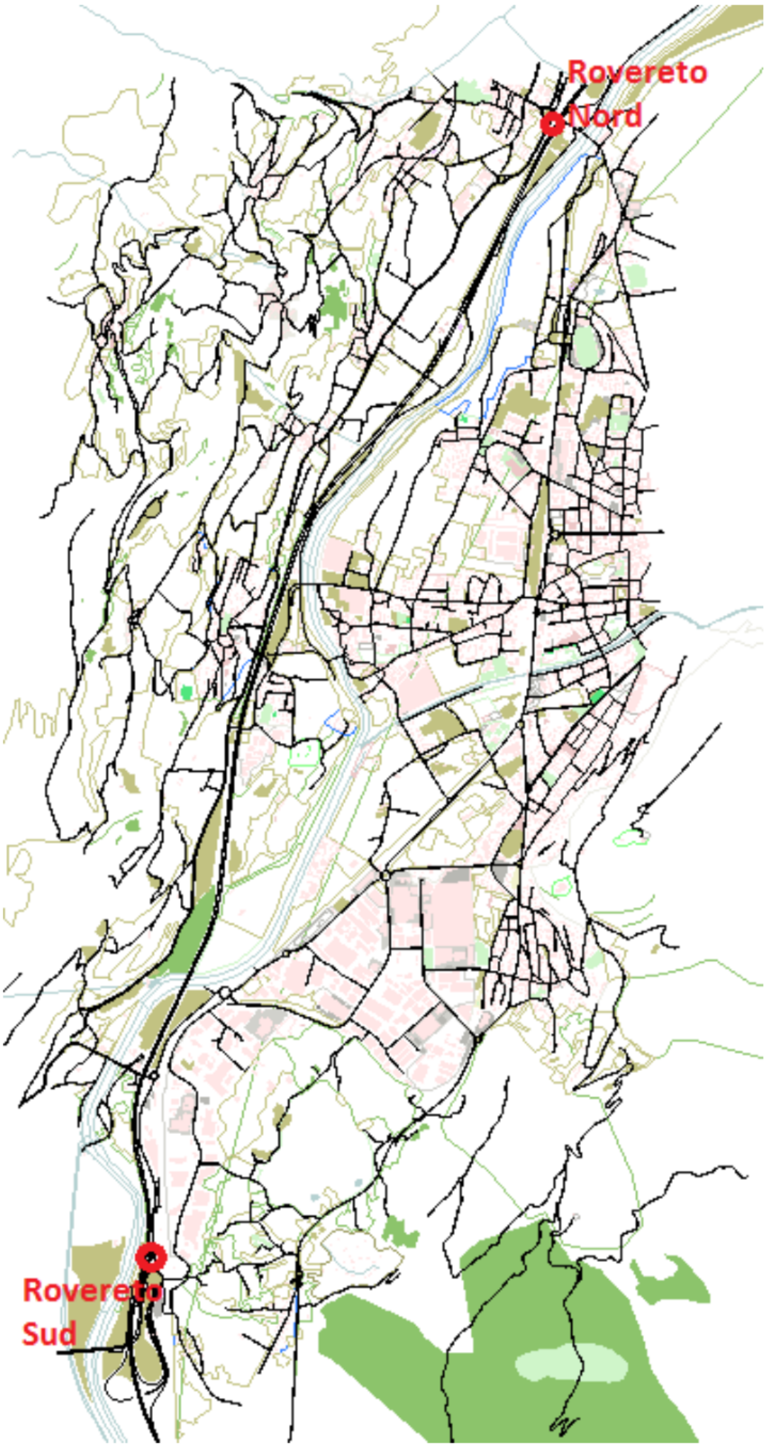


Figure 4.1: Rovereto Nord-Rovereto Sud highway test site

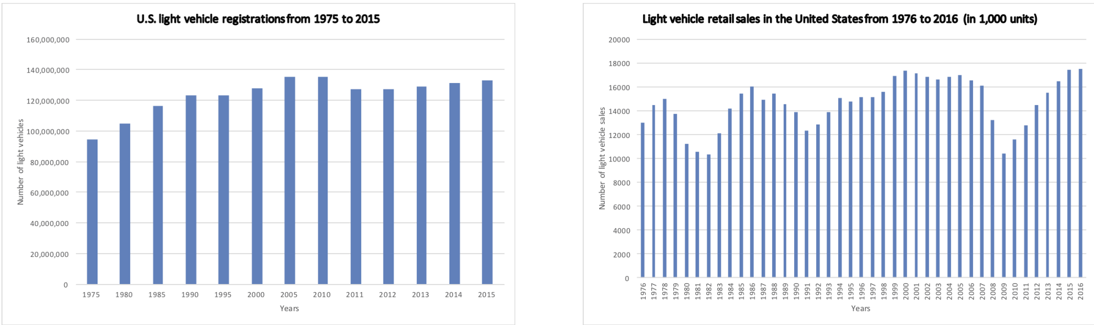


Figure 4.2: Light vehicle registration and sales course during last 40 years

Combining the data provided by [25] and [4] about light vehicles trend during the last forty years, showed in figure 4.2, and forecast on U.S. vehicles market sales, reported in the right side of figure 4.2, we've been able to extract some usefull consideration for the final penetration rate computation.
From figure 4.3 is possible to see how the retail sales of new light vehicles slightly decrease from 2020 to 2025, while instead the total amount of registered cars in the U.S. keep a small positive inclination mainly due to a constant increase of the average age of automobiles in operation in U.S., passed from a lifetime of 8.4 years in 1995 to a longeval 11.6 years in 2016, as states by the United States Department of Transportation [26].

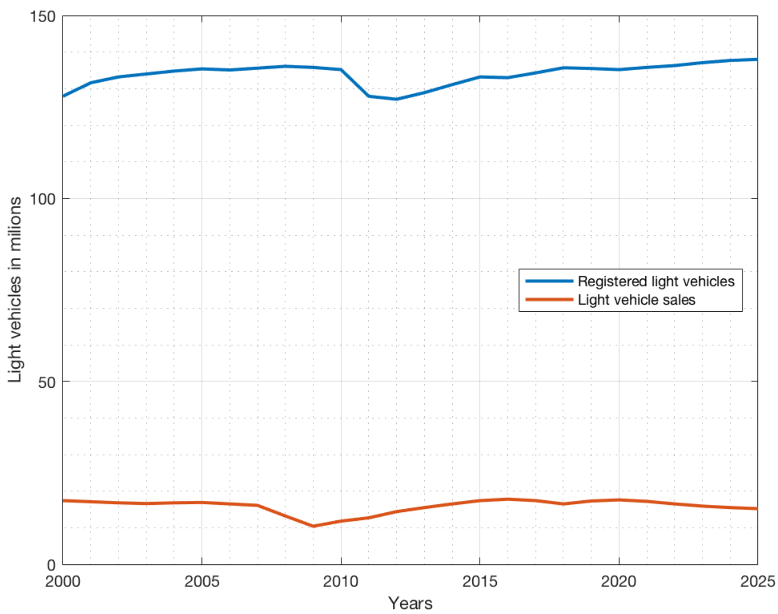


Figure 4.3: U.S light vehicle market forecast

Defining N_{i} as the number of new introduced light vehicles on the U.S. market during the $i-th$ year and PR_{i} as the percentage of those equipped with V2V communication technology, it is immediate to compute the total number of V2V equipped vehicles in the $i-th$ year specified as $V2V_{\text{i}}$:

$$V2V_{\text{i}} = N_{\text{i}} * PR_{\text{i}}$$

The case study concerned purely refers to the first years of the technology introduction, therefore the estimation of the penetration rate was considered between 2019 and 2025. Afterward, to get the overall number of equipped cars each year it was enough to add the number of V2V vehicles taking into account the presence during the previous years.

$$V2V_{\text{i}}^{\text{tot}} = \sum_{i=2019}^{2025} V2V_{\text{i}} + V2V_{\text{i-1}}$$

Finally, $PR_{\text{i}}\%$ represents the actual ratio between vehicle-to-vehicle communication technology supplied cars and the total number of circulating light vehicle in U.S. in the $i-th$ year (R_{i}) and it is computed as

$$PR_{\text{i}}\% = \frac{V2V_{\text{i}}^{\text{tot}}}{R_{\text{i}}}.$$

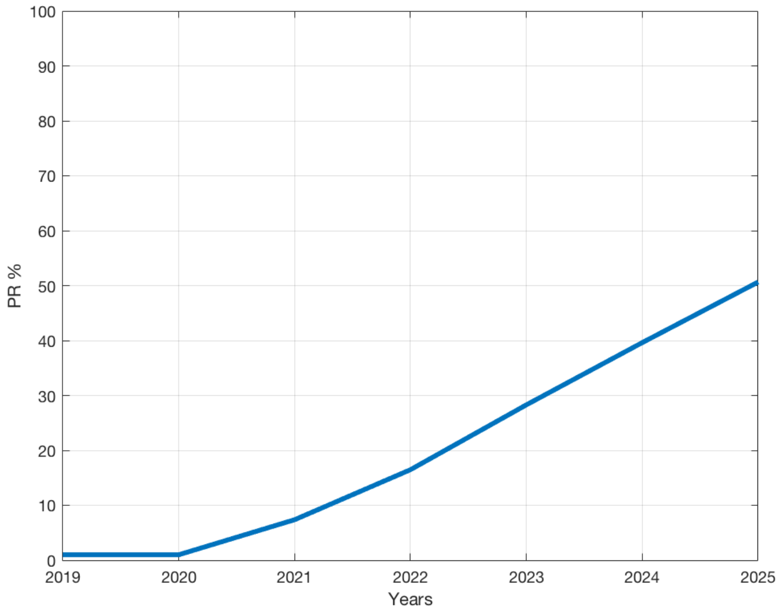


Figure 4.4: Penetration Rate estimation from 2019 to 2025

As we roughly expected, the V2V technology diffusion will follow a nearly linear trend with an increase of almost 10% each year, reaching around 50% in 2025 as depicted in

figure 4.4.
Thanks to these considerations we can now study the effectiveness and the impact of an application such as EEBL in the early years of the vehicle-to-vehicle communication technology debut, these latters considered as the most criticals in terms of user-acceptance and satisfactionary of the final driver user.

As far as *Time-to-Lock Latency (TtL)*is concerned, we've hypothesized that once a car receive the message of warning situation it automatically starts an Automatic Emergency Braking which directly acts on the braking system.
Of course, the time elapsed between the reception of the EEBL message and the effective lock of the wheels is not zero. We define this time as Time-to-Lock Latency and we varied this quantity through simulations. More explanations on values assumed by this latency will be given in 4.4.2.
For a matter of clarity, we report the PR values in the related years.

Year	**Penetration Rate %**
2019	0
2020	0
2021	8
2022	17.5
2023	29
2024	40
2025	50.5

Table 4.2: Penetration Rate percentage of V2V vehicles

4.2 EEBL Application

To evaluate the performance and the effectiveness of this Emergency Electronic Braking Light implementation, the leader of the platoon performs a complete stop (emulating for example an accident occured on the highway) braking with a deceleration intensity stronger than 4 m/s^2. This condition occurring on the host vehicle triggers the activation of the EEBL safety application, used to warns following cars of an emercency situation occurred further along the road, with the intention to prevent or moderate a possible crash from occurring.
The three main actions performed by the application are:

- Set a positive value of a flag inside the extensible part of the beacon message, we will call this boolean flag as *Hard Braking flag (HB flag)* from now on.

- Change the priority of the EEBL message (from 0 to 3, the highest possible one).

- Immediately sends the BSM, containing the hard braking information, without waiting the next BSM regular delivery.

At this stage two aspects related to the EEBL application have to be highlighted: the first one is the fact that an EEBL message, sent as a consequence of an unusual brake, is precisely a BSM with the hb flag raised, delivered from the first sending onward, with the regular beacon frequency as long as the completely deceleration of the car ends.
We purely followed the SAE J2735 International standard for the definition of the EEBL message which states: "The periodic messages could also be supplemented by an occasional message upon the occurrence of a specific event(e.g., hard-brake event)."; and again: "If a vehicle determines that it is braking hard then it could inform the surrounding vehicles by sending a MSG_BasicSafetyMessage, possibly including an optional "hard brake" flag event."[27]. Figure 4.5 shows the EventFlag field present in PartII of the BSM that we used to inform other vehicles about the emergency braking situation.
Furthermore, an emergency situation in which EEBL messages are sent in place of normal Beacon messages, does not affect the network load due to the packet size similarity in both events (normal beacon message and EEBL one).

Data item	Detail	Remarks
DF_SafetyExtension	EventFlag	
	PathHistory	
	PathPrediction	
	RTCMPackage	

Figure 4.5: SAE J2735 BSM_Safety_Extension

The other aspect to consider is the real-time of the application: in case that the message had to wait the regular beacon period to be sent, the worst system reaction time was around 0.1s for the American standard, and 1s for the European one, which is clearly too much in a safety-related context.
Once again we took inspiration from [27] that quotes "The message could be sent at the next scheduled transmissione time, or earlier, and it could use a higher priority level than the routine broadcast of a MSG_BasicSafetyMessage.".

4.3 Message Rebroadcasting

The idea of VANET was born to provide several services in automotive framework including among others entertainment, internet access, user and safety applications, this latter considered by far the most promising one.
For safety-related applications a technique to fastly and broadly disseminate warning messages is necessary, keeping into account the strict real time context and the vehicle radio-range that doesn't exceed about 300 m [4]. For this reason the broadcast protocol is in

the first place preferred in VANET networks respect the two well known and used unicast and multicast protocol in general network architectures. Indeed, in VANET the best way to disseminate as fast and widespread as possible to warn neighboors about imminent dangerous road conditions is information broadcasting, also known as flooding technique. In other words, whenever safety critical messages have to be sent to the neighborood, broadcast is of course one the best possible way to do it, but it has some drawbacks.
[28] defines *Broadcast Storming* as the increase of packet collision and data loss due to dense network.
In crowded scenarios the problem of congested channel typically arise due to the inability of 802.11 MAC layer to detect collision and properly manage the channel access. Of course, as the number of vehicles increases the probability of packet collision rises too.
Even if not implemented in the work, rebroadcasting should be inspect due to the limited coverage of the message and to the reduced presence of equipped vehicles in some different situations.
At the time of this work there aren't kind of application level protocols like rebroadcast metodology or aggregation mechanisms; this aspects are left to the research community, since usually no exactly solution exist for addressing the problem of rebroadcast, but depending on several aspects such as the scenario, number of nodes involved, time constraint and others, different alternatives can provide a realiable and accetable trade-off among channel load and transmission delay.
We present some possible emergency message rebroadcast solutions which try to address the problem of keep low broadcasting delay and, at the same time, attenuate the average channel load.
For all the succeding resolution we can afford to assume that all the considered automobile are supplied with GPS.

Replication Avoidance or broadcast suppression technique has as its final goal to reduce the total traffic load.
Once a vehicle is involved in an accident with another car, like S2 with S1 in figure 4.6, it sends a broadcast message to inform the others about the dangerous situation. This message is received and retransmitted only by car A that is the only one in the radio-range of S2. At this point both vehicles B and C receive the information sent by A and they rebroadcast the message in turn; so far everything properly worked since B and C has received only one alert each, but the problem of message redundancy arise when B as well as C resend the message towards vehicles D and E. In fact D and E will get two copies of the same message each (from B and C): in this simple example the network load remains low but in a more crowded scenario it can grows very quickly.

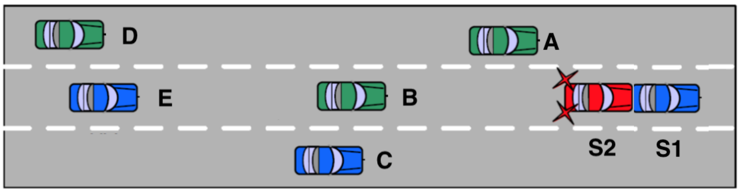


Figure 4.6: Replication Avoidance

The idea behind the replication avoidance algorithm is that if a node receive only one broadcast message it forwards the information, otherwise if a node receive more than one broadcast message it doesn't resend the message.
In our example cars D and E will resend only one message regardless of how many advices received, considerably reducing the number of packet sent out on the channel.

Position based proposals, as the name suggests, exploit the geographical position of nodes along the road.
In figure 4.7 A and B are the nodes in the radio-range of S2 and they both receive a warining message; the criteria here is that only the further vehicle will rebroadcast the message (vehicle B in this case). All of this is performed to achieve maximal spatial advanced of the information, meaning that the number of hops of the message that travel through cars is minimized.

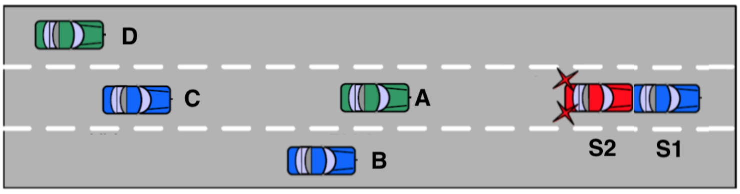


Figure 4.7: Position based

There are mainly two methods for making vehicles aware of each others position along the road:

- **Sender Based**: every node periodically delivers its GPS coordinates; in this way the transmitter results always aware about the most far reachable device in a given direction, and it sends the broadcast-warning message directly to this. The drawback of this mechanism is that each vehicle has to continuously keep update the neighbors with its own positioning informations, overloading the communication traffic.
- **Receiver Based**: on the other hand, the transmitter can send inside its broadcast message its GPS position. Each node receving the communication, computes the relative distance between itself and the transmitter. This information

will be used in the computation of the CW needed for the extraction of a waiting random time for accessing the channel. The larger the distance from the sender, the smaller the CW and the smaller will be the time to wait to resend the message.
Defining ds_{A} as the distance between vehicle S2 and vehicle A and the same for ds_{B} from figure 4.7, the related random times before reaching the backoff are computed as

$$t_{\mathrm{A}} \in [0, \frac{WTmax_{\mathrm{A}}}{ds_{\mathrm{A}}}] \qquad and \qquad t_{\mathrm{B}} \in [0, \frac{WTmax_{\mathrm{B}}}{ds_{\mathrm{B}}}].$$

Since ds_B is greater than ds_A the outcome for which t_B will be smaller than t_A will be the more probable, resulting for B in higher priority in accessing the channel, considering $WTmax$ as the maximum value that the backoff value can assume, in this situation supposed to be the same among nodes.
As a consequence, vehicle B reaches the backoff time earlier than A and it rebroadcast the message. As soon as vehicle A received the packet sent by B, it stops its backoff-value decrementation making impossible the retransmission of the broadcast message. Iterating the reasoning for all the cars reached by the first warning message, only the farther will result able to reprogate the information downstream.

Chiasserini et al.[29] propose a solution in which, given the coverage radius of the last vehicle that rebroadcasted the message, different forwarding zones are defined and for each of them different values of the contention window are assigned.

Cluster Based: thanks to periodically exchange of position informations, this mechanism relies on the fact that vehicles are grouped togheter by clusters in which a car is elected as *Cluster-Head (CH)* and entiteled to rebroadcast the message. In case that CH is too far from the next cluster, other closer nodes will take charge of the delivery of the message in place of its CH.
Looking at figure 4.8, this situation is depicted by the two cluster-head CH1 and CH2, where if CH1 result too distant from cluster 2, vehicle D will probably forward the information.
Cluster-based approach is considered difficult due to the necessity to keep update the gruop composition because of the physically freedom of nodes to enter/leave different clusters. Obviously, this scenario requires lot of traffic control information increasing the network load.
Nevertheless, this solution can be applied with trucks as a consequence of their not so relevant difference in speed among them.

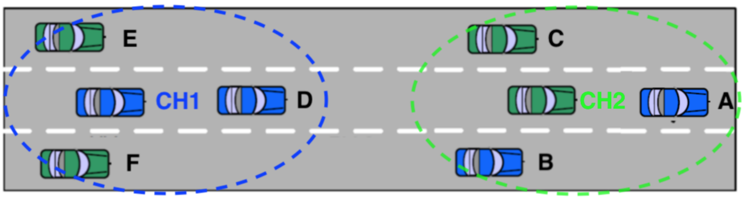


Figure 4.8: Cluster based

Gossiping: this simple broadcast storming suppression technique took inspiration from the way in which people keep secrets: someone will disclose the information while others not (of course with people is not just a matter of some matehematic probability formulas). It is based on an architecture parameter $p \in [0,1]$ representing the probability of each node to repropagate the signal.
Indeed, p symbolizes a trade-off between good system performance (high values of p) and light network overload (p small). This schema can be adopted in distributed network approach.

Network Progressive: in order to don't lead to drammatically excessive message redundancy, network progressive exploit a different solution respect to those seen so far: it doesn't try to reduce the number of retransmitted messages but instead it tries to reduce the amount of retransmitted information. This solution willing to merge and combine messages as function of their content information; if for example a node C receives a message from node A and B, its application layer inspecting the argument of the messages would subsequently forward a new packet containing an average of both informations, according to some specific and valid algorithm, as mentioned here [30].

4.4 Driver Braking Profile

The test performed for the evaluation of the EEBL application in single-lane highway context considers a flow of vehicles reacting to an emergency situation.
As explained, depending on the market penetration rate a portion of vehicles is provided with DSRC module and is aware and connected to all the others next equipped vehicles: these cars will strive to take advantage from the technology in order to react earlier, in a more controlled and less unpredictable way to an emergency situation.
As far as non equipped vehicles are concerned, their acceleration and deceleration behaviors are governed by SUMO mobility model, that implements the collision-free schema *Default Krauss Model* retracing the original Krauss prototype, as described here [31]. The basic criteria of this mobility pattern is the following: "Let vehicles drive as fast as possibly while maintaining perfect safety (always being able to avoid a collision if the leader starts braking within leader and follower maximum acceleration bounds)"[32].
It also states "This model is mainly characterized by three free parameters that describe acceleration and deceleration capabilities of the vehicles as well as a stochastic element,

introduced to model imperfections in driving."
We will investigate more in depth some possible values for these quantities, especially for the so called *human reaction time*, which will play a primary role in modeling driver's interactions profile.

The Default Krauss Model used in SUMO slighlty differs from the original one, in particualr "Different deceleration capabilities among the vehicles are handled without violating safety (the original model allowed for collisions in this case)", according to [32].
As a result, cars engaged in braking manoeuvre can achieve level of deceleration intensity above 10 m/s^2, clearly resulting in unrealistic braking intesity force, as proved by [33].
Even if not necessary at this point of the essay, introducing one of the target of the project should help to better understand some following considerations. Indeed, one of the main effort of this thesis will be expressly the evaluation and the impact of this V2V safety-application and the technology on which it relies on, in terms of prevented number of accidents and reduction of the maximum deceleration braking intensity.
Hence, a way to force accidents to occur as a consequence of the human imperfection component is strictly required in order to work with a scenario in which collisions are stochastically included in each simulation. The realized scenario aims to reproduce the situation in which a car driver involved in a braking manoeuvre, reacts with some delay to an impending danger situation due to factors such as road and weather conditions, smartphone usage, and several other aspects.

To achieve our goal, we decided to reproduce almost entirely the *Intelligent Driver Model (IDM)* mobility model, considered as one of the most known mobility traffic in literature. In both driving profiles we are next to introduce, the IDM one and the assisted AEB one, we decided to evenly randomize in each simulation the maximum allowed braking decelration intensity per each car. In this way we want to ricreate a scenario in which the car fleet will be composed by new cars featuring higher maximum deceleration values and more dated cars with worse braking system performance due to the technology obsolescence.
The interval of maximum permitted deceleration values range from a minimum of -5.9 m/s^2 to a maximum of -8.4 m/s^2 as proved here [33] in dry road surface condition.

4.4.1 Intelligent Driver Model Profile

IDM is a microscopic traffic schema born for the purpose to emulate a follow-the-leader model; furthermore, it has been proved to be equivalent to a macroscopic traffic model, which is not so common for others microscopic ones[34], [35]. We decided to rely on this prototype to emulate the human driving profile since it perfectly fits in a signle-lane scenario like the one under test.
IDM is considered in literature as a "perfect" traffic model due to the *approaching rate* (Δv) term present inside its formula, namely the difference between the speed of the current car and the one of the car in front, that makes the model collision-free since it handles the interactions among approaching cars according to Coulomb-like repulsion [34].

Analyzing the IDM formula needed to compute the variation of the acceleration profile of a given car α, is possible to highlight two main different expressions composing it:

$$\dot{v}_\alpha = a^{(\alpha)}\left[1 - \Big(\frac{v_\alpha}{{v_0}^{(\alpha)}}\Big)^\delta - \Big(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\Big)^2\right] \tag{4.1}$$

the first one $a^{(\alpha)}\big[1 - \big(\frac{v_\alpha}{{v_0}^{(\alpha)}}\big)^\delta\big]$ represents the **free road term** describing the propensity to accelerate whenever the road can be considered free, that is when the interaction with the car along the path is minimal. In the formula $a^{(\alpha)}$ is the maximum acceleration, v_α is the current speed, ${v_0}^{(\alpha)}$ is the desired target speed and δ is the acceleration exponent for shaping the acceleration slope.
On the other hand, the **interaction term** $-a^{(\alpha)}\big(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\big)^2$ is strongly dependent on the ratio among the so called *desired gap* s^*, computed as function of Δv toghether with the car current speed, and the inter-vehicle gap distance (s_α).
Below is depicted the expanded representation of the *desired gap* term.

$$s^*(v, \Delta v) = s_0 + s_1\sqrt{\frac{v}{v_0}} + Tv + \frac{v\Delta v}{2\sqrt{ab}} \tag{4.2}$$

To keep the whole model as simple as possible we assume s_1 to be equal to zero [34]; s_0 stand for the *ideal safe distance* to keep in static situation (still cars), T represents the *safe time headway* defined as the *distance in time* among the current car and the leading one, and b is the *comfortable deceleration* that drivers willing to mimic in an ideal braking manoeuvre. It is easy to notice in the aforementioned equation how the tendency to decelerate increases with the increase of the car velocity and the approaching rate. In particular, the latter dominates the mobility behaviour whenever a car moves toward a steady obstacle or a considerable slower car along its path.
As a matter of fact, is possible to characterize and approximate the formula depending on the car surrounding scenario.

1. **Equilibrium traffic**: this particular case is represented by a situation in which a car tends to drive as fast as the vehicle in front and all vehicles try to keep the same speed resulting in aproximately no accelerations ($\dot{v} = 0$) and of course $\Delta v = 0$.
   As a consequence, the inter-vehicle distance mainly depends on the istantaneous car velocity which intrinsecally depends itself on the traffic density:

   $$s^*(v{,}0) \sim s_0 + vT.$$

   In particular, the gap among vehicles is composed by the *safe distance* s_0 in standing traffic plus the product between the speed and the constant *safe time headway*, where the latter directly characterizes the driver driving style.

2. **Acceleration to the desired velocity**: whenever the road density is low, the actual gap s increases and so the *interaction term* can be neglected; the IDM formula reduces to the *free road term* only and each vehicle can freely accelerates until reaching the desired speed v_0.

3. **Braking as reaction to high approaching rates**: if a car approaches a standing obstacle or a much slower vehicle along its path, the *approaching rate* dominates over the *Equilibrium traffic* part inside the *interaction term*.
   Therefore, the interaction part reduces to $-\dfrac{(v\Delta v)^2}{4bs^2}$ resulting for the driver, in a situation *under control* if this value do not exceed the *comfortable deceleration* threshold supplied in table 5.1.
   "While in safe situations the IDM deceleration is less than the kinematic collision-free deceleration, drivers overreact in emergency situations to get the situation again under control."[34]. This surely should results in a collision-free scenario, if it were not for the highest bound we imposed for the maximum phisically achievable deceleration intensity.
   Of course, this deceleration profile strictly relies on the *comfortable deceleration*: the smaller b the earlier will be the driver response to the impending danger situation, obviously resulting in smoother braking decelerations; while instead the braking manoeuvre will start later outcoming with stronger deceleration peaks for higher values of the *comfortable deceleration*.

4. **Braking in response to small gaps**: this last possible schema depicts a rather crowded density scenario in which vehicles are separated each other by small gaps and the difference in speed among cars is practically null ($\Delta v = 0$).
   For this reason, the interaction terms becomes $-a\dfrac{(s_0 + Tv)^2}{s^2}$ which emulates a Coulomb-like repulsion which results in a oscillatory behavior of speed and inter-vehicle gap, until an equilibrium is reached. The amplitude of the oscillations depends on the value of b: the stronger the deceleration, the greater would be the oscillation amplitude, as stated here [36].

In order to have collisions we force the microscopic mobility to obey to the IDM *interaction term* as soon as the Krauss default model enters in braking or deceleration manoeuver. Consequentely, the model keeps the Krauss default implemenation regarding the acceleration component while instead is governed by the IDM deceleration profile whenever an interaction with other cars occurs.
In such scenario collisions cannot occur yet, due to the collision-free nature of IDM as explained in section 4.3.1, hence we perform two main actions to achieve our purpose:

- set a maximum lower bound for the values that deceleration can assume, as mentioned in 4.4
- randomly delay the human response time to an upcoming event

Like previously introduced, the maximum achievable deceleration braking intensity is slighlty greater than 8 $[m/s^2]$ and cars cannot brake stronger than this threshold per each simulation step even if estimated by the IDM formula.

Furthermore, we also try to emulate a *human imperfection component* delaying the time at which a driver start to react, pressing down the brake tradle.
What we want to reach is a situation whereabout careful drivers (low reaction delay) will have more time and chance to avoid a pile-up collision if allowed by braking system, and on the other hand, the distracted ones instead will likely to be involved in accidents for the sake of the greater reaction time needed to responde to an emergency situation.
To achieve our purpose, we delay the time at which a driver start acting on the braking system by a human reaction time quantity, randomly extracted in each simulation from a truncated gaussian distribution with 1.5 s average value, 1 s variance and lower and upper bounds of 0.5 and 2 s respectively; [37], with the support of CRF, investigates more in depth about several different response time elapsed from the onset of the reaction time stimulus to the beginning of the response.
Summaryzing, this driver braking profile will be put in place in non equipped vehicles, and the particular case in which they represent the totality of road traffic (PR = 0 %), will be used as a zero-reference in the assessment of the improvements made by the technology.

4.4.2 Automatic Emergency Braking Profile

As far as vehicles equipped with DSRC on-board module are concerned, another approach has been put in place to cope with impending possible accident.
In March, 2016 the NHTSA agency announced an agreement with vehicle manufacturers to voluntarily make automatic emergency braking (AEB) a standard safety on future vehicles, [4].
Our implementation of vehicles behaviour follows the aforementioned IDM profile as long as no safety related information has been received yet; as soon as an EEBL message is collected, the car triggers into an automatic emergency braking maneuver willing to control and tune the istantenous deceleration profile in order to avoid or mitigate any possible collision with the vehicle ahead, when physically granted.
The application takes advantage from the anticipated system response to the emergency situation, respect to the case delayed by the human imperfection component together with line-of-sight conditions, and also from the possibility to refine the deceleration trend that not only will try to avoid rear-end accidents but also will attempt to reduce and balance the maximum deceleration intensity, considered as one of the most significant parameter in traffic stability evaluation. [34]

We realized our AEB system as a function that assists and helps the driver during the braking maneuver to avoid or mitigate a possible crash. Last goal of AEB is computing a precise value of the istantaneous deceleration to ensure to stop at a safety distance from the vehicle in front, when possible.
Unfortunately, we cannot report the formula and its details present in the code of this safety application, since it has been provided by *FCA/CRF* automaker company who asked us to keep the algorithm protected by industrial secret.

Here again, as we did in the case of IDM, we include in the simulations the two following operations:

- set a maximum lower bound for the values that deceleration can assume, as mentioned in 4.4
- delay the braking system intervention, from the reception of the EEBL message, of the Time-to-Lock latency time.

Obviously, this latency time depends on many factors among which road surface conditions, type of vehicle, vehicle unit control, pliers, disk, etc.. . Nevertheless, when referring to AEB system as in our case, 400 *ms* can be identified as a possible default value [38]. According to these considerations, we settled the range this quantity can assume from 300 to 700 *ms* during several simulations.
Surely, the principal result that this mechanism wants to achieve is the reduction of the number of accidents or their mitigation. However, another interesting aspect that we expect as outcome is that incoming cars that receive the message will all behave similarly each other (if they clearly obey to the same interaction criterion, such as vehicles of the same brand) by tracing the behavior of a platoon of vehicles connected to each other.
The benefit of this solution is that vehicles that have to cope with the same emergency situation will have a reaction that the other involved machines will be able to guess in advance, resulting in a sort of *cooperative and automated driving*.
A similar platooning approach is proposed by Michele Segata et al. here [39].

4.5 Crash management

Once accidents among vehices have been included in the simulation, a way to directly manage them is necessary since SUMO handles collisions by default in a completely useless manner for a scenario in which possible pile-up collisions have to be investigated. More precisely, a collision in the simulator is register whenever the gap between two vehicles is smaller than the *minGap* attribute; for such circumstance the traffic simulator has four different values for the *–collision.action* configuration option: *teleport*(the default one), the following vehicle is moved (teleported) to the next edge on its route, *warn* thanks to which a warning is issued, *none* where no actions are taken and *remove* that completely removes both vehicles from the simulation [40].

The policy we decided to implement, obviuosly follow the same detection criteria as SUMO, therefore crashes are recorded when the distance among two cars is less than a certain threshold (that intrinsecally depends on cars length).
The core of the crash management algorithm is quite simple. Supposing that car A represents the car in front and car B is the coming one and no more able to stop itself in time to avoid the collision; as soon as a negative distance among these two vehicles is detected, car A will be moved ahead by a quantity equals to the negative distance registered, which actually is the amount of which they overlapped each other. At this point they both are forced to stop, decelerating until reaching zero speed.

Since the scenario describes a pile-up, we suppose that the car in front is always travelling slower than the vehicle arriving (when not still), hence collided cars roughly remains stick together in our simulations.

Chapter 5

Simulations and Results

The tests have been performed in a scenario emulating a trait of highway road, where a vehicle suddenly performs an emergency stop, braking with an intensity greater than 4 m/s^2. This car delivers an EEBL message with the aim to inform following vehicles about the dangerous situation to cope with. The vehicles able to receive the safety-traffic information will take advantage from it, starting an automatic braking profile in order to mitigate or even avoid a possible accident, when possible.
As already mentioned along in the work, the road is provided by one single line only, assuming that drivers do not try to steer to avoid collisions: as well as the difficulty to reproduce this unpredicatble behaviour, we also suppose that, since the average traffic density is around 2000 vehicles/hour, adjacent roadways are crossed by other vehicles making pointless the line-changing in such circumstances.
Figure 5.1 depicts *white* car performing a hard-braking and incoming vehicles involved in approacching maneuver. They do not execute line changing since the next-left free roadway should be thought as a flow of running cars. Furthermore, the evaluation of multi line scenario is out of the scope of the project.
All test hava been repeated varying the technology spread (PR) as 0%, 10%, 20%, 30%, 40%, 50%, 75%, 100% and the TtL in a range varying from 0.3s to 0.7s in steps of 0.1s. 50 simulations have been run per each set of different parameters, giving us a rather good estimation of the gathered outcomes.
The results have been collected among the first six cars (from *myflow.0* to *myflow.5*) following the white car. On these data we mainly investigated the following aspects:

- **Number of crashes prevented (%)**
  We averaged all the accident registered during the simulations, giving us an idea of the application impact in percentage scale.

- **Trace in time of vehicles's decelerations**
  In order to deeply know how drivers actually behavies during an appearching maneuver, we collected all the driving profiles. This operation allow us to reshape these responses according to some specific needs.

- **Variation of the *Average Maximum Deceleration (AMD)***
  As a consequence of the above result, we analyzed the variation of the overall average maximum deceleration performed to have an idea bout traffic stability.

- **Relations among two first vehicles involved in crashes (%)**
  This study want to highlight some correlation between the first and the second vehicles when PR changes.

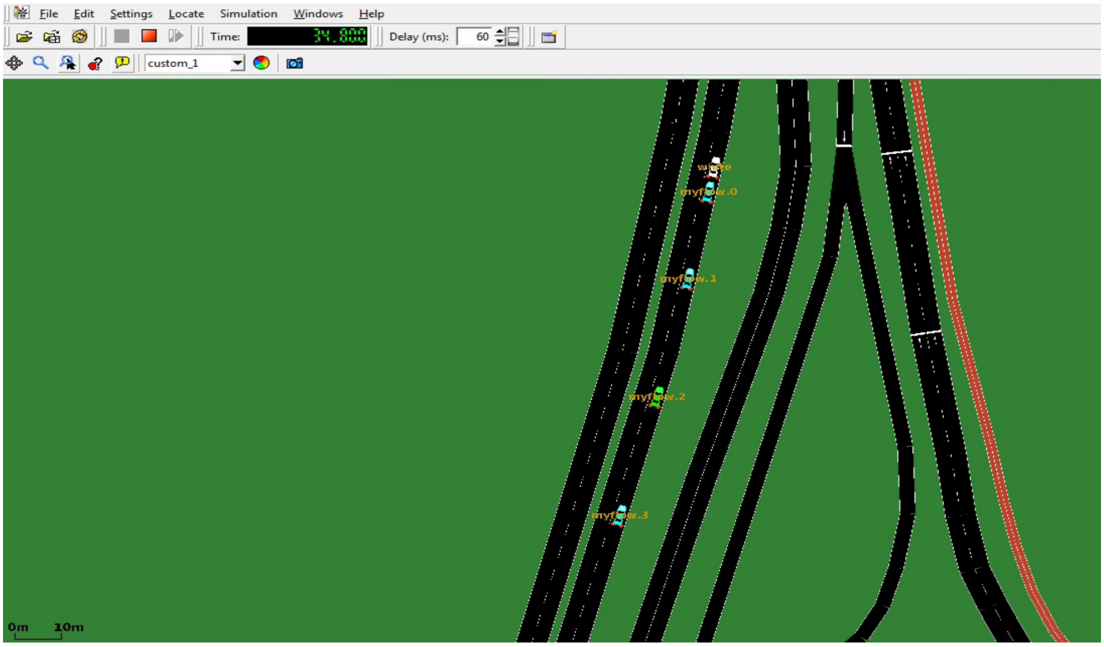


Figure 5.1: Single-Lane scenario simulation

Each simulation last for 60 seconds; inside this time interval the leader randomly performs the emergency braking. Instead of varying among several velocities, we used as reference the average value of the speed under such density situation that is 30 m/s with a confidence interval of $\pm 15\%$.
All the parameters regarding traffic enviroinment are shown in table 5.1.
Table 5.2 includes the network wireless channel parameters. As [4] suggests, the data rate has been set to 6 Mbps. *SimplePathLossModel* has been kept as Attenuation model since it fits in highway scenario where vehicles are more close each other, without any important obstacles among them obstructing direct communications.

Given the composition of the traffic as the ratio between equipped and total number of vehicles, is it possible to distinguish three different cases depending on the values of the Penetration Rate:

- **Pure IDM**
  Obviously the case for which PR = 0% represents the case in which all the cars

running in these particular simulations do not adopt the technology and they obey to IDM behaviour only. These situations are used as reference point in the evaluation of the EEBL application improvements.

- **Mixed IDM-AEB**
  Here, except for the two bounding cases with PR = 0% and 100%, all the PR values variations are considered with the task to extract some usefull mobility consideration regarding PR and TtL values.

- **Pure AEB**
  Pure AEB is when all vehicles are furnished with V2V technology with the EEBL safety application running on top of it. Of course, this describes an ideal and not immediate future condition.

Parameter	**Value**	**[*units*]**
Speed	30 ±15%	$[m/s]$
Max Acceleration	2.6	$[m/s^2]$
Max Deceleration	$\mathcal{U}[-5.6, -8.4]$	$[m/s^2]$
Headway Time	1.6	$[s]$
Deceleration Threshold	-4	$[m/s^2]$
Car length	4	$[m]$
Comfortable Dec	-4.6	$[m/s^2]$
Human Reaction Time	$\mathcal{N}_{[0.5,1.5]}(1,1)$	$[s]$
s_0	2	$[m]$

Table 5.1: Simulation parameters

Parameter	**Value**	**[*units*]**
Bandwidth	30 ± 15%	$[m/s]$
BitRate	6	$Mbps$
Tx Power	20	$[mW]$
Sensitivity	-89	dBm
Attenuation Model	SimplePathlossModel	
AC Beacon	AC_BK	
AC EEBL	AC_VO	

Table 5.2: Network protocol parameters

5.1 Pure IDM

Whenever a non-equipped vehicle has to face with a braking maneuver, it puts into effect the IDM driving profile. As introdced in 4.4.1, the implemented IDM's behaviour do not allow to overcome a maximum deceleration treshold, reuslting in simulations where collisions can occur.
In this human-reaction depentand driving profile, the declerations trend present high braking intensity represented by the almost vertical marks of vehicles in figure 5.2. As it is possible to see, after an initial *random-walk* path governing the equilibrium traffic phase, *idm0* and after *idm2* and *idm3* record abrupt braking intesity decelerations unitl reaching their respective maximum values. At a certain moment, these vehicles show deceleration intensity greater not only than their mechanical maximum performance, but also than phisycal laws as depicted in the picture when their traces reache values greater than -10 m/s^2.
This particular situation represents the case in which a car collides and it is forced to stop as a consequence of the accident.

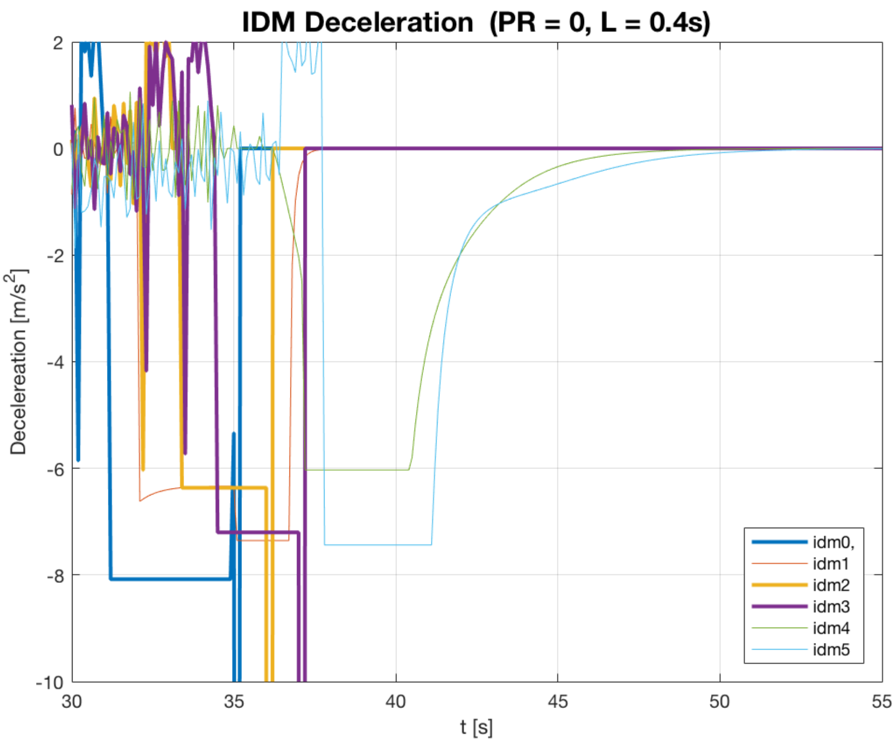


Figure 5.2: IDM deceleration traces in time.

Decelerations fall as a consequence of the high approaching rate scenario where the interaction term raise due to the big difference in speed among vehicles involved.

Besides, what figure 5.2 wants also to highlits is the absence of a uniform and similar way in which vehicles approch the emergency situation: this is mainly beacuse of the unpredictable human reaction time and of the lack of informations that a driver can have for taking emergency decisions in short amount of time.
Figure 5.2 shows almost vertical deceleration intensities, that are consequences of the approximation of human driving profile where drivers are suprised to face an emergency situation and suddenly press hard the braking pedal.
With this representation we wanted to show how violent the decelrations can be in a scenario in which technology is not present at all like this IDM traffic model.

5.2 Pure AEB

The EEBL application has been thought initially to coexists with an automatic car response anytime that particular kind of message is received. V2V furnished vehicles indeed, trigger in the AEB driving profile that has its mobility formula covered by industrial secret and we cannot report it inside this project.
However, AEB behavior depends on some general parameters also present in the IDM function like speeds, inter-vehicle distances and accelerations for example.
The peculiar case for which PR = 100% as replicated here, is a simpler traffic type exemplification with the aim to emphasis the difference bewteen the prevoiusly IDM case and the one in which the technology is totally adopted. Of Course, deceleration trends depicted here are more or less the ones performed by equipped vehicles in equivalent mixed traffic scenarios (PR $\in$]0,100[%).

The trace of decelerations of AEB controlled cars are depicted in figure 5.3; being *aeb0* the first incoming car, it strongly brakes to avoid collision, but here instead of IDM case where high peaks of deceleration were registered, the deceleration is a little bit softer also thanks to the timing notice received. Its deceleration grows until reaching its maximum, just smaller than -8 $m/^2$ in this simulation.
What is intersting to underline is the relative trend among all the involved vehicles; from vehicle *aeb1* onward, the curves are very similar each other and the decelerations intensity are considerably reduced respect vehicle 0. Again, all the trends are an equivalent and attenuated version of the aeb0 one and postponed given their delay due to their different arrival times at that point of the road.
In this particular representation, no collision among all aeb cars involved have been recorded.
We can also see that the overall braking profiles are significantly reshaped forming smoother and more coordinated andaments. This features is by far one of the most intresting results of the work; surely there is a remarkable difference respect the IDM curves and the AEB ones, opening for a way that could be considered as an important mark point regarding the possibility to implement an analogous system for *Cooperative Adaptive Cruise Control (CACC)* or similar platooning mechanisms.

Thanks to this automatic system, cars are able to take decisions and reshape their approaching maneuver according to the vehicle ahead.

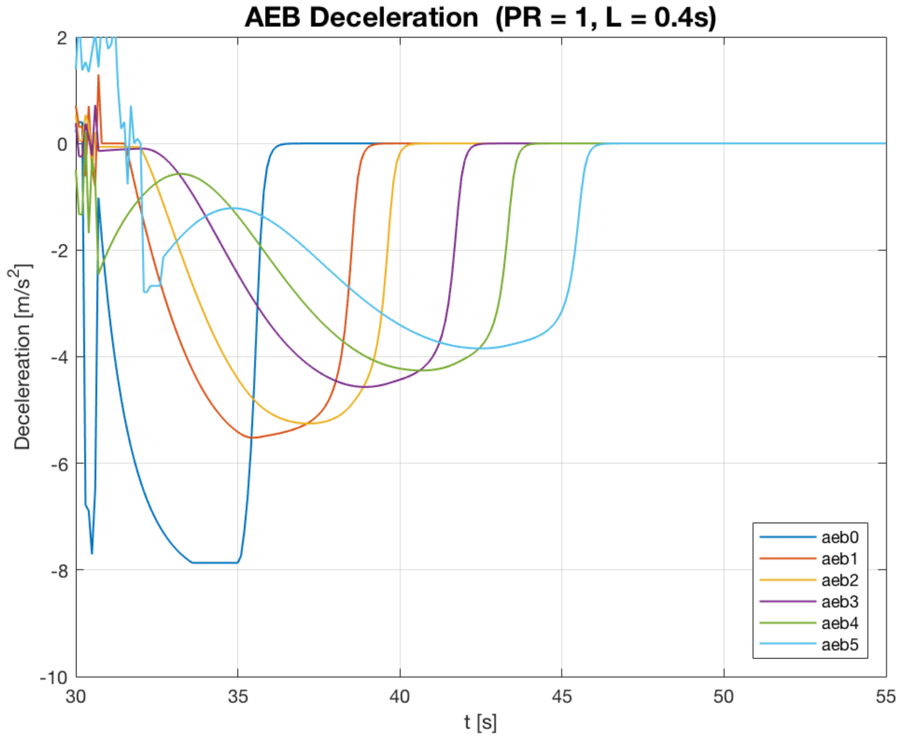


Figure 5.3: AEB deceleration traces in time

Figure 5.4 represents the case in which the vehicle aeb0, despite equipped with V2V technology, collides with white car in front of it: the condition for which an AEB car crashes as in this case, is due to some stochastic parameters such as maximum deceleration allowed and current car speed and it is moreover facilitated by the value of TtL setted equals to 0.7 s in this simulation. In such a particular situation, a vehicle even if able to receive safety EEBL message, can happen that is not capable to elude the accidents because of the values assumed by some parameters as the ones reported before.
Since the TtL value is bigger in figure 5.4 (0.7 s) than in figure 5.3 (0.4 s), the overall average deceleration intesity is bigger in the the first case, where systems are informed slightly later of the reaction to be taken; this small reduction of the available time results in brakes more abrupt.
To put more in evidence the cooperative tendancy of the AEB case of study, is possible to observe that the second car (aeb1) perfectly follows the first one (aeb0) and when aeb1 detects that aeb0 collide, it increments its deceleration intesity too, mimicking the operation performed by aeb0 for escaping from the collision even if useless in that situation. As a result, at around 35 seconds aeb1 also drastically increases it deceleration intensity going up to its maximum value, kept for about 1 second that is the time needed to avoid collision with aeb0 in front. Also all the other next vehicles (*aeb2* and *aeb3*) perform a variation in their deceleraion trends, growing slightly their braking force at around 35

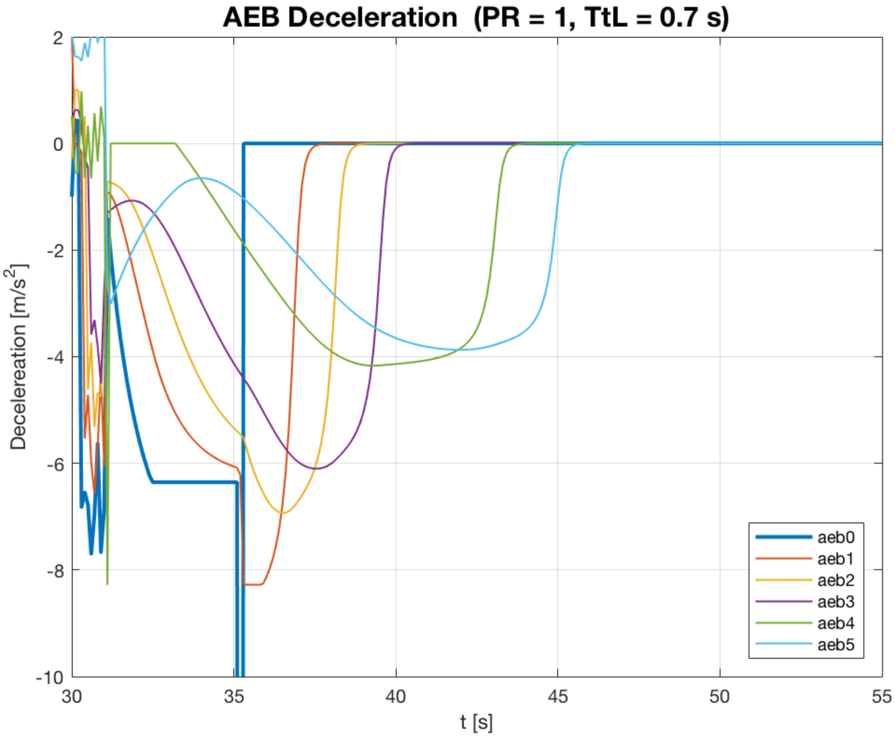


Figure 5.4: AEB deceleration traces in time

second.
Furthermore, also in case for which one or more collisions are registered, the general AEB braking profile trends are more gentle than IDM case.
We are gonna introduce the effects of these approaching maneuver profile variations in terms of evaluation of different traffic parameters.

5.3 Number of prevented crashes

To evaluate EEBL performance, we varied the number of equipped vehicle through simulations; the operations done to carry out the ratio between V2V-vehicle and the overall traffic flow are described in 4.1; so, PR values are taken from the interval [0%, 10%, 20%, 30%, 40%, 50%, 75%, 100%].
Per each value assumed by PR also the parameter TtL has been varied from 0.3 to 0.7 in steps of 0.1 seconds.
What we want to inspect is the reduction of the number of vehicles involved in collisions thanks to the EEBL message reception.
Figure 5.5 shows the number of crashes as PR changes. The case for which PR = 0% as explained, is the absence-technology reference situation stating that about 60% percent

of the first 6 cars involved in the emergency circumstance are engaged in accidents. This means that, in each simulation having these parameters three or four vehicles collide on average.
Increasing the value of PR results in a diminuition of the crash percentage. The yellow dashed line depicts a linear reduction of the number of accidents registered as the number of vehicles implementing the technology increases. This line represents an average value of the all TtL values taken. With one third of V2V presence (PR = 30%) there is a reduction of almost 20%, while to halve the collision probability a penetration rate of about 60% is necessary.
The picture describes only the values of TtL of 0.3 and 0.7 seconds respectively, since these two extreme values cases are good estimators of the whole interval given the small impact that TtL has on the general trend. However, from 0% to 20% of PR value the blue curve remains above the red one: this result could seems strange since faster, and so better, systems record more accidents than the case with TtL equals to 0.7 s; during these first years of technology spread there are not enough equipped vechiles to overcome the effects due to the IDM driving profile and the latency result can be neglected. Inreasing in the number of V2V furnished vehicles leads to a fall of both curves and from 25% onward, the systems with only 0.3 *s* of TtL performs better than the other one, remaining almost always a little bit lower then the average trend. From 70% of presence to the ideal case with PR = 100%, the trend is very similar in all simulations due to the high number of equipped cars able to compensate the variation of TtL with a more general cooperative and responsive way, making negligible a delay of some tenths of a second in this particular traffic mobility scenario.
In general we perceive that TtL variation has a rather small impact on the number of crashes saved from occurring, except for a short PR period from 40% to 60%, so where the ratio among IDM and AEB presence is inverted in favour of the latter.
Summarizing, figure 5.5 describes a situation in which the number of accidents is reduced by about 10% for a variation of PR of about 20%, coming out with a linear refinement. In other words, the higher the number of the equipped vehicles the smaller the number of vehicles involved in accidents.

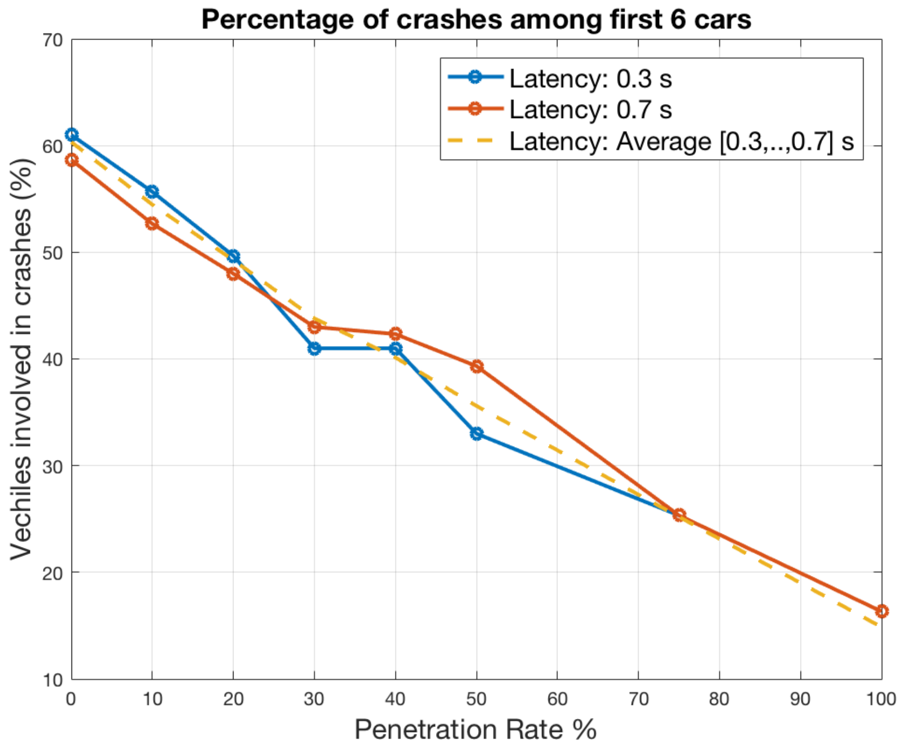


Figure 5.5: Crash percentage as a function of PR

This result is consistent with what we expected before the simulations, since the automatic braking profile implemented drastically reduce the human imperfection component and tryies to optimizie the car behaviour during the approaching maneuver given some significant informations acquired by the EEBL message.

5.4 Average Maximum Deceleration

In order to run the test regarding the maximum average deceleration intensity performed by vehicles, all the maximum decelerations of the first six cars per each simulation (given PR and TtL) have been collected and their sum has been average according to the number of total vehicles present in each scenario. This parameter should provide us a good indicator of how much vehicles sharply try to stop themselves reducing their overall control of current mobility in such situations.
Even if not considered in this study, high levels of deceleration intensity in not ideal road surface condition, like wet, little draining and worn asphalt due to different climatic/environmental conitions, can create devastating effects in terms of accidents occurred in emergency and high speed phases. For sake of simplicity we do not traten this case limiting our project to dry and ideal road surface conditions evaluation.

Another important consideration is the fact that an hypotetical reduction of maximum decelerations could be considered as a benefit due to the safety distance mantained as a consequence of the same information received by the vehicles involved.

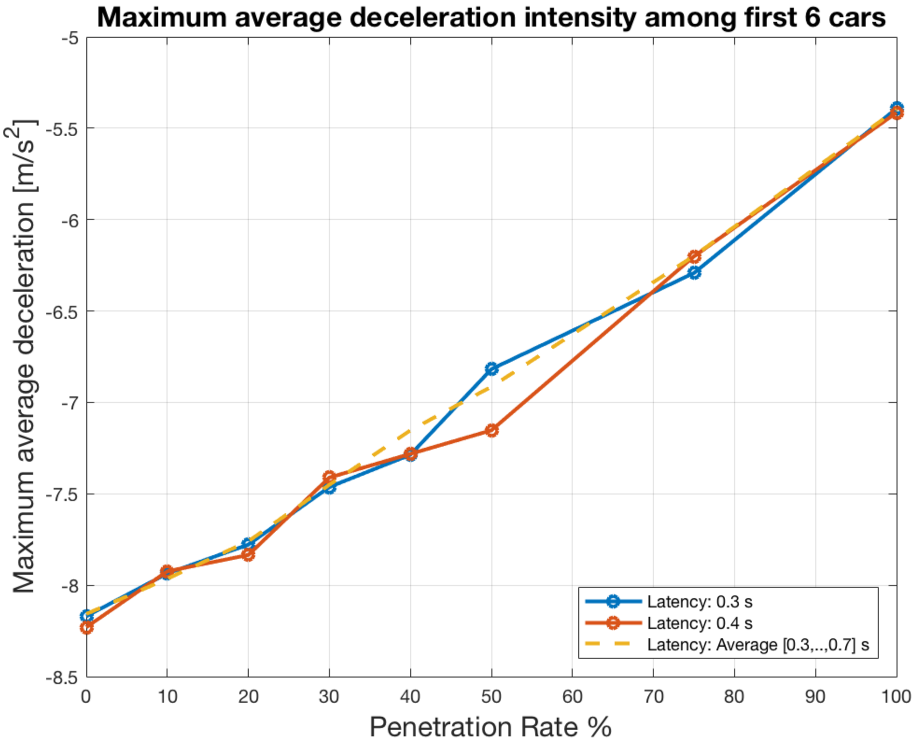


Figure 5.6: Maximum Average Deceleration as a function of PR

We plotted the variation of the maximum average deceleration in figure 5.6 at each set of parameters modification. The curve starts reporting a braking intensity around -8 m/s^2 and this number can be represented by the case driven by IDM driving profile where the majority of the fleet do not try to automatically optimize the maneuver but just brakes in order to avoid the rear end crash, as far as permitted by the human component.
Also done for figure 5.5, we report only the two bounding values of TtL parameter as well as the averaged trend of the TtL values interval. Similarly as for the collisions study, also in this case the TtL does not significantly influence the general evolution.
Another correlation among the two graphs in terms of PR-TtL relation is the higher variance of TtL curves around PR values of 50%, where the pattern seems to be more affected by the bipolar nature of the fleet composition.
Moreover, the general linear-increasing yellow curve states that also this parameter receives benefits from the technology, reducing the maximum average deceleration by about 3 m/s^2 comparing the two extreme case of no-technology and fully adopted technlogy.
In the middle PR = 0.5% case, the overall braking force is just smaller than -7 m/s^2

resulting in a gain of more than 1 m/s^2. The last part of the graph depicts the situation in which a considerable amount of vehicles are exploiting the safety EEBL application and the dependancy on other system parameters becomes neglible making uniform this piece of trend.
This aspect of EEBL performace recall what we awaited that was the more the vehicles conneted each other, the more the cooperation, the less the needed to strongly braking so as to take the vehicle under control. The benefit increase almost linearly with the increasing of PR. Indeed, the figure shows a reduction of almost 1 m/s^2 whenever PR percentage pass from to 0% to 40% and from 40% to 80%.
As introduced here 4.4.2, the maximum average deceleration can be considered an important mobility guideline for traffic stability evaluation and these outcomes argue significant improvement regarding this key aspect.
Supposing a highway scenario where the entrance of each car into the road is registered and identified by some central unit control, as nowadays worldwide daily happens: in this way is always possible to know exactly which type and how many specific vehicles (each of them characterized by different system parameters) are crossing a particular piece of the street. Once again, the possibility of characterizing the deceleration curve on the basis of some precise optimal values assessed through the maturation of the system, can fall within the Cooperative Control framework.

5.5 First two cars involved in crashes

This section aims to extract some informations about the head of the incoming-cars flow, more precisely to evaluate the collision probability of the very two first vehicles involved. Indeed, in a pile-up collision the cars immediately following the hard-braking leader are the ones more addressed by the dangerous situation and most subject to fatal consequence, because of their higher istantaneous velocity and their lower time to react to it.
In figure 5.7 the PR axes do not starts from 0 as done so far, but instead goes from 10% to 100% since we look for a connection between the first two vehicles anytime they are V2V communication capable. This means that, referring to the same figure, in a scenario with only 10% of PR, the first equipped incoming car crashes 90% of the times, while the vehicle in second position collides almost seven times over ten.
Report some practical numbers behind the graphycal representaion, can help to better understand the mobility behaviour: for PR = 10%, for 50 simulations and for a fixed value of TtL, the first car was V2V furnished only five times and in four of them it crashed; as far as second vehicle is concerned, it collided six times out of nine.

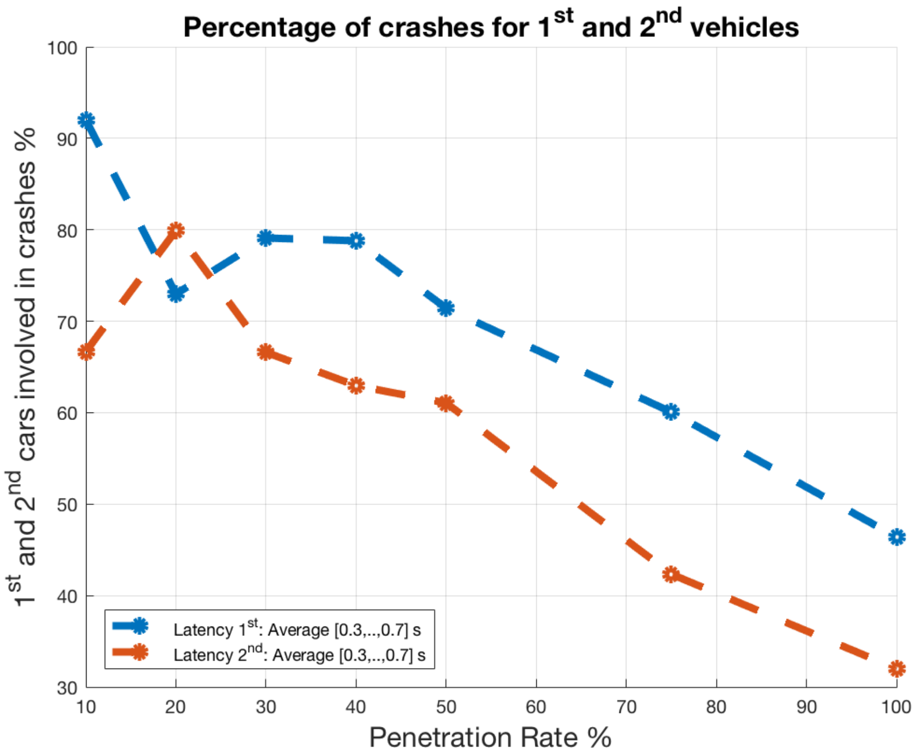


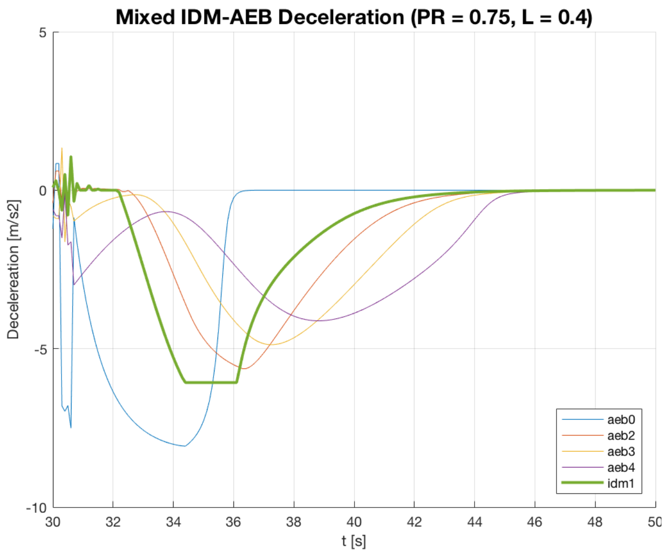
Figure 5.7: First and second collision percentage as a function of PR

If a comparison between crashes percentage in the first six position (figure 5.5) and the first two only (figure 5.7) is performed, the latter case clearly shows a rather greater percentage of number of incidents, about 20% more in the general trend. This is a normal consequence of the already stressed fact that in the back of the queue the number of collision is less present than in the head, contributing to raise the collision percentage in this case involving only the more addressed ones.
The two curves, after an initial phase of arrangement, from 25% of PR value onward coherently decrease until reaching for full technology spread a crash percentage of 50% for first vehicle and of around 30% for the second one. To enforce the hypotesis which states that the probability to be involved in collision depends on the position considered inside the queue of vehicleIs, is possibile to analyze how the blue pattern remains almost constantly larger than the red one.
This result is of course an averaged representation and there is no way to have an idea about how these vehices exactly behave each other in each simulation, apart plotting all of them and picking just some of them according to some specific criteria about traffic composition. Supposing a situation in which the first vehicle is equipped while the second one not, this case can easily comes out in the middle-left part of the PR evaluation where traffic composition probability do not descourage this outcome*. If so, the collision percentage of car two seems to be crushed-down by the one representing the first; in conclusion the second vehicle beneifts from technology also when not directly adopted, but

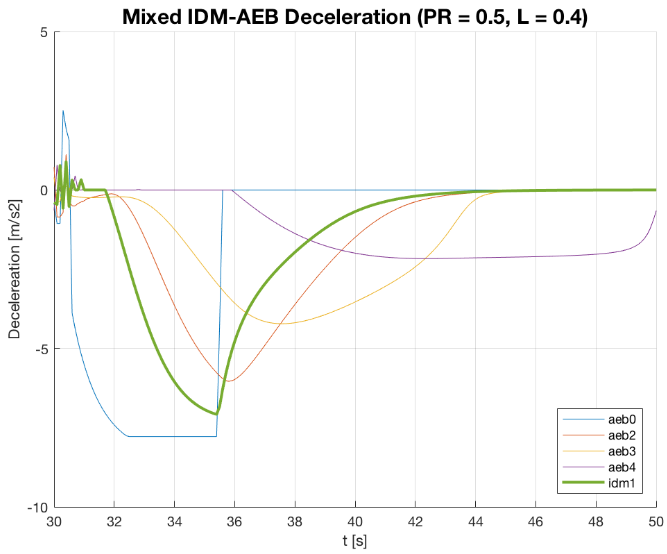
as a consequence of the automatic response of the connected car just in front of it.
The impact that EEBL application has herea bouts, is a reduction of 10% of crash percentage for a variation of PR of about 15%, from 30% up for the first vehicle involved. The following vehicle keeps almost the same lessening trend, displaying 60% of total crashes for PR = 50%.
Obviously, the system give its best when most of the vehicles are connected each other, as initially supposed.

5.6 General consequences

The work done so far has been based on the analysis of numerical results such as number of crashes prevented in several positions of the queue and the reduction of the average maximum deceleration; on the other hand, this last part of the work searches for some indirectly effects on a IDM vehicle surrounded(preceded) by other connected vehicles. This particular case willing to exemplify the firts half part of the graphs, where PR values can easily come out in mixed traffic composition scenario.
Further on are reported four images in which following idm vehicles perform approaching braking maneuver emulating the deceleration behaviour of the connected vehicle ahead, keeping in mind that no informations are exchanged among the two cars.
In section a of figure 5.8 the first incoming vehicle is aeb0 and its deceleration trend is



(a) 2$^{\text{nd}}$ IDM surrounded by AEBs

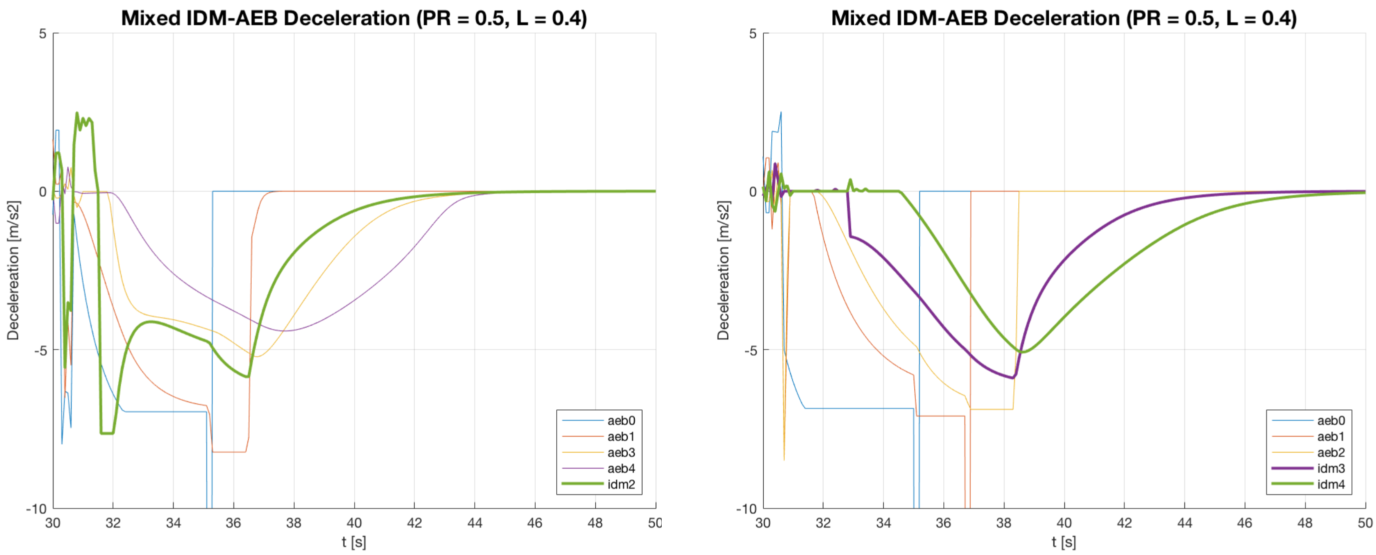


(b) 2$^{\text{nd}}$ IDM surrounded by AEBs

Figure 5.8: Simulations in which 2$^{\text{nd}}$ vehicle not equipped and preceded by AEBs

depicted by the most-left blue curve, reaching its highets peak at around 34.5 s for then

decreasing until 0. The car immediately following is idm1 and we see that its deceleration variation approximates the blue curve, achieving its maximum deceleration at the same time of aeb0. This is an evidence of how a driving braking profile can be shaped according to some automatic and undirectly traffic flow response.
Section *b* of figure 5.8 represents a similar simulation where again idm1 trend lets itself be influenced by the aeb0 that precedes it.
Moreover, first vehicle equipped and second one not, is exactly the case earlier studied in 5.5, and these interpretations of mobility enforce the number we obtained in that experiment.
Once some important considerations have been extracted regarding the behaviour of the second vehicle involved, we didn't examined the first car since it is preceded only by the one performing the hard braking, a look at the decelerations of other incoming vehicles can provide us some usefull informations about the criteria we are interesting into.
Figure 5.9 instead report two simulations in which cars in front collide: also here both representations (*a* and *b*) suggest us that idm driving profiles are in some way affected by the equipped ones immediately foreward. In the first case even if aeb0 collides, aeb1 is able to elude the accident and idm2, after an initial phase of settlement, from around 33 *s* onward seems to imitates the red curve also when this abruptly fall as a consequence of the collision of aeb0, increasing its braking intensity too.



(a) 3rd IDM surrounded by AEBs

(b) 4th & 5th IDM preceded by AEBs

Figure 5.9: Simulations in which 3nd and then 4th and 5th vehicles are not equipped and preceded by AEBs

Besides, these consequences are propagate along the traffic column also among adjacent idm vehicles, as it is possible to see from picture *b* of figure 5.9 where idm4 follow

the braking profile of vehicle idm3 which in turn is influenced by the automatic braking of aeb2.
As the titles of the figures allude, we report here only cases for which PR is equals to 0.5, but these situations also occur anytime that an aeb car precedes an idm one, so this reaction can be also found in cases where the PR value are not as big as in these particular cases, expecially during the first years of the technology spread. Indeed, according to these effects EEBL can really gives benefits in terms of traffic mobility in emergencies, although this safety application is initially utilized only by a part of circulating vehicles.

Chapter 6

Conclusions

This thesis has mainly tried to inspect various aspects of a possible implementation of an EEBL safety application. The external conditions refer to high speed scenario, typical of highway roads. In chapter 4 we characterized the roadway environment specifying simulations parameters and traffic conditions. As long as the IDM driving profile has been adopted to emulate human behaviour, we've set a maximum bound for the decelerations that vehicles can perform and we've delayed the human response in order to stochastically introduce collisions in each simulation.
In chapter 5 instead, we ran the simulations varying two parameters closely related to traffic: percentage of equipped vehicles along the road and latency time needed to activate the braking system.
Given the obtained results we can assert that VANET technology and its related safety applications, like EEBL in our case, can help to improve several dangerous road traffic conditions and roadway mobility more in general.
In this regard, sections 5.1 and 5.2 highlight the difference between a human reaction and a preempt and automatic car response, showing that in this latter case the deceleration profiles are smoother and more coordinated with each other. We reported only some of the trends registered but they were enough to observe how the traffic stability increased respect the IDM scenario.
One of the most important result of this work is reported in section 5.3 that shows the reduction of the number of vehicles involved in collisions as a function of PR and TtL. As previously mentioned, the value of latency do not influence almost the pattern, excpet for some values of PR around 30% and 60%, while instead the penetration of the technology plays a key role in this evaluation. Indeed, the higher the value of PR the higher the the number of accidents prevented. Looking at figure 5.5 we noted a reduction of 10% of crashes per each variation of PR of the order fo 20%.
Furthermore, is interesting to underline how for PR = 100% the number of registered accidents is not 0; actually, this number add credibility to our work since a situation in which no collision were reported for total technology spread case, would result in an unrealistic framework.
The results about the diminuition of the average maximum deceleration reported in section 5.4 are in line with the ones obtained for the crashes: also in this case the variation

of the TtL parameters is almost negligible and the general trend is mainly affected by PR change. As a matter of fact, when none of the incoming cars were equipped the average braking intensity was around -8 m/s^2, and it decreases with the increase of PR reaching around -7 m/s^2 for half of the fleet equipped and -5.5 m/s^2 in ideal case of PR = 100%. We expected this linear lessening of the maximum deceleration, in view of the fact that EEBL safety application was born with the aim to increase the stability and reduce the sudden braking in high-speed emergency situations.
A consistent consideration can be extract from the results depicted so far: the evaluation of the parameter TtL suggest us that it does not significantly influence the evalutions carried out.
What instead is important to emphasize is that the EEBL safety application can probably provides some practical benefits also for low values of PR, since drivers following an EEBL enabled car can decelerate with a smoother jerk because their leader are doing the same.
To summarize, our case is just one of the countless possible implementation of such a EEBL safety application, because of the vastness of variables present in the work such as parameters values, mobility scenario, automatic braking algorithm, human driving profile, etc...; but its clear that the overall traffic situation benefits from this application and so we personally think that the only way to achieve a general and approved framework to implement several and diverse safety applications would be a government mandatory rule about the implementation of V2V technology, as done in U.S with [4].

Chapter 7

Future works

The work of this thesis is only one of the possible applications of EEBL security and more generally of VANET implementations, therefore several of its aspect considered would require a deeper analysis. For example, increase the number of simulations in order to obtain more precise information about the TtL latency values, as the results obtained in our work did not seem to influence the graphs consistently.
Also the conditions of the chosen scenario can be modified such as the instant in which the leader brakes, the driving profile and some of its parameters such as the confortable and maximum deceleration. Moreover, the deceleration threshold that activates the EEBL application could be reduced in order to evaluate its performance even in scenarios outside the high-speed motorway environment.
Additionally, the same structure can be exploited to investigate the results when a FCW system is utilized. In this case, instead of activate an AEB maneuver the vehicle just informs the driver about the dangerous situation leaving him the task of braking.
The analysis of the network load can be another analysis to be weighted changing the traffic density of the proposed scenario. In [36] is proposed a reasonable way to inpect this quantity. Being the network load dependent from the number of vehicles and the mechanism to repropagate the informations along the fleet, one of the broadcasting schemas presented in 4.3 can be taken into account.
It can be intresting to evaluate the model in urban or extra-urban roads, however here it would necessary to extend the simple path loss model considered for another one which includes urban obstacles.
Considering a city environment in which intersection and junctions are present, the numbers obtained about the average maximum deceleration can be implemented for a collision avoidance system; again, it can be view also with the presence of road-side units (V2I) and/or, in a further second evolution, the awarness of pedestrian behaviour (V2P).
This project can be protract for giving the basis for a CACC platooning system; for example an application able to calibrated the safety distance in order to maximize traffic flow while keeping the risk of accidents under control.
As well as CACC models, working on automatic or assisted systems will allow to explore about autonomous driving and its comfort, with an algorithm that for example tunes the decelerations according to different external situations, like the distance between vehicles

belonging to the same platoon in case of a development of autonomuos and cooperative driving.

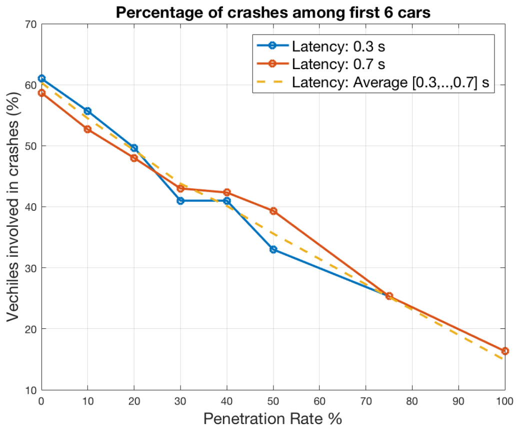


Figure 7.1: Figure 1

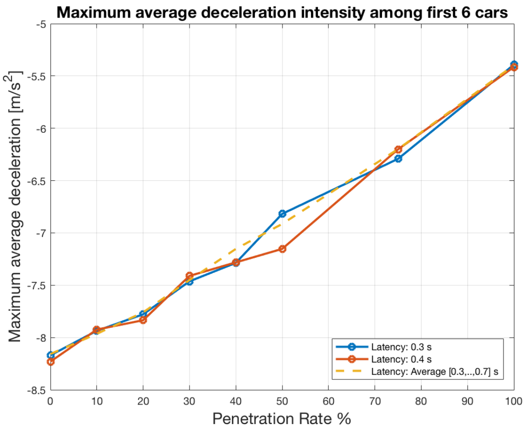


Figure 7.2: Figure 2

Nomenclature

ABS	Anti-Lock Braking System
AC	Access Categories
AC_BE	Best Effort Access Category
AC_BK	Background Access Category
AC_VI	Video Access Category
AC_VO	Voice Access Category
ACK	Acknowledge
AEB	Automatic Emergency Braking
AIFS	Arbitration InterFrame Space
AMD	Average Maximum Deceleration
AP	Access Point
ASN	Abstract Syntax Notation
BER	Basic Encoding Rule
BO	BackOff
BSM	Basic Safety Message
BSW	Blind Spot Warning
CACC	Cooperative Adaptive Cruise Control
CAP	Controlled Access Period
CCH	Control Channel
CDMA	Code Division Multiple Access
CF	Contention-Free

CH	Cluster-Head
CRF	FIAT Research Center
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CSR	Common Safety Request
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordination Function
DES	Discrete Event Simulation
DIFS	Distributed IFS
DOT	Department of Transportation
DSRC	Dedicating Short-Range Communications
DSSS	Direct Sequence Spread Spectrum
ECC	Elliptic Curve Cryprography
EDCA	Enhanced Distributed Channel Access
EEBL	Emergency Electronic Brake Lights
EIFS	Extended IFS
EPL	Eclipse Public License
ESC	Electronic Stabilty Control
EVA	Emergency Vehicle Alert
FCA	Fiat Chrysler Automobiles
FCW	Forward Collision Warning
GPS	Global Positioning System
HC	Hybrid Coordination
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
ICA	Intersection Collision Avoidance
IDM	Intelligent Driver Model

IFS	InterFrame Space
IMA	Intersection Movement Assist
ITS	Intelligent Transport System
LCW	Lane Change Warning
LTA	Left Turn Assist
MANET	Mobile Ad-hoc Network
MPDU	MAC Protocol Data Unit
NAV	Network Allocation Vector
NED	NEtwork Description
NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PCF	Point Coordination Function
PG	Process Gain
PIFS	Point Coordination IFS
PR	Penetration Rate
QoS	Quality-of-Service
RTS	Request to Send
SAE	Society of Automotive Engineers
SCH	Service Channel
SF	Spreading Factor
SIFS	Short IFS
SUMO	Simulation of Urban MObility
TraCI	Traffic Control Interface
TtL	Time-to-Lock
TXOP	Transmission Opportunity

UTC	Universal Time Coordination
V2I	Vehicle-to-Infrastructure
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc Network
VEINS	Veichular in Network Simulation
WAVE	Wireless Access in Vehicle Environments
WBSS	Wave Basic Service Set
WHO	World Health Organization
WSMP	Wave Short Message Protocol

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