Vehicular Communications 47 (2024) 100746

Contents lists available at ScienceDirect

Vehicular Communications

journal homepage: www.elsevier.com/locate/vehcom

Distributed and collaborative system to improve traffic conditions using fuzzy logic and V2X communications

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ARTICLE INFO

Keywords:
Collaborative System
Fuzzy logic
Smart mobility
Vehicular communications
Vehicular networks

ABSTRACT

Nowadays, the increase in the number of vehicles on the roads has brought about several problems such as an increase in traffic congestion and, consequently, in polluting emissions. These problems are especially severe in urban environments. It is crucial to perform a sustainable urban mobility plan to improve the traffic and therefore, reduce the negative impacts caused by traffic jams. To this end, this paper presents a smart mobility plan that employs a collaborative driving strategy. Each vehicle tries to infer traffic conditions using its own status and the information shared by other peers. Using a fuzzy logic approach, vehicles perform decisions in accordance with the traffic levels inferred in real time. The designed mobility plan has been tested through a simulation environment and considering two types of urban areas in a typical European city (a peripheral area and a more congested city centre). If we compare the performance of traffic with and without the system designed, with our approach average speeds increase by up to 11.20 % and CO_2 emissions are reduced by up to 12.27 %. Thus, our results show that the mobility plan has helped to enhance the ability of cars to be able to solve problems caused by traffic congestion and traffic jams.

1. Introduction

In recent years, the number of people living in metropolitan areas has increased significantly [1]. As a result, the number of vehicles in cities has grown constantly and both the fabrication and sales of vehicles continue to increase [2,3]. E-commerce has been another factor increasing the traffic in urban environments in recent years, because of the huge growth in these services [4] and, thus, in the number of shipments performed, especially in urban environments. Due to the fact that vehicles are one of the most harmful agents for the environment [5], more cars lead to more pollution. Even though several countries have planned the retirement of combustion cars [6], the alternative is still unclear, and this retirement is yet without worldwide consensus. The fact is that pollution levels are constantly rising, and more mechanisms are needed to reduce emissions to improve air quality. Due to this fact, governments have been deploying networks for monitoring the environment with the aim of controlling contamination levels. The situation has reached a point in which critical measures are been carried out, such as applying traffic restrictions.

Traffic jams are one of the major causes of air pollution because they create concentrations of vehicles in reduced areas. Therefore, these vehicles generate a huge quantity of pollutant gases in the affected area. Although, various approaches have been proposed to reduce traffic jams, such as the proposals of Lakas & Chaqfeh [7], Brennand et al. [8], Rocha-Filho et al. [9] or González-Aliste et al. [10], they are difficult to eliminate and, thus, they continue to be a great source of pollutants. Even in an electric vehicle scenario, traffic jams reduce the distance which may be driven with the batteries due to the usage of other electric-powered in-vehicle services [11] and are a source of stress for drivers [12]. Even in an autonomous vehicle scenario, traffic jams would continue to be a source of stress for the passengers of the vehicle. Researchers must then continue to develop new methods in order to improve traffic conditions and alleviate traffic jams and, consequently, reduce current air pollution, improve the performance of electric vehicles and reduce the stress of the citizens.

With the goal of alleviating the aforementioned problems, in this paper we present a smart mobility solution based on a collaborative driving strategy. We have implemented this system based on Vehicular Ad-hoc Network (VANET) communications using V2V (Vehicle to Vehicle) and V2I/I2V (Vehicle to Infrastructure/Infrastructure to

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https://doi.org/10.1016/j.vehcom.2024.100746
Received 26 July 2023; Received in revised form 21 December 2023; Accepted 26 February 2024
Available online 27 February 2024

Vehicle) interactions. Moreover, a fuzzy logic inference system is used to detect and adjust the behaviour of the vehicles, according to several parameters such as speed, acceleration, number of vehicles in the same area, etc. Through simulations, we have implemented two different scenarios to check the impact of our design in two different types of area in a common city: one in the city centre with a slightly haphazard development, and another in the surroundings of the city in a recently constructed urban area. For this purpose, and with the aim of achieving the most realistic results possible, we have used the roadmap of Gijón, a city in the north of Spain with many projects aligned with the smart-city concept. We have employed different vehicle creation rates in both scenarios to study different congestion levels in both types of areas.

Our results show the improvement, in terms of improved mobility and based on the reduction of greenhouse gas emissions, caused by the collaborative system proposed. We infer traffic conditions, detect traffic jams, and warn other vehicles of problematic situations, so that they can find alternative routes to their destination. This leads to an increase in the speed of vehicles and an important reduction in the generation of pollution. Our design may be applied in the context of route planning or implemented in a real-time driving assistant. Furthermore, it could even be applied in an autonomous vehicle scenario to automatically improve the routes followed.

The main contributions of this research follow:

- In this paper we present a novel system for improving traffic conditions in urban areas based on vehicular communications and fuzzy logic.
- We have conceived a fuzzy logic system to infer traffic conditions from speed and stationary times by reporting one of four values: Very Low Traffic, Low Traffic, Medium Traffic and High Traffic.
- We have designed a system to autonomously alter the behaviour of the vehicles depending on the values reported by the fuzzy logic inference system.
- We present a communications model to allow vehicles to exchange information to take decisions collaboratively when traffic conditions are considered to be suboptimal.
- Two simulation environments with different urban designs have been implemented in order to perform experiments and verify the performance of the proposed system in diverse geographical settings.
- The results show that the designed system can improve the flow of traffic at the same time it reduces the generation of pollution up to 12.27 % when combustion vehicles are used and, as a side benefit, the stress of the drivers. The improved flow of traffic may also imply an optimised usage of batteries in an electric vehicle scenario.

The rest of the paper is organized as follows: Section II shows related work about collaborative systems and Fuzzy Logic in vehicular environments. The design of the collaborative system is presented in Section III, with details of the vehicular communications and the fuzzy inference system. Section IV presents the simulation environment with the software and parameters employed in this study. Section V shows the results obtained from the simulations in the aforementioned scenarios. Section VI provides a discussion about the results obtained and about the limitations of the study. Finally, Section VII includes the conclusions and some guidelines for future work.

2. Related work

Previous work has demonstrated that a coordinated approach when trying to improve the efficiency in urban mobility benefits all the members involved. This has been shown by many studies such as Youn et al. [13], which demonstrates that in a group of drivers seeking the shortest path to a destination a Nash equilibrium is reached, so no single driver can do any better by changing his or her strategy unilaterally, or by Tientrakool et al. [14], stating the benefits of making use of sensors and V2V communications in comparison with using sensors alone. Thus, a strategy like collaborative driving can be the best way to achieve an optimal use of the urban infrastructure, with the cooperation among vehicles by using communications to navigate through urban traffic [15].

Collaborative driving has gained importance in ITS (Intelligent Transport Systems) because of the high number of applications that can make use of it, especially those that have to do with safety and efficiency. For instance, Kitwiroon et al. [16] examined the impact of various traffic measures on both traffic density and pollution emissions in London. The authors used a system called OSCAR. They apply several techniques such as reducing the number of heavy-duty vehicles (HDVs) or the effects of speed, as we do. The authors achieve improvements of up to 11 %, reducing HDVs a 20 %. Speed is a relevant factor in vehicular emissions. The impact of speed limits on the environment depends on the impact of these limits on the behaviour of drivers and may be different for different pollutants. Panis et al. [17] evaluate the impact of speed reductions on emissions, by using different modelling approaches (both microscopic and macroscopic). They found that speed limits in urban areas have a non-significant impact on CO_2 and NOx emissions. But, in the case of PM (Particulate Matter) emissions, microscopic results show a significant decrease, with a moderate increase in macroscopic results. Other works, such as Mahmod et al. [18], study the reduction of emissions in urban intersections by using ITS countermeasures. They consider restrictions in speed and heavy-duty vehicles. The analysis show that, in a specific area, the CO_2 emissions generated by vehicles may be reduced up to 23 %, but it is necessary to reduce the traffic a 20 %. We decrease car emissions by up to 12.27 %, but no traffic needs to be reduced. Previous work has also designed techniques to allow collaboration in a VANET by means of clustering techniques taking into account the particular characteristics of these networks (e.g., mobility) For example, Mukhtaruzzaman & Atiquzzaman [19] analyse intelligence-based VANET clustering techniques and compare hybrid architectures combining machine learning and fuzzy logic algorithms, or Aissa et al. [20] who propose and analyse the performance of a clustering technique based on fuzzy logic.

2.1. VANET applications

Many VANET applications have been implemented since the inception of this type of networks. Taking into account the classification performed by Toor et al. [21], we can observe 2 types of VANET applications: user and safety applications. The former may provide users with information, warnings and entertainment. Mainly, there are two types of user applications: Internet connectivity and peer-to-peer applications for sharing music, movies and even, playing games. On the other hand, safety applications are more important than user applications in the context of ITS. They are responsible for reducing road accidents or traffic congestion problems, approach followed by us. Within this field, studies such as Wang & Thompson [22] show that 60 % of the accidents could be avoided if the driver had received a collision warning half a second before. Taking into account safety applications for collaborative and cooperative environments, we find other works such as Knorr et al. [23]. The authors use V2V communications to avoid traffic jams by sending periodic beacon messages warning about congestion. Their results prove that VANET communications may be suitable to improve traffic efficiency, but their solution has been designed for highway roads only. Also, Hafner et al. [24] design, with safety in mind, a cooperative V2V communication solution to avoid collisions at intersections. They perform experiments with two instrumented vehicles engaged in an intersection collision avoidance scenario on a test track. Moreover, Ribeiro et al. [25] propose a low-cost collaborative and opportunistic system that monitors traffic using available IEEE 802.11 networks. The system provides information regarding the location of vehicles, and, with this information, the authors monitor traffic conditions collaboratively, although the solution relies on a central system in which the information is stored and treated.

Dannheim et al. [26], give examples of intelligent, networked and collaborative driving assistance systems that employ V2X communications with the aim of alerting the driver in time about external events and conditions so an increase in both safety and comfort can be achieved. Drawil & Basir [27] present a collaborative technique used to improve the location accuracy of vehicles in a VANET. Two more examples of collaborative transportation applications are presented by Piorkowski [28]. In this case, both applications pursue different aims to those seen previously. One of them has the goal of coordinating drivers to free parking spaces and the other, of matching drivers who offer empty seats in their cars with pedestrians who want a ride to reach their destinations.

Due to the fact that collaborative driving relies on the information shared among vehicles, it is necessary to take some measures in order to make cooperative driving applications function in a safer way. Thus, protocols such as the one presented by Gu et al. [29] could be used with the aim of guaranteeing fail-safe operations in driving environments.

Despite the problems arising from the dependency of these systems on communications in order to work properly, the use of V2X communications has many more significant advantages. The architecture of most of the ITS used so far often separates sensing from computing, as well as decision making from actuation. In fact, many of them, such as the traffic congestion detection and dissemination system proposed in Jayapal & Roy [30], use external data servers to process the information that they collect, which implies that a long period of time must be spent until the vehicle acts in accordance with the previously collected information. Thus, if the information can be interchanged between vehicles, and the vehicles are able to process it themselves, these systems could be used to solve traffic problems in real time.

3. Fuzzy logic in VANET applications

Regarding the usage of fuzzy logic [31], there has been extensive previous research carried out in the VANET field in which this technique has been used. For example, that carried out by Dimitrou et al. [32], who use a fuzzy rule-based system with the aim of modelling and predicting the traffic flow. Another example of these studies is Zrar-Ghafoor et al. [33], which proposes an intelligent Adaptive Beaconing Rate (ABR) approach based on fuzzy logic that takes traffic characteristics into consideration to control the frequency of beaconing. Also, research carried out to detect network traffic congestion such as Sonmez et al. [34] or Naja & Matta [35], where fuzzy logic is also used to provide information for a vehicular admission control. Another example is Miao et al. [36], employing fuzzy logic to manage resources such as text, audio and video in a VANET. Luo et al. [37] present a fuzzy logic collaborative solution to specifically allow file transfers in a VANET, mainly designed for infotainment applications in highway vehicular networks. Balasubramani and Aravindhar [38] focus their research on routing and present an optimized next hop node selection process for VANETs using fuzzy logic and compare their solution with Greedy Perimeter Stateless Routing (GPSR). Mukhtaruzzaman & Atiquzzaman [19] discuss intelligence based VANET clustering strategies and analyse hybrid architectures combining fuzzy logic with other techniques. Similarly, Aissa et al. [20] propose and assess a fuzzy logic based clustering technique designed to select the best cluster head (CH) in a potential safety scenario. Abbasi et al. [39] also focus on data transmission issues and present a vehicle-weighted clustering model based on fuzzy logic (FWDP), designed to improve data propagation in VANETs. Arena et al. [40] present a fuzzy logic solution designed to control, dynamically, traffic lights in road intersections in a city, adapting their behaviour to traffic conditions.

Although fuzzy-logic has been extensively used in VANET scenarios with different goals, in contrast with previous work our solution includes a fuzzy logic-based decision system to allow vehicles not only to infer traffic conditions, but also to perform real time decisions in order to use alternative routes to avoid congested areas of a city. This will also lead to the reduction of pollution generated by these vehicles and the level of stress of the drivers. Also, we do not rely on any central system, in contrast with previous work such as Ranjita and Acharya [41]. Instead, vehicles interact with each other to perform decisions collaboratively, reducing the infrastructure needed by the solution. Moreover, we use V2X communications thanks to the use of IEEE 802.11p solutions, due to the fact that this standard continues to be evolved and that it generally outperforms other vehicular communication technologies such as those based on LTE-V2X [42]. This is in contrast with other works which rely on Wi-Fi communications such as Stolfi and Alba [43] or the recent Ranjita and Acharya [41]. In fact, although we follow a similar approach to that of Stolfi and Alba [43], their solution uses several parameters included in our work, but they do not consider pollution. Moreover, they take into account accelerations and the speed of vehicles, but as static parameters for each type of vehicle. In contrast, our work is focused on dynamic accelerations and speeds. We adjust them depending on the status of traffic.

3.1. Differences with previous work

In summary, our approach is novel as it is based on a totally autonomous and distributed approach for urban scenarios, based on the collaboration between vehicles through the use of vehicular communications.

Table 1 shows aspects in previous work clearly differing from the approach followed by our design. If compared with previous research, our proposal has been designed to improve traffic conditions and, thus, to reduce the effects of traffic density on the environment and the drivers. Most previous work focus on other aspects such as traffic prediction, safety, passenger comfort or data communications. Also, we do not apply restrictions on traffic such as denying certain types of vehicles, blocking certain roads, or reducing speed limits as other proposals do. Furthermore, our proposal is collaborative and decentralised and does not rely on any central system like other works do. There is previous work focusing on motorway traffic, whereas our proposal has been designed to improve urban traffic, due to the fact that traffic density is particularly problematic in cities. Finally, there is previous work also focused on providing a theoretical solution, in contrast to our proposal which is eminently practical. Section 6 includes a comparison of our results with the achievements in other proposals.

Table 1
Main differences between our proposal and previous research.

Proposed system	Feature in previous work	References
Designed to improve traffic conditions	Not focused on improving traffic conditions	[15,19,20,22,24, 26–29,32–39]
No traffic restrictions	Traffic restrictions applied	[13,16–18]
Distributed system	Centralised system	[25,30,41,43]
Urban areas	Motorway roads only	[14,23,35]
Practical approach	Theoretical approach	[13–15,40]

4. Design of the smart collaborative system

Basically, our fuzzy logic inference system infers traffic conditions from speed and stationary times by reporting one of four values: *Very Low Traffic, Low Traffic, Medium Traffic* and *High Traffic*. These values allow vehicles to take decisions and adjust their behaviour:

- When the fuzzy logic inference system considers that the traffic is *Low* or *Very Low*, it increases the speed of vehicles by 10 % or 30 % respectively to take advantage of traffic conditions. It is also important to take into account that the resulting speed after the increase will never exceed the urban maximum speed in Spain, which is currently 13.889 m/s (50 km/h).

- When the traffic level is categorized as *Medium* or *High*, V2X communications are employed. This permits a collaborative approach when trying to avoid traffic jam formations. There are two different types of messages: "Alert" and "Traffic". "Alert" messages are sent using V2V communications to vehicles in range when a car detects that the level of traffic is *Medium*. The cars will therefore be aware that a 5 % speed decrease is needed in order to enhance the distance between vehicles and so, to avoid, if possible, traffic congestion. Only the vehicles that are travelling in the same street and direction reduce their speed, which is the reason why fields with the road identification and the direction are included. Furthermore, "Traffic" messages are sent when a car detects that the level of traffic is *High*. "Traffic" messages are broadcasted to other cars using V2V communications and to RSUs using V2I communications. RSUs, using I2V communications, forward "Traffic" messages to other cars to ensure information propagation. This kind of message affects the behaviour of all the vehicles that receive them and that have a certain street in their paths. As with what happened with "Alert" messages, they include the road identification but, in this case, when a car receives this type of message, it employs it with the aim of changing its route in order to avoid the street in which dense traffic was detected.

The design of the smart collaborative system is shown in Fig. 1. There are cars stopped in a traffic jam inferring that traffic is *High*. They are broadcasting "Traffic" messages which are also forwarded by a RSU available in the area, warning the rest of the vehicles about a congested street. The cars that receive the messages that were going to go through that road, calculate a new route to avoid said road. There are other vehicles inferring that the traffic is *Medium*. These cars broadcast "Alert" messages (not forwarded by the RSU) warning other vehicles travelling in the same street and direction to decrease their speed. The rest of the vehicles in the example infer *Low* or *Very Low* traffic conditions, so they simply increase their speed.

The increase and decrease speed reference values used by the fuzzy logic inference system have been chosen after some preliminary tests.

4.1. Collaborative driving and traffic congestion reduction

The designed system is based on the idea that speed and stationary times are indicators of traffic conditions. Each vehicle is aware of its own speed and the time spent without moving and, thus, may infer the conditions of traffic autonomously (without the need of a central system). Collaboration means that said information may be then shared with other vehicles in an effort to alleviate the situation. In our approach, control information is shared when a vehicle considers that traffic is high, so the system reacts to an already existing problem, or when the traffic is medium in order to try to improve a potential problem. Reacting to a problem means that some vehicles may be stuck in a traffic jam, but other vehicles receiving the information generated by the former may avoid the traffic jam by selecting a different route. A fast propagation of this information using combined V2V, V2I and I2V communications will help to finish the congestion situation. Avoiding the problem means that when there is evidence of a deterioration in traffic conditions, that situation may be improved by decreasing the speed of the vehicles and enhancing the distance between them. This information may be propagated backwards to other vehicles travelling in the same direction, so that the concentration of vehicles in a single area is reduced and, thus, the traffic jam is ultimately avoided. Finally, when a vehicle infers that traffic is low or very low, an increase of speed will reduce trip times and, thus, the general time vehicles occupy city roads. This will improve overall traffic conditions reducing, at the same time, pollution and the stress of the drivers.

The system is also able to react to sudden changes in traffic caused by accidents or other external factors. The vehicles driving in the affected

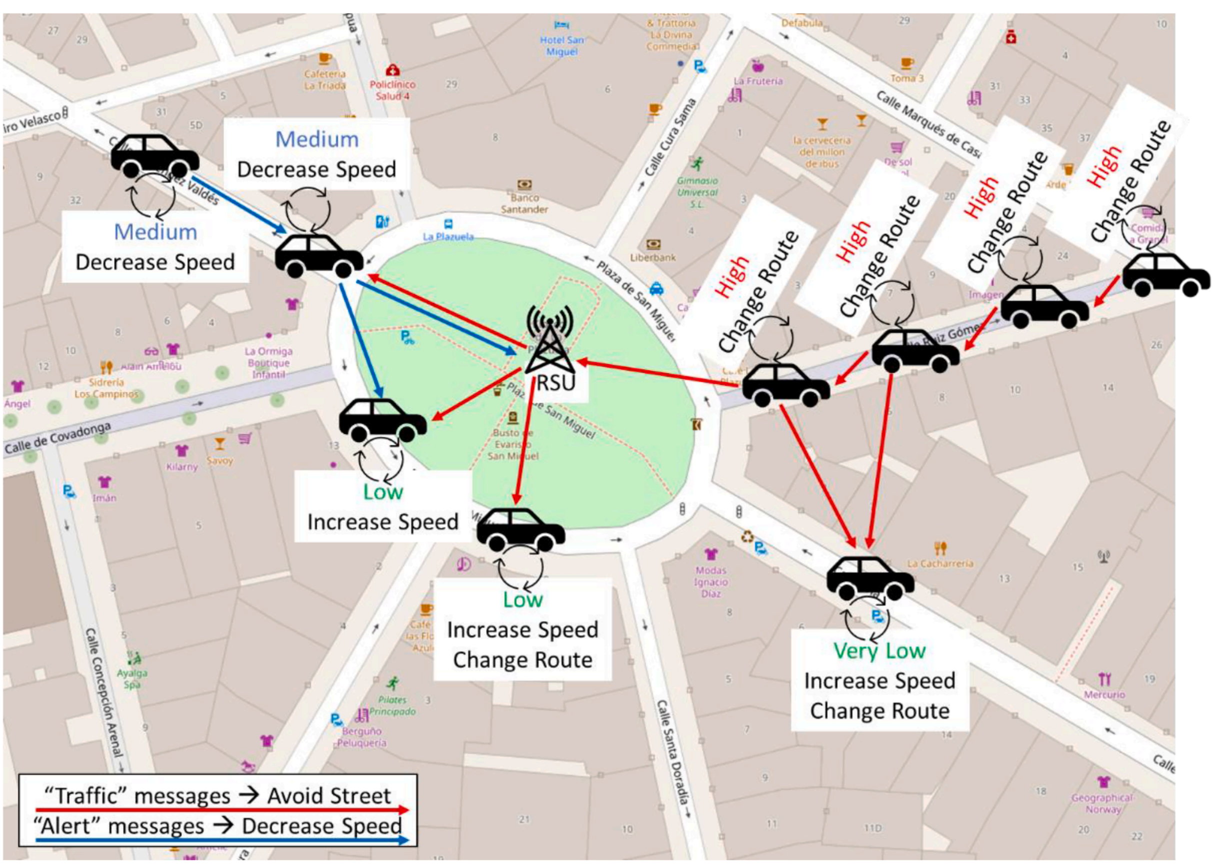

Fig. 1. Design of the smart collaborative system.

road would suddenly infer that traffic is high because of their reduced speed or because they have to stop for a long period. This will immediately trigger the generation of "Traffic" messages which will be broadcasted by the affected cars and by the RSUs in the area. Vehicles receiving these messages, which were going to traverse the affected road, proceed to calculate a new route to avoid the problem. Once the traffic conditions are recovered, the affected vehicles would infer an improvement in the situation and, thus, stop sending "Traffic" messages and gradually start to increase their speeds back to normality.

5. Usage of fuzzy logic

Transportation problems, including traffic congestion, follow complex behaviours as they change over time depending on various factors. These behaviours are difficult to define accurately (with precise numerical data) and, thus, it is not easy to make decisions to solve said problems since they are based on uncertain information. The most suitable artificial intelligence technology to deal with uncertainty and pervasive fuzzy information is precisely fuzzy logic. This technology may be used in order to make decisions in contexts in which there is no accurate numerical data, as already stated by Zadeh [31], and an approximation of the real world is adequate. Accordingly, fuzzy logic can be seen as a useful tool when it comes to letting vehicles make decisions regarding, for instance, traffic in an efficient way. Detecting whether there is a traffic jam or not, will not depend on a combination of binary decisions. It will be determined as the result of an inference system based on more interpretable and user-friendly concepts such as the volume of traffic (e.g., very low, low, medium, or very high). Furthermore, the system may consider parameters which are numerical in nature, including the speed of the cars or the time they spend stationary, without the need of classifying data into discrete categories. This contrasts with other artificial technologies which relay on binary or probabilistic representations of data. Moreover, most of these technologies are based on doing predictions learnt from large datasets, but a rule-based approach may be more suitable, self-explanatory, and more computationally-efficient without the need of extensive training processes or massive datasets. It also important to take into account that there has been extensive previous research carried out in the VANET field in which fuzzy logic has been used [19,32–40].

6. Configuration of the fuzzy inference system

A fuzzy logic inference system, based on Mamdani [46] and shown in Fig. 2, is composed by three differentiated blocks: a *Fuzzifier*, an Inference Engine and a *Defuzzifier*.

The first block is in charge of converting the crisp input into fuzzy, so it can be used by the Inference Engine. The second is comprised by the Rules block, in which its input is compared with the membership functions to obtain the membership value of each linguistic label that makes up the IF-THEN linguistic rules, and the Aggregation block. In this way, once that the membership values have been obtained, they are evaluated according to the Fuzzy Logic rules, so an output value is obtained with each one of them. It is worth mentioning that the resulting values are calculated by using MINIMUM or MAXIMUM operations in accordance with the way the membership values or antecedents are linked with either AND or OR operations. After completing all the evaluations, the Aggregator then combines the results to obtain output values for all the output parameters. Once the membership value for each of the linguistic labels that compose the output parameters is known, the *Defuzzifier* block is able to obtain a resulting value out of it.

Once the structure of a fuzzy inference system is known, the first step to design one is to determine the number of input parameters and output variables that will be considered, as well as the shape of their membership functions. Since the purpose of cars employing this system is to detect traffic conditions, the parameters chosen are their speed and the time that they are stationary. These parameters have been chosen because both of them are clearly affected by the level of traffic. The higher the traffic level is, the lower the speed of the vehicles and, when a traffic jam occurs the higher the time that vehicles are stationary. Also, when designing the membership functions, it is necessary to take into account that the more complex they are, the more accurate results can be obtained so, for that reason, four linguistic labels were employed for each input variable: *low speed, medium speed, high speed, very high speed, low time, medium time, high time* and *very high time*. Furthermore, as the purpose of this system is to determine the level of traffic around the vehicle, this parameter is employed as output variable, also with four different labels: *very low traffic, low traffic¸ medium traffic* and *high traffic*. The shape of the membership functions designed is shown in Fig. 3, Fig. 4 and Fig. 5.

The second step is to define the set of IF-THEN rules which will be used to obtain the membership value of each linguistic label for the output values. These rules connect the different values of input variables with values of the output variable based on expert knowledge. Table 2 presents the set of rules that make up the fuzzy logic base.

As mentioned above, each of the rules will produce an output associated to one of the linguistic labels of the output parameter, as shown in Table 2. According to that table, r_i would be the specific value of each rule, i being the rule number. The value of each r_i is calculated by using MINIMUM or MAXIMUM operations with the corresponding values of the membership functions of input variables shown in Figs. 3 and 4. The value of each r_i is used to calculate Eqs. (1) to (4) and obtain the values corresponding to each output linguistic label. For example, the rules needed to determine if the traffic is very low are r_9, r_{10}, r_{13} and r_{14}, as shown in Table 2. Root square sum operations have been performed, as this type of operation is able to give a good, weighted influence on all the implied rules. The resulting values are used by the *Defuzzifier* block to calculate the final output value.

$$\textit{very low traffic} = \sqrt{r_9^2 + r_{10}^2 + r_{13}^2 + r_{14}^2} \tag{1}$$

$$\textit{low traffic} = \sqrt{r_5^2 + r_{15}^2} \tag{2}$$

$$\textit{medium traffic} = \sqrt{r_1^2 + r_2^2 + r_6^2 + r_{11}^2 + r_{12}^2 + r_{16}^2} \tag{3}$$

$$\textit{high traffic} = \sqrt{r_3^2 + r_4^2 + r_7^2 + r_8^2} \tag{4}$$

The *Defuzzifier* is able to obtain from the calculated values a particular number with which the traffic conditions can be assessed. The

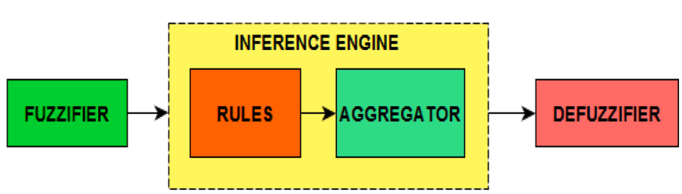

Fig. 2. Fuzzy inference system with inference engine included.

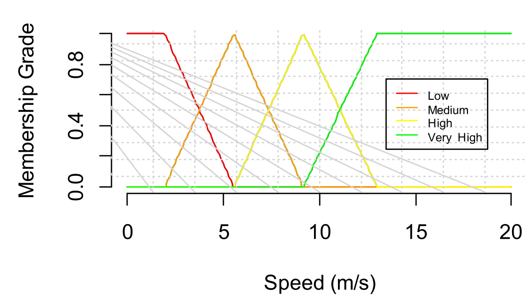

Fig. 3. Speed membership functions.

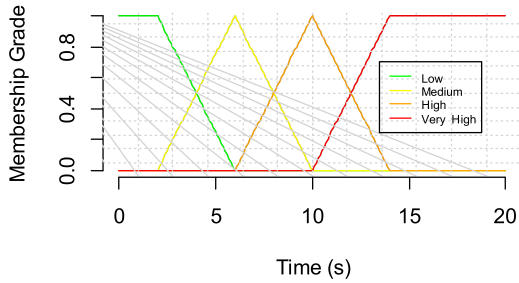

Fig. 4. Time membership functions.

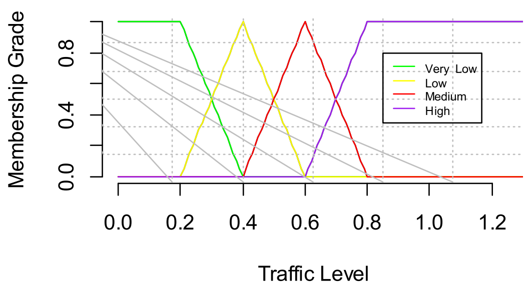

Fig. 5. Traffic level membership functions.

Table 2
Set of rules for fuzzy logic base.

Rule Number	IF Speed	Time	THEN Traffic
1	Low	Low	Medium
2	Low	Medium	Medium
3	Low	High	High
4	Low	Very High	High
5	Medium	Low	Low
6	Medium	Medium	Medium
7	Medium	High	High
8	Medium	Very High	High
9	High	Low	Very Low
10	High	Medium	Very Low
11	High	High	Medium
12	High	Very High	Medium
13	Very High	Low	Very Low
14	Very High	Medium	Very Low
15	Very High	High	Low
16	Very High	Very High	Medium

operation used to obtain this result is the centroid method. The crisp output value is calculated according to Eq. (5), where centre refers to the central point of the membership function of each linguistic label considered (ranging from 0 to 1) and strength, to the firing strength associated with it. When Eq. (5) is applied to our study, we obtain Eq. (6). Eq. (6) shows that we have used different centre values for each linguistic label, wheighin more the labels implying higher levels of traffic.

$$output = \frac{\sum_{i=1}^{N}(center_i \cdot strength_i)}{\sum_{i=1}^{N} strength_i} \tag{5}$$

6.1. Description of V2X communications

"Alert" and "Traffic" messages are both WSM (Wave Short Message). These messages are sent using the WSMP (Wave Short Message Protocol) through the CCH (Control Channel). This is the channel provided by the 802.11p standard [44] which has been designed to distribute critical data packets.

Both messages are identified by the vehicles by using the PSID (Provider Service Identifier) field according to the standard. Thus, the value given to this field will be 1 when delivering "Alert" messages and 0, in the case of "Traffic" messages.

WSMs are sent in broadcast mode but it is important to take into account that the characteristics of urban environments make their dissemination difficult. Although this is not so critical in the case of "Alert" messages, it is very important when dealing with "Traffic" messages, since they should be received by the highest number of vehicles possible in order to prevent traffic jams. Due to this, "Traffic" messages are also spread by RSUs (Roadside Units), so each time that any of these units receive one of these messages, it forwards the message with the purpose that a higher number of vehicles can modify their routes.

It must be considered that, due to the rapid variability of the traffic, the validity of the messages is short. They should not be reporting about traffic situations that no longer exist, e.g., traffic jams. For this reason, the messages are not always sent again each time a vehicle receives them since the longer their dissemination takes, the lower their validity lasts. Besides, it must also be kept in mind that a high amount of traffic information in the network could have negative effects on the traffic since, for instance, if a vehicle receives many "Traffic" messages at the same time it could lead it to adopt a much longer route unnecessarily. This change of route could mean that it will take longer to reach the desired destination and so could favour the increase of the traffic density in the network.

It is important to mention that, while the vehicles are always allowed to modify their speed, this does not happen with the delivery of the messages. It may be the case that a given car detects repeatedly that the traffic is low or medium, sending many times the same message. Moreover, it is important to bear in mind that the system has been designed to be used in urban areas, where the number of vehicles is usually high, and, for this reason, this problem may lead to causing a broadcast storm in the VANET [45]. Therefore, with the aim of avoiding these problems, a minimum inter-message time lapse was employed. Firstly, a vehicle may send its first message after a time lapse of 5 s since the start of the simulation. We consider this period as the minimum necessary to consider a vehicle as part of the network. Moreover, after a certain vehicle sends a message, it must wait for 300 s before it is allowed to send another message. These values have been chosen thanks to previous simulation experiments. They are high enough to avoid an unnecessary generation of control messages and low enough to achieve good results when traffic density is high.

It is worth mentioning that as RSUs are used to disseminate messages within a specific area. They should be located in such a way that they can cover a wide area avoiding, at the same time, the overlapping of their coverage areas. Besides, as will be explained in depth when describing the scenarios used in the study, when choosing their location, it is also necessary to consider that the best option is to deploy them in spots near the points where traffic jams tend to take place.

$$output = \frac{0.1\ \textit{very low traffic} + 0.2\ \textit{low traffic} + 0.5\ \textit{medium traffic} + 0.9\ \textit{high traffic}}{\textit{very low traffic} + \textit{low traffic} + \textit{medium traffic} + \textit{high traffic}} \tag{6}$$

Table 3
Simulation and network parameters.

Simulation Parameters	
Type of Maps	Real (City of Gijón)
Vehicular traffic (packet size)	256 B
Vehicle creation rates	1v/s, 1v/1.25 s, 1v/1.5s
Number of vehicles Scenario #1	1894/1596/1276
Number of vehicles Scenario #2	2601/2096/1750
Simulation area Scenario #1	700 m × 400 m
Simulation area Scenario #2	500 m × 600 m
Number of RSUs	3
Network Parameters	
Network type	WAVE/802.11p
Frequency	5.890 GHz
Channel	CCH (Control)
Channel Bandwidth	10 MHz
Transmission power	−89 dBm
Data Rate	18 Mbps
Antenna type	Omnidirectional antenna

7. Simulation environment

With the purpose of testing the collaborative system, two different scenarios were implemented. These implementations were performed using Veins, a hybrid VANET simulator which makes use of the network simulator OMNet++ and SUMO as a traffic simulator. We chose this simulator not only because of its simulation characteristics as a whole, but also because of the possibilities that SUMO offered to create networks based on real scenarios. The main parameters used in the simulations of the scenarios chosen are shown in Table 3. These parameters are not only related with the simulation environment, but also with the vehicular network.

Furthermore, the origins and destinations of the routes followed by the vehicles are generated randomly. During their generation we aim to achieve that trips start and end at the fringe of the network. Also, a shortest path computation mechanism establishes the path followed by the vehicles. When needed, according to the classification of vehicular mobility models described in Harri et al. [47], the vehicles use a "car--following" mobility model. Specifically, we employ the default model implemented in SUMO, which is based on traditional models such as Gipps [48] and the Intelligent Driver Model [49].

Fig. 7. Scenario 2 – Peripheral Area of the city of Gijón.

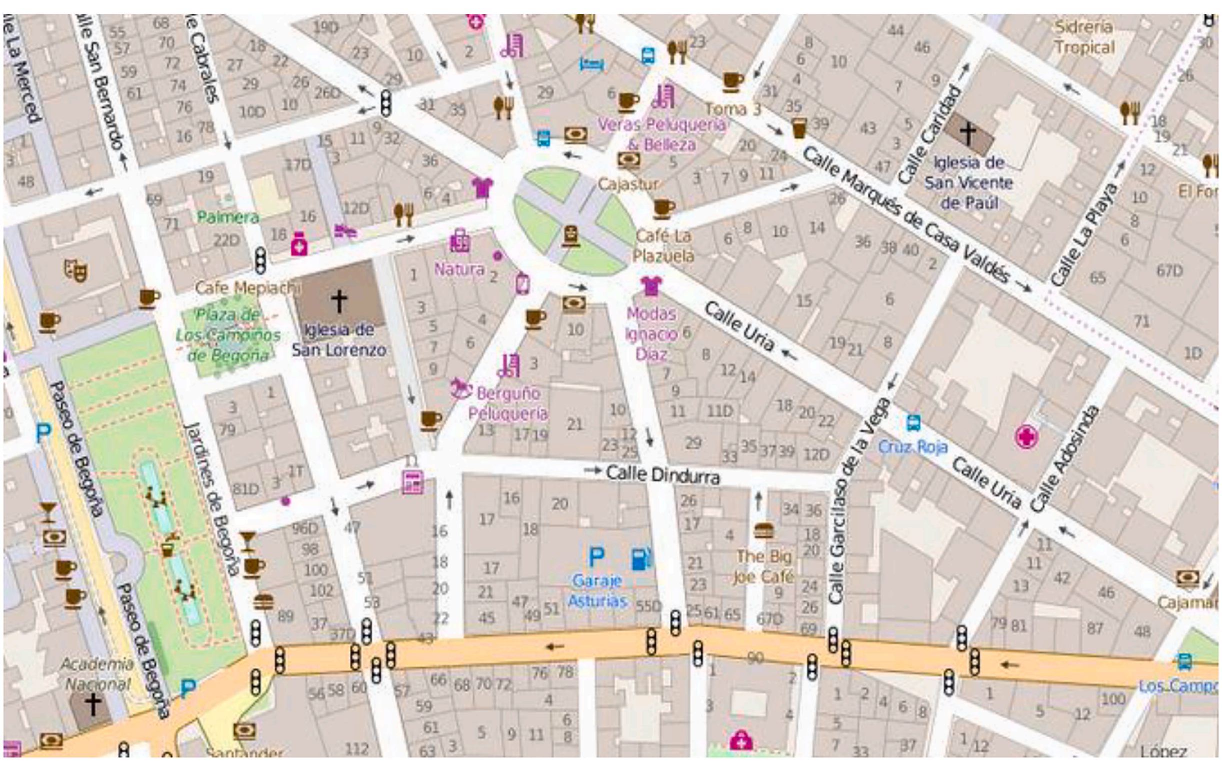

Fig. 6. Scenario 1 – Centre of the city of Gijón.

7.1. Simulation scenarios

When choosing the real-based employed scenarios, their location was taken into account, since they had to belong to an urban area, as well as the topology of their streets. It was necessary for them to be as different as possible with the aim of checking the correct functioning of the mobility plan. Taking these considerations into account, the two chosen scenarios belong to the urban area of the city of Gijón, in Asturias, Spain. The first scenario (Scenario #1), shown in Fig. 6, is located in the centre of the city while the second scenario (Scenario #2), which can be seen in Fig. 7, belongs to a peripheral area.

The different locations of these scenarios explain their unique characteristics. The first scenario is located in an old part of a typical European city. It is a complex area in which the roads are narrow and there is an asymmetric disposition of the buildings. Besides, it also includes a roundabout that eases the change of direction of the vehicles. This situation is quite different in the case of the second scenario, in which there are wide avenues and most of the roads have multiple lanes, thanks to a modern and better urban planning. The urban design in this second scenario is similar to the design found in cities around the world. We chose this second scenario to perform experiments with a geographical setting which may be found in any world city, allowing us to extrapolate the results to other places.

Apart from the differences that the roads of both scenarios present, the same happens with the buildings as they are not only more asymmetrically distributed in the centre of the city but are also taller. This fact is especially relevant when choosing the location of the RSUs in the scenario since it is important that they are located in such a way that they are able to ease the V2I communications. Due to this, when distributing the RSUs in the scenario, in addition to their coverage area, it is also important to take into account the height at which they are located so the surrounding buildings do not disturb the communications.

Three RSUs have been deployed in both scenarios to cover their whole area. Regarding their height, this parameter does not represent a problem in the second scenario where, as mentioned above, the separation between the blocks of buildings is considerable and they are not very high. However, in the first scenario we have carefully chosen their height in order to guarantee that no building in the nearby area impedes the communications. In order to place the RSUs, it was also important to consider their coverage area so, apart from choosing a location suitable to cover the whole scenario, their coverage areas did not overlap, impeding the interchange of messages between each other.

It is important to keep in mind that despite the possibility of calculating the transmission range based on the transmission power of the antennas and the sensitivity of the radios, parameters that can be set in OMNet++, there is no guarantee that the vehicles located within this range are going to receive the messages properly since transmission also depends on path loss and fading effects.

8. Implementation

Once both locations had been chosen, maps were exported from OpenStreetMap and transformed into networks that could be handled by SUMO. This was carried out using NETCONVERT, one of the applications included in the SUMO software package.

It is worth mentioning that before the importation of the maps, they were edited with JOSM, a software that allowed us to delete wrong lanes, unconnected lines, as well as other elements that were included in the maps that had no relevance for creating the SUMO network.

We also used the OMNet++ network simulator. This simulator is extensible, so it is not only possible to add the necessary modules that allow the use of Veins, but it is also possible to create new modules in order to add complexity to the created scenarios.

In the case of this study, new modules were created to implement the smart collaborative system. These modules have allowed us to adapt the application layers of the vehicles and the RSUs to our needs. In this way, the module in charge of emulating the application layer of the vehicles will run two of the main parts of the system. Firstly, the functions responsible for the delivery and reception of the WSMs. Secondly, the method from which the function that contains the fuzzy inference system is going to be invoked and, depending on its output, will make a decision. The latter method is executed in every time step of the simulation, so that the vehicle can react to the changing traffic conditions.

Regarding the RSU application layer, the module used for this purpose does not include some of the methods used in the same layer of the vehicles since RSUs are not going to make decisions and their actions are limited. They only need to have the functions necessary to process the WSMs in such a way that they can detect their type and, depending on this type, forward or not the messages to the vehicles within their coverage areas.

In order to carry out the experiments, the routes of the vehicles need to be generated. Therefore, to this end, the script randomTrips.py, included among the tools offered by SUMO, was used. This script permits to create source and destination edges uniformly at random for the vehicles. A fringe factor of 20 allows us to increase the probability that trips start/end at the fringe of the network. Also, in order to ensure that, for every vehicle, the point of arrival can be reached from the point of departure, invalid (origin, destination) tuples are automatically discarded. The output of this script is fed into the DUAROUTER module of SUMO, to calculate the routes between each origin and destination pair using a shortest path algorithm. When necessary the default "car-following" mobility model implemented in SUMO is used [50]. When a car needs to avoid a traffic jam, routes are changed using the TraCI module of Veins, so that the street in which the traffic jam is located, is avoided.

In spite of the possibility of specifying some of the characteristics of the vehicles, we decided to maintain the default values offered by the simulator. It must be considered that most of the vehicles that make up urban traffic are cars and usually with similar physical characteristics. Besides, although the presence of motorcycles is also common, according to traffic legislation their behaviour regarding traffic should be the same as that of cars, so their consideration would not have any repercussion in this study.

As mentioned above, since Veins is a hybrid simulator, it is possible to visualize it either by using the network simulator OMNet++ or by making use of the graphic interface of SUMO, (SUMO-GUI). Thanks to this, it is possible to use OMNet++ to visualize the exchange of messages performed by the vehicles in detail, using SUMO-GUI at the same time to view the movement of the cars in the scenario. OMNet++ offers the possibility of introducing visual effects in the visualization tool during the simulation (Tkenv). In order to check whether the vehicles were inferring traffic conditions correctly, we used colour codes to identify the different traffic levels in the scenario. Thus, when vehicles detected that the traffic level was low, it was indicated by using a green circle, when it was medium, yellow and in the case it was low or very low, red and violet respectively. Moreover, to indicate that the vehicles had received the messages correctly, the colour of these circles was also altered on their reception. They turned pink in the case of receiving a "Traffic" WSM and orange, in the case of receiving an "Alert" WSM (see Fig. 8). Also, message interchanges were presented in the global view of SUMO-GUI, as shown in Fig. 9.

9. Performance evaluation

In order to check the effectiveness of the system designed, two situations were taken into account for each scenario: one without using the collaborative system (i.e., the default behaviour) and another using the collaborative system. By comparing both situations it is possible to check the improvements achieved with the collaborative system. Moreover, a total amount of 12 simulations were carried out for each scenario. Six simulations were performed without using the collaborative system and, therefore, without interchanging WSMs. Another six simulations were

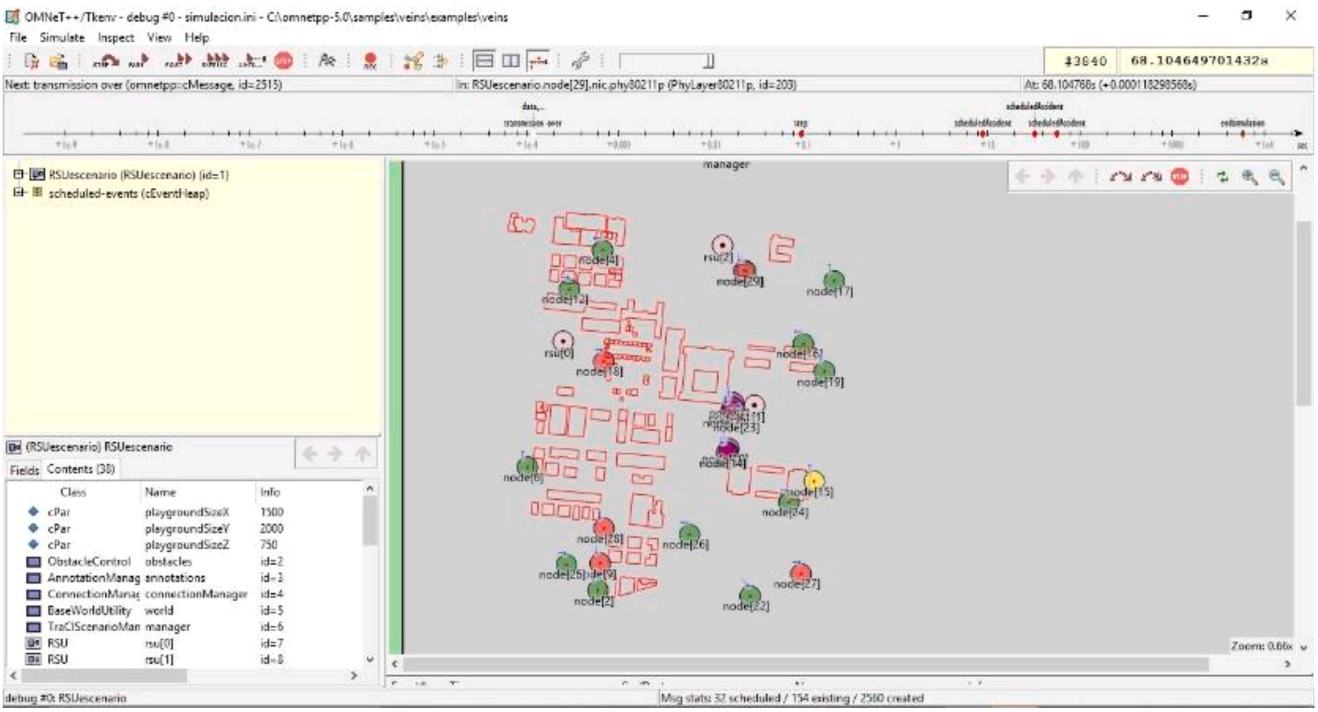

Fig. 8. Simulation view in Tkenv.

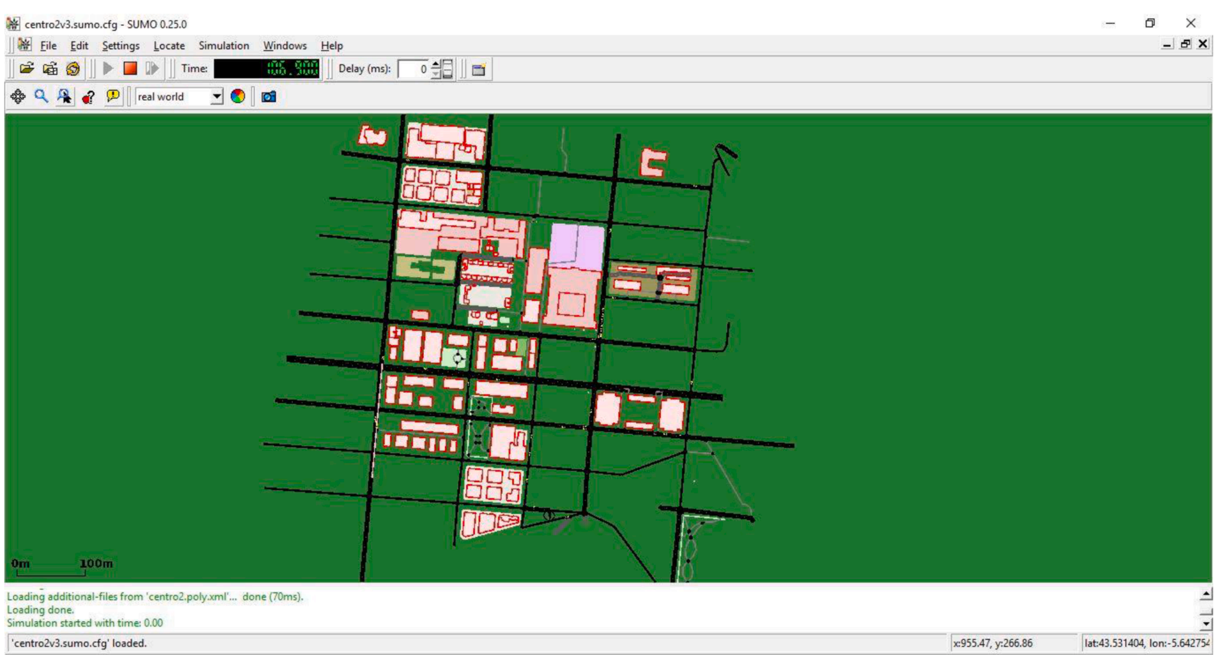

Fig. 9. Global view in SUMO-GUI.

performed using the collaborative system. When the collaborative system was used, all the vehicles were equipped with the designed functionality and, thus, were allowed to make decisions depending on the level of traffic detected and to collaborate with each other in order to avoid traffic congestion.

Apart from considering the aforementioned situations for each scenario, we have also performed experiments with different traffic densities. Thus, we have considered different vehicle creation rates, having more or less cars in the simulations and, accordingly, better or worse traffic conditions. For this purpose, we have used the aforementioned randomTrips.py script to adjust the time interval used to create the cars in the simulator, as explained in Section IV. Three vehicle creation rates were considered in the experiments. The first of them, one vehicle per second (1 v/s), allowed us to emulate a high density of traffic in the city. The second, one vehicle each second and a quarter (1 v/1.25 s), allowed us to create a considerable amount of traffic. Finally, the third was to create one vehicle every second and a half (1 v/1.5 s), to simulate a low density of traffic.

In both situations and scenarios, we allow all the vehicles to finish their routes. Thus, the departure of the last car is scheduled to happen

3000 s after the beginning of the experiment, leaving enough time for it to reach its destination.

Once the simulation has been launched, statistics are collected from both the vehicles and the RSUs. In order to compare both situations (with or without the collaborative system) in both scenarios, we analyse the differences in minimum, maximum and average speeds of the vehicles, CO_2 emissions and acceleration of the vehicles and the distance of their routes. It is worth mentioning that the amount of emissions of CO_2 of the cars is calculated thanks to a model developed by Capiello et al. [51] which employs the speed and acceleration of the vehicles.

With the aim of determining whether the obtained data gathered for both situations show significant differences or not, we began by studying their normality and homoscedasticity. In order to check the normality of data we performed Shaphiro–Wilk tests and to evaluate their homoscedasticity we used Levene's tests. Once the results of those tests were obtained, since all the data sets turned out not to be normal and homoscedastic, Kruskal–Wallis tests using a 0.01 significance level were employed in order to check if there is a statistically significant difference between the usage or not of the collaborative system. If the p value of the test is lower than 0.01, there are statistically significant differences, while if the p value is equal to or greater than 0.01, we fail to reject the null hypothesis. The latter indicates that we do not have sufficient evidence to affirm that there is a statistically significant difference between the situations being compared.

9.1. Scenario #1 – centre of Gijón city

This scenario, as explained before, was based on an area of the centre of Gijón. The average distance covered by vehicles is showed in Table 4. Another relevant result, is the number of vehicles that achieve the maximum speed in the scenario, depending on whether they use the collaborative system or not. As we can see in Table 5, the percentage of vehicles that achieve the maximum speed is much higher when the collaborative system is used. Moreover, Table 6 shows the mean of the minimum and maximum values of speed for all the cars that take part in the simulation, collected when varying the traffic in the area.

It can be noticed that, although the length of the routes increase trying to avoid congested streets, cars are able to move faster when using the collaborative system designed. This can also be seen if we compare the average speed of the vehicles, also shown in Table 6. Kruskal–Wallis tests show that these differences are statistically significant for all the vehicle creation rates with p values < 0.01, proving the positive effects caused by the collaborative system. Moreover, there are slight changes in the acceleration of the vehicles. Table 7 shows average accelerations for the three vehicle creation rates considered in the experiments. As in the case of speeds, Kruskal–Wallis tests show statistically significant differences for all the vehicle creation rates with p values < 0.01. These results are obtained thanks to the improvements in the flow of traffic achieved by the system.

Thanks to these parameters, it is possible to work out the total amount of CO_2 emissions generated by the vehicles, according to Capiello et al. [51]. This parameter, whose values for the simulations performed are shown in Table 8, gives an idea of the pollution caused by the traffic. As can be seen in this table, the emissions are significantly reduced when the collaborative system is used (up to 6.73 %). This difference in the emissions can also be explained by the particular characteristics of the scenario. It is important to remember that it is located in the centre of a city, which implies that cars travel most of the time on one-way streets with a high number of intersections. Thus, they tend to suffer severe traffic problems when traffic jams appear and so increase the generation of pollutants.

Regarding the messages interchanged in the network, the number matches up to the expectations. In the scenario with the highest traffic, vehicles send, on average, 1.01 messages while they receive 10.78. However, when the lowest vehicle creation rates are used, the average of messages sent by the vehicles is 1 and they receive an average of 5.72 messages, almost 50 % less. The reduction of the messages interchanged in accordance with the vehicle creation rate is also reflected in the messages sent by RSUs. Thus, the average number of messages sent with the highest rate is 203.33, 154.67 with the medium rate and 136.67 messages with the lowest.

Table 4
Average distance covered (meters) by vehicles in Scenario #1 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour $\bar{x}$	Collaborative system $\bar{x}$
1 v/s	594.628	619.363
1 v/1.25 s	580.953	598.302
1 v/1.5 s	561.158	578.230

Table 5
Number of vehicles that achieve maximum speed in Scenario #1 for different creation rates (v/s).

Rate of Vehicle Creation	Default behaviour $\bar{x}$	Collaborative system $\bar{x}$
1 v/s	153 (8.1 %)	1843 (97.3 %)
1 v/1.25 s	133 (8.3 %)	1571 (98.4 %)
1 v/1.5 s	93 (7.3 %)	1254 (98.3 %)

Table 6
Average and standard deviation values for minimum, maximum and average speeds (m/s) in Scenario #1 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour		Collaborative system	
	$\bar{x}$	σ	$\bar{x}$	σ
	Minimum speed			
1 v/s	0.056	0.103	0.075	0.113
1 v/1.25 s	0.077	0.114	0.086	0.117
1 v/1.5 s	0.083	0.115	0.098	0.121
	Maximum speed			
1 v/s	13.788	0.750	13.811	0.698
1 v/1.25 s	13.816	0.635	13.835	0.578
1 v/1.5 s	13.816	0.657	13.824	0.646
	Average speed			
1 v/s	6.446	2.502	6.956	2.748
1 v/1.25 s	7.243	2.485	7.639	2.578
1 v/1.5 s	7.516	2.542	7.849	2.658

Table 7
Average and standard deviation values for acceleration (m/s^2) in Scenario #1 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour		Collaborative system	
	$\bar{x}$	σ	$\bar{x}$	σ
1 v/s	0.215	0.299	0.243	0.314
1 v/1.25 s	0.236	0.288	0.254	0.298
1 v/1.5 s	0.253	0.300	0.275	0.313

Table 8
Average and standard deviation values for CO_2 emissions (g/s) in Scenario #1 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour		Collaborative system	
	$\bar{x}$	σ	$\bar{x}$	σ
1 v/s	241.695	119.871	225.418	125.261
1 v/1.25 s	219.192	103.542	205.378	101.741
1 v/1.5 s	207.367	97.177	196.828	99.211

9.2. Scenario #2 – peripheral area of gijón city

This second scenario covers a peripheral area of Gijón. As mentioned

Table 9
Number of vehicles that achieve maximum speed in Scenario #2 for different creation rates (v/s).

Rate of Vehicle Creation	Default behaviour	Collaborative system
	$\bar{x}$	$\bar{x}$
1 v/s	229 (8.8%)	2557 (98.3%)
1 v/1.25 s	187 (8.9%)	2054 (98.0%)
1 v/1.5 s	151 (8.6%)	1717 (98.1%)

Table 10
Average distance covered (meters) by vehicles in Scenario #2 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour	Collaborative system
	$\bar{x}$	$\bar{x}$
1 v/s	690.699	700.171
1 v/1.25 s	647.759	689.643
1 v/1.5 s	648.511	688.377

Table 11
Average and standard deviation values for minimum, maximum and average speeds (m/s) in Scenario #2 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour		Collaborative system	
	$\bar{x}$	σ	$\bar{x}$	σ
	Minimum speed			
1 v/s	0.083	0.291	0.088	0.117
1 v/1.25 s	0.106	0.122	0.106	0.121
1 v/1.5 s	0.114	0.123	0.116	0.123
	Maximum speed			
1 v/s	13.808	0.682	13.829	0.603
1 v/1.25 s	13.801	0.705	13.814	0.695
1 v/1.5 s	13.809	0.714	13.817	0.708
	Average speed			
1 v/s	7.006	2.919	7.791	2.612
1 v/1.25 s	7.985	2.618	8.311	2.478
1 v/1.5 s	8.370	2.325	8.601	2.348

before, several vehicle creation rates are used in order to test the collaborative system in this scenario. The same vehicle creation rates used in the previous scenario. The reason for choosing the same rates again, despite the differences of topology in both scenarios, is that it makes it their comparison easier, while also checking the effects of the different topologies on traffic. The number of vehicles achieving the maximum speed is shown in Table 9. The results are similar to those obtained in scenario #1. Also, the average distance covered by the vehicles is shown in Table 10. As shown in the table, routes are longer when the collaborative system is used. This is caused by the system altering the initial routes of the vehicles when congestion is detected. Table 10 shows a maximum difference of 42 m with a 1v/1.25 s vehicle creation rate.

The gathered speed values, shown in Table 11, present the same pattern observed in the first scenario. The ability of the vehicles to react to the traffic conditions when the collaborative system is used achieves an improvement in their speed. This not only affects the minimum and maximum values but, as in the first scenario, the average speed of the vehicles. Again, Kruskal–Wallis tests show that the differences are statistically significant with p values < 0.01.

Table 12
Average and standard deviation values for acceleration (m/s^2) in Scenario #2 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour		Collaborative system	
	$\bar{x}$	σ	$\bar{x}$	σ
1 v/s	0.187	0.242	0.209	0.256
1 v/1.25 s	0.228	0.262	0.234	0.280
1 v/1.5 s	0.224	0.246	0.227	0.248

Table 13
CO_2 emissions (g/s) for Scenario #2 for different vehicle creation rates (v/s).

Rate of Vehicle Creation	Default behaviour		Collaborative system	
	$\bar{x}$	σ	$\bar{x}$	σ
1 v/s	273.564	160.131	240.013	122.299
1 v/1.25 s	226.285	110.881	224.644	110.826
1 v/1.5 s	212.931	90.456	218.229	107.053

As seen in the first scenario, the acceleration values gathered when the collaborative system is used are slightly higher, as shown in Table 12.

Unlike what happened to the simulation data obtained in the first scenario, on this occasion there are not so many differences in pollution values if we compare the default behaviour with the collaborative system. As shown in Table 13, CO_2 emissions are lower if we use the collaborative system when the highest and the medium creation rates are used. This is also shown in Fig. 10, which represents the CO_2 emissions generated by the cars in scenario #2, when the 1v/s vehicle creation rate is used. Nevertheless, when the lowest creation rate is employed, there is a slight increase in CO_2 emissions when the collaborative system is used. This can be explained by taking into account the topology of the scenario. Since the scenario covers a peripheral area of the city, there is a higher separation between buildings, so cars have to travel longer distances in order to avoid congested streets and reach their destination.

The use of the Kruskal–Wallis test on these values shows that when the highest creation rate is employed, the emission values registered are significantly different with p values < 0.01, so the collaborative system clearly improves the situation. Nevertheless, when the lowest creation rate is used, the p value obtained is 0.8486 ($>$0.05) which reflects that the values do not present significant differences.

Regarding the communications, the collected data are consistent with those obtained in the first scenario. The lower the traffic, the lower the number of messages exchanged. Vehicles send, on average, 1.010 when one vehicle per second is created, 1.001 with the chosen medium rate and 1, when the lowest rate is used. The same happens with the average number of messages received. When the traffic density is very high, this number is 43.96, when it is medium, 31.01 messages and when it is low, 24.43. Therefore, 55.58 % fewer messages are generated if we compare the highest and the lowest traffic densities.

Since this scenario is more prone to road congestion, it is especially important for the RSUs not only to be correctly located in order to cover the whole area but also to be close to the most problematic points. In this way, the highest number of problems that might arise is reflected in an increase in the number of messages sent by the RSUs. Thus, when the highest vehicle creation rates are used, these devices send, on average, 396.33 messages while, in the case of the lowest rates, 348.67 messages are sent. These values are 94% and 155% higher than the same situations in the first scenario.

10. Discussion and limitations

Thanks to the simulation experiments carried out, we have been able to demonstrate the effectiveness of the proposed system. By comparing the behaviour of traffic with and without the collaborative system, using several traffic densities (i.e., vehicle creation rates) on two different urban scenarios, we have checked the usefulness of the system designed.

When the collaborative system is used, most of the vehicles travelling in both scenarios are able to achieve the maximum legal speed, independently of the volume of traffic and urban design. The worst conditions are met when one vehicle per second is created in the centre of the city. With these conditions, an average of 97.3 % of the vehicles achieve said speed. Nevertheless, when the system is not used, only 8.1 % of the vehicles achieve this speed. Fig. 11 shows the average speeds of the

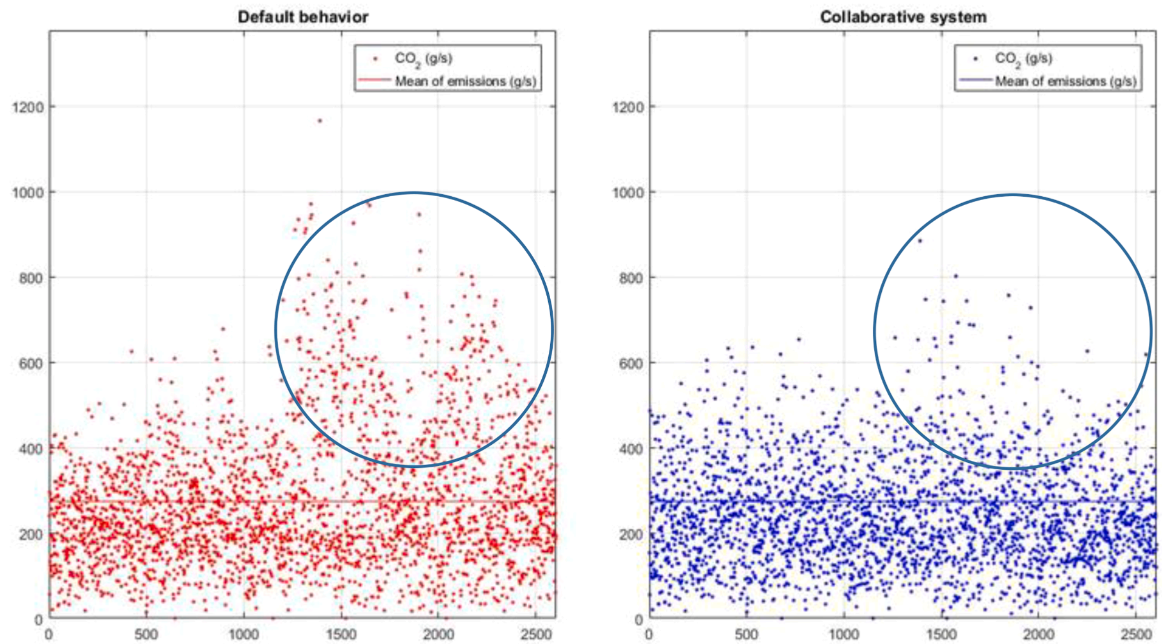

Fig. 10. . CO_2 emissions in Scenario #2 for a 1/v vehicle creation rate.

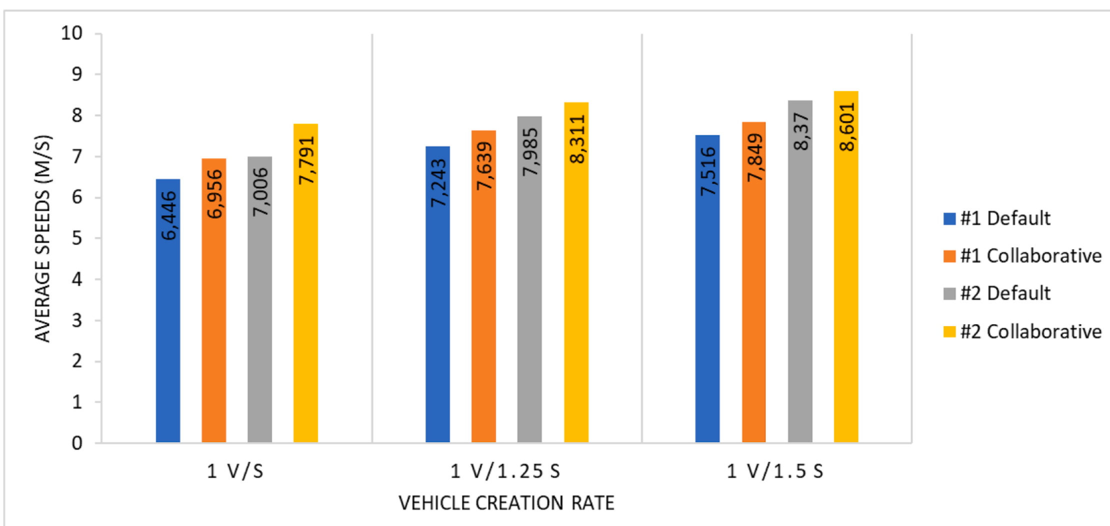

Fig. 11. Average speeds in Scenarios #1 and #2.

vehicles in both scenarios. When the system is used, average speed improvements range from 2.75 % when one vehicle is created every 1.5 s in the city outskirts to 11.20 % when one vehicle per second is created in the same urban environment. Speed improvements range from 4.43 % to 7.91 % in the city centre. The worse traffic conditions are, the higher the increase in average speeds. This result is logical since the traffic flow improves, making it possible for vehicles to maintain higher speed values for most of their journey. The increase of speed also has an impact on the acceleration of the vehicles since the changes of speed are translated in a slight increase in this parameter as well.

As a result of the decisions performed by the collaborative system, average routes are up to 6.46 % longer. When congestion is detected, the system changes the initial routes of the vehicles, forcing them to travel longer distances than those initially planned. Nevertheless, although the length of the routes increase trying to avoid congested streets, cars are able to move faster when using the collaborative system.

Regarding the generation of pollutants, Fig. 12 shows the average CO_2 emissions generated in both scenarios. Pollutants are significantly reduced when the collaborative system is used, achieving an improvement to 12,26 % when 1 vehicle per second is created in the second scenario. The greatest improvements are obtained when the volume of traffic is high because of an increase in the number of vehicles or because of the design of the urban topology (i.e., there are traffic jams) The centre of the city is full of one-way streets and intersections, so vehicles tend to suffer severe problems when traffic jams appear, increasing the pollutants generated. In this case, the system allows us to reduce CO_2 between 5 % and 6,73 %. Nevertheless, when there are no traffic jams in a peripheral area of the city, the increase in the speed of cars and in the distances travelled because of the decisions made by the collaborative system get to produce a slight increase in the pollutants generated (not statistically significant). When traffic density is low, the results between using and not using the collaborative system are very

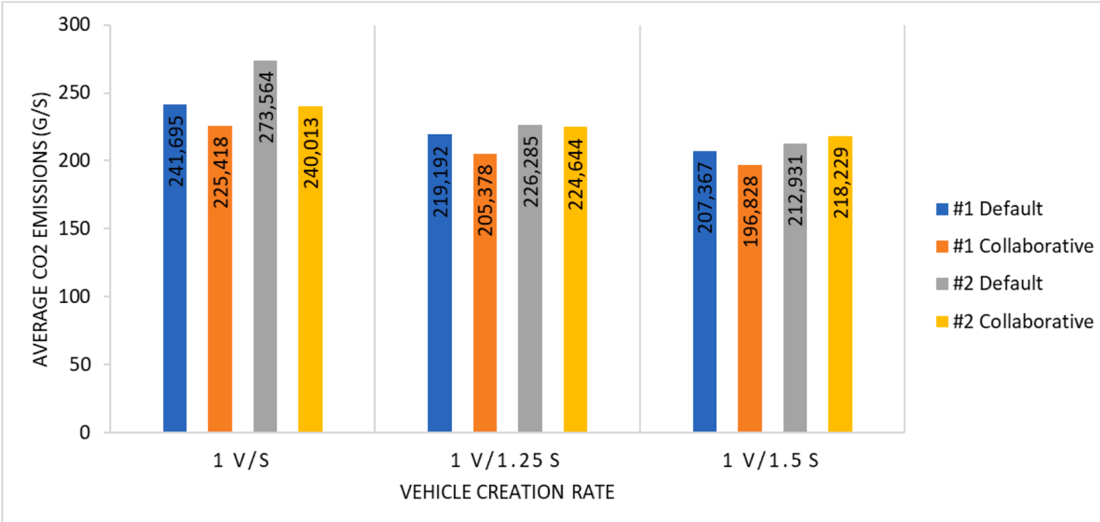

Fig. 12. Average CO_2 emissions in Scenarios #1 and #2.

close. The reason can be attributed to the low number of traffic jams when the density of cars is low. Furthermore, there are fewer changes in the routes of the vehicles when the system is employed under low traffic conditions. Under these conditions, the collaborative system does not take effect.

The conclusions are in line with our expectations since the lower the traffic density in the network, the closer the results are between using and not using the collaborative system. Such behaviour is explained by the decrease in the number of cars that are travelling in the scenarios, since this brings with it a reduction in the number of traffic jams. This reduction means that vehicles make a lower use of the collaborative system designed to reduce the traffic congestion because they will detect low and very low traffic. Therefore, most of their decisions will be translated into changes of speed instead of changes of route. The collected experimental values can be used to prove the positive repercussions that these speed changes have on the traffic flow. Nevertheless, since in the original situation there are hardly any traffic jams and most of the vehicles follow the same route, the improvements are less noticeable than when the traffic density is higher. It is necessary to emphasize that we have demonstrated that the system is able to improve traffic conditions reducing, at the same time, the stress of drivers and pollution. Nevertheless, the exact grade of improvement depends on the complexity of the urban environment and the density of vehicles in the scenario. A sudden and massive deployment of vehicles in a complex urban scenario cannot be handled simply because of the existence of physical limitations.

The system may help governments to reduce congestion and pollution in urban areas. In recent years, public administrations have been carrying out different interventions to reduce pollution. Some of these policies are general and mainly imply a movement toward zero or low-emission vehicles [52]. Other policies are primarily local and have been designed to improve traffic and pollution specially in the centre of the cities. General measures have been usually planned to be deployed on a long term. For instance, the plan of the European Union to achieve climate neutrality includes restrictions on new passenger cars and new light commercial vehicles from 2030 onwards. Nevertheless, vehicles sold before that date will continue to be used for years. This same plan also includes a 90 % reduction in transport emissions, but the deadline is 2050 [6]. Our solution can bring immediate benefits while those long-term policies finish to be deployed. It is not an alternative to those policies, but a complement. Regarding local policies, major cities around the world have been applying certain restrictions to traffic in recent years. Some cities have reduced speed limits in urban areas, but previous work has demonstrated that this policy is not very effective [17]. Other cities have created low emission zones -LEZ- to avoid certain vehicles to enter specific areas of the city [53,54]. In some cases, those restrictions are not applied to cars (only to other heavier vehicles) or even if they are applied, drivers may enter those areas paying a fee [53] In other occasions, certain vehicles may enter without restrictions depending on their engine, the activity of the owner, the route which will be followed or other aspects [54] These policies clearly improve the situation but they do not ultimately finish with traffic congestion and the generation of pollution, thus, our solution may help those policies to be more effective.

In view of the obtained results, it can be concluded that the smart collaborative mobility system designed meets expectations since it allows to decrease the number of traffic jams by improving the traffic flow and, at the same time, decreasing the generation of pollution. The system is decentralized and autonomous, therefore, there are no single points of failure nor the need of Internet connectivity. The usage of fuzzy logic has allowed us to design a low-resource consuming solution, in contrast with other artificial intelligent techniques and without the need of extensive training processes or massive datasets.

Our approach is novel as it is based on a totally autonomous and distributed approach for urban scenarios, based on the collaboration between vehicles through the use of vehicular communications. A comparative study with other similar solutions follows. Tientrakool et al. [14] focus their study on collision avoidance in vehicles driving on a motorway, whereas our solution has been designed for urban traffic. Kitwiroon et al. [16] achieve improvements of up to 11 % in vehicular emissions. Even though these values are similar to the improvements in pollutant emissions obtained with our solution, they have to reduce heavy-duty vehicles a 20 %. Thus, they are restricting the most-polluting vehicles in the road. Similarly, Mahmod et al. [18] are able to reduce CO_2 emissions up to 23 %, but by reducing the traffic a 20 %. In our study, we decrease car emissions by up to 12.27 % but no traffic needs to be restricted or reduced. Knorr et al. [23] aim their study at avoiding traffic jams and, although they are able to improve traffic efficiency, their solution has been designed for highway roads only. The solution proposed by Ribeiro et al. [25] is focused on communication aspects and relies on a central system as opposed with our study, in which we present a holistic solution. Furthermore, they perform experiments with IEEE 802.11 b/g and report high association delays, whereas in our study we employ IEEE 802.11p communications. Jayapal & Roy [30], present a traffic congestion detection and dissemination system but relays on a central system, does not use vehicular communications and it does not provide any improvement metric. Dimitrou et al. [32] describe an adaptive hybrid fuzzy rule-based system to predict the evolution of traffic in an urban environment, but they do not take action to improve traffic conditions. Naja & Matta [35] also present a method to avoid traffic congestion, but their solution is tailored to motorways and not to cities. Ranjita and Acharya [41] proposed a method to detect congestion and to avoid it by proposing an alternative route. Although these ideas are also part of our design, their study is based on a central system and has been specifically designed for emergency vehicles only. Stolfi and Alba [43] propose a rerouting mechanism for vehicles to optimize the distribution of traffic. Their solution is infrastructure dependant as opposed to our solution which is autonomous. Also, their approach is different because they try to balance traffic by rerouting all the vehicles, whereas in our case we only reroute vehicles when needed, adjusting speeds depending on the status of traffic. Finally, they rely on non-vehicular communication technologies which may be problematic in certain situations, and they do not report pollution improvements.

Even though the results are promising, this study has certain limitations. Firstly, all the results are based on simulation experiments. There are certain limitations inherent to the simulation environments which may not fully replicate real-world complexities. For instance, the routes followed by the vehicles are generated randomly. Starting and ending points of every trip are generated in the fringe of the scenarios and a shortest-path algorithm is used to calculate the path. This does not reflect how real traffic behaves, as certain avenues and streets usually concentrate most of the traffic because of the urban design. Moreover, trips do not necessarily start and finish in any preestablished border (e.g., the boundaries of a suburb). Also, cars behave using the default "car-following" mobility model implemented in SUMO when needed. While this approach is useful to perform simulations, it does not realistically imitate the behaviour of real drivers. Finally, another limitation of the simulations carried out is that vehicle creation rates are fixed. This has also been convenient because it has allowed us to examine the behaviour of the system by gradually increasing the load in the scenarios with changing speeds, but it does not accurately reflect how real vehicles enter and exit a certain urban area. In order to fully check the efficacy of the collaborative system designed it would be necessary to carry out a pilot test in a real-world setting with real drivers.

When we carried out the experiments, we assumed that when the collaborative system is used, all the vehicles are equipped with the designed functionality. In a mixed scenario with standard vehicles travelling together with vehicles using the system, only the latter would benefit from the decisions made. Vehicles equipped with the system will continue taking decisions based on their speed, the time they stay stationary, and the messages sent by similar cars, but the rest of vehicles will continue with the default behaviour. Thus, the results in terms of pollutants reduced would not be so beneficial. But it is necessary to consider that this is a decentralized collaborative system and needs the vehicles to exchange information. If the density of vehicles using the system is very low, the solution is not effective because most of those vehicles would not be able to act proactively, as they are not receiving messages generated by other vehicles already entering a traffic jam. The lack of vehicles using the system may be alleviated by deploying a great number of RSUs which, on the other hand, would help to deal with range limitations and adverse environmental conditions. The availability of these systems is another assumption of the study. This may be feasible if current public infrastructure is upgraded for said purpose (e.g., streetlights and traffic lights) Nevertheless, considering the recent controversy about the deployment of 5 G infrastructure this may be definitely polemical and social acceptance is not guaranteed. A not so noticeable option would be to deploy the system in public transport vehicles. Although they need to follow preestablished routes independently of the volume of traffic, they can behave like RSUs and, thus, operate as exchange points. Deploying the system in other types of public vehicles such as shared scooters or electric bicycles would extend the model by adding V2P (Vehicle-to-Pedestrian) communications. These vehicles may operate as well as infrastructure elements, helping vehicles to exchange control information. All these public vehicles may relay control messages when they are stationary, or they may even implement a "store-carry-forward" communication model. These actions may be included in the interventions targeted by public administrations at reducing pollution and improving urban mobility.

It is also necessary to take into account that there may be legal restrictions in the deployment of the solution since the communications of the system are based on the IEEE 802.11p standard and this technology uses a licensed frequency band. In fact, although this technology has been specifically designed for vehicular communications, there has not been a significant deployment of this type of solutions. Although it is optimal for the type of communications we perform, the fact that it is not available in current vehicles hinders the adoption of the proposed solution. On the hand, the fact that solutions of this type are proposed and used, may promote the usage of the technology.

11. Conclusions and future work

In this paper we have presented a novel system for improving traffic conditions in urban areas reducing, at the same time, the generation of pollution when combustion vehicles are used and, as a side benefit, the stress of the drivers. Furthermore, an improved flow of traffic may also imply an optimised usage of batteries in an electric vehicle scenario. Our solution can bring immediate benefits to society while the policies designed by public administrations finish to be deployed.

The system is based on vehicular communications and fuzzy logic. Given the obtained results, we can affirm that fuzzy logic is a better approach to determine and correct traffic jams than deterministic or random methods, providing a new system for traffic control. Moreover, the designed system has proved the effectiveness of collaborative solutions in avoiding traffic jams, confirming the outcomes of previous work. The deployment of the designed collaborative system using VANETs with both vehicles and infrastructure, and Fuzzy Logic may reduce pollution in a city up to 12.27 % reducing, at the same time, the stress of the drivers as stated by Gulian et al. [12] and optimizing the autonomy of electric vehicles according to Yan et al. [11].

The simulations have been performed using realistic scenarios, and they have also shown that the designed system is effective not only in the centre of a city, but also in peripheral areas with different traffic densities. Moreover, the fact that the urban designs chosen resemble both the typical structure of an old European city and the design of a modern city which may be found in any continent, has allowed us to demonstrate that the system may be effective in any geographical setting. Nevertheless, the experiments have only been carried out in a simulation environment. Therefore, in order to fully check the efficacy of the collaborative system designed, as future work it would be interesting to carry out a pilot test in a real-world setting and apply the solution in a real scenario with real drivers. We aim to perform such pilot test by deploying the system in professional bus fleets, thanks to our collaboration with the ADN Mobile Solutions company, similarly to what was done in the UrVAMM project [55]. In fact, the first actual outcomes of the system may be obtained in said environment by helping to deal with congestion situations in heavy-loaded bus routes. To develop the model in a real environment we would need devices to work as either On-Board Unit (OBU) or RSU stations. We have carried out a preliminary revision of commercial vehicle side devices (OBU) and found several options used in the current market such as CohdaWireless MK6 [56] or Unex OBU-352 [57]. Possible solutions for RSU devices are the same CohdaWireless MK6 [56] and Unex RSU-352 [58]. An implementation of our fuzzy inference system could be deployed in these devices, in order to take decisions and generate the messages we need.

It is also worth researching into the acceptance of this type of systems by drivers. New intelligent transportation systems may be used to reduce pollution, but it is not clear whether users like them or not. Subjective evaluations may be a good option to check whether they accept them or not. This is something we would like to research with our pilot tests.

Even though they will be carried out with professional drivers in an urban transport environment, their feedback may be useful to obtain preliminary conclusions on the acceptance of the system.

Furthermore, in light of the current growth in the number of alternative means of transport in urban areas, such as bicycles, it could also be interesting to work on the design of collaborative systems with the goal of facilitating the integration of these other means into the urban traffic, improving several aspects such as the safety of their users.

CRediT authorship contribution statement

José Antonio Sánchez: Conceptualization, Investigation, Software, Writing – original draft. **David Melendi:** Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Roberto García:** Formal analysis, Validation. **Xabiel G Pañeda:** Funding acquisition, Methodology, Project administration, Resources. **Víctor Corcoba:** Software, Visualization. **Dan García:** Software, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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