Analysis of the most representative factors affecting Warning Message Dissemination in VANETs under real roadmaps

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Abstract— **In recent years, new architectures and technologies have been proposed for *Vehicular ad hoc networks* (VANETs). However, the experiments to validate these proposals tend to overlook the most important and representative factors. Moreover, the scenarios simulated tend to be very simplistic (highways or Manhattan-based layouts), which could seriously affect the validity of the obtained results.**

In this paper, we present a statistical analysis based on the 2^k factorial methodology to determine the most representative factors affecting traffic safety applications under real roadmaps. Our purpose is to determine which are the key factors affecting *Warning Message Dissemination* (WMD) in order to concentrate on such parameters, thus reducing the amount of simulation time required. Simulation results show that the key factors affecting warning messages delivery are the density of vehicles, and the roadmap used. Based on this statistical analysis, we consider that VANET researchers must evaluate the benefits of their proposals using different vehicle densities and city scenarios.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) belong to a type of wireless network that does not require any fixed infrastructure. These networks are considered essential for cooperative driving among cars on the road.

The development of VANETs is backed by strong economical interests since *vehicle-to-vehicle* (V2V) communication allows the sharing of wireless channels for mobile applications, improving route planning, controlling traffic congestion, and improving traffic safety. Most of these applications depend on services to disseminate warning messages, which are alert messages sent by a vehicle to warn other vehicles of any potential danger. In the coming future, vehicles will not only distribute information about themselves and their environment using warning messages, but they will also be able to communicate with other vehicles and the infrastructure via multihop wireless communications.

Deploying and testing VANETs involves high cost and intensive labor. Hence, simulation is a useful alternative prior to actual implementation. Moreover, VANET simulations must account for some specific characteristics found in vehicular environments. For instance, VANET simulations often involve large and heterogeneous scenarios. Traditional mobile systems also present a large number of parameters potentially affecting their performance, thus increasing considerably the simulation time required to correctly evaluate any proposal in a wide variety of scenarios. In recent years, new architectures and technologies have been proposed for VANETs, thanks to the use of simulation. However, the experiments to validate these proposals tend to overlook the most important and representative factors. Moreover, the scenarios simulated tend to be very simplistic (highways or Manhattan-based layouts).

In this paper, we present a statistical analysis based on the 2^k factorial methodology [1] to determine the most representative factors that govern the warning message dissemination performance in 802.11p-based VANETs. The aim of this methodology is to reduce the simulation time required to analyze the performance of a given VANET system, since it allows researchers to focus on the key factors affecting their proposals.

We start our analysis by selecting the following eight factors which have been widely used in the literature: (i) the number of warning mode vehicles, (ii) the density of vehicles, (iii) the channel bandwidth, (iv) the broadcast scheme, (v) the message priority, (vi) the periodicity of messages, as well as (vii) the mobility model used, and (viii) the simulated roadmap.

In a factorial design strategy, all factors are varied together (as opposed to one-at-time). So, a key advantage of this methodology is that it allows researchers to find out not only the most representative factors, but also the possible interactions and interdependencies among them.

Based on the aforementioned statistical analysis, we consider that VANET researchers must carefully evaluate the benefits of their proposals using different vehicle densities and roadmap scenarios, in order to make their conclusions more representative and closer to reality.

This paper is organized as follows: Section II describes related work on 2^k factorial analysis in wireless networks. Section III presents the 2^k factorial analysis fundamentals. Section IV describes the main factors of interest in VANET research. In Section V we determine the key factors in VANET simulation using the 2^k factorial analysis and based on the simulation results, we provide some guidelines for future research. Finally, Section VI concludes this paper.

II. RELATED WORK

In the networking literature we can find several works that adopted the 2^k factorial approach to discriminate among the many available parameters so as to determine the most relevant ones. Gupta et al. [2] studied *Distributed Network Control Systems* (D-NCS), a network structure and components that are capable of integrating sensors, actuators, communication, and control algorithms to suit real-time applications. They addressed the issue of D-NCS information security, as well as its time-sensitive performance with respect to network security schemes. Standard statistical approaches, such as 2^k factorial experiment design, analysis of variance, and hypothesis testing, were used to study and estimate the effect of each factor on the system performance, with an emphasis on its security features.

Liu et al. [3] studied the use of multipath routes to improve throughput, end-to-end delay, and the reliability of data transport in *Wireless Sensor Networks* (WSNs). They reported the results of a series of simulations based on a factorial experimental design. Results showed that both the congestion window size, and the retry limit are key factors.

Perkins et al. [4] studied and quantified the effects of various factors and their two-way interactions on the overall performance of MANETs. Using 2^k factorial experimental design, they isolated and quantified the effects of five factors: (i) node speed, (ii) pause-time, (iii) network size, (iv) number of traffic sources, and (v) type of routing. They evaluated the impact that these factors have over the throughput, routing overhead, and power consumption.

Although the use of standard statistical approaches such as the 2^k factorial analysis is found in many other fields, it is seldom used in ad hoc network communications. Moreover, to the best of our knowledge, this sort of statistical analysis has not been used in VANET research, and none of the research work currently available has formally identified the factors that significantly affect performance of warning message dissemination systems for VANETs.

III. THE 2^k FACTORIAL ANALYSIS

VANET simulations often involve large and heterogeneous scenarios. The number of possible factors and their values, or levels, can be very large. In this section, we will explain how the 2^k factorial analysis [1] can be used to determine the most relevant factors that govern a system's performance.

The use of 2^k factorial is important for several reasons: (i) to reduce the overall number of simulations needed, (ii) to evaluate the relationship between different factors, and (iii) to reduce the amount of simulation time required. The basic approach of this method is based on selecting a set of k parameters and determining 2 extreme levels (tagged with -1 and 1). An experiment is run for all the 2^k possible combinations of the parameters. From each experiment, we can also extract the $\binom{k}{2}$ two-factor interactions, the $\binom{k}{3}$ three-factor interactions, and so on.

For example, suppose that we have proposed a Warning Message Dissemination system, and that we want to study the impact of the density of vehicles (factor A) and the speed of these vehicles (factor B) in the warning notification time, i.e., the time required by normal vehicles to receive a warning message sent by a warning mode vehicle.

TABLE I

EXPERIMENTS DEFINED BY A 2^2 DESIGN

Experiment	A	B	y
1	-1	-1	y_1
2	1	-1	y_2
3	-1	1	y_3
4	1	1	y_4

TABLE II

EXAMPLE OF RESULTS OBTAINED IN TERMS OF WARNING NOTIFICATION TIME VARYING 2 FACTORS

Density of vehicles	Speed 10 km/h	Speed 80 km/h
10	$1\ second$	$0.8\ seconds$
100	$0.5\ seconds$	$0.4\ seconds$

If we make a 2^2 factorial analysis, we can find out the impact of each factor (density of vehicles and speed), and their combination, in the studied metric (warning notification time). Table I shows the different experiments defined by the 2^2 design, and Table II shows the results obtained after the simulations.

Let us define two variables x_A and x_B as presented in Equations 1 and 2:

$$x_A = \begin{Bmatrix} -1 & \text{if} & vehicles = 10 \\ 1 & \text{if} & vehicles = 100 \end{Bmatrix} \tag{1}$$

$$x_B = \begin{Bmatrix} -1 & \text{if} & speed = 10\ km/h \\ 1 & \text{if} & speed = 80\ km/h \end{Bmatrix} \tag{2}$$

The warning notification time (y) can be regressed on x_A and x_B using a non linear regression model of the form:

$$\mathbf{y} = q_0 + q_A x_A + q_B x_B + q_{AB} x_A x_B \tag{3}$$

Substituting the four observations in the model, we get the following four equations:

$$1 = q_0 - q_A - q_B + q_{AB} \tag{4}$$

$$0.5 = q_0 + q_A - q_B - q_{AB} \tag{5}$$

$$0.8 = q_0 - q_A + q_B + q_{AB} \tag{6}$$

$$0.4 = q_0 + q_A + q_B + q_{AB} \tag{7}$$

These equations can be solved uniquely for the four unknowns. The regression equation is:

$$\mathbf{y} = 0.675 - 0.225 x_A - 0.075 x_B + 0.025 x_A x_B \tag{8}$$

The result is interpreted as follows: the mean warning notification time is 0.675 seconds, the effect of the density of vehicles is -0.225 seconds, the effect of the speed of the vehicles is -0.075 seconds, and the interaction between speed and density of vehicles accounts for 0.025 seconds.

A. *Calculating the Effects of the Factors*

In a 2^k factorial analysis, by using the sign table method, we can get the results and detect variations which depend on the combination of factors. For a 2^2 design, the effects can be computed easily by preparing a 4×4 sign matrix as shown in Table III. The first column of the matrix is labeled I, and it consists of all 1's. The next two columns, titled A and B, contain basically all possible combinations of -1 and 1. The fourth column, labeled AB, is the product of the entries in columns A and B. The four observations are listed in a column vector next to this matrix. The column vector is labeled y and consists of the results corresponding to the factor levels listed under columns A and B. The next step is to multiply the entries in column I by those in column y and put their sum under column I. The entries in column A are now multiplied by those in column y and the sum is entered under column A. This operation of column multiplication is repeated for the remaining two columns of the matrix. The sums under each column are divided by 4 to give the corresponding coefficients of the regression model.

The importance of a factor depends on the proportion of the metric *total variation* explained by the factor. The total variation of y is also known as *Sum of Squares Total* (SST), which can be calculated as follows:

$$Total\ variation\ of\ y = SST = \sum_{i=1}^{2^2} (y_i - \overline{y})^2 \tag{9}$$

where $\overline{y}$ denotes the mean of the responses from all four experiments. For a 2^2 design, the variation can be divided into three parts:

$$SST \quad = \quad 2^2 q_A^2 + 2^2 q_B^2 + 2^2 q_{AB}^2 \tag{10}$$

These parts can be expressed as a fraction; for example:

$$Fraction\ of\ variation\ explained\ by\ A = \frac{SSA}{SST} = \frac{2^2 q_A^2}{SST} \tag{11}$$

Hence, we can indicate the percentage of variation of each studied metric explained by each factor. The more percentage of variation, the more impact this factor has in the measured metric. In our example, we found that the density of vehicles accounts for 89.01% (i.e. $\frac{2^2 \cdot -0.225^2}{0.2275}$) of the total variation of the warning notification time, the speed of the vehicles accounts for 9.89% (i.e. $\frac{2^2 \cdot -0.075^2}{0.2275}$), and their combination accounts for the remaining 1.10% (i.e. $\frac{2^2 \cdot 0.025^2}{0.2275}$). Therefore, in our selected example the density of vehicles is the most important factor which affects the warning notification time.

TABLE III

SIGN TABLE METHOD OF CALCULATING THE EFFECTS OF THE FACTORS IN A 2^2 DESIGN

I	**A**	**B**	**AB**	**y**
1	-1	-1	1	1 *second*
1	1	-1	-1	0.5 *seconds*
1	-1	1	-1	0.8 *seconds*
1	1	1	1	0.4 *seconds*
2.7	-0.9	-0.3	0.1	Total
0.675	-0.225	-0.075	0.025	Total/4

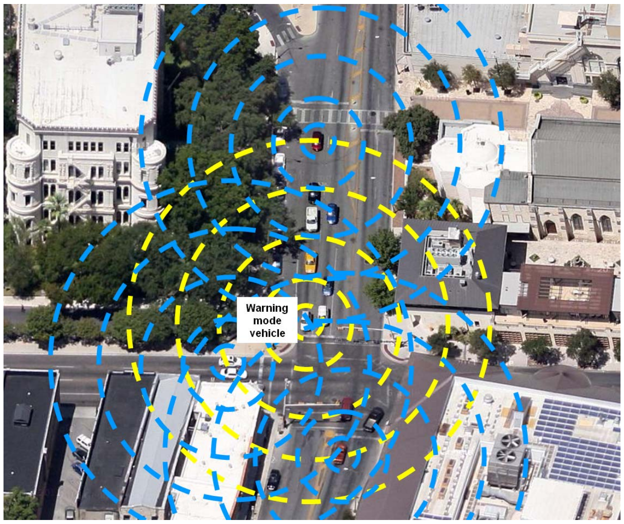

Fig. 1. Warning Message Dissemination (WMD) in a VANET (image of San Antonio, Texas from Google maps).

The outcome of the 2^k factorial analysis allows us in sorting out factors in the order of impact. At the beginning of any performance study, the number of factors and their levels could usually be large. A full factorial design with such a large number of factors and levels may not be the best use of available effort. The first step should be to reduce the number of factors and to choose those factors that have a significant impact on performance.

IV. FACTORS TO STUDY IN VANETS

Some previous works have studied the most important factors in MANETs. Nevertheless, VANETs have special characteristics that make them different from MANETs. Hence, more research is required in order to identify the key factors that impact its performance. In this section we identify and describe the most important factors associated with VANET *Warning Message Dissemination* (WMD).

A. *Number of Warning Vehicles*

In traffic safety applications, vehicles may send safety messages to other vehicles in order to prevent collisions or to ask for emergency services. We consider that vehicles may operate in warning or normal mode. Warning mode vehicles inform other vehicles about their abnormal status by sending warning messages periodically. Normal mode vehicles participate in the diffusion of these warning packets and, periodically, they also send *beacons* with information about themselves, such as their position and speed.

This factor is important since the more vehicles in the warning mode are there in a scenario, the more network traffic there will be, thus increasing redundant rebroadcasts which provoke heavy contention and long-lasting collisions. Figure 1 shows an example of a WMD scheme in a VANET.

B. *Density of Vehicles*

In VANETs, the density of vehicles can be particularly high, which usually causes that VANET simulations require quite a long time to finish. Moreover, many network simulators do not scale well, and so simulating VANETs with high density of vehicles consumes a significant amount of time and resources.

As shown in previous works, this factor seems to be important to measure WMD performance in VANET scenarios.

C. *Channel Bandwidth*

In radio communications, bandwidth is the width of the frequency band used to transmit the data. Channel spacing is a term used in radio frequency planning that describes the frequency difference between adjacent allocations in a frequency plan. The 802.11p [5] standard supports 10MHz and 20Mhz bandwidths. Using a 10Mhz bandwidth, the supported data rates are 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps, depending on the modulation and coding scheme considered.

Since vehicular information delivery systems support applications such as cooperative driving among cars on the road, traffic safety, or infotainment applications, we think that channel bandwidth requirements could change based on the selected application. For the specific case of WMD mechanisms, the overall capacity of the channel can affect the effectiveness of warning dissemination schemes if the density of potential transmitters is high.

D. *Broadcast Scheme*

Another important factor in Warning Message Dissemination in VANETs is the selected broadcast scheme. In VANETs, intermediate vehicles act as relays to support end-to-end vehicular communications. For applications such as route planning, traffic congestion control, and traffic safety, flooding of broadcast messages commonly occurs. However, flooding results in many redundant rebroadcasts, heavy channel contention, and long-lasting message collisions (usually known as the broadcast storm problem).

Over the years, several schemes have been proposed to address the broadcast storm problem in wireless networks. In [6] we can find some of the most interesting approaches: (i) the counter-based scheme, which uses a counter to keep track of the number of times the broadcast message is received in order to decide whether to inhibit the rebroadcast, (ii) the distance-based scheme, in which the relative distance between vehicles is used to decide whether to rebroadcast or not, and (iii) the location-based scheme, which is very similar to the distance-based scheme, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation of the additional coverage of a rebroadcast. More recently, we proposed a scheme called *enhanced Street Broadcast Reduction* (eSBR) [7], which uses location and roadmap information to facilitate an efficient dissemination of warning messages in 802.11p-based VANETs.

In our experiments we use the location-based scheme, and our eSBR scheme to assess the relevance of the broadcast scheme adopted.

E. *Message Priority*

Wireless technologies such as the IEEE 802.11p *Wireless Access for Vehicular Environment* (WAVE) [8] enable peer-to-peer mobile communication among vehicles (V2V) and communication between vehicles and the infrastructure (V2I), and are expected to be widely adopted by the car industry in the next years.

The 802.11p MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA), and *Quality of Service* (QoS) extensions. Therefore, application messages are categorized into different *Access Classes* (ACs), where AC0 has the lowest and AC3 the highest priority.

In our experiments, $warning\ messages$ have the highest priority (AC3) at the MAC layer, while $beacons$ have lower priority (AC0) than warning messages and are not propagated by other vehicles.

F. *Message Periodicity*

As mentioned previously, warning mode vehicles inform other vehicles about their status by sending warning messages periodically. Normal mode vehicles participate in the diffusion of these warning packets and, moreover, they also send periodic $beacons$ with information such as their positions, speed, etc.

Similarly to the number of warning vehicles, the more warning messages are sent at the same time, the more redundant rebroadcasts, channel contention, and message collisions there will be. Thus, message periodicity seems to be an important factor that offers a trade-off between performance and overhead.

G. *Mobility Model*

To perform realistic simulations, it is especially important that the chosen mobility generator could obtain a detailed microscopic traffic simulation by importing network topologies from real maps. Our mobility simulations are performed with SUMO [9], an open source traffic simulation package which has interesting microscopic traffic capabilities such as: collision free vehicle movement, multi-lane streets with lane changing, junction-based right-of-way rules, traffic lights, etc.

Our mobility simulations account for areas with different vehicle densities. In a real town, traffic is not uniformly distributed; there are downtowns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* [10] to add points of attraction in roadmaps. To generate the movements for the simulated vehicles, we used two different mobility models available in SUMO: (i) the Krauss mobility model [11] with some modifications to allow multi-lane behavior [12], and (ii) the Wagner mobility model [13]. The Krauss model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)}{\tau(t) + 1} + \eta(t), \qquad (12)$$


(a) (b) (c)

Fig. 2. Scenarios used in our simulations as street graphs in SUMO: (a) fragment of the city of New York (USA), (b) fragment of the city of Rome (Italy), and (c) fragment of the city of San Francisco.

where v represents the speed of the vehicle, v_1 is the speed of the leading vehicle, g is the gap to the leading vehicle, τ is the driver's reaction time (set to 1 second in our simulations) and η is a random variable with a value between 0 and 1.

The Wagner model, unlike most driving models which assume an instantaneous or even delayed reaction of the driver to the surrounding situation, considers two important features of human driving and of human actions in general. Firstly, humans usually plan ahead, and secondly, the type of control that humans apply is not continuous, but discrete in time: they act only at certain moments in time.

H. Roadmap

The roadmap (road topology) is an important factor accounting for mobility in simulations, since the topology constrains cars' movements. Simulated road topologies can be generated ad hoc by users, randomly by applications, or obtained from real roadmap databases. Using complex layouts implies more computational time, but the results obtained are closer to the real ones. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). These approaches are simple and easy to implement in a simulator. However, layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the results obtained are likely to be similar in realistic environments.

Our simulation scenarios used in the 2^k factorial analysis are based on two different real roadmaps, which were obtained from real cities using OpenStreetMap. The two locations represent environments with different street densities and average street lengths. The chosen scenarios were the South part of the Manhattan Island from the city of New York (USA), and the area located at the North of the Colosseum in the city of Rome (Italy). The fragments selected have an extension of 4 km^2 (2 km $\times$ 2 km). Figure 2 depicts the street layouts used. As shown, the fragment from New York presents the longest streets, arranged in a Manhattan-grid style. The city of Rome represents the opposite situation, with short streets in a highly irregular layout. The third fragment was extracted from the city of San Francisco, and the results of its simulation are presented in Section V-C.

V. SIMULATION RESULTS

Simulation results presented in this paper were obtained using the ns-2 simulator. We modified the simulator to follow the upcoming WAVE standard closely[1], extending the ns-2 simulator to implement IEEE 802.11p.

We observe that the most widely used simulators, such as ns-2, Glomosim, QualNet and OPNET have not accurately simulated the *Radio Propagation Model* (RPM) in vehicular environments [14]. In particular, they do not take into account the physical obstacles present in urban environments (mostly buildings). However, for 802.11p-based VANETs, the received signal will largely depend on the presence of obstacles.

In this work, we use the *Real Attenuation and Visibility Model* (RAV) [15], a realistic RPM specifically designed for IEEE 802.11p-based VANETs that increases the level of realism of phenomena occurring at the physical layer, thereby allowing researchers to obtain more accurate and meaningful results. Figure 3 shows an example of the visibility scheme used in RAV, where vehicle (A) is trying to disseminate a message. In that case, and assuming that any vehicle receiving a message will rebroadcast it the first time, the result will be that some vehicles (B, C, D, F, G, and I) receive the message, while the others (E, H, and J) will never be reached by such message. The RAV visibility scheme calculates the angular difference between the streets where the vehicles are located, and then determines whether two vehicles are in line-of-sight.

Each simulation lasted for 120 seconds. In order to achieve a stable state before gathering data traffic, we only started to collect data after the first 60 seconds. All results represent

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[1] All these improvements and modifications of the simulator are publicly available at http://www.grc.upv.es/software/

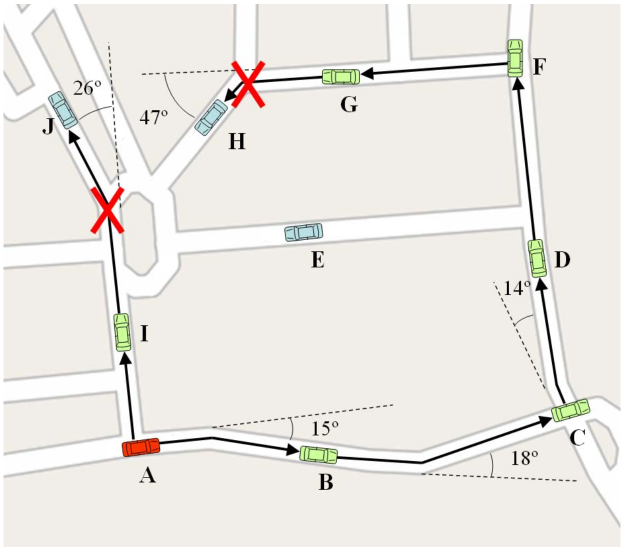

Fig. 3. RAV visibility scheme: example scenario.

TABLE IV

PARAMETERS USED FOR THE SIMULATIONS

Parameter	Value
roadmap size	$2000m \times 2000m$
downtown size	$1000m \times 1000m$
downtown probability	0.5
downtown attraction	0.5
warning packet size	$256B$
normal packet size	$512B$
warning messages priority	$AC3$
MAC/PHY	802.11p
radio propagation model	RAV[7]
maximum transmission range	$400m$

an average over several executions with different random scenarios, presenting all of them a maximum error of 10% with a degree of confidence of 90%. We evaluated the following performance metrics: (i) the warning notification time, (ii) the percentage of blind vehicles, and (iii) the number of packets received per vehicle. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle. The percentage of blind vehicles is the percentage of vehicles that does not receive the warning messages sent by the warning mode vehicles. These vehicles can remain blind because of their positions, due to collisions, or due to signal propagation limitations. Table IV shows the parameters used for the simulations. The downtown probability and the downtown attraction are the probability that a vehicle is within the downtown and the probability that a vehicle travels into the downtown area, respectively. The maximum transmission range was obtained empirically.

A. *Factors Determination Using 2^k Factorial Analysis*

In this section, we use the 2^k factorial analysis [1] to determine the most relevant factors that govern Warning Message Dissemination performance. We consider 8 factors, previously presented in Section IV. They are listed in Table V.

TABLE V

FACTORS CONSIDERED AND THEIR VALUES

Factor	Level -1	Level 1
warning vehicles (A)	3	10
density of vehicles (B)	$25\ vehicles/km^2$	$100\ vehicles/km^2$
channel bandwidth (C)	$3Mbps$	$6Mbps$
broadcast scheme (D)	location-based [6]	eSBR [7]
normal messages priority (E)	AC0	AC3
periodicity of messages (F)	$1\ packet/s$	$20\ packets/s$
mobility model (G)	Krauss modified [12]	Wagner [13]
roadmap (H)	New York	Rome

TABLE VI

THE PERCENTAGE OF VARIATION EXPLAINED USING THE SIGN TABLE METHOD UP TO THE COMBINATION OF 2 FACTORS

Factors	**Variation explained (%)**		
	warning notification time	*% of blind vehicles*	*number of packets received*
A	5.26	5.12	**29.91**
B	**9.87**	**24.18**	**21.73**
C	0.07	0.00	1.11
D	5.17	0.37	0.55
E	0.00	0.00	0.00
F	0.00	0.00	0.00
G	1.69	7.24	0.00
H	5.10	**37.77**	**21.25**
AB	2.03	3.55	**9.10**
AC	0.12	0.00	0.54
AD	0.04	0.08	0.00
AE	0.00	0.00	0.00
AF	0.00	0.00	0.00
AG	1.96	0.95	1.12
AH	0.76	0.41	6.05
BC	0.07	0.00	0.86
BD	2.87	0.18	0.00
BE	0.00	0.00	0.00
BF	0.00	0.00	0.00
BG	**16.62**	1.17	0.81
BH	**34.60**	**15.14**	3.73
CD	0.14	0.00	0.00
CE	0.00	0.00	0.00
CF	0.00	0.00	0.00
CG	0.09	0.00	0.01
CH	0.10	0.00	0.53
DE	0.00	0.00	0.00
DF	0.00	0.00	0.00
DG	2.59	0.17	0.34
DH	2.46	0.37	0.17
EF	0.00	0.00	0.00
EG	0.00	0.00	0.00
EH	0.00	0.00	0.00
FG	0.00	0.00	0.00
FH	0.00	0.00	0.00
GH	8.40	3.32	2.19

We tag each of the factors with A, B, C, ...H accordingly, as stated in the table. Thereafter, we specify two representative environments, which are described by two different levels, i.e. Level -1 and Level 1. Each level provides different parameter values to define the environment.

After having executed the 2^k factorial analysis, Table VI indicates the percentage of variation of each studied metric explained by each factor. The more the percentage of variation, the more impact this factor has in the measured metric.

Results of our 2^k factorial analysis show that:

- The average time required to complete the propagation process is largely affected by the density of vehicles

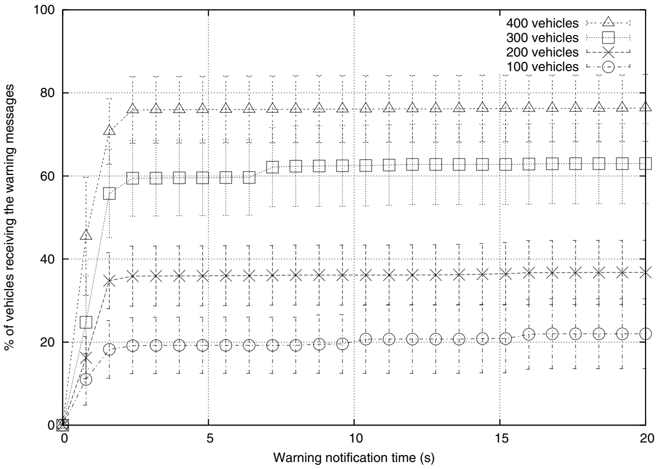

Fig. 4. Warning notification time when varying the density of vehicles.

(B), the combination of the density and the mobility model (BG), and the combination of the density and the simulated roadmap (BH).

- The average number of blind vehicles is largely affected by the density of vehicles (B), the simulated roadmap (H), and their combination (BH).
- The average number of packets received per vehicle is largely affected by the number of warning vehicles (A), the density of vehicles (B), the simulated roadmap (H), and the combination of warning vehicles and the density of vehicles (AB).

Based on the above outcome, we can state that the key factors to be accounted for when studying warning dissemination systems are the density of vehicles and the simulated roadmap. The number of warning vehicles is only important when accounting for the average number of packets received. This characteristic is explained because the more vehicles in warning mode are there in a scenario, the more warning message generators and network traffic there will be.

We now perform a detailed study to evaluate the impact of the most representative factors one by one.

B. Evaluating the Impact of the Density of Vehicles

Figure 4 shows the simulation results when varying the number of vehicles. We selected 100, 200, 300, and 400 vehicles (i.e. 25, 50, 75, and 100 vehicles/km^2). Table IV shows some of the parameters used for the simulations; the rest of parameters are the following: the roadmap used is Rome, vehicles follow the Krauss mobility model, there are 3 warning mode vehicles, the periodicity of messages is 1 message per second, normal message priority is AC0, the broadcast scheme applied is eSBR, and the channel bandwidth is 6 Mbps.

As expected, the warning notification time is lower when the vehicle density increases. When simulating with 400 vehicles, information reaches about 60% of the vehicles in only 1.3 seconds, and the propagation process is completed in 2.4 seconds.

TABLE VII

BLIND VEHICLES AND PACKETS RECEIVED PER VEHICLE WHEN VARYING THE DENSITY OF VEHICLES

Vehicles	% of blind vehicles	packets received
100	76.63%	197.37
200	60.92%	229.07
300	36.40%	432.60
400	21.01%	949.40

TABLE VIII

BLIND VEHICLES AND PACKETS RECEIVED PER VEHICLE WHEN VARYING THE ROADMAP

Roadmap	% of blind vehicles	packets received
New York	2.92%	1542.07
San Francisco	20.55%	885.13
Rome	60.92%	229.07

Table VII shows the percentage of blind vehicles and the number of packets received per vehicle when varying the density of vehicles. The behavior in terms of percentage of blind vehicles highly depends on this factor. This characteristic is explained because the flooding propagation of warning messages works better with higher vehicle densities. As for the number of packets received per vehicle, this number highly increases when increasing vehicle density.

C. Evaluating the Impact of the Roadmap

Figure 5 shows the warning notification time when varying the roadmap used. We selected scenarios from New York, San Francisco, and Rome. Table IV shows some of the parameters used for the simulations; the rest of parameters are the following: 200 vehicles are simulated, vehicles follow the Krauss mobility model, there are 3 warning mode vehicles, the periodicity of messages is 1 message per second, normal message priority is AC0, the broadcast scheme applied is eSBR, and the channel bandwidth is 6 Mbps.

As shown, the warning notification time is lower when simulating the New York map. Information reaches about 60% of the vehicles in less than 0.8 seconds, and propagation is completed in 5 seconds. When simulating the map of San Francisco, information needs more time (1.4 seconds) to reach the same percentage of vehicles. As for Rome, the propagation process was completed in only 2.4 seconds, but less than 40% of the vehicles are informed. The behavior in terms of percentage of blind vehicles and the number of packets received also highly depends on this factor (see Table VIII). In fact, when simulating New York, the percentage of blind vehicles is almost negligible, while we find 60.92% of blind vehicles when simulating Rome. So, when the simulated layout is more complex, the percentage of blind vehicles increases, and more time is needed to reach the same percentage of vehicles. This occurs mainly because the signal propagation is blocked by buildings. Moreover, the average number of packets received per vehicle highly differs depending on the map. Compared to New York, the number of packets received decreases considerably for San Francisco and even more for Rome since signal propagation encounters more restrictions.

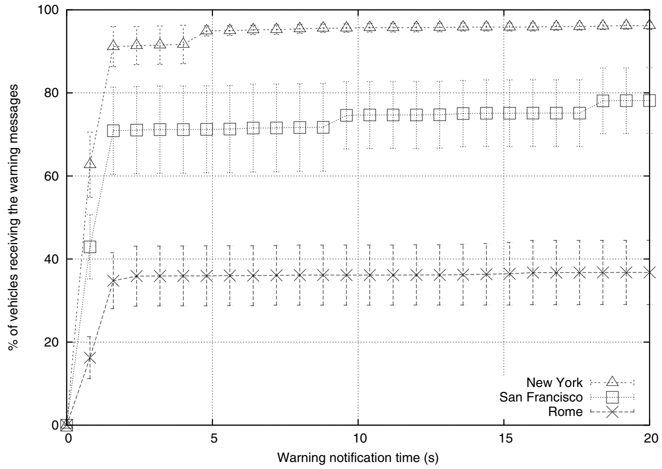

Fig. 5. Warning notification time when varying the roadmap.

D. Lessons Learnt and Guidelines for Future Research

The 2^k factorial analysis reflected that the key factors to take into account when simulating VANETs are the density of vehicles, and the roadmap used. By evaluating the impact of each factor one by one, we confirmed the outcome of the 2^k factorial analysis. We observed that the results obtained are highly affected by the selected roadmap and the density of vehicles. The propagation of warning messages works better with simpler layouts and higher vehicle densities.

Results also showed that other important factors, such as the broadcast scheme used, the channel bandwidth, and the priority and the periodicity of messages, have little impact in the warning message delivery process. Nevertheless, we believe that these parameters could be important factors in other VANET scenarios and applications, such as live video streaming services to driving vehicles. Although the selected roadmap is a key factor in VANETs, the majority of VANET proposals tend to use very simplistic scenarios. We consider that the use of more realistic topologies is required in order to obtain meaningful results.

VI. CONCLUSION

In this paper, we identified and described the different factors to be taken into account when simulating VANETs. Since the number of possible factors can be very large, we identified the representative factors by using the 2^k factorial analysis. The purpose is to reduce the required simulation time in future research.

The key factors affecting the delivery of warning messages are the density of vehicles, and the roadmap used. Some other factors, such as the broadcast scheme used, the channel bandwidth, and the priority and the periodicity of messages, did not have a significant impact on the metrics considered in our study. We believe that the results of our analysis can save researchers' time by discarding unnecessary factors when performing simulations for VANET-related research.

Moreover, results obtained from our simulations confirmed that the selected roadmap is a crucial factor. In fact, performance parameters such as warning notification time, the percentage of blind vehicles, and the number of packets received per vehicle highly depend on it. Thus, we consider that researchers must carefully determine the scenarios to assess their proposals.

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