Vehicular Traffic Management Based on Traffic Engineering for Vehicular Ad Hoc Networks

DANIEL L. GUIDONI[ID]1, **GUILHERME MAIA**[ID]2, **FERNANDA S. H. SOUZA**[ID]1,
LEANDRO A. VILLAS[ID]3, **AND ANTONIO A. F. LOUREIRO**[ID]2

[1]Department of Computer Science, Federal University of São João del-Rei, São João del-Rei 36307-352, Brazil
[2]Department of Computer Science, Federal University of Minas Gerais, Belo Horizonte 31270-901, Brazil
[3]Institute of Computing, University of Campinas, Campinas 13083-970, Brazil

Corresponding author: Daniel L. Guidoni (guidoni@ufsj.edu.br)

ABSTRACT Urbanization causes many problems to human mobility, since people living in the cities tend to increase the vehicular traffic flow. City road infrastructure does not increase faster than the number of vehicles, thus causing traffic congestion in dense urban centers. Besides travel delay, vehicular traffic congestion results in serious problems to human beings (e.g., health problems due to stress), to the planet (e.g., increase in pollution) and to the economy (e.g., waste of a large amount of money due to time spent in traffic jams). In order to improve vehicular traffic flow in dense urban areas, this paper presents a new Vehicular Traffic Management Service based on Traffic Engineering theory, called Re-RouTE. The Re-RouTE service relies on the density of vehicles in roads and applies the flow-density macroscopic traffic engineering model to identify congested routes. Roads are represented by a weighted graph, which is then used to discover routes without traffic jams and with a small increase in the travel distance. The main goal of Re-RouTE is to reduce traffic jams while increasing the global vehicular traffic flow of the road network. Moreover, the service was designed to reduce traffic jams instead of moving them to a different road/area. Simulation results show the ability of Re-RouTE to improve travel time, travel distance, speed and the number of messages transmitted when compared to a literature solution.

INDEX TERMS Vehicular ad hoc network, re-routing algorithm, vehicular traffic management, traffic engineering.

I. INTRODUCTION

With the industrialization of countries, there is an increase in population living in metropolitan areas. One of the main problems related to urbanization is vehicular traffic congestion, since it causes disorganization in traffic flow and wasted time. People living on the edge of cities use their vehicles to go to work, which is usually located in city centers. In this scenario, maintaining a good vehicular traffic flow has a great impact on people's quality of life and even safety [1]. There are a number of issues related to traffic congestion and, in addition to the impact on the delay, congestion affects people's health. The delay also causes the inability to estimate the travel

The associate editor coordinating the review of this manuscript and approving it for publication was Razi Iqbal[ID].

time. Another issue is the fuel consumption, which increases due to time wasted on traffic jams. Finally, vehicular traffic congestion affects emergency vehicles, since they are unable to perform the service in the expected/requested time.

Some cities around the world introduced management schemes to overcome vehicular traffic congestion, such as car-pooling by encouraging drivers to share available spots in the vehicle, charging areas of the city, where drivers have to pay to go in, bike lanes and intelligent park zones. Although these solutions mitigate the problem, traffic congestion tends to increase in urban areas. The UK Centre for Economics and Business Research (Cebr) evaluates the direct and indirect cost of congestion in British, French, German and American scenarios [2]. The direct cost is related to the fuel consumption and wasted time in traffic,

where the indirect cost considers the cost of doing business. The study was released in 2013 and forecasted the congestion cost until 2030. The cumulative cost between 2013 and 2030, considering the four countries, reaches the amount of US$ 4.4 trillion, where 2.8 trillion is the USA congestion cost. Considering specific cities, Paris had a congestion cost of US$ 11.6 billion in 2013 and a projection cost of 18.7 Billion in 2030, an increase of 60%. The total cost considering the 17 years is US$ 266.9 billion. According to the study, Los Angeles has the world's biggest traffic congestion (among the considered cities) related to traffic delays; the traffic cost in 2013 was US$ 23.2 billion. In 2030, the expected cost grows to US$ 38.5 billion, an increase of 65% with a cumulative cost of US$ 559.1 billion.

Based on the report of the US Federal Highway Administration [3], vehicular traffic congestion has three main sources: (i) Traffic-Influencing Events (working zone, weather and traffic incidents); (ii) Traffic Demand (fluctuations in normal traffic, special events); and (iii) Physical Highway Features (traffic control devices and physical capacity). The city urbanization increases the working zones as well as the traffic demand. Incidents and weather are unpredictable and can affect instantly the traffic conditions, and the road physical infrastructure demands cost and time. In this scenario, technological solutions rise as an alternative to reduce traffic congestion. In this technological scenario, Vehicular Traffic Management Services (VTMS) play an important role to improve driver's mobility, quality of life and security [1], [4]. A Vehicular Traffic Management Service integrates user/road data, communication and computing to improve various problems in the traditional transportation systems of large cities. One of the goals of VTMS is the road management and to achieve it, a VTMS uses Information and Communication Technologies (TICs) to provide services and convenient applications for users of transportation systems to reduce traffic jams, increasing road capacity, reducing accidents and travel cost [4].

A VTMS should consider the following tasks [5]: vehicular traffic monitoring, congestion detection and routing suggestion. To monitor the traffic, it is possible to use different sensing solutions such as a sensor network, induction loops, and cameras. However, due to the installation and maintenance cost, these solutions have many drawbacks. Instead of using a fixed infrastructure, it is possible to use the capacity of communication and processing of a vehicular ad hoc network (VANET) [6], [7]. Vehicles equipped with wireless communication, GPS and a navigation system are able to communicate among them and with the infrastructure to notify the traffic management service and perform the traffic monitoring. Roadside Units (RSU) and 5G cellular communications are examples of an infrastructure that could be used to exchange messages in real time due to the dynamic topology of a VANET [8], [9]. The advent of 5G will facilitate continuous, ubiquitous and Vehicle-to-everything communication. This scenario with high carrier frequencies and massive bandwidths will introduce and create the basis for

the development of various applications, including vehicular traffic management services that require ultra-reliable and low-latency communication [10], [11].

Literature solutions for traffic jams in vehicular networks are based on road/street features, specially travel time [5], [12], [13], to manage the flow of vehicles aiming to decrease traffic congestion. However, there are other important features that could be considered by a VTMS solution if the service designer considers the road physical features together with the Traffic Engineering theory. Traffic Engineering applies engineering principles to solve user transportation demand and deals with the planning, geometric design of streets, bridges, intersection and its relationships with transportation models. Thus, an efficient solution for traffic management in vehicular networks should consider general vehicular traffic conditions, such as number of vehicles and flow conditions to improve traffic congestion.

This work presents a new Vehicular Traffic Management Service based on Traffic Engineering for VANETs, which is called Re-RouTE. The proposed solution addresses all aspects that should be considered in the design of a VTMS. The Re-RouTE solution monitors the traffic conditions, detects a traffic jam and suggests alternative routes to reduce traffic congestion. Vehicles equipped with a navigation system notify the Re-RouTE service regarding their location. By locating the vehicle's position within the city map, the service builds a road graph representation, where the edges are streets and vertices are the street junctions. The weight of each edge represents the number of vehicles at each street. The solution introduces the Traffic Engineering Theory to classify if a specific street is congested or not considering only the street density of vehicles. For this, we employ a density-flow macroscopic model [14] to verify the vehicle flow behavior at each street. When executed and a traffic congestion is detected, the Re-RouTE service calculates a new route of the vehicle and the new path is suggested with the aim to reduce the traffic congestion and improve the global traffic flow. An important feature of Re-RouTE is its ability to reduce the traffic congestion instead of moving it to a different area of the city. The proposed solution was evaluated considering real-road scenarios of Paris and Los Angeles metropolitan regions and compared to two state-of-the-art literature solutions that are the closest to our proposed solution. Considering both scenarios and different number of vehicles in the road network, Re-RouTE outperforms the literature solution regarding travel time, travel distance, average speed, transmitted messages and packet loss. We also evaluate VTMS solutions considering different values for the driver route acceptance, where only a fraction of all drivers accept the route suggestion.

The rest of this work is organized as follows. Section II presents an overview of related VTMS solutions. Section III proposes Re-RouTE VTMS solution. Section IV discusses the simulation results for different scenarios. Section V examines the applicability of the proposed solution. Finally, Section VI presents the conclusion and future work.

II. VEHICULAR TRAFFIC MANAGEMENT

Services such as TomTom [15] or Sygic [16] provide traffic information, which allows drivers to find better routes regarding the travel time. Waze [17], Google [18] and Microsoft [19] navigation systems are able to merge multiple and different data sources, including GPS enabled devices, street sensors, mobile phone sensors, public transport and social networks in order to forecast traffic jams. These services typically use advanced statistical and traffic prediction methods to provide real-time traffic information. However, these solutions suffer from a similar problem: new routes are suggested without considering the emergence of a new traffic congestion in another road [13]. Another problem is how to efficiently and effective perform the acquisition, management and massive data processing from heterogeneous data sources.

In the vehicular traffic management literature considering a vehicular network, there are a number of proposals that study the causes of congestion and how to overcome it [5], [20]–[22]. Some of these studies focus on V2V communication to collect and estimate the best route in congested scenarios. Knorr et al. [20] proposed a beacon-based solution to warn drivers about changes in the flow of vehicles when considering the perturbations caused by drivers during vehicles' movement. Wang et al. [21] proposed an adaptive beacon-based system for unexpected traffic congestion avoidance. These two solutions are effective to increase locally the traffic flow, however, there are some issues to consider: (i) a high number of transmitted messages among vehicles; (ii) low quality in the traffic estimation of alternative routes; and (iii) selfish decisions. It is worth noticing that, to estimate traffic relying only on V2V communication, vehicles need to send periodic beacons to their neighbors (every 1 to 10 seconds [5]). If a vehicle does not properly receive these beacons, the traffic estimation of alternative routes may not be accurate, which in turn will not decrease the travel time in case a vehicle decides to take one of these alternative routes. Therefore, hereafter, we only discuss solutions similar to the proposed solution and focus on improving the global traffic flow.

To overcome the high network overhead and improve the global traffic flow, ICARUS [12] uses vehicles' location using the GPS coordinates. In this solution, all vehicles send their position and velocity to a central service. Whenever a vehicle enters a previously defined area of interest, it receives congestion information regarding the roads it will pass. The area of interest defines a specific region of the city where vehicles should send their location. ICARUS uses this approach to reduce the number of transmitted messages. When a vehicle receives a congestion message, it forwards the message to close vehicles that might use this information to estimate alternative routes, based on three techniques: Dijikstra, A* and Probabilistic k-shortest paths (PkSP). All strategies are based on shortest paths, where the latter considers more than one shortest path in order to balance the traffic flow. However, based on the results, PkSP improves only 5% of the travel time when compared to the other two approaches.

Other solutions found in the literature also use *k*-shortest path algorithms to achieve load balancing during alternative route estimations. Hashemi and Khorsandi [23] argued that the direct application of the shortest path can simply move the traffic congestion from one road to a different one. Therefore, they propose a VANET Load Balancing Routing (VLBR) solution to overcome this problem. VLBR stores geographic information of vehicles in a central server and employs a *k*-shortest path algorithm [24] to find a load balancing when alternative routes are created. In order to achieve a global system load balancing, Bazzan et al. [25] proposed an evolutionary solution to traffic assignment to reduce the travel time. The proposed genetic algorithm computes different *k*-shortest alternative paths of each vehicle and picks the best one to improve the global system performance. However, that solution assumes that the overall traffic condition is previously known.

Pan et al. [26], [27] proposed three re-routing strategies named Dynamic Shortest Path (DSP), Random *k* shortest path (RkSP) and Entropy Balanced *k* Shortest Path (EBkSP). The proposed solutions use the road segment expected travel time to find alternative routes when the network is congested. The travel time (T_i) of a road segment is computed by $T_i = L_i/V_i$, where L_i and V_i are the length and expected speed of the road segment *i*. To represent the network, the authors created a directed weighted graph, where the weight of an edge corresponds to the road segment travel time T_i. The weights are periodically updated to represent the accurate travel time of all road segments in the network. DSP selects for each vehicle the path with the lowest travel time (used in our comparison), and RkSP calculates *k*-shortest paths to consider load balancing. Based on the vehicle's urgency (affected by congested roads), EBkSP selects some vehicles to be re-routed first. In [13] the authors present DIVERT: A Distributed Vehicular Traffic Re-Routing System for Congestion Avoidance. DIVERT uses EBkSP, cellular communication and a central server to implement a Vehicular Traffic Management service. DIVERT was compared using a 75 km^2 (Brooklyn) and 155 km^2 (Newark) road network considering 1000 vehicles and a re-routing frequency of 450 seconds. However, as the street average speed quickly changes with time and number of vehicles, the re-routing period must be large enough (450 seconds) to represent the characteristics of the streets.

Congestion could happen due to peak hours or some incident, such as a temporary street closure or an accident. In these cases, Wang et al. [28] proposed the Next Road Rerouting (NRR) solution based on Multi-Agent System where each intersection or traffic light represent an intelligent agent. NRR is able to operate in the presence of en route event or to improve global road traffic. The proposed solution is designed as a 3-tier architecture considering the Traffic Operator Center (central server), Regional Computers and intelligent agents installed on traffic lights at each intersection.

The traffic lights, also named as intelligent Traffic Light (iTL), are equipped with communication capabilities in order to perform V2I communication and an induction loop detector to verify the road occupancy. To improve global traffic congestion, iTL sends to the central server information regarding road occupancy and travel time. When necessary or considering a re-routing frequency, the vehicles request alternative routes to iTL, which request information to other iTL. The next road route is estimated considering four metrics: road occupancy, travel time, geographic distance to destination and geographic closeness of congestion. The proposed solution was evaluated considering a real-world and synthetic scenario and is able to decrease and mitigate traffic congestion. However, the demand to equip traffic lights with communication capabilities and induction loops means that such solution may lead to high installation and maintenance costs.

In this paper, we propose a new vehicular traffic management solution using traffic engineering and transportation concepts. Instead of using periodic beacon messages, street average speed, multiple data from heterogeneous sources or intelligent traffic light to estimate features from city roads, the proposed approach considers only the density of vehicles in the street to classify and manage the traffic flow of vehicles. Our simulation results show that relying only on the street density of vehicles rather than on street average speed, it is possible to reduce traffic jams in urban scenarios. Conversely, the street average speed is related to the travel time on the street and both need to be estimated considering a time window. Moreover, the use of intelligent traffic light may also increase its cost, where it should be deployed at each road intersection to have accurate estimations. These issues reduce the capacity to represent traffic flow in a dynamic urban scenario.

III. RE-ROUTE TRAFFIC MANAGEMENT SERVICE

In this section, we propose a vehicular traffic management service called **Re-RouTE** – **R**e-**Rou**ting based on **T**raffic **E**ngineering for vehicular ad hoc networks. The main goal of Re-RouTE is to efficiently manage the global traffic flow to reduce traffic jams. In the following, we describe in detail the proposed solution.

A. SERVICE DESIGN AND FEATURES

Vehicles equipped with a navigation system can access the Re-RouTE vehicular traffic management service to update their route to avoid a traffic jam. The Re-RouTE service is built considering three main assumptions. The first one is the vehicle's capability to determine the road/street identification it is currently moving. This can be determined by mapping a vehicle's geographic position (GPS) with the city street map stored in the vehicle navigation system. Second, the vehicle is able to communicate with the traffic management service using a communication network. Finally, each vehicle sends to the traffic management service its initial path containing the beginning and destination streets. Using the current street and the final destination, the service is able to find alternative

routes to avoid traffic jams. The proposed vehicular traffic management service could be implemented considering a central cloud server or a decentralized service approach running on RSUs deployed throughout the city. Section III-F discusses the communication issues to execute the Re-RouTE service in both scenarios.

The Re-RouTE service is divided into four modules/tasks: (i) Location Information; (ii) Network Representation; (iii) Network Classification; and (iv) Route Suggestion. Fig. 1 shows the Re-RouTE modules and the interactions among them. The *Location Information* module is responsible for receiving the vehicle's information. Considering the received information and the city map, the *Network Representation* module creates a weighted graph. Based on this graph and considering the traffic engineering theory, the *Network Classification* module classifies the road/street into congested or not congested. Finally, the *Route Suggestion* module verifies alternative routes for vehicles that are stuck at a traffic jam or vehicles that are about to reach a congested road. As soon as the module finds a new route, the vehicle is notified and the driver may choose to accept it or not. The *Route Suggestion* also computes alternative routes in such way to not create new traffic jams in different regions/streets of the city. The following sections present the proposed solutions and specific features to address each traffic management task in order to develop the Re-RouTE Service.
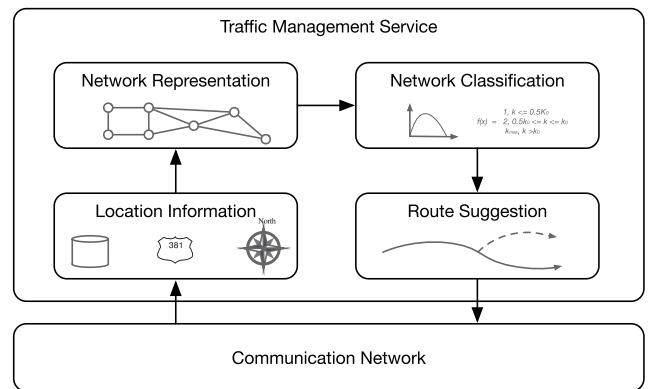

FIGURE 1. Re-RouTE service design.

B. LOCATION INFORMATION

During its trip, the vehicle moves through streets until it reaches its destination. The vehicle route R is composed of a number of streets $S = [S_1, S_2, S_3, \ldots, S_{n-1}, S_n]$. S_1 is the route origin and S_n is the route destination. Each vehicle sends its location information using a communication protocol to the Re-RouTE service as it moves through S. When a vehicle travels from one street to another one, i.e., from S_{j-1} to S_j, it issues an update to the Re-RouTE service with its new location by sending a message $m_{id} = (V_{id}, S_n, S_j)$, where V_{id} is the vehicle unique identification and S_j is the street identification that the vehicle just entered.

The Location Information module stores all received messages m in a database. Since the Re-RouTE service is based

on street density only, the database stores the street identification S_j that the vehicle is currently crossing and not its actual geographic position. When the vehicle moves from S_j to S_{j+1}, the vehicle updates its position by sending a new message $m'_{id} = (V_{id}, S_n, S_{j+1})$. The location information removes from the database the entry m_{id} and stores m'_{id}. The Re-RouTE service is designed in such way to store the minimum amount of information about routes to preserve the vehicle's (and driver's) privacy. The number of messages to update the Location information module of the Re-RouTE service is directly related to the size ($|S|$) of the vehicle's route R.

It is important to highlight that if for some reason the location information update fails (e.g., a message loss occurs), as soon as the vehicle sends a new message, the location information database is updated and errors in the counting do not propagate. However, during a period, the location database will be outdated and this might influence the Re-RouTE performance. We evaluate the proposed solution under this specific scenario in Section IV-D5.

C. NETWORK REPRESENTATION

The Network Representation module receives all the information stored in the database to create a street density map (Fig. 2). The density map is created by joining the city street map and the location information (street) of vehicles. Fig. 2(a) illustrates a typical street block with four intersections (Points A, B, C and D) and different number of lanes, directions and vehicles.

A directed weighted graph $G = (V, E)$ represents the city density map, where $V = \{v_1, v_2, v_3, \ldots, v_{n-1}, v_n\}$ corresponds to the street intersections and $E = \{e_1, e_2, e_3, \ldots, e_{n-1}, e_n\}$ represents the lanes of all streets. Fig. 2(b) shows the corresponding $G = (V, E)$ related to the density map shown in Fig. 2(a). In this graph representation, $V = \{A, B, C, D\}$ and $E = \{AB_1, AB_2, BA_1, BA_2, AC, BD, CA, CD, DB, DC\}$, where AB_1, AB_2, BA_1 and BA_2 represent each lane in the streets AB and BA, respectively. The weight of each edge in G corresponds to the number of vehicles on the lane/street. Each lane (i.e., graph edge) has a maximum allowed weight, which is the maximum number of vehicles that could be on the lane. For instance, edges AB_1, AB_2 BA_1, BA_2, CD and DC have a maximum weight of 7 vehicles and edges AC, CA, BD and DB have a maximum weight of 5 vehicles.

D. NETWORK CLASSIFICATION

Network Classification is not an easy task to perform due to a number of conditions that affect the street flow. Accidents, traffic light, weather and rush hours are examples of issues that affect vehicle traffic. Even though it is a difficult task, vehicular traffic flow has been investigated since 1950s and can be divided into three models [14]: microscopic, mesoscopic and macroscopic. The microscopic model investigates the interaction between two consecutive vehicles. The mesoscopic model describes the behavior of a group of vehicles.
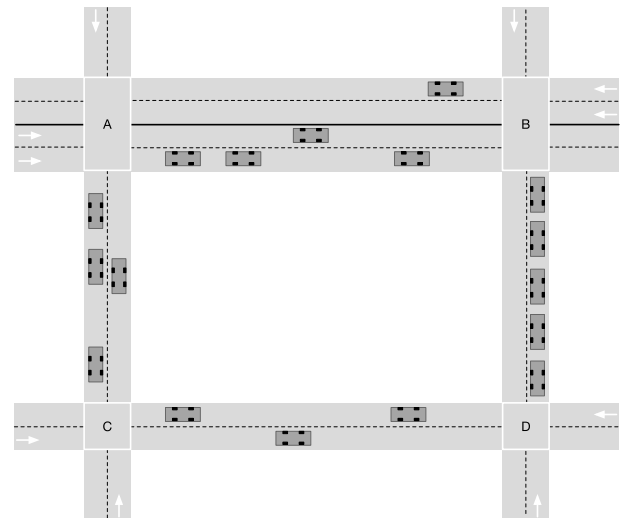
(a) Street density map
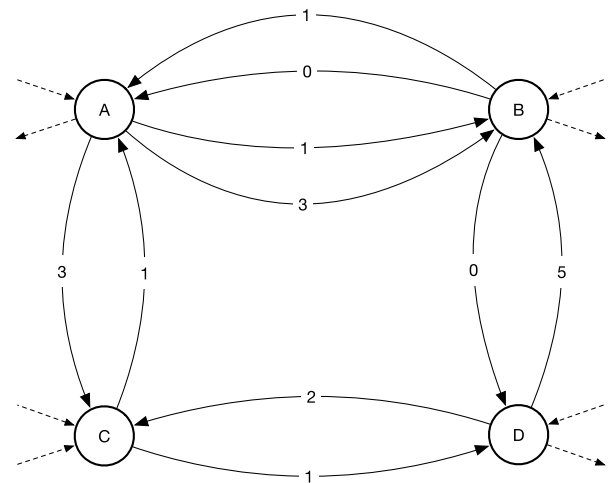
(b) Corresponding graph $G = (V, E)$

FIGURE 2. Street representation.

The macroscopic model describes the behavior of a general vehicle flow.

Traffic Engineering and Transportation researchers showed that in the macroscopic model there is an empirical relationship between density-flow of vehicles [14]. This relationship represents the expected ideal vehicle flow when the city streets/roads were planned. The proposed traffic classification method is based on the theoretical features of the density-flow macroscopic model, which have the following variables:

- q: flow
- d: density of vehicles
- v: speed
- d_{max}: maximum density of vehicles in the street
- v_{max}: speed limit of the street
- q_{max}: maximum flow of vehicles
- d_0: density of vehicles when the maximum flow is reached (q_{max})

- v_0: vehicle speed when the maximum flow is reached (q_{max}) and it is less than the average maximum speed of vehicles

Given a lane segment (e.g., edge/lane AC in Fig. 2(a)), the traffic flow q is a temporal variable and it corresponds to the number of vehicles passing through an induction loop on the lane when considering a given period of time. The lane segment density d means the number of vehicles in the lane extension and v is the speed of the considered vehicles. Equation 1 defines the flow q, given d, v_0 and d_{max}.

$$q = dv_0 \ln\left(\frac{d_{max}}{d}\right). \tag{1}$$

The variable d_{max} can be estimated considering the expected average vehicle's length and the lane extension. In the flow-density model, d_0 can be estimated by doing $\frac{dq}{dd} = 0$ (first derivative test equal to zero) and having Equation 2, where e is the Euler number. As we can verify in Fig. 3, the point (q_{max}, d_0) is where the street/lane has its maximum flow.

$$d_0 = \frac{d_{max}}{e} \tag{2}$$

Fig. 3 illustrates the relationship between density and flow considering Equation 1. For values smaller than d_0, the lane is not congested. When $d > d_0$, the lane becomes congested and when $d = d_{max}$, the lane is completely congested. Each lane has its own v_{max}, d_{max}, v_0 and d_0. Considering Fig. 2, an illustration of vehicles and streets, the lane DC has a maximum capacity of $d_{max}^{DC} = 7$ vehicles and at the given time, $d^{DC} = 2$ vehicles. The density of vehicles to achieve the maximum flow is $d_0^{DC} = \frac{d_{max}}{e} = \frac{7}{e} \approx 2.57$. In this case, $d^{DC} < d_0^{DC}$ and the lane is not congested. On the other hand, considering the lane DB, $d_{max}^{DB} = 5$ and $d^{DB} = 5$, indicating a fully congested lane. The lane AC has $d_{max}^{AC} = 5$ and $d^{AC} = 3$. In this lane, $d_0^{AC} = 1.83$, indicating that the lane is congested ($d^{AC} > d_0^{AC}$).
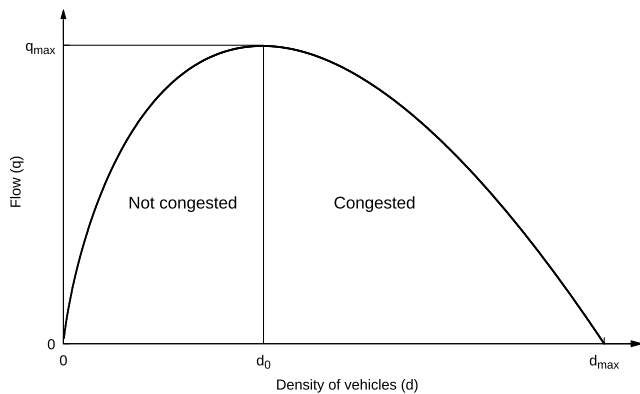

FIGURE 3. Relationship between density and flow.

It is important to point out that each street in the city map has its own v_{max}, d_0 and d_{max}, which depends on the road width or number of lanes. Based on these values, each road has its flow-density function (Fig. 3). The length of vehicles and driver imperfections, which also affect the flow function,

are described in Section IV-A and were considered in our evaluations.

E. ROUTE SUGGESTION – RE-ROUTE ALGORITHM

When the Route Suggestion module is executed and detects traffic jams, it sends a message to the vehicles so they can update their routes accordingly. The service updates a vehicle's route only if it will reach congestion, i.e., if there is a congested road in its route. Otherwise, the vehicle is not notified. The new route is calculated considering the current street where the vehicle is and its final destination. The main goal of the traffic management service is to improve the global road network flow.

Algorithm 1 shows the Re-RouTE main steps and the route suggestion module. After starting the algorithm, each vehicle monitors, using GPS and the city map, if it is crossing a new street. If yes, the vehicle sends the identification of the current lane and the previous one to the location information module. The module updates its database to represent the network density at each street. Procedure **LocationInformation** of Algorithm 1 illustrates the database maintenance task. In the case where the vehicle reaches its destination, it notifies the service and is not considered anymore.

A network classification is performed to find the network density of each street/lane (Procedure **Classification** of Algorithm 1). The procedure uses the Location Information (LocInfo) database to update each edge of the corresponding graph G (lines 7 and 8). After the classification, the service verifies the vehicles that will not pass through a congested lane. In this case, it is not necessary to update their vehicles' route. Otherwise, a new route is calculated and the network graph is updated (Procedure **RouteSuggestion**). The new route is calculated based on the minimum cost path and considering the weighted density graph G (line 13). If there is more than one minimum path, the proposed solution chooses one path at random to improve the flow load balance. For each street in the new route, the corresponding edge in $G(V, E)$ is updated by taking into account that a new vehicle will cross the considered street in the near future, according to Equation 3, where $f(d)$ is the edge weight function, d, d_0, d_{max} are the corresponding values of the considered street (lines 14 – 22).

$$f(d) = \begin{cases} 1, & \text{if } d \leq 0.5 \times d_0 \\ 2, & \text{if } 0.5 \times d_0 < d \leq d_0 \\ d_{max}, & \text{if } d > d_0 \end{cases} \tag{3}$$

Equation 3 considers whether the street density (d) is less than $0.5 \times d_0$ (i.e., 50% of the ideal street density d_0). In this case, a new vehicle may cross the street without decreasing the street flow and the corresponding edge in the graph is updated with 1. When the street density is in the range $0.5d_0 < d \leq d_0$, a new vehicle may decrease the lane's flow and the density graph is updated with 2. In the case the density is greater than d_0, a new vehicle will decrease the flow and G is updated with d_{max} of the considered street/lane.

Thereafter, the Re-RouTE service sends the new route to the vehicle and the load balancing of flow is reached by updating the graph density. It is important to point out that procedure **Classification** is executed every time a new route is assigned to a vehicle and before the procedure **Route-Suggestion**. In the case of multiple vehicles crossing a new street at the same time or within a short interval, the procedure **RouteSuggestion** will be executed concurrently. This scenario can lead to different route suggestions, once the graph G is updated based on the *newRoute* and different execution orders may result in different route suggestions. The proposed traffic management service considers that the execution order is performed considering the received order by the **RouteSuggestion** queue.

The *newRoute* path contains all lanes (and their streets) a vehicle should follow. It is important to highlight that a specific street may have one (or more) congested lane and one (or more) not congested. The *newRoute* will show the correct lane to travel.

Algorithm 1 Route Suggestion Module

1: **procedure** LocationInformation(*vehicleLane*, *vehicle-LastLane*)
2:      *LocInfo.vehicleLastLane*$--$
3:      *LocInfo.vehicleLane*$++$
4: **end procedure**
5: **procedure** Classification($G(V, E)$, *LocInfo*)
6:      **for all** *edge* $\in E$ **do**
7:          *edge.d*$_0 \leftarrow \frac{edge.d_{max}}{e}$
8:          *edge.d* $\leftarrow$ *LocInfo.edge*
9:      **end for**
10: **end procedure**
11: **procedure** RouteSuggestion($G(V, E)$, *LocInfo*)
12:     *Classification*($G(V, E)$, *LocInfo*)
13:     *newRoute* $\leftarrow$ *MinimumCostPath*($G(V, E)$)
14:     **for all** *edge* $\in$ *newRoute* **do**
15:         **if** *edge.d* $\leq 0.5 \times$ *edge.d*$_0$ **then**
16:             *G.edge* $\leftarrow$ *G.edge* $+ 1$
17:         **else if** $0.5 \times d_0 <$ *edge.d* $\leq d_0$ **then**
18:             *G.edge* $\leftarrow$ *G.edge* $+ 2$
19:         **else**
20:             *G.edge* $\leftarrow$ *G.edge* $+ d_{max}$
21:         **end if**
22:     **end for**
23:     **return** *newRoute*
24: **end procedure**

F. RE-ROUTE SERVICE IMPLEMENTATION

Considering the Re-Route service described above, a hybrid architecture could by used to implement the proposed traffic management service as shown in Fig. 4. The architecture is composed of an on-board unit device (OBU) at each vehicle, the network infrastructure (Road Side Unit and Cellular Infrastructure) and a central server. The OBU is equipped with processing, memory and it is able to communicate
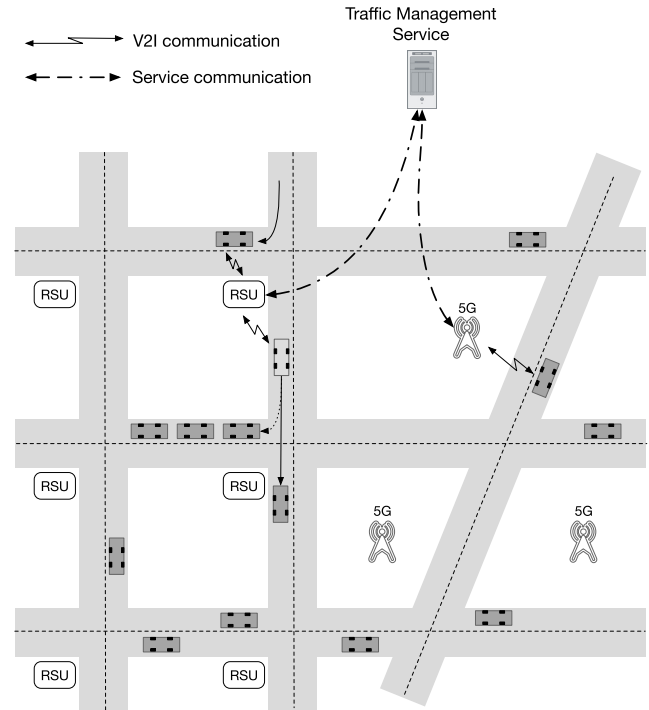

FIGURE 4. Re-RouTE implementation.

with other vehicles and the Road Side Unit (RSU) using the IEEE 802.11p protocol [29], [30], or using the 5G cellular network infrastructure [31]–[35], which can be used to increase the network capacity [8], [36]. In the case of RSU usage, they are responsible for receiving messages from vehicles in the crossing streets. However, if a vehicle is not covered by a RSU, i.e., the vehicle do not have communication with any RSU, a V2I data dissemination algorithm [29], [30], [37]–[39] can be used to send the location information of the vehicles to the closest RSU or the vehicle can use the cellular network. Some works employ V2X (Vehicle-to-everything), where vehicles are able to communicate with different devices, infrastructures and communication technologies [34], [35], [40], [41]. The problem of RSU deployment is investigated in [42], where the authors investigate the trade-off between the number of RSUs and the communication coverage. Antenna Placement and Performance Trade-offs in 5G networks is investigated in [43].

As the vehicle moves through the streets, it sends a message to an RSU/5G Cellular antenna and the message is forwarded to the vehicular traffic management service. The service uses the vehicle updates to build a global view of the network traffic flow. When a street shows signs of congestion, the service notifies the vehicles (new routes) using the RSUs or 5G communication. Without loss of generality, the proposed traffic management service is evaluated considering the 5G cellular communication infrastructure.

IV. SIMULATION RESULTS

This section describes the simulation tools, parameters and scenarios used to assess the proposed Re-RouTE traffic

management service. The Re-RouTE is compared to DIVERT [27] and NRR [28], as described in Section II, since these solutions are the most similar traffic management services found in the literature. We also compare the solutions to the Original route, i.e., an approach where vehicles follow the shortest path and do not employ any kind of vehicle re-routing strategy to avoid congested roads.

A. SIMULATION SETUP

To evaluate the solutions, Re-RouTE, DIVERT, NRR and the Original routing were implemented in the OMNeT++ network simulator [44], [45]. We also used SUMO (Simulator for Urban Mobility) [46], [47] to create and manage the vehicles' mobility, and the TraCI API from SUMO to change the vehicles' routes and to get the simulation results. We relied on the OpenStreetMap Service [48], [49] to get the city roads of the metropolitan region of Los Angeles, USA, and downtown Paris, France (detailed in Section IV-B).

Based on the city roads imported from OpenStreetMap, we used the SUMO's tool NETCONVERT to create a network input for SUMO considering all real features from OpenStreetMap, e.g., length, width, number of lanes, speed limit etc. Moreover, we used the DUAROUTER tool from SUMO to generate random trips for each vehicle. DUAROUTER is a static traffic assignment algorithm that chooses at random two streets in the considered city map as the beginning and destination of the route and applies a shortest distance algorithm to create the vehicle trip between the two streets. Hence, all vehicles start the simulation with a predefined route. However, the VTMS solutions may change the routes of vehicles during their trips aiming to improve the overall traffic flow. Notice that, the solution "Original route" corresponds to the routes initially assigned by DUAROUTER, i.e., no re-routing is performed during the simulation time. We created 33 different trip files using different seeds in order to have a confidence interval of 95%. The number of vehicles in the network changes from 1250 to 6250, the former representing a network with a low number of congested streets and the latter representing a highly congested network. We employed cellular communication to update the location information in the traffic management service and send new route suggestions for vehicles, as in DIVERT [27]. For the NRR solution, we used the same infrastructure as in [28], where each junction has a RSU with a loop detector to estimate the street number of vehicles. The length of vehicles were set considering a Gaussian Distribution with an average of 5 m and standard deviation of 3 m in order to have vehicles with different sizes. We also set the SUMO driver imperfection (Krauß model [50]) to simulate drivers with different perceptions related to maximum speed, acceleration and deceleration.

The performance analysis is divided into two classes of traffic flow: (i) Fixed number of vehicles (Section IV-D), and (ii) Fixed simulation time (Section IV-E). The first one inserts a specific number of vehicles into the network; as they arrive at their destinations, the number of vehicles in

the network decreases and the task of re-routing becomes easier to perform. The goal of this scenario is to evaluate the behavior of re-routing strategies to eliminate a network congestion peak. In the second scenario, we keep the simulation time in 1800 seconds and a constant number of vehicles in the network, i.e., whenever a vehicle arrives at its destination and leaves the network, we introduce a new vehicle into it. The goal of this scenario is to evaluate the solution under rush hours when the network is highly congested during a period of time. In both scenarios, we introduce the vehicles into the network at the beginning of the simulation at random positions.

We evaluate all solutions considering different traffic flow metrics: (i) *Travel time* – average travel time of all vehicles; (ii) *Distance* – average travel distance of all vehicles; (iii) *Speed* – computed based on the travel time and distance traveled by all vehicles, including lost time at traffic lights and congestion; (iv) *Transmitted messages* – average total number of messages sent by each vehicle to update the traffic management service and receive route suggestions, whenever required; (v) *Packet loss* – the influence of packet loss on the evaluated algorithms to decrease congestions. To better represent the real world, we performed an analysis when the vehicle's driver does not accept the route suggestion. We evaluate four different driver acceptances (25%, 50%, 75% or 100%), which mean that only a percentage of drivers accept the service route suggestion. We also evaluate the number of vehicles that arrived at their final destination.

B. SIMULATION SCENARIOS

Fig. 5 shows the evaluated scenarios obtained from the OpenStreetMap, which provides the road map with the real number of lanes, directions, traffic lights, speed limits, vehicle preference in conversion etc. Both scenarios have 25 km², however they possess different topological features, such as the number of streets, traffic lights and number of intersections. Some streets have more than one lane (dark lines in Fig. 5).The most important feature is the street map layout, in which Los Angeles (Fig. 5(a)) is similar to a Manhattan Grid and Paris (Fig. 5(b)) is similar to an Organic layout, with bridges and squares.

Table 1 shows the topological features of the scenarios. As discussed in Sections III-A, we assume the vehicle navigation service contains the city map. Since in our solution the central server is responsible for calculating alternative routes, the city map stored in the vehicles could be as simple as the one with street IDs and its geographical information to perform geo-referencing. For instance, if each street uses 1Kbyte

TABLE 1. Scenario topological features.

Parameters	Los Angeles	Paris
Size	25 km²	25 km²
Number of roads	5162	9374
Number of intersections	2034	5383
Number of traffic lights	48	115

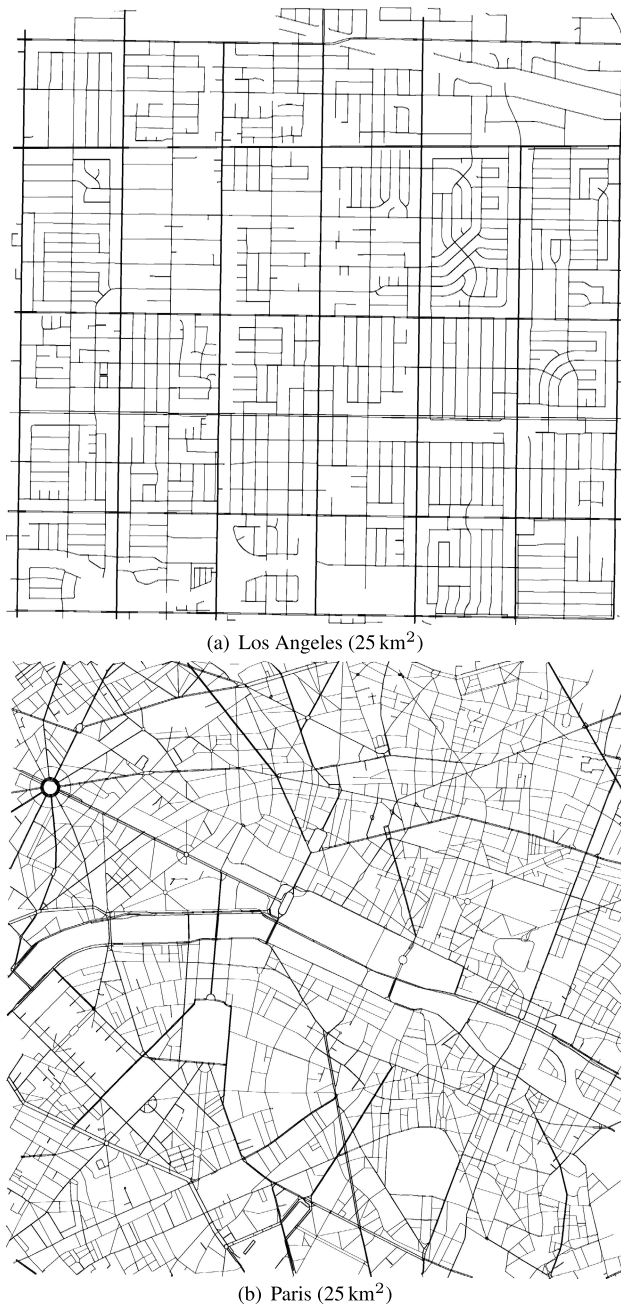(a) Los Angeles (25 km^2)

(b) Paris (25 km^2)

FIGURE 5. Maps of los angeles and paris.

to represent its features, the considered Los Angeles and Paris scenarios uses 5.1Mbytes and 9.3Mbytes. In the case where the on-board unit does not have the necessary memory space, the city map could be downloaded as the vehicle moves through its path. On the other hand, the central server must have the city map with all features. Hence, the computational and storage tasks can be performed in a Cloud server with powerful resources. Let N be the number of vehicles and $G(V, E)$ be the city map used in Algorithm 1. Since procedure RouteSuggestion is executed for all vehicles, its complexity cost is $O(N \times V \times logV)$, which is the complexity of a minimum path algorithm for all vehicles. Considering this

complexity cost, the central server is able to execute the proposed algorithm under timing constraints.

C. RE-ROUTING FREQUENCY

As we described in Section IV-A, we assess different vehicular flow metrics under two classes of traffic flow. In both classes, we are interested in knowing the ability of the re-routing strategies to reduce the traffic congestion and, consequently, travel time, distance, etc. Fig. 6 shows the average travel time when the network has 3750 vehicles and considering a constant number of vehicles. Instead of re-routing a specific vehicle that will cross a congested street (greedy approach), we evaluate the strategies by considering a pre-defined re-routing frequency. The re-routing frequency specifies the time interval between two consecutive re-routing processes. The algorithms were evaluated considering that a re-routing is performed every 60, 90, 120, 180, 240, 300 or 360 seconds. Such an approach presented better results for both strategies, since the main objective of the Re-RouTE and DIVERT is to optimize the global traffic flow and not only a vehicle travel time. DIVERT also uses a pre-defined re-routing frequency in [13] and we employed re-routing frequency in NRR.
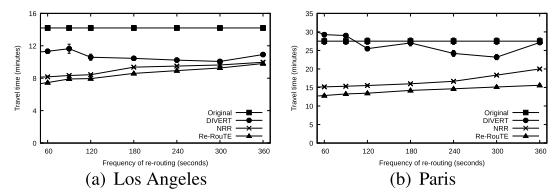

(a) Los Angeles   (b) Paris

FIGURE 6. Travel time for different re-routing frequencies. 3750 vehicles.

In both scenarios, Re-RouTE and NRR increase the average travel time when the re-route frequency increases. Considering Fig. 6(b) and when the frequency is 30 seconds, the average travel time is 12.5 minutes for Re-RouTE and 15.2 minutes for NRR. When the frequency is 360 seconds, the travel time is 15.7 and 20.1 minutes considering Re-RouTE and NRR respectively. However, in many scenarios it is not practical to have a re-routing process every 30 seconds since it may annoy the driver. Considering the DIVERT, the best re-routing results are achieved when the re-routing frequency is 300 seconds for both Los Angeles and Paris. This is due to the fact that DIVERT requires stable information regarding the average travel time to improve its efficiency.

For the next sections, we set the re-route frequency of the DIVERT in 300 seconds and 120 seconds for the Re-RouTE and NRR. The frequency of 120 seconds does not lead to the best performance of both solutions, however it is a reasonable and fair re-routing frequency.

D. FIXED NUMBER OF VEHICLES
1) TRAVEL TIME
Fig. 7 shows the average travel time for Re-RouTE, NRR, DIVERT and Original routing considering different number of vehicles in the network. For all solutions, as the number
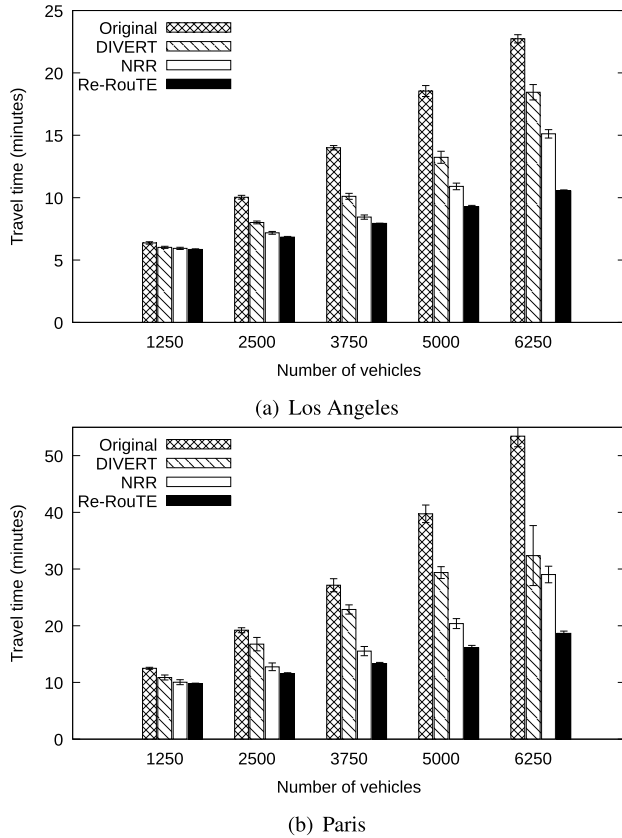
(a) Los Angeles

(b) Paris

FIGURE 7. Travel time.

employed by DIVERT. Moreover, the use of Equation 3 improves the global vehicle flow in the network, which also has a positive impact on the other flow metrics presented hereafter. NRR uses a set of traffic features (road occupancy, travel time, geographic distance to destination and geographic closeness of congestion) to minimize congestion. The combination of these values presents better results compared to DIVERT, but inferior results compared to the density of vehicles in Re-RouTE. Thus, it is possible to verify that the use of vehicle density can detect and minimize traffic congestions.

2) TRAVEL DISTANCE AND AVERAGE SPEED

Despite different characteristics of both scenarios, the average travel distance of the Original routing is similar in Los Angeles (Fig. 8(a)) and Paris, as depicted in Fig. 8(b) (3.5–4 km), since both scenarios have 25 km^2. In both cases, the re-routing strategies increase the average travel distance, since they try to avoid congested roads by finding new routes, which are longer, though not congested. Such an increase is greater in the DPS solution than in the Re-RouTE and NRR. Considering the Los Angeles scenario with 3750 vehicles, the travel distance for Re-RouTE and DIVERT are, respectively, 9% and 12% greater than in the Original routing. Re-RouTE and NRR present similar results. This is due to the fact that both solution uses the number of vehicles in streets. However, as the network becomes more congested
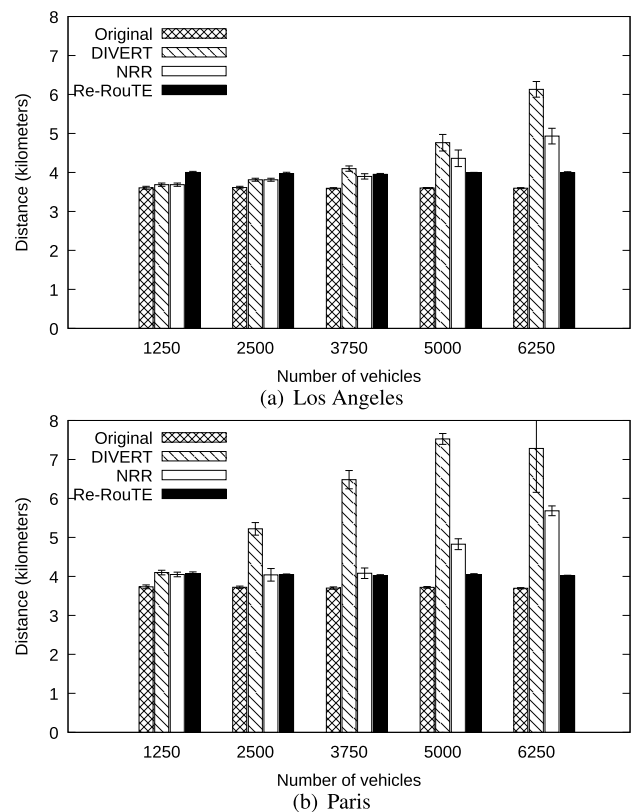
of vehicles increases, the average travel time per vehicle also increases, as expected. However, the increase is more pronounced in the Original and DIVERT solutions. When the network has 1250 vehicles, the network is not congested and all solutions have similar travel times (≈ 6 minutes) in the Los Angeles scenario (Fig. 7(a)). Considering the Paris scenario (Fig. 7(b)), which is not like a Manhattan grid, the travel time of the Original Routing, DIVERT, NRR and Re-RouTE are, respectively, 12.4, 10.8, 10.2 and 9.7 minutes.

When the network becomes congested (3750 vehicles), the difference among the solutions increases. In the Los Angeles scenario, the average travel time of the DIVERT is 27% lower than the Original and is 21% higher than the Re-RouTE solution. For the same number of vehicles, NRR and Re-RouTE present similar results. Considering 6250 vehicles, the Re-RouTE is 53%, 42% and 30% lower than Original, DIVERT and NRR, respectively. In the Paris scenario, which has 11 bridges (congestion points), the effectiveness of the re-routing strategies presents a greater impact in the flow of vehicles when compared to the Los Angeles scenario. Considering 6250 vehicles, the travel time for DIVERT is 39% lower than the Original routing. The Re-RouTE solution is 65%, 42% and 35% lower than the Original, DIVERT and NRR, respectively.

The density strategy, employed by Re-RouTE, proved to be better when compared to the average travel time strategy,

(a) Los Angeles

(b) Paris

FIGURE 8. Travel distance.

(6250 vehicles), DIVERT and NRR increase the travel distance compared to Original and Re-RouTE. Considering the Paris scenario with 3750 vehicles, DIVERT increases the travel distance in 45%, 41% and 39% when compared to the Original, Re-RouTE and NRR strategies, respectively. In both scenarios, DIVERT and NRR increase the travel distance when the network becomes more congested, while the Re-RouTE strategy maintains a small variation on such an increase. Therefore, we can see that considering only the street density rather than travel time considered by DIVERT or a set of features considered by NRR, the propose Re-RouTE finds routes with lower travel distances. We also note that the proposed strategy does not increase considerably the travel distance.

When the network has a few congested points (1250 vehicles), the average speed of the Original routing is 33.9 km/h and 17.8 km/h considering Los Angeles and Paris, respectively. Despite not having many congested points, the re-routing strategies increase the average speed by avoiding such points. Even though the Re-RouTE algorithm does not consider the street travel time to re-route vehicles, it is able to increase in 10.5% and 9.7% the vehicle speed when compared to the DIVERT solution in Los Angeles and Paris with 1250 vehicles, respectively. When the network becomes congested, NRR has the lower speed compared to DIVERT and Re-RouTE. Despite the fact that the re-routing strategies possess a longer travel distance when compared to the Original routing, the average global travel time decreases (Fig. 7), since the strategies increase the average speed.

3) TRANSMITTED MESSAGES

Fig. 10 presents the total number of transmitted messages during the re-routing process considering the entire simulation time. The goal of this evaluation is to identify the cost (in terms of transmitted messages) of each strategy in the re-routing process. Since the DIVERT algorithm considers the average travel time of each street in the re-routing process, each vehicle in the DIVERT was configured to send information about the average speed of the vehicle in predefined intervals that can be of 15, 30 or 60 seconds. For the sake of simplicity and to perform a fair comparison, our implementation of DIVERT considers the real average travel time of all streets, which corresponds to the best case scenario for this solution. When we increase the pre-defined interval, the number of transmitted messages decreases. Notice, however, when the pre-defined interval increases, the information sent by vehicles may not represent the real travel time of the city streets. As a consequence, the performance of DIVERT may decrease. The proposed Re-RouTE strategy updates the traffic management service every time a new road is reached. Thus, if the vehicle's route passes through, for example, 20 different streets, the vehicle updates its position 20 times.
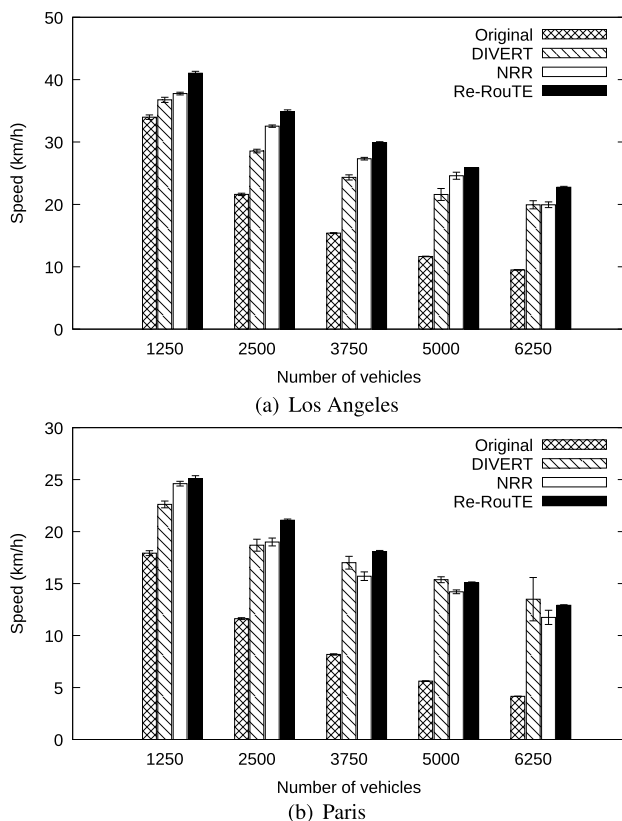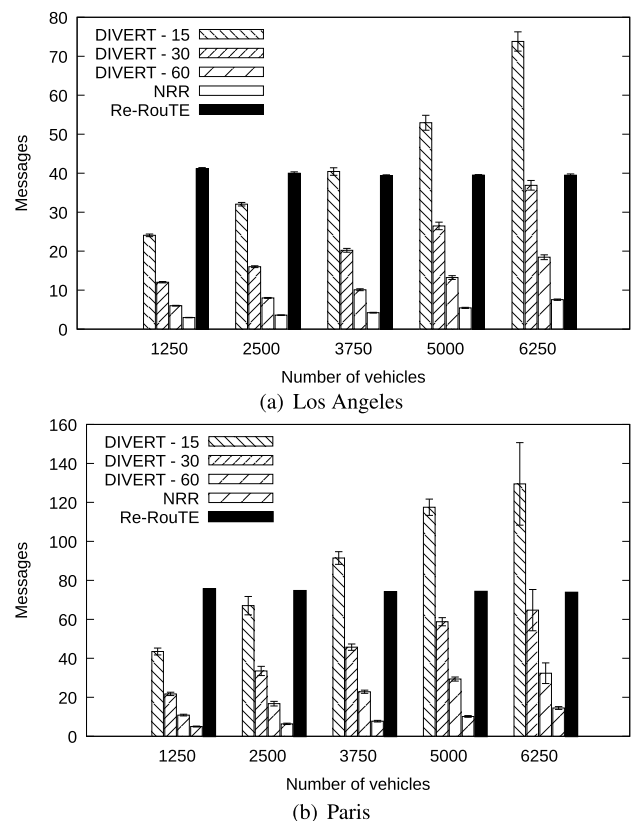

FIGURE 9. Average speed.

FIGURE 10. Transmitted messages.

The NRR solution uses loop detectors to estimate the road occupancy, thus, it is not necessary the use of communication to estimate congestion. However, each vehicle sends to the central server a request at each re-route frequency to get alternative routes.

When the number of vehicles in the network is 1250, the average transmitted messages per vehicle is reduced (compared to 6250 vehicles), since there is a lower number of congested roads and DIVERT takes advantage of this feature. However, since the travel distance does not increase significantly in the Re-RouTE (Fig. 8), when considering different number of vehicles, the number of transmitted messages is practically the same in both scenarios. Considering the Los Angeles scenario (Fig. 10(a)) with 1250 vehicles, Re-RouTE sends about 41% more messages than DIVERT-15s and 85% more messages than DIVERT-60s When the number of vehicles is 6250, Re-RouTE sends 45% less messages than DIVERT-15s and 56% more messages than DIVERT-60s. However, the pre-defined interval of one message every 60 seconds is infeasible to achieve a suitable average travel time representation. Considering the Paris scenario (Fig. 10(b)), the results are similar. However, as the travel time and distance increase, the number of transmitted messages also increases for DIVERT and Re-RouTE. In the NRR solution, each vehicle sends a message to the central server and receive alternative paths considering only the re-route frequency. Thus, NRR needs a lower number of messages compared to the other solutions.

4) ACCEPTANCE RATIO

Fig. 11 shows the average travel time when the vehicle's driver does not accept the route suggestion from the traffic management service. The number of vehicles in the network is 3750. Considering Fig. 11(a), Los Angeles scenario, as the acceptance ratio increases, the average travel time decreases for DIVERT, NRR and Re-RouTE. When the driver acceptance is 25% (i.e., only 25% of all drivers accept the suggested route), the average travel time for DIVERT, NRR and Re-RouTE have similar results. Even when a small fraction of drivers accepts the suggested routes, the strategies are able to significantly reduce the travel time. It is possible to verify that NRR and Re-RouTE that use road occupancy and vehicle density have better results compared to the use of travel time.

Fig. 11(b) shows the results for the Paris scenario. When the acceptance ratio is 75%, Re-RouTE decreases in 45%, 27% and 11% the travel time when compared to the Original, DIVERT and NRR, respectively. It is important to point out that the DIVERT solution with a higher acceptance ratio does not improve the travel time, as expected. As we can see, when considering high values for the acceptance ratio, DIVERT only moves the congestion to a different area in the city. DIVERT-100% increases the travel time in 5% when compared to DIVERT-25%. Thus, it is possible to verify that the proposed Re-RouTE strategy is able to reduce a traffic jam without moving it to a different area in the city. The same behavior is observed in NRR.
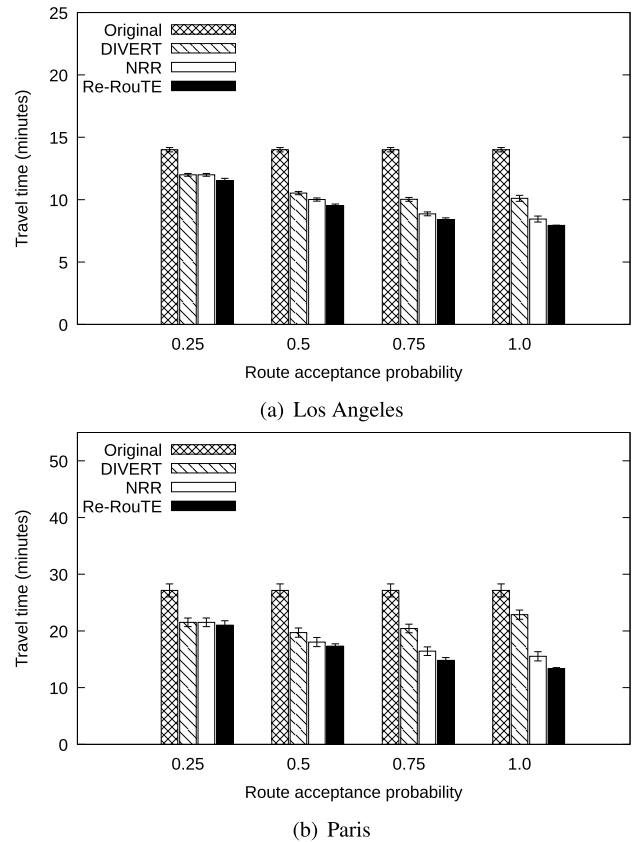

(a) Los Angeles

(b) Paris

FIGURE 11. Acceptance ratio. 3250 vehicles.

5) PACKET LOSS

Fig. 12 illustrates the influence of the packet loss in the travel time considering DIVERT, NRR and Re-RouTE solutions. The x-axis represents the probability of a packet loss and the goal of this evaluation is to simulate, for instance, a noisy wireless channel or a high network traffic load due to other services using the wireless channel. On average, the packet loss has a greater impact on DIVERT when compared to Re-RouTE.

Fig. 12(a) shows the travel time for different values of packet loss in the Los Angeles scenario. Considering a packet loss probability of 10%, the travel time of DIVERT, NRR and Re-RouTE increases in 8%, 5% and 3%, respectively when compared to the results with a packet loss probability of 0%. The same behavior is observed for a packet loss probability of 40%. The travel time of DIVERT, NRR and Re-RouTE increases in 26%, 24% and 20%, respectively. Even considering a probability of 60%, (i) the travel time of DIVERT, NRR and Re-RouRE are 6%, 15% and 25% lower than the Original routes, and (ii) the travel time of Re-RouTE is 18% and 12% lower than DIVERT ans NRR. We can observe that the packet loss has a low impact in our proposed solution. This is due to the use of a weight function (Eq. 3) in the Route Suggestion phase of Re-RouTE. For a density d greater than d_0, the weight is d_{max}. When $d' = d/2$ (due to 50% of packet loss containing the location information), but still $d' > d_0$, the weight is d_{max} and the proposed
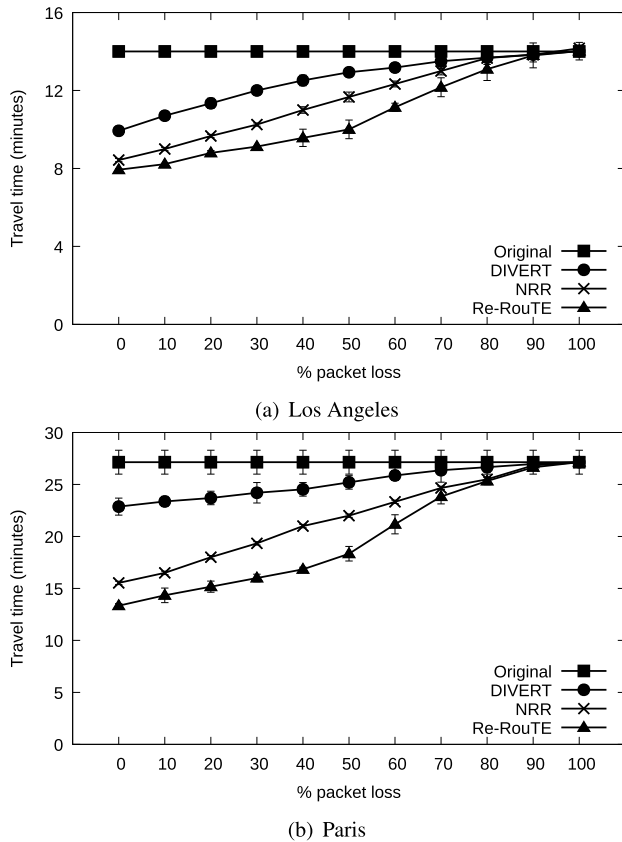
(a) Los Angeles

(b) Paris

FIGURE 12. Packet loss. 3750 vehicles.

(a) Los Angeles

(b) Paris

FIGURE 13. Travel time.

algorithm will work without interference. This is a feasible scenario, since $d_0 = \frac{d_{max}}{e}$ (Equation 2). For $d' < d_0$, the weight may change and for a packet loss probability greater than 50%, the travel time of Re-RouTE increases fast. The behavior of these algorithms are, on average, similar when considering the Paris scenario (Fig. 12(b)).

E. FIXED SIMULATION TIME
1) TRAVEL TIME
The previous section showed the results when a given number of vehicles is inserted into the network and decreases as they reach their destinations. Here, we show the results when the number of vehicles in the network is constant throughout a fixed simulation time. In this setup, the average travel time gain, when the vehicles are re-routed, is not greater than 15% in the Los Angeles scenario (Fig. 13(a)). When the network has 1250 vehicles, the Re-RouTE travel time is 14% and 3% less than DIVERT and NRR. In the Paris scenario (Fig. 13(b)), the average travel time actually increases in 7% for the re-routing solutions when the network has 6250 vehicles. In this section, we forced the network to be congested during the entire simulation time. By doing this, the re-routing solutions are not able to decrease the travel time.

However, Fig. 14 shows the average travel time considering different moments of the simulation for 3750 vehicles. The x-axis represents the simulation time interval
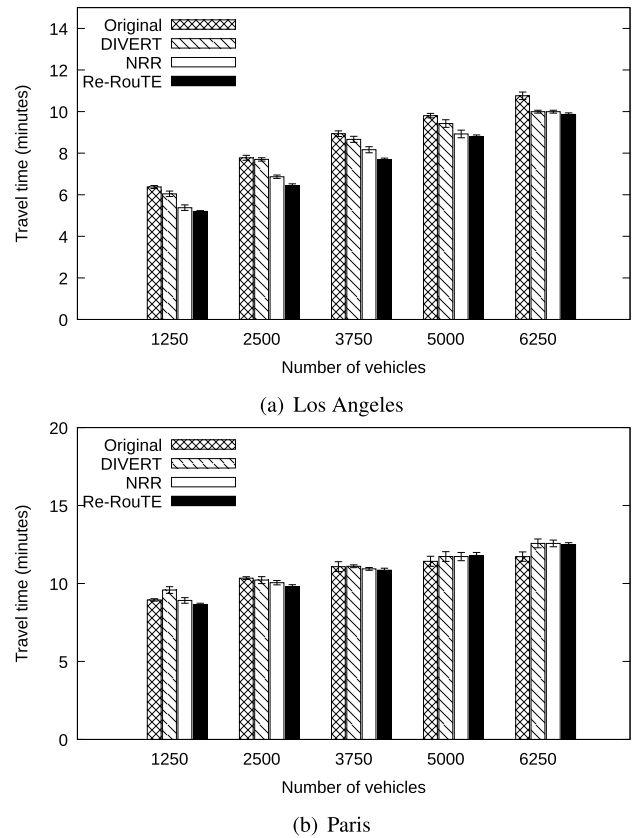
[Label 5 (0–5) minutes, Label 10 (5–10) minutes, Label 15 (10–15) minutes, Label 20 (15–20) minutes, Label 25 (20–25) minutes, Label 30 (25–30) minutes] and the y-axis represents the average travel time of all vehicles that arrived at their destinations in a specific time interval. Considering the Los Angeles scenario (Fig. 14(a)) and the interval of 5 (0–5) minutes, the average travel time is similar for all solutions, since the network is not congested yet. As the simulation goes forward, the re-routing solutions decrease the average travel time when compared to the Original routing. Considering the interval of 30 (25–30) minutes, DIVERT decreases the average travel time in 13% when compared to the original routing. Meanwhile, Re-RouTE decreases the travel time in 41%, 32% and 15% when compared to Original, DIVERT and NRR, respectively. It is important to notice that when the time interval is greater than 15 minutes, the average travel time for Re-RouTE does not increase anymore, differently from DIVERT and NRR. This is because the proposed solution is able to find streets that are not fully congested. Moreover, the solution does not move the traffic jam to a different area. The use of a set of features by NRR decreases the travel time compared to DIVERT, however, the use of travel time influences the solution and Re-RouTE presents better results than NRR.

Considering the Paris scenario (Fig. 14(b)), all solutions present similar results when the simulation time is up to
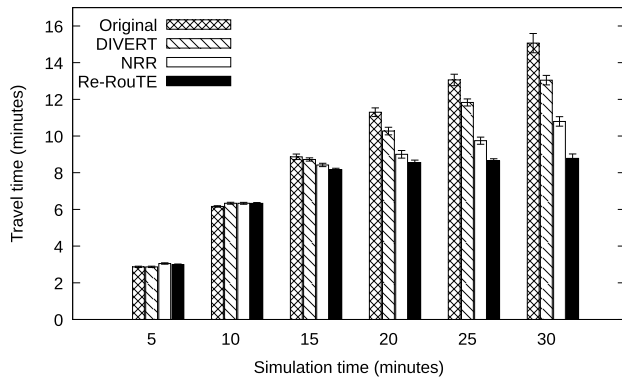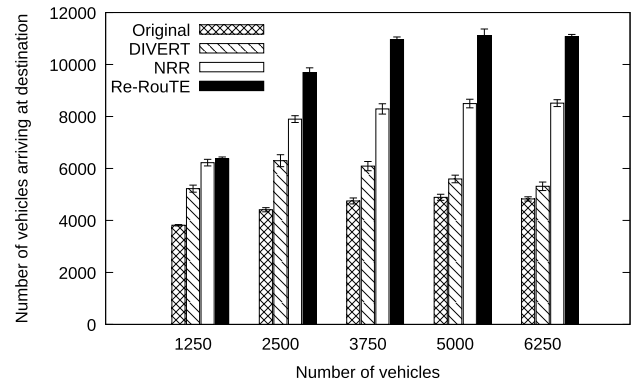
(a) Los Angeles
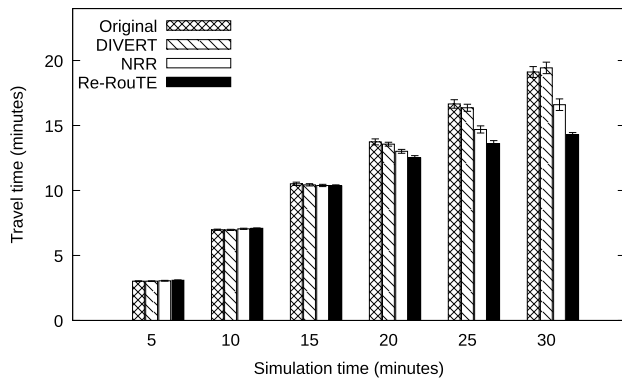
(b) Paris

FIGURE 14. Travel time over simulation time. 3750 vehicles.

(a) Los Angeles
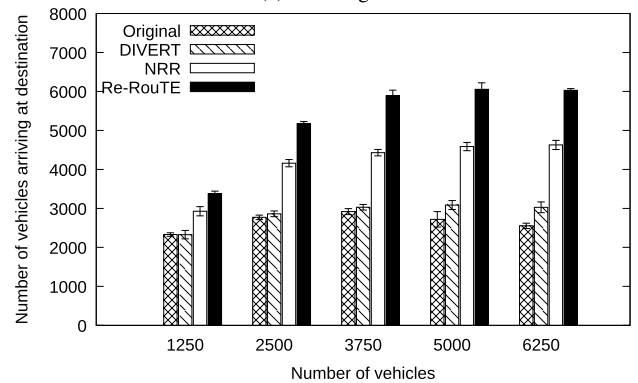

(b) Paris

FIGURE 15. Number of vehicles.

15 minutes. Considering all intervals, the DIVERT solution is not able to decrease the travel time when compared to the Original solution. On the other hand, Re-RouTE reduces the travel time when the interval is greater than 20 minutes. Considering the last 5 minutes of the simulation (25–30), Re-RouTE decreases the travel time in 25% when compared to the Original and DIVERT solutions and 15% compared to NRR. After 20 minutes of simulation, the travel time of Re-RouTE does not increase significantly. When compared to Los Angeles, Paris has different characteristics, such as small street length, squares and bridges. In spite of that, the proposed solution is able to find streets not congested, thus increasing the global network flow.

2) NUMBER OF VEHICLES

The re-routing solutions do not reduce the global average travel time, but they increase the number of vehicles arriving at their destinations. Fig. 15 shows the number of cars that were able to finish their route during 1800 seconds. In the Los Angeles scenario (Fig. 15(a)) with 2500 vehicles, DIVERT, NRR and Re-RouTE increased the number of vehicles that arrived at their destinations in about 30%, 45% and 54%, respectively, when compared to the Original routing. Moreover, the solutions were able to reduce the traffic jam even when the network has a small number of congested roads. As we increase the number of vehicles,

the performance of DIVERT decreases. Considering 6250 vehicles, DIVERT is only 9% better when compared to the Original routing. For the same number of vehicles, Re-RouTE doubled the number of vehicles that arrived at their destination compared to Original and DIVERT. It is important to note that when considering 6250 vehicles, the Original and DIVERT solutions were not able to have more than 5500 vehicles arriving at their destinations. Using a set of variables, NRR is able to increase the number of vehicles arriving at their destinations. Here we can verify that the proposed network classification and route suggestion algorithm are in fact able to efficiently re-route vehicles. When the number of vehicles is greater than 3750 and the network becomes congested, the performance of Re-RouTE and NRR does not decrease, as observed in DIVERT, which uses the travel time to determine whether a road is congested or not.

In the Paris scenario (Fig. 15(b)), DIVERT presents similar results when compared to the Original routing, surpassing it only when considering 6250 vehicles, while Re-RouTE out-performs DIVERT and NRR in all results. When the network has 6250 vehicles, DIVERT increases the number of vehicles that arrive at their destinations in 17% when compared to the Original routing, while Re-RouTE increases such number of vehicles in 136%, 99% and 45% when compared to Original, DIVERT and NRR solutions, respectively. In the Paris scenario, the total number of vehicles that finished the route is

smaller than in the Los Angeles scenario, since the former has bridges and squares, which make the task of re-routing more challenging and, in some cases, infeasible (the vehicle must pass through a bridge to reach its destination).

Fig. 16 shows the number of vehicles that reach their destinations at different simulation moments. In the Los Angles scenario (Fig. 14(a)), DIVERT, NRR and Re-RouTE outperform the original routing when the simulation time is greater than 10 minutes. Notice that, Re-RouTE outperforms DIVERT and NRR in all moments. When the simulation time is up to 15 minutes (considering the vehicles that arrived at their destinations between 10–15 minutes), DIVERT increases the number of vehicles in 32% when compared to the Original routing while Re-RouTE increases such number in 79% and 25% when compared to DIVERT and NRR. As the simulation time goes forward, Original routing and DIVERT are not able to maintain good results. In fact, instead of decreasing congestion, DIVERT creates new congestion points and decreases the number of vehicles that arrived at their destinations. On the other hand, Re-RouTE and NRR are able to keep high values of vehicles reaching their destinations even when the network is congested. DIVERT presents similar results when compared to the Original routing in the Paris scenario (Fig. 14) and Re-RouTE is able to improve the number of vehicles finishing their trips.

(a) Los Angeles

(b) Paris

FIGURE 16. Number of vehicles over simulation time. 3750 vehicles.

V. APPLICABILITY

There are a number of factors that can be considered in the design of a vehicular traffic management solution, such as, time spent in traffic lights, accidents or streets with more than one lane. The latter issue is addressed by the Re-RouTE as illustrated in Fig. 2. For each lane in the street, we create an edge in the corresponding graph $G(V, E)$. The total number of vehicles in the considered street is the sum of each lane capacity. A natural driving behavior is to choose the lane with fewer vehicles and the SUMO Urban Mobility used in our performance analysis simulates this behavior. SUMO also simulates driver imperfections, where there is a difference among driver choices, such as acceleration, deceleration, maximum speed, gap between vehicles, lane changes, etc. It is important to highlight that Equation 3 defines different density intervals to calculate the weight of the edges (roads). Such an approach mitigates wrong estimations caused by different vehicle's sizes (motorcycle, trucks, buses etc) and packet losses.

The proposed Re-RouTE solution uses only the road density and does not directly consider the traffic light influence on the street flow. The scenario where some vehicles stop at a traffic light may happen and the solution will detect this as a free flow if the number of stopped cars is less than d_0. However, if the traffic light only induces a small number of stopped vehicles, then the lanes after the traffic light are not congested and the vehicles are stopped only because of the red signal. Otherwise, vehicles stopped at traffic lights would not continue their trajectory (congested lanes after traffic light), increasing the number of stopped vehicles. In this case, the number of vehicles would be greater than d_0, indicating a congested road.

In case of an accident, the vehicle may send a notification to the traffic management service, which can immediately update the corresponding edge on $G(V, E)$ or temporarily remove the specified edge. Thus, new routes will not pass through the street with an accident. After an accident resolution, the service does not need to be notified about it. When monitoring the number of cars that send information while crossing the lane which had the accident, the service is able to detect that the accident has been resolved and the routes can again consider such lane.

VI. CONCLUSION AND FUTURE WORK

This work proposed Re-RouTE, a novel Vehicular Traffic Management Service to reduce traffic congestion in dense urban scenarios. Re-RouTE employs the concepts of flow-density model of Traffic Engineering theory to classify network congestion. Instead of using street travel time or average speed, Re-RouTE considers only the street density of vehicles, which turn out to be effective and simple to implement in a real-life vehicle network. The street density can be used to detect, classify and suggest new routes by avoiding congested points and, at the same time, load balancing the road traffic without creating new congestion points. We have conducted an extensive simulation analysis, considering real
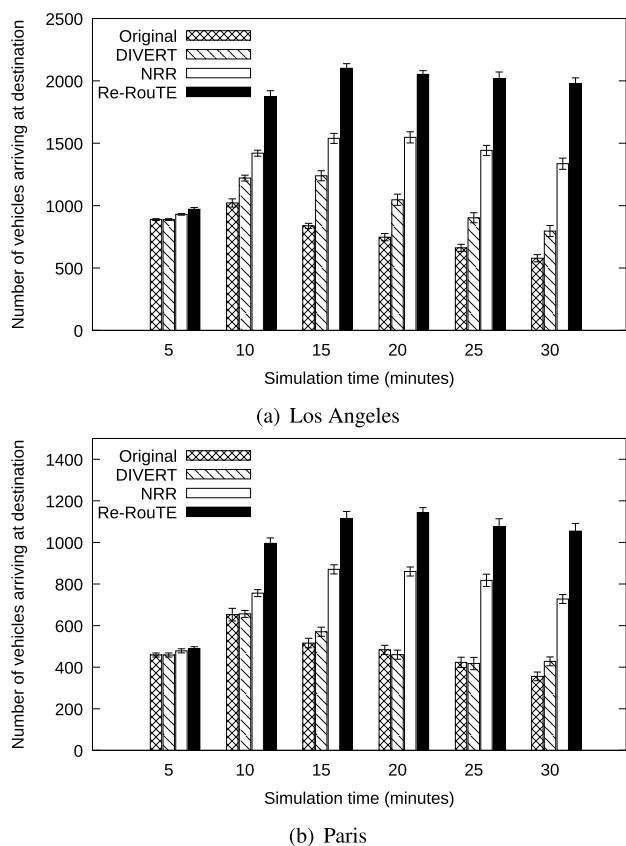
street scenarios, to illustrate the ability of Re-RouTE in reducing traffic jams and increasing the global traffic flow. Re-RouTE outperforms the closest literature approach regarding the travel time, travel distance and average speed. As a consequence, the proposed solution is able to reduce traffic congestion and allow more vehicles to reach their destinations. Even in scenarios where drivers do not accept route suggestions, Re-RouTE is able to reduce traffic jams.

As future work, we plan to extend Re-RouTE to perform traffic prediction, and, eventually to act proactively rather than reactively when making route suggestions.

REFERENCES

[1] S. Djahel, R. Doolan, G.-M. Muntean, and J. Murphy, "A communications-oriented perspective on traffic management systems for smart cities: Challenges and innovative approaches," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 125–151, 1st Quart., 2015.

[2] *The Future Economic and Environmental Costs of Gridlock in 2030*, Center Econ. Bus. Res., INRIX, Kirkland, WA, USA, 2013.

[3] *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation*, I. Cambridge Syst., U.S. Federal Highway Admin., Washington, DC, USA, 2005.

[4] C. Bila, F. Sivrikaya, M. A. Khan, and S. Albayrak, "Vehicles of the future: A survey of research on safety issues," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 5, pp. 1046–1065, May 2017.

[5] M. Gramaglia, M. Calderon, and C. J. Bernardos, "ABEONA monitored traffic: VANET-assisted cooperative traffic congestion forecasting," *IEEE Veh. Technol. Mag.*, vol. 9, no. 2, pp. 50–57, Jun. 2014.

[6] T. Darwish and K. Abu Bakar, "Traffic density estimation in vehicular ad hoc networks: A review," *Ad Hoc Netw.*, vol. 24, pp. 337–351, Jan. 2015.

[7] F. Cunha, L. Villas, A. Boukerche, G. Maia, A. Viana, R. A. F. Mini, and A. A. F. Loureiro, "Data communication in VANETs: Protocols, applications and challenges," *Ad Hoc Netw.*, vol. 44, pp. 90–103, Jul. 2016.

[8] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G," *IEEE Commun. Standards Mag.*, vol. 1, no. 2, pp. 70–76, Jul. 2017.

[9] J. Liu, J. Wan, D. Jia, B. Zeng, D. Li, C.-H. Hsu, and H. Chen, "High-efficiency urban traffic management in context-aware computing and 5G communication," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 34–40, Jan. 2017.

[10] S. A. A. Shah, E. Ahmed, M. Imran, and S. Zeadally, "5G for vehicular communications," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 111–117, Jan. 2018.

[11] Z. Khan, P. Fan, F. Abbas, H. Chen, and S. Fang, "Two-level cluster based routing scheme for 5G V2X communication," *IEEE Access*, vol. 7, pp. 16194–16205, 2019.

[12] A. M. de Souza, R. Yokoyama, A. Boukerche, G. Maia, E. Cerqueira, A. A. Loureiro, and L. A. Villas, "ICARUS: Improvement of traffic Condition through an Alerting and Re-routing System," *Comput. Netw.*, vol. 110, pp. 118–132, Dec. 2016.

[13] J. Pan, I. S. Popa, and C. Borcea, "DIVERT: A distributed vehicular traffic re-routing system for congestion avoidance," *IEEE Trans. Mobile Comput.*, vol. 16, no. 1, pp. 58–72, Jan. 2017.

[14] J. H. Banks, *Introduction to Transportations Engineering*. New York, NY, USA: McGraw-Hill, 2002.

[15] (2019). *Tomtom*. [Online]. Available: https://www.tomtommaps.com/livetraffic/

[16] (2019). *Sygic*. [Online]. Available: https://www.sygic.com

[17] (2019). *Waze*. [Online]. Available: https://www.waze.com

[18] (2019). *Google Maps*. [Online]. Available: https://www.google.com/maps

[19] (2019). *Bing Maps*. [Online]. Available: https://www.bing.com/maps

[20] F. Knorr, D. Baselt, M. Schreckenberg, and M. Mauve, "Reducing traffic jams via VANETs," *IEEE Trans. Veh. Technol.*, vol. 61, no. 8, pp. 3490–3498, Oct. 2012.

[21] S. Wang, S. Djahel, and J. Mcmanis, "An adaptive and VANETs-based next road re-routing system for unexpected urban traffic congestion avoidance," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2015, pp. 196–203.

[22] I. Ahmad, R. M. Noor, M. R. Zaba, M. A. Qureshi, M. Imran, and M. Shoaib, "A cooperative heterogeneous vehicular clustering mechanism for road traffic management," *Int. J. Parallel Program.*, pp. 1–20, Jan. 2019. [Online]. Available: https://link.springer.com/article/10.1007%2Fs10766-019-00629-y, doi: 10.1007/s10766-019-00629-y.

[23] H. T. Hashemi and S. Khorsandi, "Load balanced VANET routing in city environments," in *Proc. IEEE 75th Veh. Technol. Conf. (VTC Spring)*, May 2012, pp. 1–6.

[24] J. Y. Yen, "Finding the K shortest loopless paths in a network," *Manage. Sci.*, vol. 17, no. 11, pp. 712–716, Jul. 1971.

[25] A. L. C. Bazzan, D. Cagara, and B. Scheuermann, "An evolutionary approach to traffic assignment," in *Proc. IEEE Symp. Comput. Intell. Vehicles Transp. Syst. (CIVTS)*, Dec. 2014, pp. 43–50.

[26] J. Pan, M. A. Khan, I. S. Popa, K. Zeitouni, and C. Borcea, "Proactive vehicle re-routing strategies for congestion avoidance," in *Proc. IEEE 8th Int. Conf. Distrib. Comput. Sensor Syst.*, May 2012, pp. 265–272.

[27] J. Pan, I. S. Popa, K. Zeitouni, and C. Borcea, "Proactive vehicular traffic rerouting for lower travel time," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3551–3568, Oct. 2013.

[28] S. Wang, S. Djahel, Z. Zhang, and J. Mcmanis, "Next road rerouting: A multiagent system for mitigating unexpected urban traffic congestion," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 10, pp. 2888–2899, Oct. 2016.

[29] R. Atallah, M. Khabbaz, and C. Assi, "Multihop V2I communications: A feasibility study, modeling, and performance analysis," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 2801–2810, Mar. 2017.

[30] G. G. M. N. Ali, M. A. Rahman, P. H. J. Chong, and S. K. Samantha, "On efficient data dissemination using network coding in multi-RSU vehicular ad hoc networks," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.

[31] W. Li, X. Ma, J. Wu, K. S. Trivedi, X.-L. Huang, and Q. Liu, "Analytical model and performance evaluation of long-term evolution for vehicle safety services," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 1926–1939, Mar. 2017.

[32] K. Katsaros, M. Dianati, R. Tafazolli, and X. Guo, "End-to-end delay bound analysis for location-based routing in hybrid vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7462–7475, Sep. 2016.

[33] S. Chen, J. Hu, Y. Shi, and L. Zhao, "LTE-V: A TD-LTE-based V2X solution for future vehicular network," *IEEE Internet Things J.*, vol. 3, no. 6, pp. 997–1005, Dec. 2016.

[34] M. Fallgren, T. Abbas, S. Allio, J. Alonso-Zarate, G. Fodor, L. Gallo, A. Kousaridas, Y. Li, Z. Li, Z. Li, J. Luo, T. Mahmoodi, T. Svensson, and G. Vivier, "Multicast and broadcast enablers for high-performing cellular V2X systems," *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 454–463, Jun. 2019.

[35] P. Wang, B. Di, H. Zhang, K. Bian, and L. Song, "Cellular V2X communications in unlicensed spectrum: Harmonious coexistence with VANET in 5G systems," *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5212–5224, Aug. 2018.

[36] S.-H. Sun, J.-L. Hu, Y. Peng, X.-M. Pan, L. Zhao, and J.-Y. Fang, "Support for vehicle-to-everything services based on LTE," *IEEE Wireless Commun.*, vol. 23, no. 3, pp. 4–8, Jun. 2016.

[37] Y. Wang, Y. Liu, J. Zhang, H. Ye, and Z. Tan, "Cooperative store-carry-forward scheme for intermittently connected vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 777–784, 2017.

[38] P. Li, T. Zhang, C. Huang, X. Chen, and B. Fu, "RSU-assisted geocast in vehicular ad hoc networks," *IEEE Wireless Commun.*, vol. 24, no. 1, pp. 53–59, Feb. 2017.

[39] Y. Li, X. Zhu, D. Jin, and D. Wu, "Multiple content dissemination in Roadside-Unit-Aided vehicular opportunistic networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 8, pp. 3947–3956, Oct. 2014.

[40] K. Abboud, H. A. Omar, and W. Zhuang, "Interworking of DSRC and cellular network technologies for V2X communications: A survey," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9457–9470, Dec. 2016.

[41] F. Abbas, P. Fan, and Z. Khan, "A novel low-latency V2V resource allocation scheme based on cellular V2X communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 6, pp. 2185–2197, Jun. 2018.

[42] C. M. Silva, W. Meira, and J. F. M. Sarubbi, "Non-intrusive planning the roadside infrastructure for vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 4, pp. 938–947, Apr. 2016.

[43] V. Raghavan, M.-L. Chi, M. A. Tassoudji, O. H. Koymen, and J. Li, "Antenna placement and performance tradeoffs with hand blockage in millimeter wave systems," *IEEE Trans. Commun.*, vol. 67, no. 4, pp. 3082–3096, Apr. 2019.

[44] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Proc. 1st Int. Conf. Simulation Tools Techn. Commun., Netw. Syst. Workshops (Simutools)*, ICST, Brussels, Belgium, 2008, pp. 60-1–60-10.

[45] OMNET++. (2019). *Network Simulation Framework*. [Online]. Available: http://omnetpp.org/

[46] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker, "Recent development and applications of SUMO-simulation of urban mobility," *Int. J. Adv. Syst. Meas.*, vol. 5, nos. 3–4, pp. 128–138, Dec. 2012.

[47] Sumo. (2019). *Simulation of Urban Mobility*. [Online]. Available: http://www.sumo.dlr.de/

[48] M. Haklay and P. Weber, "OpenStreetMap: User-generated street maps," *IEEE Pervasive Comput.*, vol. 7, no. 4, pp. 12–18, Oct. 2008.

[49] OSM. (2019) *OpenStreetMap*. [Online]. Available: https://www.openstreetmap.org

[50] S. Krauss, P. Wagner, and C. Gawron, "Metastable states in a microscopic model of traffic flow," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 55, no. 5, pp. 5597–5602, May 1997, doi: 10.1103/PhysRevE.55.5597.

DANIEL L. GUIDONI received the Ph.D. degree in computer science from the Federal University of Minas Gerais, Belo Horizonte, Brazil, in 2011. He is currently an Assistant Professor with the Federal University of São João del-Rei, Minas Gerais, Brazil. His research interests include wireless sensor networks, small world networks, vehicular networks, and communication protocols. In 2012, he received the CAPES Award for the Best PhD Thesis in Computer Science, Brazil.

GUILHERME MAIA received the Ph.D. degree in computer science from the Federal University of Minas Gerais, Brazil, in 2013. He is currently an Assistant Professor in computer science with the Federal University of Minas Gerais. His research interests include distributed algorithms, mobile computing, wireless sensor networks, and vehicular ad hoc networks.

FERNANDA S. H. SOUZA received the Ph.D. degree in computer science from the Federal University of São João del-Rei, Brazil, in 2013. He is currently an Assistant Professor in computer science with the Federal University of São João del-Rei. His research interests include heuristics and metaheuristics, combinatorial optimization, traffic management, and communication networks.

LEANDRO A. VILLAS received the degree in computer science from the Colleges Integrated Adamantinenses, Adamantina, Brazil, in 2004, the master's degree in computer science from the Federal University of Sao Carlos, São Carlos, Brazil, in 2007, and the Ph.D. degree in computer science from the Federal University of Minas Gerais, Belo Horizonte, Brazil, in 2012. He held a postdoctoral position at the University of Sao Paulo, in 2013. He is currently an Assistant Professor with the Institute of Computing, University of Campinas, Campinas, Brazil. His research interests include context interpretation, distributed algorithms, routing algorithms, wireless sensor networks, and vehicular ad hoc networks. He spent a year in the lab PARADISE SITE, University of Ottawa, as part of his doctoral sandwich. Over the past five years, he had eight papers in journals, and more than 30 papers at conferences. He received the award for Best Article in the XXV Brazilian Symposium on Computer Networks and Distributed Systems 2007 and a Prominent Researcher Award at PARADISE Lab, University of Ottawa, in 2011.

ANTONIO A. F. LOUREIRO received the B.Sc. and M.Sc. degrees in computer science from the Federal University of Minas Gerais (UFMG), Brazil, and the Ph.D. degree in computer science from The University of British Columbia, Canada. He is currently a Full Professor of computer science with UFMG, where he leads the research group in wireless sensor networks. His main research areas are wireless sensor networks, mobile computing, and distributed algorithms. In the last ten years, he has published regularly in international conferences and journals related to those areas, and also presented tutorials at international conferences.

● ● ●