An Adaptive System Based on Roadmap Profiling to Enhance Warning Message Dissemination in VANETs

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Abstract— In recent years, new applications, architectures and technologies have been proposed for Vehicular Ad hoc Networks (VANETs). Regarding traffic safety applications for VANETs, warning messages have to be quickly and smartly disseminated in order to reduce the required dissemination time and to increase the number of vehicles receiving the traffic warning information. In the past, several approaches have been proposed to improve the alert dissemination process in multi-hop wireless networks, but none of them was tested in real urban scenarios, adapting its behavior to the propagation features of the scenario. In this paper, we present the Profile-driven Adaptive Warning Dissemination Scheme (PAWDS) designed to improve the warning message dissemination process. With respect to previous proposals, our proposed scheme uses a mapping technique based on adapting the dissemination strategy according to both the characteristics of the street area where the vehicles are moving, and the density of vehicles in the target scenario. Our algorithm reported a noticeable improvement in the performance of alert dissemination processes in scenarios based on real city maps.

Index Terms— Vehicular ad hoc networks, broadcast storm, adaptive mechanism, inter-vehicle communication, roadmap scenarios, alert dissemination.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are wireless networks that do not require any fixed infrastructure. These networks are considered essential for cooperative driving among cars on the road. VANETs are characterized by: (a) a constrained but highly variable network topology, (b) a great number of nodes with very specific speed patterns, (c) variable communication conditions (e.g., signal transmissions can be blocked by buildings), (d) road-constrained mobility patterns, and (d) no significant power constraints. Such features make standard networking protocols inefficient or unusable in VANETs; hence, there is a growing effort in the development of specific communication protocols and methodologies for vehicular networks. 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, thereby increasing the passengers' comfort, improving route planning, controlling traffic congestion, and improving traffic safety.

VANETs have many possible applications, ranging from inter-vehicle communication and file sharing to obtaining real-time traffic information (such as jams and blocked streets). In this work we focus on traffic safety and efficient warning message dissemination, where the main goal is to reduce the latency and to increase the accuracy of the information received by nearby vehicles when a dangerous situation occurs.

In a VANET, any vehicle detecting an abnormal situation (i.e. accident, slippery road, etc.) should notify the anomaly to nearby vehicles that could face this problem in a short period of time. Hence, broadcasting warning messages can be useful to alert nearby vehicles. However, a simple retransmission of warning messages yields an exponential growth of messages over time, and broadcast storm (serious redundancy, contention and massive packet collisions due to simultaneous forwarding) will occur, situation which must be avoided or reduced [1].

Adapting to the specific environment where the vehicles are located can be beneficial in order to reduce broadcast storm related problems, and also to increase the efficiency of the warning message dissemination process. Existing adaptive techniques for VANETs only make use of the vehicle density to adapt the process; however, this information in not enough in many situations to determine the most effective configuration. In this paper we propose PAWDS, a *Profile-driven Adaptive Warning Dissemination System* that dynamically modifies some of the key parameters of the propagation process, such as the interval between notifications and the selected broadcast scheme, to achieve an optimal performance depending on the features of the roadmap in which the propagation takes place. Our proposal is combined with the *enhanced Street Broadcast Reduction* (eSBR) [2], to improve performance when the dissemination process takes places in real urban scenarios where the signal can be seriously affected by nearby buildings.

The rest of the paper is organized as follows: Section II reviews the related work on the broadcast storm problem and adaptive schemes in VANETs. Section III justifies the importance of the specific roadmap in VANET simulations and shows a classification of real urban environments depending on their density of streets and junctions. Section IV presents our proposed adaptive scheme. Section V shows the simulation environment used to validate our proposal. Section VI presents and discusses the obtained results. Finally, Section VII concludes this paper.

II. RELATED WORK

In the networking literature, we can find several works that proposed either broadcast storm reduction techniques or adaptive mechanisms to enhance message dissemination. In this section we present some of the most representative works.

A. Broadcast storm reduction techniques

Tseng et al. [1] proposed different schemes to mitigate broadcast storms. The *Counter-based scheme* uses a counter to keep track of the number of times the broadcast message is received, inhibiting rebroadcast when it exceeds a threshold. The *Distance-based scheme* calculates the distance between the sender and the receiver and only allows retransmission when the additional coverage area is large enough. The *Location-based scheme* is similar to the previous one, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation (with convex polygons) of the additional coverage of a warning message.

Wisitpongphan et al. [3] developed the *weighted p-persistence*, the *slotted 1-persistence*, and the *slotted p-persistence* techniques. These three probabilistic and timer-based broadcast suppression techniques are not designed to solve the broadcast storm problem, but they can mitigate the severity of the storm by allowing nodes with higher priority to access the channel as quickly as possible. Unlike our proposal, these schemes are specifically designed for use in highway scenarios.

The Last One (TLO) scheme, presented in [4], tries to reduce the broadcast storm problem finding the most distant vehicle from the warning message sender, so this vehicle will be the only allowed to retransmit the message. Although it brings a better performance than simple broadcast, this scheme is only effective in a highway scenario because it does not take into account the effect of obstacles (e.g. buildings) in urban radio signal propagation. The TLO approach was extended using a protocol which utilizes adaptive wait-windows and adaptive probability to transmit, named *Adaptive Probability Alert Protocol* (APAL) [5]. This scheme shows even better performance than the TLO scheme, but it is also only validated in highway scenarios.

More recently, a stochastic broadcast scheme was proposed in [6] to achieve an anonymous and scalable protocol where relay nodes rebroadcast messages according to a retransmission probability. The performance of the system depends on the vehicle density, and these probabilities must be tuned to adapt to different scenarios. However, the authors only test this scheme in an obstacle-free environment, thus not considering urban scenarios where the presence of buildings could interfere with the radio signal.

The *Cross Layer Broadcast Protocol* (CLBP) [7] uses a metric based on channel condition, geographical locations and velocities of vehicles to select an appropriate relaying vehicle. This scheme also supports reliable transmissions exchanging *Broadcast Request To Send* (BRTS) and *Broadcast Clear To Send* (BCTS) frames. CLBP reduces the transmission delay but it is only conceived for single-direction environments (like highway scenarios), and its performance in urban environments has not been tested.

These mentioned techniques have not been further studied in realistic urban scenarios where buildings could interfere with the wireless signal. All of them use free space environments where no blocking obstacles are considered at all. The consequences derived from those incomplete analysis can be observed when their performance is tested in urban topologies, showing that they are unable to choose suitable relaying vehicles or proving to be too restrictive to achieve an efficient dissemination [2]. Therefore, we make use of the *enhanced Street Broadcast Reduction* (eSBR) scheme, a technique specially designed to work in urban environments allowing dissemination to overcome obstacles such as buildings.

B. Adaptive mechanisms to enhance message dissemination

With respect to adaptive schemes for message dissemination in VANETs, not much research can be found in the literature. Mariyasagayam et al. [8] proposed an adaptive forwarding mechanism to improve message dissemination in VANETs. Vehicles compute the density of neighbor nodes to calculate a forwarding sector in which vehicles are not allowed to rebroadcast the message.

The *Adaptive-ADHOC* (A-ADHOC) protocol [9] uses a variable frame length to increase channel utilization and to reduce response time. Another adaptive algorithm is the *Junction-based Adaptive Reactive Routing* (JARR) [10], a reactive position-based routing protocol that estimates the vehicle density of the available paths to be taken to send a message, also accounting for the direction and speed of traveling nodes in order to choose the optimal path.

Existing VANET adaptive systems only consider features related to the vehicles in the scenario such as density, speed and position to adapt the performance of the dissemination process. Moreover, most authors only evaluate their schemes using very simple scenarios and topologies that are not constrained by any obstacles, and where all the vehicles are in line-of-sight with each other. Unlike our proposal, these scenarios are not realistic enough to conclude that the proposed protocols and schemes could work efficiently in real VANET scenarios.

III. CITY PROFILE CLASSIFICATION

In previous works, we identified the most representative factors to be taken into account in VANETs [11]. We showed that the roadmap, which serves as scenario for the warning dissemination, has a considerable influence in the effectiveness of the process. So, next we demonstrate the impact that the roadmap will have over the performance of dissemination processes in VANETs.

A. Importance of the roadmap in VANET simulation

The roadmap (road topology) is an important factor accounting for mobility in simulations, since the topology constrains cars' movements. Roughly described, an urban topology is a graph where vertices and edges represent, respectively,

Fig. 1. Scenarios used in prior simulations as street graphs in SUMO: (a) fragment of the city of New York (USA), (b) fragment of the city of San Francisco (USA), and (c) fragment of the city of Rome (Italy).

TABLE I

MAIN FEATURES OF THE SELECTED MAPS

Selected city map	New York (USA)	San Francisco (USA)	Rome (Italy)
Streets/km^2	175	428	695
Junctions/km^2	125	205	298
Avg. street length	$122.55m$	$72.71m$	$45.89m$
Avg. lanes/street	1.57	1.17	1.06

junction and road elements. 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.

To prove how the results in VANET simulations depends on the chosen scenarios, we selected three different roadmaps from real cities using OpenStreetMap [12], representing 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), the streets around Market Street in the city of San Francisco (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 1 depicts the street layouts used, and Table I includes the main features of the chosen fragments of the cities. 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 city of San Francisco shows an intermediate layout between these two in terms of regularity and average street length.

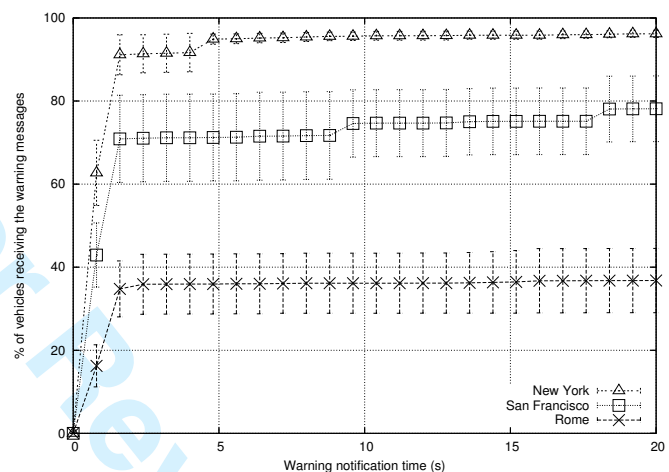We simulate the three selected scenarios using the same

Fig. 2. Warning notification time when varying the roadmap under the same simulation configuration.

configuration: 200 vehicles are simulated, there are 3 warning mode vehicles, the radio propagation model used is RAV [13], the channel bandwidth is 6 Mbps, warning mode vehicles send 1 message per second, the broadcast scheme applied is eSBR [2], and vehicles follow the Krauss mobility model [14] (further information about our simulation parameters can be found in Section V). Figure 2 shows that 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 II). 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,
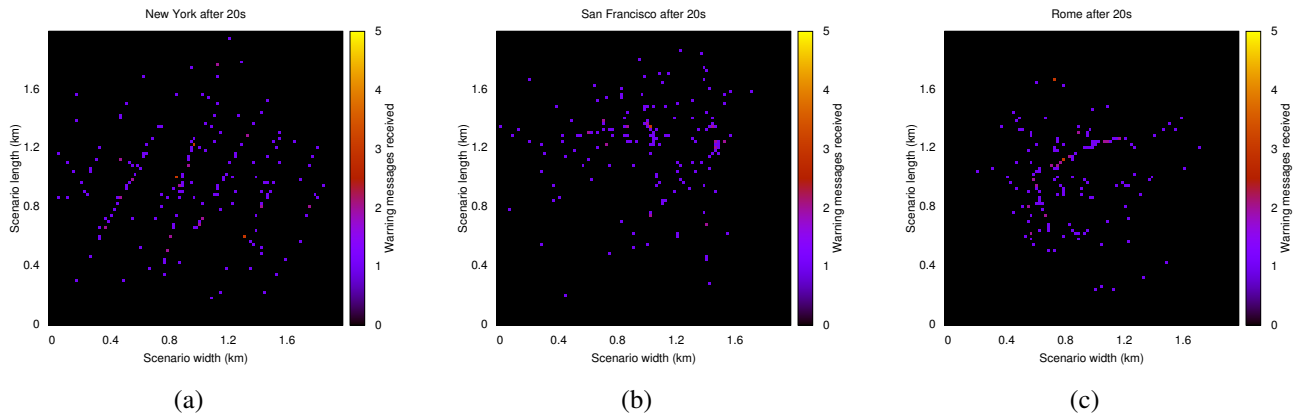
Fig. 3. Evolution of the warning message dissemination process after 20 seconds, when simulating (a) New York, (b) San Francisco, and (c) Rome scenarios.

TABLE II
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

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 city 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.

Figure 3 shows the number of warning messages received in each area when simulating New York, San Francisco, and Rome, respectively. As mentioned before, when simulating the New York scenario the dissemination process is able to reach a wider area since streets are longer and wider, and there are fewer junctions, so messages can be disseminated more easily.

B. Roadmap layout clustering

We can easily deduce from the previously presented results that the selected topology has a great influence on the obtained results in a VANET simulation. Hence, aiming at using the specific features of the scenarios to improve performance, a wide set of maps from several existing cities have been tested to obtain a classification that allows warning dissemination to dynamically adapt its parameters based on the scenario type. The chosen area tries to represent the overall layout of the streets in each city, and is usually taken from the downtown area. We selected cities from Europe (Berlin, Lisbon, London, Milan, Moscow, Munich, Paris, Rome, Seville, Teruel, Valencia), Asia (Beijing, Hong Kong, Istanbul, Kuala Lumpur, New Delhi, Seoul, Shanghai, Taipei, Tokyo), North America (Boston, Chicago, Los Angeles, Manhattan, Mexico City, New York, San Francisco, Washington DC), South America
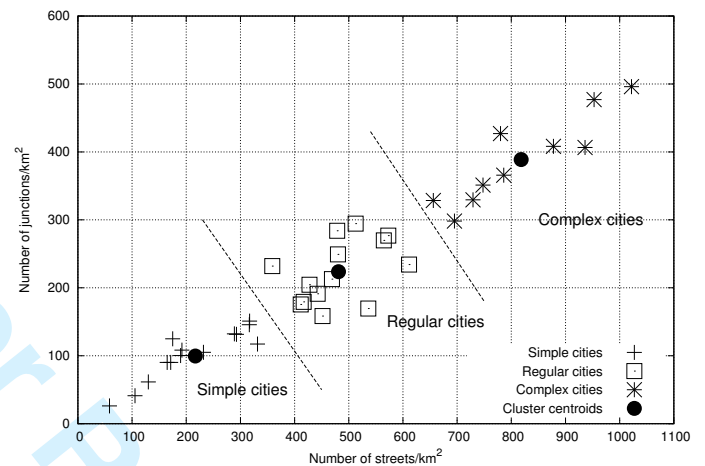

Fig. 4. Classification of different cities based on the density of streets and junctions.

(Bogotá, Buenos Aires, Montevideo, Rio de Janeiro), and Africa (Cape Town, Casablanca, Cairo, Kinshasa, Rabat).

Figure 4 shows the number of streets and junctions present in a 4 km^2 square area in these cities. As shown, the relationship between the number of streets and the number of junctions is almost linear, in an approximate ratio of 2 streets per junction. Since three different groups of cities can be distinguished in the figure, the well-known *k-means* clustering algorithm [15] was used with a number of clusters $k = 3$ to obtain a precise classification of the cities. By using the results of the clustering process in Figure 4, we can classify a new city according to the cluster whose centroid is the nearest (using the Euclidean distance as a measure). We can classify existing cities by their street profiles into:

- *Simple layouts*: maps with low density of streets and junctions that are usually arranged orthogonally like a Manhattan style grid. Examples of these cities are New York (USA), Rio de Janeiro (Brazil) and Seoul (South Korea).
- *Regular layouts*: maps with medium density of streets and junctions. Some cities in this group are San Francisco

TABLE III

MAP PROFILES CLASSIFICATION

Roadmap profile	Street and junction density	Cluster centroid		Max. acceptable vehicle density
		Streets/km^2	Junctions/km^2	
Simple	Low	216.79	99.57	25 veh./km^2
Regular	Medium	480.96	223.70	50 veh./km^2
Complex	High	818.23	388.80	75 veh./km^2

TABLE IV

WORKING MODES IN THE ADAPTIVE ALGORITHM

Working mode	Interval between consec. messages	Broadcast scheme	Min. rebroadcast distance
Full dissemination	2 seconds	counter-based [1]	—
Standard dissemination	4 seconds	eSBR [2]	200 m.
Reduced dissemination	5 seconds	distance-based [1]	250 m.

(USA), Madrid (Spain) and Hong Kong (China).
- *Complex layouts*: maps with high density of streets and junctions. Cities which belong to this group are Rome (Italy), London (UK), and Tokyo (Japan).

As shown, each one of the previously studied roadmaps (Figure 1) belongs to different street profiles clusters, causing noticeable differences in the performance of warning message dissemination. Table III summarizes the classification process of the studied cities, and shows the location of the centroid of the cluster assigned to each profile. It also shows the maximum vehicular density accepted in our simulations before the number of received messages grows excessively, thereby provoking broadcast storm problems with the base configuration used in the previous section. Results show that the roadmap which serves as scenario for the warning dissemination has a considerable influence in the effectiveness of the process. Moreover, we can differentiate three groups of city profiles in which the propagation process is likely to behave in a similar way. This is the basis for our proposal, the *Profile-driven Adaptive Warning Dissemination Scheme* (PAWDS), which is based on the fact that the effectiveness of the alert dissemination can be increased if vehicles determine the city profile of their current area.

Algorithm 1: PAWDS() pseudo-code

use standard dissemination mode
while *(1)* **do**
  obtain street-profile *from the current map*
  estimate vehicle-density *from messages sent by neighbor vehicles*
  if *(street-profile **is** Simple)* **then**
    if *(vehicle-density > 25 vehicles/km^2)* **then**
      └ *use* reduced dissemination mode
    else
      └ *use* standard dissemination mode
  else if *(street-profile **is** Regular)* **then**
    if *(vehicle-density > 50 vehicles/km^2)* **then**
      └ *use* standard dissemination mode
    else
      └ *use* full dissemination mode
  else if *(street-profile **is** Complex)* **then**
    if *(vehicle-density > 75 vehicles/km^2)* **then**
      └ *use* standard dissemination mode
    else
      └ *use* full dissemination mode
  └ sleep(T_r);

IV. THE PROFILE-DRIVEN ADAPTIVE WARNING DISSEMINATION SYSTEM (PAWDS)

In [16] we demonstrated that the propagation process is likely to behave in a similar way when vehicles are moving in different cities as long as they belong to a same roadmap profile group (i.e., dissemination processes behave similarly in New York and Seoul, but differently than in San Francisco, Rome, or Tokyo). This is the basis for our proposal: the effectiveness of the alert dissemination can be increased if vehicles determine the city profile of their current area, and adapt their dissemination schemes accordingly.

To enhance the performance of the alert dissemination, we propose to tune the warning dissemination system using the information provided by the on-board GPS system (with integrated street maps from the city that is being evaluated) to determine the profile of the city and select the most effective parameters to achieve a proper warning message dissemination. Previously proposed schemes use a fixed set of parameter values, or they only consider the vehicle density to adapt the system. Instead, our algorithm can obtain a preliminary estimation of the parameters to use just by checking the map of the area where the vehicle is located in.

It is also beneficial to use a more restrictive dissemination scheme when the vehicle density is high to avoid broadcast storm problems. Hence, it is helpful to estimate the vehicle density in the surrounding area to maximize the effectiveness of the dissemination scheme. This estimation is done in our system using the beacons periodically sent among the vehicles with information about their position and speed. Moving vehicles use this information to compute the predicted position of nearby vehicles in order to determine how many vehicles are there in their proximities.

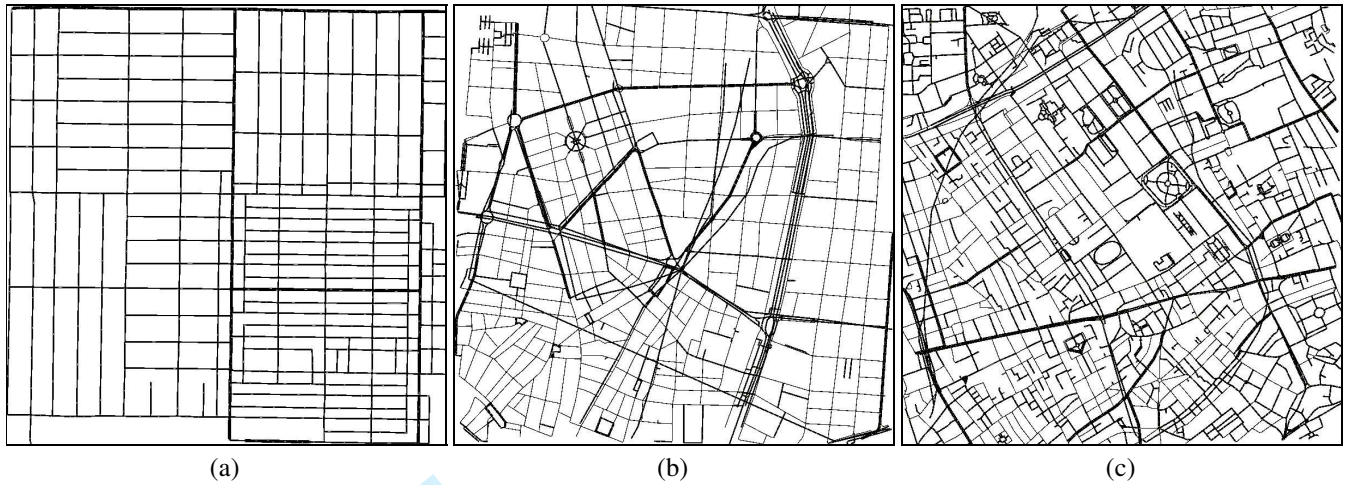We observed that three parameters have a notable influence

Fig. 5.   Additional scenarios used in our simulations as street graphs in SUMO: (a) fragment of the city of Los Angeles (USA), (b) fragment of the city of Madrid (Spain), and (c) fragment of the city of London (UK).

in both warning notification time and the induced overhead in terms of number of messages received in the dissemination process. These three parameters are: (a) the interval between consecutive messages, (b) the broadcast scheme used, and (c) the minimum rebroadcast distance. If we vary their values, we observed how the target performance indexes of our scheme are mutually exclusive, i.e. we cannot increase the percentage of notified vehicles and decrease the notification time at the same time if we do not increase the number of messages involved, and vice versa. Hence, our scheme must be able to find a balance among all these metrics. To facilitate the selection of the parameters, we have defined three adaptive working modes specially adapted to different situations. The dissemination scheme will select the most suitable one depending on the profile of the roadmap and the estimated vehicle density. The defined operation modes are:

- *Full dissemination*: vehicles move in low density areas, and hence they can send a high number of messages with little danger in term of inducing broadcast storm problems.
- *Standard dissemination*: vehicles try to achieve a balance between the number of informed vehicles and the number of messages received.
- *Reduced dissemination*: vehicles send as few messages as possible due to the high density of vehicles detected in the area that could easily lead to broadcast storm problems.

Table IV contains the parameter values used in each working mode. Several preliminary simulations representing different environments were performed in order to select the sets of values with an optimal behavior in different situations. Algorithm 1 summarizes the PAWDS algorithm, where the values of vehicle density are obtained from Table III, and T_r is the interval between reconfigurations of the system (30 seconds).

According to our algorithm, PAWDS is configured to use the *Full dissemination* mode in low vehicle density scenarios to inform as many vehicles as possible, except when the density of streets and junctions is low (Simple profile cities), which

TABLE V

MAIN FEATURES OF THE ADDITIONAL MAPS

Selected city map	Los Angeles (USA)	Madrid (Spain)	London (UK)
Streets/km^2	263	479	878
Junctions/km^2	77	284	408
Avg. street length	$111.58m$	$67.23m$	$45.38m$
Avg. lanes/street	1.45	1.26	1.15
Profile cluster	Simple	Regular	Complex

causes the number of messages to grow excessively. In this situation, the *Standard dissemination* is more suitable.

When the vehicle density is high, the *Full dissemination* mode should not be used, as it produces a huge amount of messages and it could easily yield broadcast storms. The *Standard dissemination* mode can be appropriate in most of cases, but the number of messages received when the street density is too low (Simple profile cities) may be excessive. In these cases, the *Reduced dissemination* mode is the most suitable one.

V. SIMULATION ENVIRONMENT

Since deploying and testing VANETs involves high cost and intensive labor, simulation is a useful alternative prior to actual implementation [17]. Simulation experiments have shown that different dissemination strategies are associated with a different behavior in an urban environment, but they also showed that the features of each specific scenario determine the efficiency of the process. To prove how maps from the same cluster produce similar results using them as simulation scenarios, we selected three street maps in addition to those presented in Figure 1. These additional roadmaps are taken from different cities and they belong to different clusters, as shown in Table V. The scenarios were obtained from OpenStreetMap, each one representing 4 km^2 of square area.

Figure 5a shows the area between Martin Luther King Boulevard and West Slauson Avenue in the city of Los Angeles (CA, USA), which belongs to the Simple layout cluster. It has

a very regular street layout where the simulations should have a similar behavior compared to simulations performed using synthetic Manhattan-grid layouts. The street map around Paseo de la Castellana in the city of Madrid (Spain), shown in Figure 5b, is classified as a Regular profile. It is an example of town with medium density of streets and junctions, arranged in a complex layout different from typical Manhattan-grid layouts. Finally, Figure 5c presents the area around Russell Square in the city of London (UK), which contains an extremely high density of streets and junctions, and therefore it belongs to the Complex topologies cluster. We will study warning message dissemination efficiency in these scenarios and we will compare the results with those obtained with the formerly presented roadmaps.

Simulations to test our experiments were done using the ns-2 simulator [18], modified to include the IEEE 802.11p [19] standard so as to follow the upcoming WAVE standard closely. In terms of the physical layer, the data rate used for packet broadcasting is of 6 Mbit/s, as this is the maximum rate for broadcasting in 802.11p. The MAC layer was also extended to include four different priorities for channel access. Therefore, application messages are categorized into four different *Access Categories* (ACs), where AC0 has the lowest and AC3 the highest priority.

The simulator was also modified to make use of our *Real Attenuation and Visibility* (RAV) scheme [13], which proved to increase the level of realism in VANET simulations using real urban roadmaps in presence of obstacles. In order to mitigate the broadcast storm problem, our simulations use: (a) the counter-based scheme [1], (b) the distance-based scheme [1], and (c) the *enhanced Street Broadcast Reduction* (eSBR) scheme [2], which employs a minimum distance under which vehicles are refrained from forwarding, except if they are close enough to a junction.

With regard to data traffic, vehicles operate in two modes: (a) warning mode, and (b) normal mode. Warning mode vehicles inform other vehicles about their status by sending warning messages periodically with the highest priority at the MAC layer; each vehicle is only allowed to propagate them once for each sequence number. Normal mode vehicles enable the diffusion of these warning packets and, periodically, they also send *beacons* with information such as their positions, speed, etc. These periodic messages have lower priority than warning messages and are not propagated by other vehicles.

Mobility is performed with CityMob for Roadmaps (C4R)[1], a mobility generator which can import maps directly from OpenStreetMap. C4R is based on SUMO [20], an open source traffic simulation package. Our mobility simulations account for areas with different vehicle densities. In a realistic town setting, traffic is not uniformly distributed; there are down-towns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* [21] to add points of attraction in roadmaps. Hence, we include points of attraction in the roadmaps used in our simulations. To generate the movements for the simulated vehicles, we used the Krauss mobility model [14] (with some modifications to allow multi-

[1]C4R is available at http://www.grc.upv.es/software/

TABLE VI
PARAMETER VALUES USED FOR THE SIMULATIONS

Parameter	Value
number of vehicles	$100, 400$
simulated area	$2000m \times 2000m$
number of warning mode vehicles	3
warning message size	$256B$
normal message size	$512B$
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
maximum transmission range	$400m$
mobility generator	C4R
mobility models	Krauss [22] and Downtown model [21]
maximum speed of vehicles	$23\ m/s \approx 83\ km/h$
maximum acceleration of vehicles	$1.4\ m/s^2$
maximum deceleration of vehicles	$2.0\ m/s^2$
driver reaction time (τ)	$1\ s$

lane behavior [22]) found in SUMO. 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:

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

where v represents the speed of the vehicle, t represents the period of time, 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.

All results represent an average over several executions with different random scenarios, presenting all of them a degree of confidence of 90%. Each simulation run lasted for 450 seconds, and we only collect data after the first 60 seconds in order to achieve a stable state. We are interested in the following performance metrics: (a) warning notification time, (b) percentage of blind vehicles, and (c) 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 do not receive the warning messages sent by warning mode vehicles. The number of packets received per vehicle (including beacons and warning messages) gives an estimation of channel contention. Table VI summarizes the parameter values used in our simulations.

VI. SIMULATION RESULTS

In this section, we first present the impact of the roadmap and vehicle density in warning message dissemination per-formance and, afterwards, we evaluate and demonstrate the benefits of using our proposed adaptive scheme.

A. Evaluating the Impact of the Roadmap and Vehicle Density

Results in this section are obtained using the maps of New York, San Francisco and Rome from Figure 1, and also the roadmaps from Los Angeles, Madrid and London from Figure 5. There is a city from each defined cluster in these two
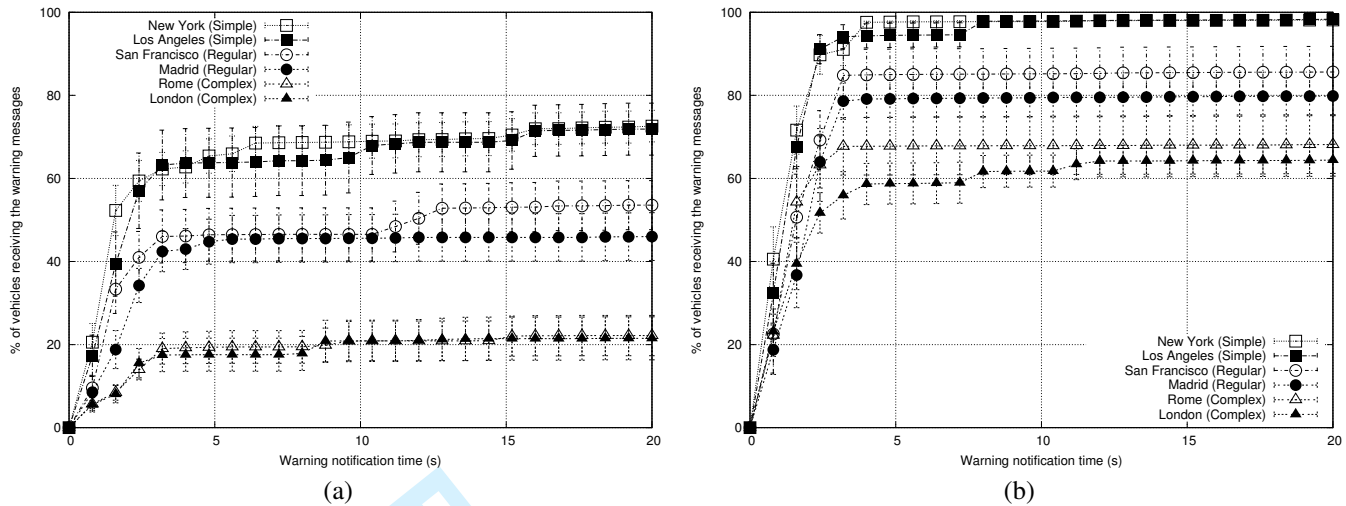
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Fig. 6.   Warning notification time in different scenarios simulating (a) 100 vehicles (25 vehicles/km^2) and (b) 400 vehicles (100 vehicles/km^2).
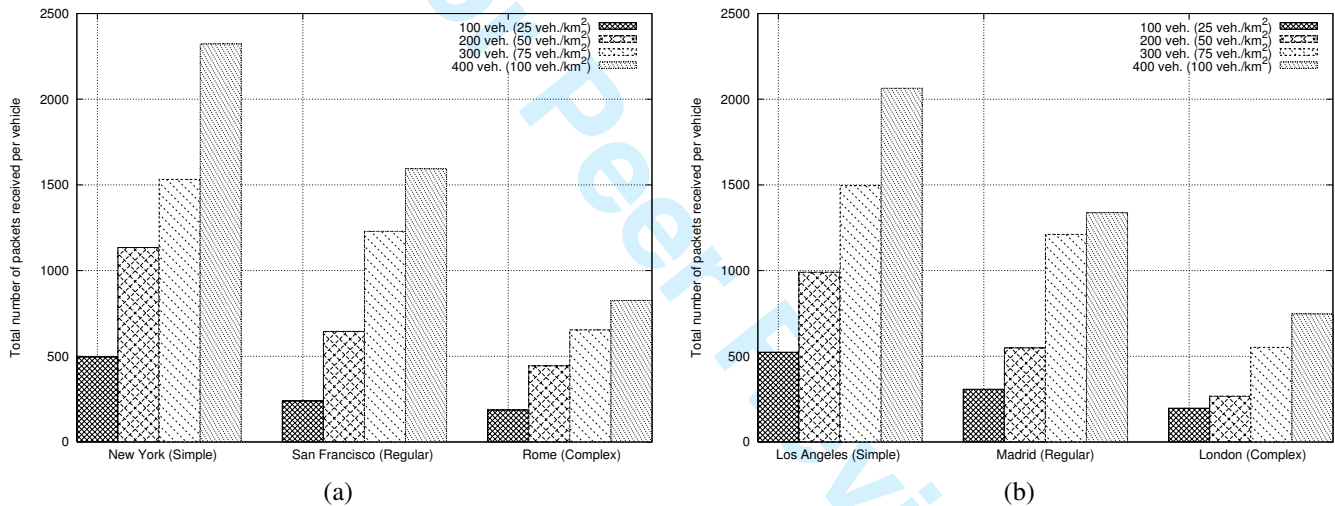

Fig. 7.   Number of messages received per vehicle simulating (a) the formerly presented scenarios, and (b) the additional street maps, under different vehicle densities.

sets of roadmaps, and we will compare warning message dissemination using these different topologies. Figures 6 and 7 show the differences in terms of both warning notification time and messages received per vehicle when varying the density of vehicles in the aforementioned city scenarios. In all these simulations we used the same base configuration: 2 seconds between messages, 200 meters for minimum rebroadcast distance, and the broadcast scheme used was eSBR.

Results in Figure 6 show that the selected scenario notably affects the efficiency of the dissemination process, especially in scenarios with low vehicle density. As the density of vehicles grows, the differences become smaller but they are still noticeable. In addition, roadmaps from the same cluster present a very similar behavior in both low and high vehicle density scenarios. Topologies from the Simple layout cluster obtains the best performance in warning notification time and percentage of blind vehicles in all scenarios, since the wireless signal propagates more easily in environments with few long streets. As the layout becomes more irregular and

the density of streets and junctions grows, the dissemination process develops more slowly and the number of uninformed vehicles increases.

In the six scenarios, increasing the density of vehicles yields better performance in terms of both warning notification time and percentage of blind vehicles (i.e. not receiving warning messages), especially in roadmaps like Rome and London where the streets are the shortest and the most irregular, producing very poor results when there are few vehicles in the simulated scenario. Complex layout scenarios need higher vehicle densities to obtain satisfactory results in terms of warning notification time and blind vehicles.

As shown in Figure 7, topologies from the same cluster also produce a similar number of messages. For Simple roadmaps there is a sudden increment in the amout of received messages when the vehicle density grows more than 25 vehicles/km^2, whereas Regular ones support up to 50 vehicles/km^2 and Complex roadmaps obtain sustainable results up to 75 vehicles/km^2, with complete coherence with
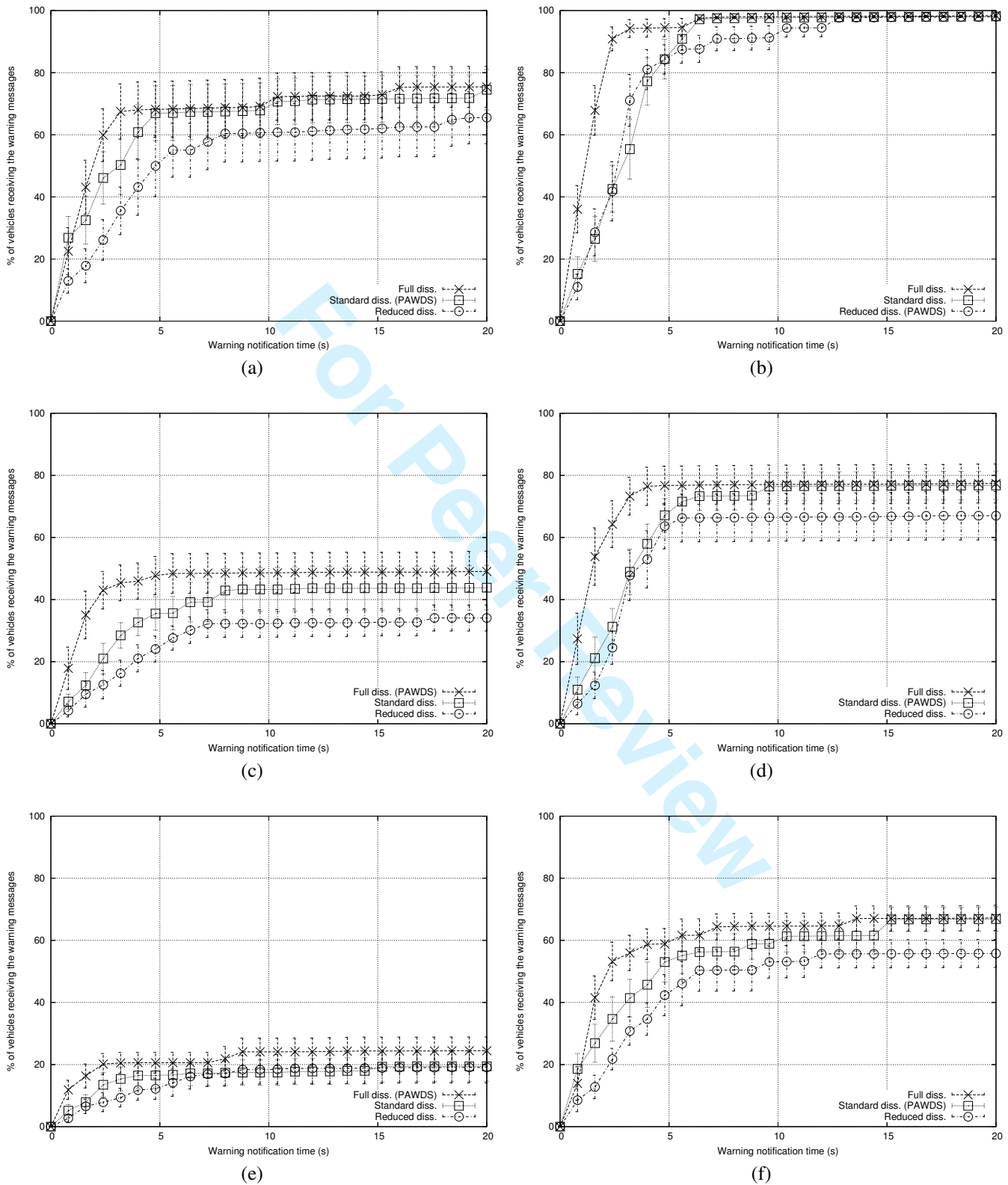
Fig. 8.   Warning notification time with the different PAWDS working modes in different cities: Los Angeles with (a) 100 and (b) 400 vehicles, Madrid with (c) 100 and (d) 400 vehicles, and London with (e) 100 and (f) 400 vehicles.
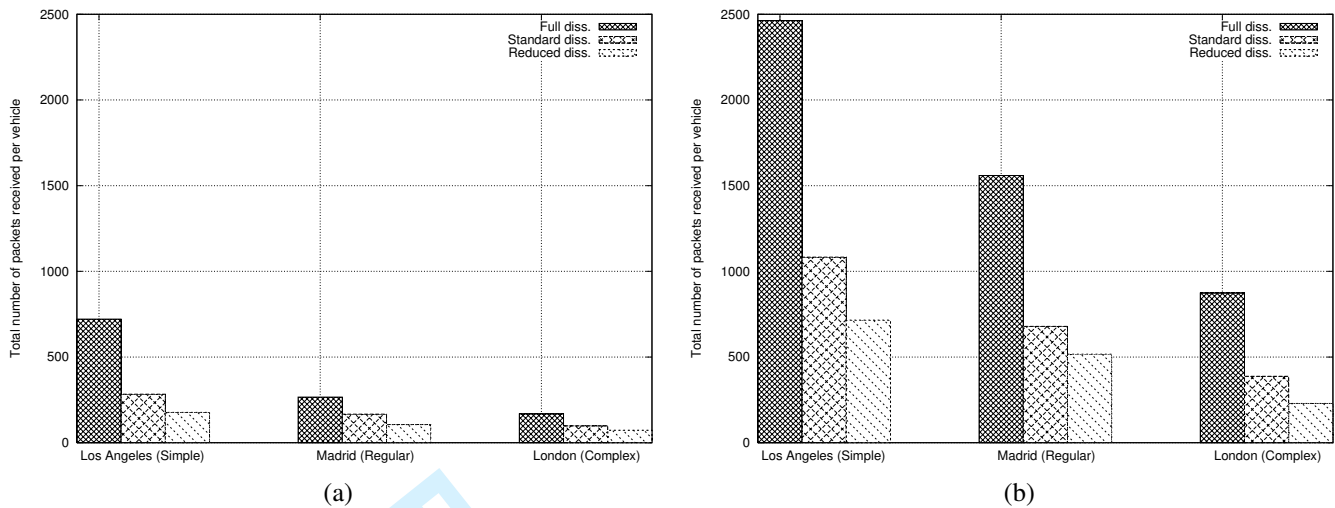
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Fig. 9.   Number of messages received per vehicle with the different PAWDS working modes simulating (a) 100 and (b) 400 vehicles.

respect to Algorithm 1. Urban scenarios with low density of streets and junctions greatly increase the number of messages received per vehicle because of the higher number of vehicles reached by the wireless signal, thanks to the long streets forming the layout that make easier to find vehicles in line-of-sight. This substantial increment of the amount of produced messages could produce broadcast storms even in scenarios with relatively low presence of vehicles relaying warning messages. We conclude that, in these environments, the dissemination process should be tuned to use operation modes with low message generation rates. On the contrary, topologies with higher density of streets and junctions allow using less restrictive dissemination schemes since the number of messages received per node remains low even for high density scenarios, reducing the probability of broadcast storms. This is especially important in Complex roadmaps, where more vehicles are needed to increase dissemination efficacy and the *Full dissemination* mode could reduce this problem.

To sum up, it is very important to reduce the amount of messages generated when the density of vehicles is high, but with low densities it is a good idea to produce enough messages to reach as many vehicles as possible, as the probability of broadcast storms becomes small.

B. Performance Testing

In this subsection we show the result of a wide set of experiments whose goal is to prove the effectiveness of our proposed adaptive algorithm when disseminating warning messages. The proposed technique consists of determining the adequate selection of working modes in every possible situation. The maps used in this case are taken from the cities of Los Angeles, Madrid and London (Figure 5), representing Simple, Regular and Complex topologies, respectively.

Figure 8 shows the warning notification time using the three configurations in diverse scenarios, and Figure 9 depicts the average number of messages received per vehicle.

Focusing on Simple profile cities like Los Angeles, the *Full dissemination* mode produces a very high number of messages

both in low and high vehicle density scenarios, thus being unsuitable for this environment. When the density of vehicles is low, the *Reduced dissemination* mode allows reducing the total amount of messages disseminated; however, the notification time and the percentage of blind vehicles is far greater than for the *Standard dissemination* mode, which is more balanced and more suitable for this situation. Thereby, this is the selected mode in low vehicle density scenarios. In high density scenarios, the differences in performance between these two modes diminish: the *Standard* mode only informs about 5% more vehicles, while the number of messages involved is reduced by a third part with the *Reduced dissemination* mode. This effect confirms its selection as the most suitable mode for this environment.

In Regular cities (e.g. Madrid), the *Reduced dissemination* mode does not obtain a good performance in terms of notification time and blind vehicles (about 30%-40% more blind nodes with respect to the rest of modes). In low vehicle density scenarios, using the *Full dissemination* mode yields a notable reduction of notification time and blind vehicles, without requiring a large amount of messages. Nevertheless, if the vehicular density is high, the number of messages grows excessively, and using the *Standard dissemination* mode allows reducing them by more than half with similar values for the percentage of blind nodes, and an affordable increment of the warning notification time. Hence, the most appropriate scheme would use the *Full dissemination* mode when there are few vehicles, and the *Standard* mode when their density increases.

Finally, in Complex profile cities (e.g. London), the *Full dissemination* mode selected by the PAWDS algorithm clearly outperforms the rest of the modes in terms of blind vehicles and warning notification time when only 100 vehicles are involved. In addition, the number of messages received is not very high (below 200 messages per vehicle), meaning that this mode would indeed be suitable for this environment. When the number of vehicles increases to 400, the *Reduced dissemination* mode remains unsuitable as it slows down the dissemination process and increases the percentage of blind

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TABLE VII

AVERAGE SIMULATION RESULTS AFTER 30 RUNS. THE WORKING MODES SELECTED BY PAWDS ARE IN BOLDFACE.

Map	Veh. density	Working Mode		
		Full diss.	Standard diss.	Reduced diss.
Los Angeles (Simple profile)	Low (25 veh./km^2)	WNT(50%): 1.93 s BV: 24.57% MR: 721.53	**WNT(50%): 3.14 s** **BV: 25.50%** **MR: 283.30**	WNT(50%): 4.81 s BV: 34.47% MR: 176.83
	High (100 veh./km^2)	WNT(50%): 1.15 s BV: 1.60% MR: 2463.07	WNT(50%): 2.86 s BV: 1.87% MR: 1083.07	**WNT(50%): 2.62 s** **BV: 1.97%** **MR: 715.43**
Madrid (Regular profile)	Low (25 veh./km^2)	**WNT(30%): 1.37 s** **BV: 50.93%** **MR: 266.43**	WNT(30%): 3.49 s BV: 56.17% MR: 166.70	WNT(30%): 6.36 s BV: 65.93% MR: 105.47
	High (100 veh./km^2)	WNT(50%): 1.48 s BV: 22.62% MR: 1559.33	**WNT(50%): 3.29 s** **BV: 23.24%** **MR: 678.77**	WNT(50%): 3.54 s BV: 33.00% MR: 516.53
London (Complex profile)	Low (25 veh./km^2)	**WNT(15%): 1.36 s** **BV: 75.57%** **MR: 168.33**	WNT(15%): 3.05 s BV: 80.57% MR: 98.17	WNT(15%): 5.93 s BV: 80.93% MR: 72.87
	High (100 veh./km^2)	WNT(50%): 2.18 s BV: 32.77% MR: 873.17	**WNT(50%): 4.47 s** **BV: 33.13%** **MR: 387.60**	WNT(50%): 6.34 s BV: 44.23% MR: 229.03

nodes with respect to the other schemes in more than 30%. The *Full* and *Standard* modes present a similar behavior in percentage of blind vehicles, but the *Full dissemination* mode produces more than 850 messages per vehicle, which could yield broadcast storms. The *Standard* mode is slower during the first 5 seconds of the propagation process, but after this initial time the two schemes present very similar results, with less than half messages produced by the *Standard dissemination* scheme. Hence, in high vehicles density scenarios, this mode is the most appropriate when the roadmap profile is Complex.

Table VII summarizes the average results after 30 runs and presents: (i) the warning notification time (WNT), (ii) the percentage of blind vehicles (BV), and (iii) the number of messages received (MR) per vehicle in the different studied situations. When the warning notification time is shown, the percentage in brackets represent how many vehicles were informed at that time, since some of the studied configurations produce very poor results and using a common basic percentage (for example, 50%) for all scenarios is very difficult. In Figure 10, all the results are normalized, i.e., divided by the highest value for each metric in each scenario, and thus the presented results vary between 0 and 1. The most balanced configurations are highlighted, matching with the specific operation mode used in our proposed scheme. When the vehicle density is low, the number of received messages is not critical (Figures 10c and 10e), whereas in high density scenarios the scheme tends to reduce messages by slightly increasing the other metrics.

VII. CONCLUSIONS

In this paper we introduced PAWDS, a new adaptive approach that allows increasing the efficiency of warning message dissemination processes using the information about the urban environment where the vehicles are moving. Our solution requires vehicles to make use of the information contained in their integrated maps to determine the profile type. Additionally, the beacons exchanged with neighbors are used to estimate the density of vehicles in the area. By combining these two inputs, our algorithm is able to tune the parameters of the dissemination process and mitigate broadcast storm related problems. The objective is to find a balance among different performance metrics. With this aim, three different working modes (*Full*, *Standard* and *Reduced* dissemination) were proposed to be selected depending on their efficiency in each situation.

The PAWDS system has proven to be extremely effective when the density of vehicles is high, especially in maps with low density of streets and junctions. In those cases, selecting a balanced working mode allows maintaining an acceptable level of performance in terms of notification time and percentage of blind vehicles, while reducing the number of messages by more than 70% compared to other base configurations. In the rest of the maps, using the most suitable mode allows reducing message duplicates by about 60%. The effectiveness of the proposed system in scenarios with low density of vehicles becomes less meaningful as it is unlikely to find broadcast storm problems in such environments. Instead, the system is configured to reach as many vehicles as possible without concentrating on reducing the number of messages involved in the process.

Simulation results show that reducing the interval between messages increases the convergence speed of the system, but it also notably rises the number of messages received per vehicle. Hence, as future work, we plan to modify our approach to adapt the time between messages depending on the time elapsed since the last dangerous situation was detected.
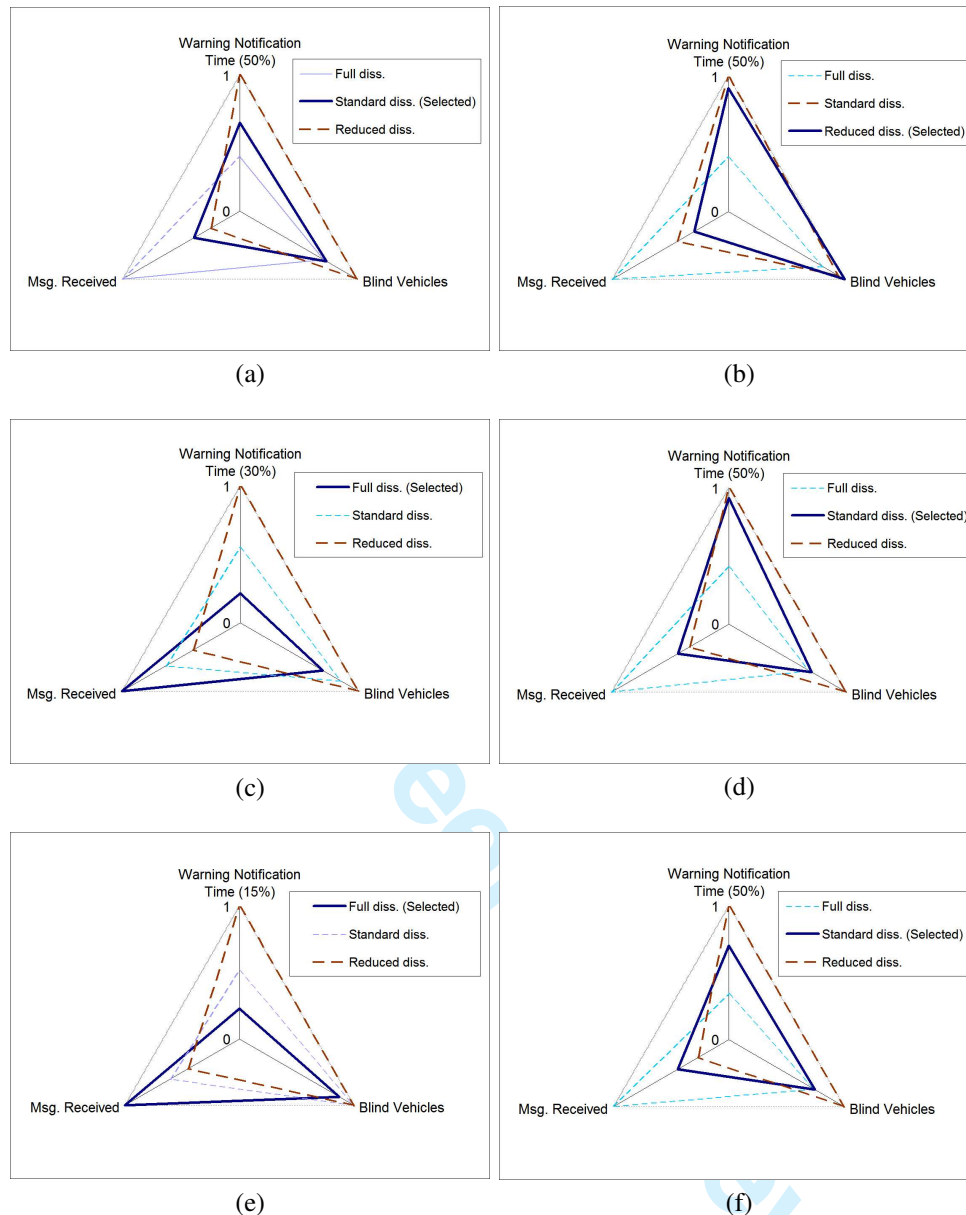
Fig. 10. Average simulation results after 30 runs in: Los Angeles with (a) 100 and (b) 400 vehicles, Madrid with (c) 100 and (d) 400 vehicles, and London with (e) 100 and (f) 400 vehicles. The working modes selected by our algorithm are represented using solid lines.

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