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Determining the Representative Factors Affecting Warning Message Dissemination in VANETs

Francisco J. Martinez · Chai Keong Toh ·
Juan-Carlos Cano · Carlos T. Calafate ·
Pietro Manzoni

Abstract In this paper, we present a statistical analysis based on the 2k factorial methodology to determine the representative factors affecting traffic safety applications in *Vehicular ad hoc networks* (VANETs). Our purpose is to determine what are the key factors affecting *Warning Message Dissemination* (WMD) in order to concentrate on such parameters, thus reducing the amount of required simulation time when evaluating VANETs. Simulation results show that the key factors affecting warning messages delivery are: (i) the transmission range, (ii) the radio propagation model used, and (iii) the density of vehicles. Based on this statistical analysis, we evaluate a compound key factor: neighbor density. This factor combines the above-mentioned factors into a single entity, reducing the number of factors that must be taken into account for VANET researchers to evaluate the benefits of their proposals.

Keywords Vehicular ad hoc networks · Performance evaluation · Inter-vehicle communication · 2k factorial analysis

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F. J. Martinez (✉)
University of Zaragoza, Teruel, Spain
e-mail: f.martinez@unizar.es

C. K. Toh
ALICO Systems, Inc., Torrance, CA 90501, USA

C. K. Toh
National Cheng Kung University, Tainan, Taiwan
e-mail: ck_away@hotmail.com

J.-C. Cano · C. T. Calafate · P. Manzoni
Universitat Politècnica de València, Valencia, Spain
e-mail: jucano@disca.upv.es

C. T. Calafate
e-mail: calafate@disca.upv.es

P. Manzoni
e-mail: pmanzoni@disca.upv.es

1 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. VANETs are characterized by: (i) a constrained but highly variable network topology, (ii) a great density of nodes, (iii) poor communication conditions (signal transmissions can be blocked by buildings), (iv) vehicle specific mobility patterns (frequent network partitioning due to the high mobility), and (v) no significant energy constraints.

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 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. Compared to *Mobile ad hoc Networks* (MANETs), 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. Hence, it is necessary to correctly identify the key factors that must be taken into account when simulating VANET scenarios, thereby avoiding to waste time repeating simulations by varying irrelevant parameters.

In this paper, we present a statistical analysis based on the 2k 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. We start our analysis by selecting the following nine 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 mobility model, (vi) the radio propagation model, (vii) the periodicity of messages, as well as (viii) the maximum speed in the outskirts, and (ix) the transmission range.

In a factorial design strategy, all factors are varied together (as opposed to one-at-time). So, a key advantage of the factorial design is that it allows researchers to find out the possible interactions among different factors. This methodology will allow us to also determine interdependencies among different factors.

This paper is organized as follows: Sect. 2 describes related work on 2k factorial analysis in wireless networks. Section 3 presents the 2k factorial analysis fundamentals. Section 4 describes the main factors of interest in VANET research. In Sect. 5 we determine the key factors in VANET simulation using the 2k factorial analysis and present the simulation results. Finally, Sect. 6 concludes this paper.

2 Related Work

In the networking literature we can find several works that adopted the 2k 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 its time-sensitive performance with respect to network security schemes. Standard statistical approaches, such as 2k 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. Vaz de Melo et al. [4] studied how different WSNs can cooperate and save their energy. Simulation results revealed that different densities and data collecting rates among WSNs, the routing algorithm and the path loss exponent had major impact in the establishment of cooperation. The initial assessment of the impact of these factors was made through 2k factorial experimental analysis.

Perkins et al. [5] studied and quantified the effects of various factors and their two-way interactions on the overall performance of MANETs. Using 2k 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 of these factors on the throughput, routing overhead, and power consumption. In [6], authors investigated the impact of some characteristics on the performance of TCP in MANETs. Moreover, a factorial design experiment was conducted to quantify the effects and interactions that node speed and node pause time have over the throughput of TCP. Buchegger and Le Boudec [7] proposed a protocol, called CONFIDANT, based on selective detection and isolation of misbehaving nodes. They presented a performance analysis of DSR fortified by CONFIDANT and compare it to regular defenseless DSR. A 2k factorial design was performed to find out which factors affect performance. McClary et al. [8] designed a transport protocol that uses *Artificial Neural Networks* (ANNs) to adapt the audio transmission rate to changing conditions in a MANET. The response variables of throughput, end-to-end delay, and jitter were examined.

As shown, the use of standard statistical approaches such as the 2k factorial analysis, is found in many other fields but seldom used in data 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 impact performance of warning message dissemination systems for VANETs.

3 The 2k Factorial Analysis

In research, deploying and testing different proposals may involve high cost and intensive labor. Hence, simulation is a useful alternative prior to actual implementation. Nevertheless, 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 2k factorial analysis [1] can be used to determine the most relevant factors that govern a system's performance.

The use of 2k 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 required amount of simulation time needed. The basic approach of this method is

Table 1 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 2 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 s	0.8 s
100	0.5 s	0.4 s

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 a Warning Message Dissemination system, and 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.

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 1 shows the different experiments defined by the 2^2 design. Table 2 shows the results obtained after the simulations.

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

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

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

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:

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

Table 3 Sign table method of calculating effects in a 2^2 design

I	A	B	AB	y
1	−1	−1	1	1 s
1	1	−1	−1	0.5 s
1	−1	1	−1	0.8 s
1	1	1	1	0.4 s
2.7	−0.9	−0.3	0.1	Total
0.675	−0.225	−0.075	0.025	Total/4

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

3.1 Calculating the Effects of the Factors

In a 2k 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 3. 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:

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

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

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

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

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

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 obtained 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 this example the density of vehicles is the most important factor which affects the warning notification time.

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

4 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 have a strong impact on its performance. In this section we identify and describe the most important factors in VANET *Warning Message Dissemination* (WMD).

4.1 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 in 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 positions 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.

4.2 Density of Vehicles

In VANETs, the density of nodes can be particularly high, which usually provokes that VANET simulations require quite a long time to finish. Moreover, many network simulators do not scale well, and so simulating VANETs with more that 500 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.

4.3 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 [9] standard supports 10 and 20 MHz bandwidths. Using a 10 MHz 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.

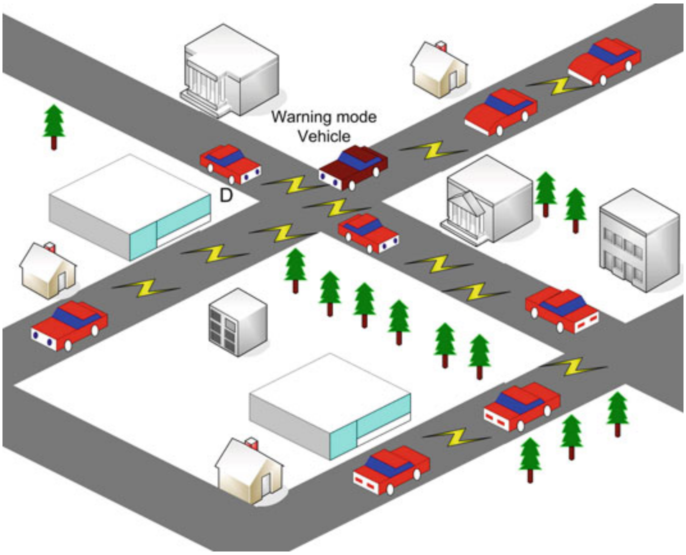

Fig. 1 Warning message dissemination (WMD) in a VANET

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.

4.4 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) [10].

In the past, several approaches have been proposed to solve the broadcast storm problem in ad hoc networks. They include: (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 inhibit the rebroadcast in case a message is received a certain number of times, (ii) the distance-based scheme, in which the relative distance between vehicles is used to decide whether to rebroadcast or not, (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, and (iv) the cluster-based scheme, where vehicles are grouped in clusters, and only one member of each cluster (the cluster head) can rebroadcast the warning messages. In our experiments we use both the counter-based scheme and the location-based scheme to assess the relevance of the broadcast scheme adopted.

4.5 Mobility Model

Based on previous studies of mobility behavior of mobile users [11], existing models try to closely represent the movement patterns of users. These models provide a suitable environment for the simulation and evaluation of ad hoc communication performance.

For results to be useful, it is important that the simulated model is as close to reality as possible [12]. For MANETs, the random waypoint model (RWP) is by far the most popular mobility model [13]. However, in vehicular networks, nodes (vehicles) can only move along streets, prompting the need for a road model. Moreover, vehicles do not move independently of each other; they move according to well established vehicular traffic models, so the results for MANETs are not directly applicable.

Our mobility simulations are performed with the CityMob[1] mobility generator [14] that we proposed and validated for use in VANETs. CityMob provides three different mobility models that combine a certain level of randomness, while trying to represent some realistic environments. The models are: (i) the *Simple Model* (SM), which models vertical and horizontal mobility patterns without direction changes. Traffic lights are not supported either; (ii) the *Manhattan Model* (MM), which models the city as a Manhattan style grid, with a uniform block size across the simulation area. All streets are two-way, with one lane in each direction. Car movements are constrained by these lanes. The direction of each vehicle in every moment will be random, and it can not be repeated in two consecutive movements. Moreover, this model simulates traffic lights with different delays. When a vehicle meets a red traffic light, it comes to a stop until the traffic light turns to green; (iii) the *Downtown Model* (DM), which adds traffic density behavior similar to a real town, where traffic is not uniformly distributed. Hence, there will be zones with a higher vehicle density. These zones are usually in the downtown, and vehicles must move more slowly than those in the outskirts.

4.6 Radio Propagation Model

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. In particular, they do not take into account the physical obstacles present in urban environments (mostly buildings). For example, the commonly used *Two Ray Ground* (TRG) radio propagation model ignores effects such as *Radio Frequency* (RF) attenuation due to buildings and other obstacles. Nevertheless, for 802.11p-based VANETs, the received signal will largely depend on the presence of obstacles.

In the literature, most works related to VANETs employ very simplistic RPMs, ignoring the effects that buildings have on radio signals propagation. In this work, we include as an alternative the *Building and Distance Attenuation Model* (BDAM), 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 [15]. BDAM considers that communication will only be possible when the received signal is strong enough and vehicles are within line-of-sight. It also takes into consideration that, at a frequency of 5.9 GHz (i.e., the frequency band of the 802.11p standard), the signal is highly directional and will experience a very low depth of penetration. Hence, in most cases, buildings will absorb radio waves at this frequency, making communication only possible when the vehicles are in line-of-sight.

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[1] `CityMob's` source code is available at http://www.grc.upv.es/.

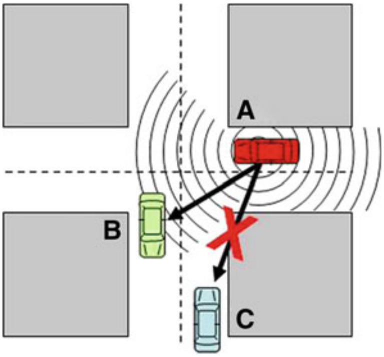

Fig. 2 The building and distance attenuation model (BDAM): example scenario

Figure 2 shows an example of this model where dark rectangles represent buildings. In ns-2 supported models, vehicle C may receive the message from A. Nevertheless, with the BDAM model, only communication between vehicles A and B is possible. Vehicle C does not receive the message from A due to the presence of a building.

4.7 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.

4.8 Speed of Vehicles

In VANETs, nodes move within a constrained but highly variable topology due to the high mobility. In fact, vehicles move at higher speeds, especially in highways. In MANETs, node speed ranges from 0 to 5 m/s, while in VANETs speed ranges from 0 to 40 m/s.

4.9 Transmission Range

The transmission range (Tx) is a very important factor in wireless networks, and also in VANET simulations, since the wider the transmission range, the easier the warning message dissemination will be.

When simulating wireless networks, most network simulators assume that the warning packets sent by warning mode vehicles can be received by all vehicles within the radio range. For example, ns-2 assumes that signals have a perfect 250 m radius range, which is overly optimistic for urban environments. Nevertheless, for 802.11p-based VANETs, the received signal strength will largely depend on the distance from the sender. Consequently, simulation results so obtained are unlikely to accurately reflect system performance in the real world.

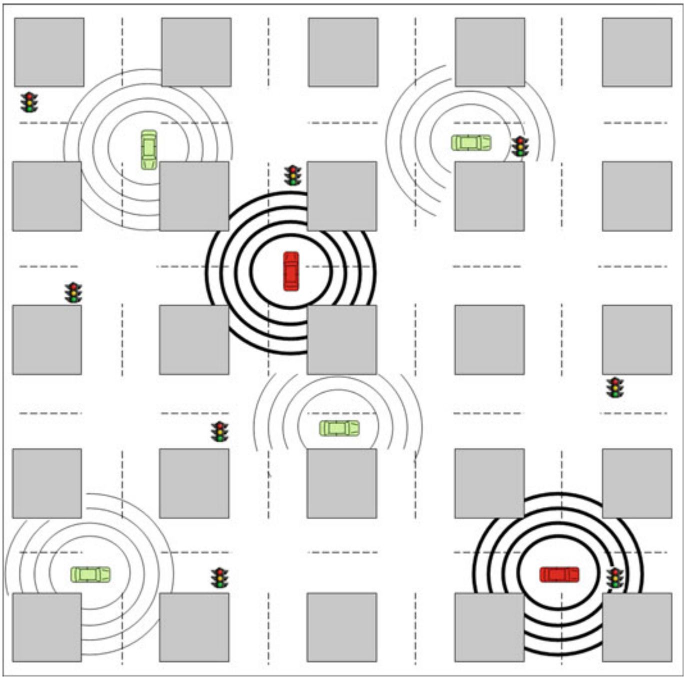

Fig. 3 Simulated topology

In our simulations, we compare two different RPMs: (i) the Two Ray Ground model, that considers a perfect radius range, and (ii) the BDAM model, that considers the signal attenuation due to the distance between vehicles by adding a probability function to estimate whether messages are correctly received or not within the radio range.

5 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[2], extending the ns-2 simulator to implement IEEE 802.11p. We chose the IEEE 802.11p technology because it is expected to be widely adopted by the industry. 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.

Each simulation lasted for 450 s. In order to achieve a stable state before gathering data traffic, we only started to collect data after the first 60 s. We evaluated the following performance metrics: (i) the percentage of blind vehicles, (ii) the number of packets received per vehicle, and (iii) the warning notification time. 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

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

Table 4 Parameters used for the simulations

Parameter	Value
Distance between streets	100 m
Map size	2,000 m × 2,000 m
Warning packet size	256 B
Normal packet size	512 B
Warning messages priority	AC3
Normal messages priority	AC0
MAC/PHY	802.11p

Table 5 Factors considered and their values

Factor	Level -1	Level 1
Warning vehicles (A)	3	10
Density of vehicles (B)	25 vehicles/km^2	75 vehicles/km^2
Channel bandwidth (C)	3 Mbps	6 Mbps
Broadcast scheme (D)	Counter-based	Location-based
Mobility model (E)	Simple model	Downtown model
Radio propagation (F)	TRG	BDAM
Periodicity of messages (G)	1 packet/s	20 packets/s
Maximum speed (H)	4 m/s	28 m/s
Maximum Tx range (I)	100 m	500 m

due to signal propagation limitations. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle.

Figure 3 shows the simulated urban topology. Red vehicles are collided vehicles which send warning messages. Table 4 shows the parameters used for the simulations.

5.1 2k Factorial Analysis

In the simulation of VANETs, the number of possible factors and their values, or levels, can be very large. In this section, we use the 2k factorial analysis [1] to determine the most relevant factors that govern Warning Message Dissemination performance, and to reduce the required amount of simulation time.

We consider 9 factors, previously presented in Sect. 5, which we felt are necessary. They are listed in Table 5. We tag each of the factors with A, B, C, ...I accordingly, as stated in the table. Thereafter, we specify two possible 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.

In Table 6 we indicate 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 2k factorial analysis show that:

- The average number of blind vehicles is largely affected by factors B, I, and BI.
- The average number of packets received per vehicle is largely affected by factors F, I, and FI.
- The average time required to complete the propagation process is largely affected by factors F, I, and FI.

Table 6 The percentage of variation explained using the sign table method up to the combination of 2 factors

Factors	Variation explained (%)		
	% of blind vehicles	Number of packets received	Warning notification time
A	0.00	7.11	1.01
B	**14.61**	1.55	4.57
C	0.00	1.27	0.09
D	0.00	2.36	0.19
E	0.00	0.12	0.77
F	0.24	**18.21**	**26.55**
G	0.00	0.00	0.00
H	0.08	0.09	0.01
I	**62.96**	**29.85**	**30.41**
AB	0.00	0.36	0.24
AC	0.00	0.36	0.08
AD	0.00	0.16	0.00
AE	0.00	0.02	0.00
AF	0.00	3.75	0.00
AG	0.00	0.00	0.00
AH	0.00	0.02	0.00
AI	0.00	6.97	0.01
BC	0.00	0.29	0.00
BD	0.00	0.11	0.02
BE	0.02	0.00	2.44
BF	0.16	0.07	1.25
BG	0.00	0.00	0.00
BH	0.04	0.10	0.29
BI	**21.58**	1.44	0.09
CD	0.00	0.32	0.01
CE	0.00	0.01	0.01
CF	0.00	1.19	0.00
CG	0.00	0.00	0.00
CH	0.00	0.00	0.09
CI	0.00	1.26	0.09
DE	0.00	0.24	0.01
DF	0.00	2.09	0.01
DG	0.00	0.00	0.00
DH	0.00	0.00	0.01
EF	0.01	0.00	1.09
EG	0.00	0.00	0.00
EH	0.00	0.00	0.00
EI	0.01	0.07	1.67
FG	0.00	0.00	0.00
FH	0.05	0.05	0.02
FI	0.23	**18.16**	**28.69**

Table 6 continued

Factors	Variation explained (%)		
	% of blind vehicles	Number of packets received	Warning notification time
GH	0.00	0.00	0.00
GI	0.00	0.00	0.00

Bold values indicate the factors that have more impact in the metrics

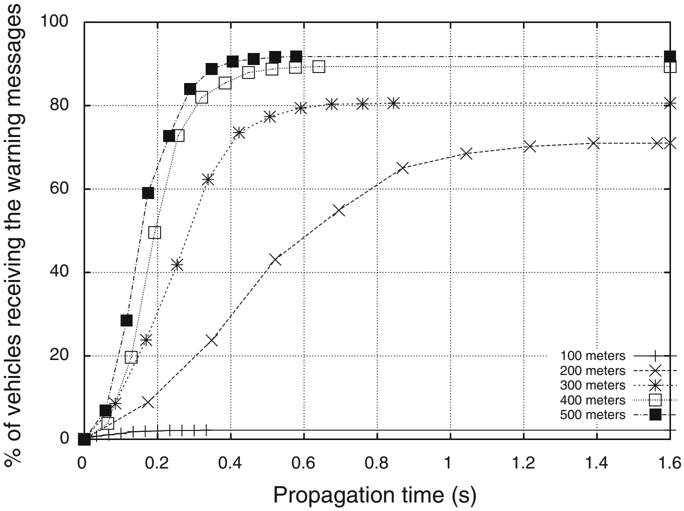

Fig. 4 Cumulative histogram for the time evolution of disseminated warning messages when varying the transmission range

Based on the above outcome, we can state that having both a higher transmission range (i.e., I), and a higher density of nodes (i.e., B) is very important for reducing the number of blind nodes. Also, to reduce the time required for complete propagation of warning messages and the number of packets received per node, the key factors to be accounted for are the transmission range and the selected radio propagation model (i.e., factors I and F).

Now we proceed with a sensibility analysis to evaluate the impact that the representative factors, obtained using the 2k factorial analysis, have on the performance of Warning Message Dissemination in VANETs.

5.2 Evaluating the Impact of the Maximum Transmission Range

Figure 4 and Table 7 show the simulation results when varying the maximum transmission range of vehicles while maintaining the rest of the parameters unaltered. As expected, the warning notification time is lower when the transmission range increases. Information reaches about 60% of the vehicles in less than 0.8 s when the transmission range is 200 m, and in only 0.17 s when the range is equal to 500 m.

The behavior in terms of percentage of blind vehicles also depends highly on this factor. In fact, when the transmission range is higher, information reaches more vehicles (up to 92% for 500 m, so that there are only 8% of blind vehicles). Nevertheless, when the transmission range is reduced to 100 m, there are 98% of blind vehicles, which prevents the WMD from

Table 7 Blind vehicles and packets received per vehicle when varying the transmission range

Tx range (in meters)	% of blind vehicles	Packets received
100	98	254.20
200	28	835.00
300	19	1,401.40
400	10	1,603.07
500	8	2,030.00

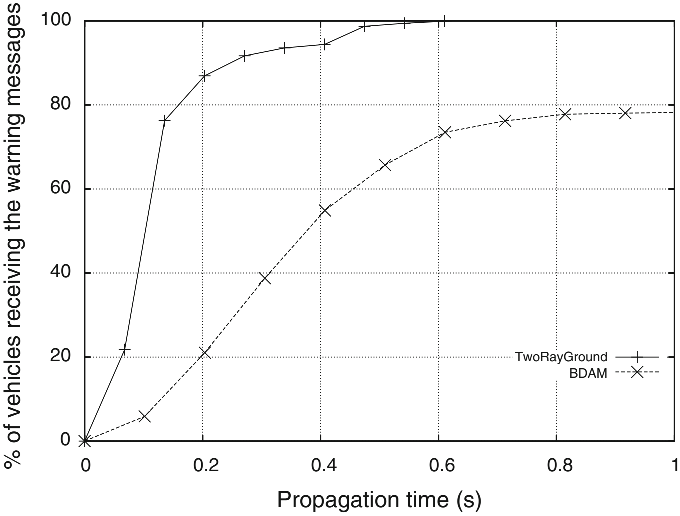

Fig. 5 Cumulative histogram for the time evolution of disseminated warning messages when varying the RPM used

operating correctly. This occurs because the flooding propagation of the messages works better with higher transmission ranges. Finally, as shown in Table 7, the number of packets received per vehicle also increases substantially when the transmission range increases.

5.3 Evaluating the Impact of the Radio Propagation Model

Figure 5 shows the warning notification time when varying the radio propagation model from the traditional *Two Ray Ground* (TRG) model to the more realistic BDAM model.

As shown, the warning notification time is lower when using the TRG model. Information reaches about 60% of the vehicles in less than 0.12 s, and propagation is completed in only 0.62 s. When using the BDAM model, the system needs 0.45 s to reach 60% of the vehicles, and propagation was completed in 1 s.

The behavior in terms of percentage of blind vehicles and the number of packets received also highly depends on this factor. In fact, when using the TRG model, there are no blind vehicles, while we find 22% of blind vehicles when using BDAM. So, when the model is more realistic, more time is needed to reach the same percentage of vehicles, and thus the percentage of blind vehicles increases. This occurs because the TRG model is really optimistic, and it does not account for the presence of obstacles in signal propagation. Moreover, the average number of packets received per vehicle highly differs depending on the model (see

Table 8 Blind vehicles and packets received per vehicle when varying the Radio Propagation Model

RPM	% of blind vehicles	Packets received
TRG	0	4,783.93
BDAM	22	1,179.00

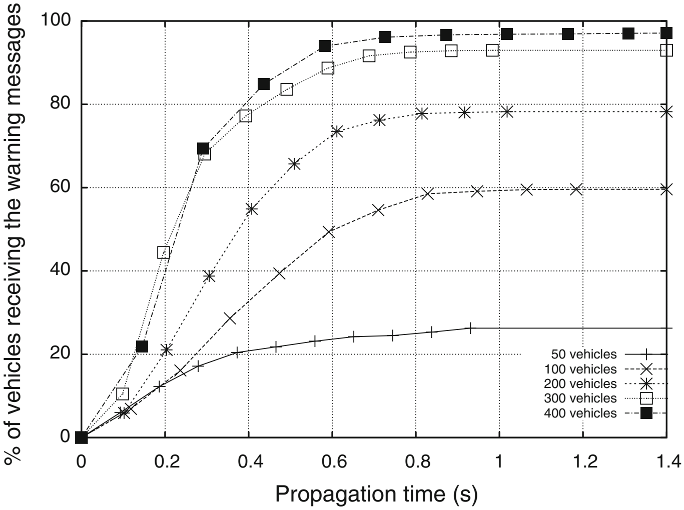

Fig. 6 Cumulative histogram for the time evolution of disseminated warning messages when varying the number of vehicles

Table 8). The number of packets received decreases considerably for BDAM since signal propagation encounters more restrictions [15].

The results show that using more realistic models tends to reduce protocol performance, allowing us to better understand the impact of buildings and obstacles along the road on car-to-car communications. Although the BDAM model yields poorer performance results than TRG, it is in fact a more realistic radio propagation model, which should be considered in future VANET simulations.

5.4 Evaluating the Impact of the Number of Vehicles

Figure 6 shows the simulation results when varying the number of vehicles while maintaining the rest of the parameters unaltered. We selected 50, 100, 200, 300, and 400 vehicles. As expected, the warning notification time is lower when the vehicle density increases. When simulating with 300 and 400 vehicles, information reaches about 60% of the vehicles in only 0.26 s, and the propagation process is completed in 1.4 s.

Table 9 shows the percentage of blind vehicles and the number of packets received per vehicle when varying the number of vehicles. The behavior in terms of percentage of blind vehicles highly depends on this factor. In fact, when vehicle density is high, the percentage of blind vehicles is almost negligible. 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 increases when increasing vehicle density.

Table 9 Blind vehicles and packets received per vehicle when varying the number of vehicles

Vehicles	% of blind vehicles	Packets received
50	73	364.00
100	40	481.73
200	22	1,085.47
300	6	2,116.33
400	2	2,215.67

Note that, due to collisions, the number of packets received per vehicle slightly differs when simulating 300 or 400 vehicles.

5.5 Lessons Learnt and Guidelines for Future Reseach

The 2k factorial analysis reflected that the key factors to take into account when simulating VANETs are: (i) the transmission range, (ii) the radio propagation model used, and (iii) the density of vehicles. By evaluating the impact of each factor one by one, we confirmed the outcome of the 2k factorial analysis. We observed that the propagation of warning messages works better with higher transmission ranges and higher vehicle densities. Moreover, although the use of more realistic RPMs tends to reduce protocol performance, realistic RPMs such as the BDAM model are required in future VANET simulations.

Results also showed that other important factors, such as the broadcast scheme used, the channel bandwidth, the speed of vehicles, the mobility model, and the periodicity of messages, have little impact in the warning message delivery process.

The obtained results suggest us to account for a compound key factor: neighbor density. This factor combines two of the key factors (see Eq. 12) into a single one, thus reducing the number of factors that must be taken into account by researchers for future VANET studies:

$$\text{neighbor density} = \frac{\text{number of vehicle} \cdot \text{maximum Tx range}}{\text{map area}} \tag{12}$$

Some authors have previously used this term in Intelligent Transportation Systems [16,17], although in [17] they really referred to the average number of the potential neighbors, i.e., the density of vehicles (see Eq. 13).

$$\text{neighbor density} \neq \text{vehicle density} = \frac{\text{number of vehicles}}{\text{map area}} \tag{13}$$

To calculate the neighbor density, we account for the transmission range (as other authors in [18–20]) since we consider that one vehicle is a neighbor of another only if this vehicle can be reached in only one hop, i.e. it is within its transmission range. However, unlike the aforementioned works, our radio propagation model also considers the signal attenuation due to the distance between vehicles.

Figure 7 and Table 10 show the simulation results when varying the number of neighbors per vehicle while maintaining the rest of parameters unaltered. As shown, all the metrics highly depend on neighbor density. With a small number of neighbors, the warning notification time is higher, the percentage of blind vehicles is very high, and the number of packets received is very low. Nevertheless, with a large number of neighbors, the system needs less time to complete the propagation process, the percentage of blind vehicles is null, and the number of packets received increases. Results show that, when there are 50 or more neighbors

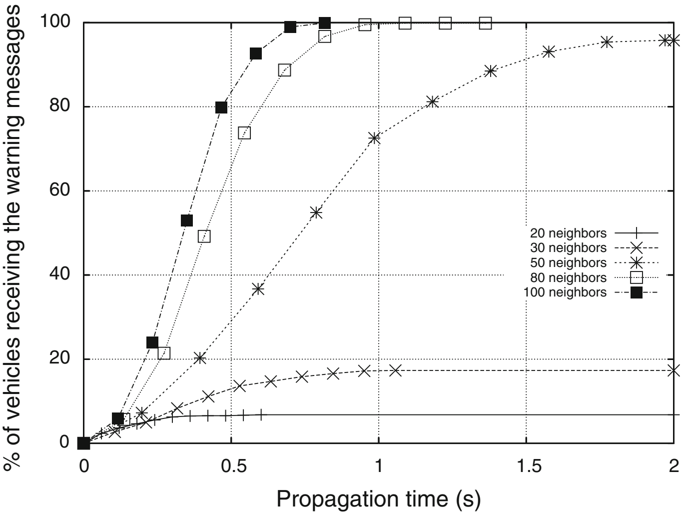

Fig. 7 Cumulative histogram for the time evolution of disseminated warning messages when varying the number of neighbors per vehicle

Table 10 Blind vehicles and packets received per vehicle when varying the number of neighbors

Neighbors	% of blind vehicles	Packets received
20	93	272.20
30	83	295.20
50	4	625.40
80	0	1,355.53
100	0	1,428.20

per vehicle, the percentage of blind vehicles is almost negligible and the warning information reaches all vehicles in a reasonable time, meaning that the Warning Message Dissemination scheme achieves the desired degree of effectiveness.

6 Conclusion

In this paper, we identified the important and influencing representative factors that govern the performance of VANETs. Additionally, this identification and narrowing down of factors also help in reducing the simulation time in VANETs.

The key factors affecting the delivery of warning messages are: (i) the transmission range, (ii) the radio propagation model used, and (iii) the density of vehicles. Some factors such as message periodicity, channel bandwidth, the broadcast scheme used, the speed of vehicles, and the mobility model did not have a significant impact on the metrics considered in our study. Based on this analysis, we evaluated a compound key factor: neighbor density. This factor combines the density of vehicles with the transmission range and the map area to allow a reduction on the number of factors to be considered in VANET simulations.

Results obtained from our simulations confirmed that neighbor density is a crucial factor. In fact, performance parameters such as propagation delay, the percentage of blind vehicles, and the number of packets received per vehicle highly depend on it.

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Author Biographies

Francisco J. Martinez is an associate professor in the Department of Computers and Systems Engineering at the University of Zaragoza in Spain. He graduated in Computer Science and Documentation at the Technical University of Valencia in 1996 and 1999, respectively. He received his Ph.D. degree in Computer Engineering from the Technical University of Valencia in 2010. His current research interests include VANET simulation, intelligent transportation systems, traffic safety, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. He is member of the IEEE.

Chai Keong Toh received his Ph.D. in Computer Science from Cambridge University (1996) and earlier EE degrees from Manchester University (1991) and Singapore Polytechnic (1986). He was a visiting professor at YALE (USA), Fudan (China), KTH (Sweden), KNU (Korea), NCKU (Taiwan), and Osaka University (Japan). From 2004–2009, he was an Honorary Full Professor at the University of Hong Kong. Previously, he was a tenured Chair Professor at the University of London and the Director of Research at TRW Tactical Systems Inc., USA. Earlier on, he led the DARPA Deployable Ad Hoc Networks program at Hughes Research Labs, USA. Dr. Toh has two sole-authored books: (a) "Ad Hoc Mobile Wireless Networks" (Prentice Hall, ISBN 0130078174, 2001), and (b) "Wireless ATM" (Kluwer, ISBN 079239822X, 1997). He has consulted for various companies, including KDDI (Japan), Hughes (USA), and Mitsubishi (USA). Dr. Toh is a Fellow of the British Computer Society (BCS), New Zealand Computer Society (NZCS), Hong Kong Institution of Engineers (HKIE), and Institution of Electrical Engineers (IEE). He is a recipient of the 2005 IEEE Institution Kiyo Tomiyasu Medal (for pioneering contributions to communication protocols in ad hoc mobile networks) and the 2009 IET Ambrose Fleming Medal (for achievements in communications engineering). In 2009, he was named an IEEE Fellow and AAAS Fellow.

Juan-Carlos Cano is an associate professor in the Department of Computer Engineering at the Polytechnic University of Valencia (UPV) in Spain. He earned an M.Sc. and a Ph.D. in computer science from the UPV in 1994 and 2002 respectively. Between 1995–1997 he worked as a programming analyst at IBM's manufacturing division in Valencia. His current research interests include power aware routing protocols and quality of service for mobile ad hoc networks and pervasive computing.

Carlos T. Calafate is an associate professor in the Department of Computer Engineering at the Polytechnic University of Valencia (UPV) in Spain. He graduated with honors in Electrical and Computer Engineering at the University of Oporto (Portugal) in 2001. He received his Ph.D. degree in Computer Engineering from the Technical University of Valencia in 2006, where he has worked as an assistant professor since 2005. He is a member of the Computer Networks research group (GRC). His research interests include mobile and pervasive computing, security and QoS on wireless networks, as well as video coding and streaming.

Pietro Manzoni is a full professor in the Department of Computer Engineering at the Polytechnic University of Valencia (UPV) in Spain. He received the M.S. degree in computer science from the "Universitá degli Studi" of Milan, Italy, in 1989, and the Ph.D. degree in computer science from the Polytechnic University of Milan, Italy, in 1995. He is an associate professor of computer science at the Polytechnic University of Valencia, Spain. His research activity is related to wireless networks protocol design, modelling, and implementation. He is member of the IEEE.