

On the Effectiveness of an Opportunistic Traffic Management System for Vehicular Networks

Ilias Leontiadis, Gustavo Marfia, David Mack, Giovanni Pau, Cecilia Mascolo, and Mario Gerla

Abstract—Road congestion results in a huge waste of time and productivity for millions of people. A possible way to deal with this problem is to have transportation authorities distribute traffic information to drivers, which, in turn, can decide (or be aided by a navigator) to route around congested areas. Such traffic information can be gathered by relying on static sensors placed at specific road locations (e.g., induction loops and video cameras) or by having single vehicles report their location, speed, and travel time. While the former approach has been widely exploited, the latter has come about only more recently; consequently, its potential is less understood. For this reason, in this paper, we study a realistic test case that allows the evaluation of the effectiveness of such a solution. As part of this process, (a) we designed a system that allows vehicles to crowd-source traffic information in an ad hoc manner, allowing them to dynamically reroute based on individually collected traffic information; (b) we implemented a realistic network-mobility simulator that allowed us to evaluate such a model; and (c) we performed a case study that evaluates whether such a decentralized system can help drivers to minimize trip times, which is the main focus of this paper. This study is based on traffic survey data from Portland, OR, and our results indicate that such navigation systems can indeed greatly improve traffic flow. Finally, to test the feasibility of our approach, we implemented our system and ran some real experiments at UCLA's C-Vet test bed.

Index Terms—Ad hoc, intelligent transportation system (ITS), realistic traffic flow simulation, vehicular ad hoc networks (VANET), wireless communication.

I. INTRODUCTION

ACCORDING TO “The 2007 Urban Mobility Report” published by the Texas Transportation Institute, in 2005, the traffic congestion cost to the nation (in the 437 U.S. urban areas) added up to \$78.2 billion. The same report also observes that more and more time is spent in cars due to congestion. A measure of this phenomenon is the increase in the travel time index, i.e., the ratio of travel time in rush hours to travel time at

quiet periods, which has steadily risen from 1.09 in 1982 to 1.26 in 2005. This trend has led to the development of intelligent transportation system (ITS) technologies. Although there is a general consensus about the role ITSs may play in reducing traffic, such systems are not necessarily guaranteed to succeed in reducing congestion.

During the last few years, a wealth of research has studied how to optimize the internetworking of vehicles utilizing short-range radios (e.g., WiFi and dedicated short-range communications) to support a wide range of services. In particular, ITSs could benefit from the use of vehicular ad hoc networks (VANETs) in metropolitan areas by enabling each vehicle to act as a traffic probe that measures and afterward spreads traffic-related information. This information can then be used by other vehicles to efficiently select their routes to avoid congested areas. In essence, an intelligent transport system can use the vehicles themselves to crowd-source traffic information.

Clearly, the advantages deriving from the deployment of a VANET-based ITS are manifold. Many more streets than those nowadays equipped with a monitoring infrastructure could be easily observed without requiring additional costs. (Currently, only major urban areas can afford monitoring infrastructure.) Furthermore, many more services that may utilize the same infrastructure (e.g., pollution management and accident prevention) could be provided, thus requiring only limited additional investments.

While cellular networks can be used to offer some of these services [1], this solution can also create a number of issues. First, the service providers in each country impose different rules and restrictions as to what kind of data can be exchanged through their network or even what type of applications can access it, making it impossible for vehicular applications to be globally deployed (e.g., at least a per-country agreement will be required). Additionally, the cost of cellular data communication is restrictively high, as it can reach a few pence per kilobyte. Even expensive “unlimited” plans are usually capped to a few hundred megabytes per month, making large-scale communication (such as real-time fine-grained traffic information) between millions of vehicles unfeasible. Furthermore, although third-generation (3G) connections can support up to 128 kb/s inside a moving vehicle, the bandwidth is shared between all users inside the cell. Even today, when 3G is not widely used, the network is swamped by traffic, resulting in very low throughput in densely populated areas. Finally, ad hoc connectivity is more sensible to disseminate local information. The use of one-hop local ad hoc communication does not require any kind of license or any infrastructure deployment and, most importantly, local wireless communication between vehicles is becoming

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a reality: There is increasing industrial interest and support for vehicular networks [2], [3] led mainly by the interest to maximize road safety (i.e., to avoid vehicle collisions).

However, before being implemented, VANET-based ITS systems require further assessments, as their beneficial effects on traffic conditions are not yet fully understood. In fact, in a fully decentralized ITS, each vehicle bases its own traffic knowledge and routing decisions on only partial data, as only part of the generated traffic information could be received. As a result, many new research initiatives have taken place with the scope of understanding the impact of distributed ITSs on urban congestion [4].

In this context, we would like to examine the effects of such a distributed system on traffic. To conduct this study, we designed a distributed ITS and an evaluation platform based on two realistic simulators: 1) a vehicular mobility and 2) a network simulator, which interact and depend, at each step, on the output of each other. Moreover, the key contribution of this work is that we used these tools to examine the impact of this system in a realistic city scenario. Finally, we implemented and ran small-scale proof-of-concept field tests at UCLA's C-Vet test bed.

Summarizing, with this paper, we aim at understanding the impact of a distributed ITS system in a realistic scenario. To the best of our knowledge, this work is the first to consider a real city topology and realistic traffic flows in evaluating such systems. *In fact, origin-destination pairs of all vehicles utilized in our simulations are derived from large-scale surveys on the population of Portland, OR* [5]. These data allow us to study a realistic case study where traffic patterns are matching real observations. Our results show that such systems can be beneficial for minimizing traffic conditions in metropolitan areas but also open new interesting research directions, as we show that its improvements on traffic vary as a function of different parameters (e.g., flow intensities, traffic information aggregation algorithms, and percentage of malicious vehicles).

The remainder of this paper is organized as follows: We start by describing the existing related work in Section II and our main motivation scenarios in Section III. In Section IV, we illustrate our Computer-Assisted Traveling Environment (CATE), which is our distributed ITS system. In Section V, we present our evaluation platform, which is a simulation platform that combines a mobility and a network simulator. In Section VI, we present the extensive study on how such an ad hoc system could affect traffic conditions in a realistic scenario, whereas Section VII discusses a few simple experimental trials that we have conducted to test the feasibility of this solution. Finally, Section VIII concludes the paper by listing possible future directions.

II. RELATED WORK

An extensive body of literature exists on traffic congestion causes and effects. Therefore, we only directly cite those works that are particularly relevant in the present study.

First, there was a lot of research on how perfect traffic information does not guarantee lower congestion. In fact, assuming all vehicles were provided with real-time traffic information about every road segment and each vehicle selfishly selects the

shortest-time path, then this may not always result in a global minimization of trip times. This result, due to Beckmann *et al.* [6], may be used as an argument against navigation systems that implement traffic guided routing. On the other hand, no proof exists that a suboptimal solution is worse than the absence of any control.

The Comprehensive Automobile Traffic Control System (CACS), which was developed in Japan in the 1970s, laid the foundations for the use of vehicular traffic sensors. The CACS system was designed to test the effectiveness of the provision of real-time traffic information to vehicles. Tests were run on a 4-km \times 7-km urban area in Tokyo, which is an area that contained 85 intersections. Traffic information was recorded with 103 roadside units, 255 loop antennas, and 1000 taxis. The impact of traffic information dissemination was observed on 330 CACS vehicles. After this seminal work, many researchers have begun to investigate the impact of traffic information dissemination on traffic flows.

In [7], authors implement an integrated traffic flow and behavioral and traffic information model. The goal of this work is to show the impact of traffic information on a vehicular network, as the penetration ratio increases. Interestingly, in this study, higher penetration ratios lead to poor overall performance. In [7], a fully informed traffic network attains the same performance of a system with no information feedback. However, this and other studies [8], [9] focus on very simple traffic networks, which is far from the complexity of the network that is under study in this paper.

In [10], a framework is defined to disseminate traffic information. This work describes in detail the architecture of a distributed traffic information system. However, authors do not investigate the effects that the traffic information system may have on traffic. The evaluation only considers a 15-km straight street with four lanes in both directions. Similar observations were also independently found in [11].

More recently, Sommer *et al.* [12] implemented a bidirectionally coupled simulator, integrating a vehicular and a telecommunications simulator. The analysis of the impact of a smart navigation system is limited to a test case with 200 vehicles that leave a single location and all head to the same destination.

A key role in this area is played by traffic measurement methodologies and by the technologies employed to gather the measurements [13]. One of the oldest and most widely spread technologies is induction loops. Induction loops are usually placed in the asphalt and provide punctual measurements for speed and traffic flow for that location. This metric suffers from a number of problems that limit its reliability. Intuitively, induction loops record speed information at certain locations on a street; thus, results may be misleading with urban stop-and-go traffic. A more complete analysis of induction loops may be found in [14]. Video cameras are slowly replacing induction loops, but their widespread deployment is limited by their cost. The advantage in using video cameras is of recording end-to-end times rather than a punctual speed samples. While these methods are well established and their impact on traffic is well understood, we aim to compare them with a fully decentralized crowd-sourced solution.

Finally, in this paper, we do not directly deal with security and privacy concerns. In vehicular networks, it is important that the disseminated information is trustworthy, as it can affect driving decisions. Furthermore, the disseminated information can even raise safety issues (e.g., cause accidents) and raise privacy concerns. Privacy mechanisms could be built over our system to make sure that such a framework can be widely used [15]–[17]. Numerous trust mechanisms were also devised [18]–[20] to improve the cooperation and quality of the disseminated information. Finally, security mechanisms [21], [22] can also be enforced to ensure safety and privacy. All these systems are orthogonal to our approach.

III. SCENARIO AND SYSTEM REQUIREMENTS

Vehicles provided with a computerized system can be aided in navigation by continuously assessing and correcting the best route prediction to a destination. To do this, each vehicle should be capable of the following: 1) sensing traffic information; 2) sharing it with neighboring vehicles (in an ad hoc manner); and 3) dynamically recomputing the best route to destination from the current position based on the collected information. Therefore, a navigation system (NavSys) becomes an element of a distributed system that cooperatively collects and exchanges traffic conditions and, at the same time, a sophisticated traffic estimator, based on real-time information.

Such a system would be useful in many traffic scenarios, beyond regular traffic management operations. For instance, a VANET-based ITS may be used where infrastructure-based traffic monitoring systems are not deployable for various reasons. This is, in fact, quite common; only a few cities around the world implement an infrastructure that is capable of recording traffic data and providing them to drivers. Other possible applications span from traffic management under uncommon conditions (i.e., accidents, disasters, and evacuations) to less critical applications like constrained navigation (e.g., reach the closest station before gas runs out).

A number of basic characteristics identify a system able to offer the solution just described.

- 1) *Traffic sensing*. Each vehicle should be able to act as a traffic sensor. The requirement for a traffic-sensing module is to measure a quantity closely related to traffic. Speed, traffic volume, traffic density, and trip time are the most commonly used metrics;
- 2) *Traffic information dissemination*. Afterward, vehicles will exchange the sampled information in an ad-hoc manner. The right traffic information should reach the right vehicles with the minimum delay. Excessive redundancy risks congesting the feedback channel; too little can lead to uninformed decisions;
- 3) *Traffic estimation*. Finally, each vehicle should be able to independently evaluate the traffic conditions based on the traffic samples received through the network. Raw samples should be filtered and transformed in correct traffic estimates. For instance, a red traffic light phase should not be mistaken for a congested state. Moreover, as samples arrive at different rates, we need a model to

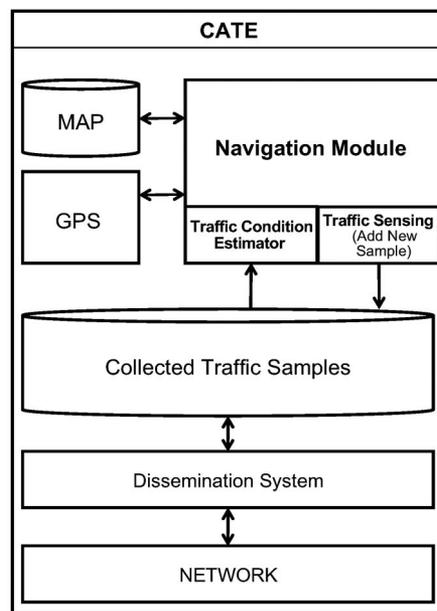


Fig. 1. CATE's architecture.

estimate the traffic conditions when only a few or only very old samples are available.

To understand how such a system affects *global traffic conditions*, it is important to evaluate the consequences of each design choice. However, the complexity and the scale of the real system make an “on-the-field” evaluation prohibitive. Therefore, there is a need for tools that are capable of producing realistic traffic data and handling dynamic routing. This is a very important piece of the puzzle. As we have seen in the related work section, in the past, many studies [7]–[9] have concluded that informed navigation can lead to traffic disruption. In the next section, we will describe our prototype system, and we will later describe the tools that we designed to study its impact on traffic.

IV. COMPUTER-ASSISTED TRAVELING ENVIRONMENT

We now briefly examine CATE's architecture (see Fig. 1). CATE is a smart navigation system designed to answer the requirements described the previous section. We will now provide more details about each one of the three key modules.

A. Traffic-Sensing Module

CATE assumes that every vehicle can become a traffic sensor. Therefore, the vehicle's navigation systems should be able to accurately take these measurements. Street section delay is widely accepted as one of the most effective measures of the degree of congestion. Therefore, the vehicular navigation problem can be modeled as a search of the shortest path on a weighted graph. In such a model, street sections are links, intersections are nodes, and a link's weight is given by the time required to traverse it. The graph model well applies to the majority of map databases [23] and navigation systems.

In CATE, every time a vehicle exits a road segment, it creates a traffic sample of type $\{\text{linkID}, \text{delay}, \text{timeStamp},$

carID}. linkID is unique per street segment and direction throughout the vehicular network. The delay field represents the time spent by the vehicle on link linkID. The Global Positioning System (GPS) and the map information is used to identify the time when the vehicle entered/exited a certain road segment. timeStamp is the GPS time at which the sample was collected and, more specifically, the time when the vehicle exited the measured road segment.

B. Dissemination Module

The dissemination module primarily deals with spreading these samples throughout the VANET in an efficient way.

Previous studies [24]–[28] show how the performance of traditional ad hoc routing dissemination is heavily affected by vehicle density in urban areas. Conversely, gossip-based ad hoc routing is very effective [29] in disseminating large amounts of information in dense networks, and this is why we choose a utility-based gossip model in CATE. We will now provide more details about our traffic sample dissemination protocol.

Periodically, CATE selects a subset of the samples that are available in the buffer (notice that the buffer contains both the vehicle's collected information and information generated by other vehicles) and broadcasts this information to its neighbors. One-hop neighbors will combine the received samples with those that were already in their buffer and later spread them even further.

A key element of the dissemination module is the *sample selection algorithm*: how to select which subset of information to broadcast, assuming only a fraction of a vehicle's knowledge can be sent within given bandwidth restrictions. Therefore, we designed a simple mechanism to *prioritize the samples*. To take these decisions, each sample is ranked with the help of a *utility function*, which is a metric that represents the effectiveness of each sample. Afterward, the K links with the highest utility are broadcasted to the neighbors.

There are numerous ways to design an appropriate utility function, but we chose to emphasize two simple factors.

- 1) **Prefer fresh samples**: Rank the links based on how recent the information is. In that case, $r_{\text{mostRecent}}$ is calculated based on $\text{timeStamp}_{\text{linkID}}$.
- 2) **Maximize coverage**: Rank the links based on how rare the disseminated information is. In that case, $r_{\text{lessbroadcasted}}$ is defined as $1/NB_{\text{Link}}$, where NB_{Link} is the number of times information about this *link* was received during the last t minutes. (If $NB_{\text{Link}} = 0$, we move the link to the top of the ranking.)

Afterward, we linearly combine these two rankings to not only prioritize fresh links but encourage high geographical coverage of the disseminated information as well. Therefore, our utility is $U_{\text{Link}} = r_{\text{mostRecent}} + r_{\text{lessbroadcasted}}$. As we shall see in Section V, this simple approach provides satisfactory results in a 4-km \times 7-km realistic urban scenario. Numerous optimizations can improve the information dissemination procedure (e.g., use a utility that includes topology information to disseminate only information that is needed by nearby vehicles). However, an in-depth study of such algorithms is beyond the scope of this paper.

C. Traffic Estimation and Dynamic Routing Module

As we described before, each vehicle will individually collect a set of measurements (samples) through the network interface. The key challenge is how to estimate the current traffic conditions and dynamically reroute the vehicle.

CATE periodically computes the route of a vehicle using the modified Dijkstra algorithm described in [30] (although other algorithms specifically devised for vehicular networks can be easily integrated [31]). In practice, the modified version of Dijkstra only considers those links (road segments) that are inside the geographical area between the current position and the destination. Each link has a weight w that allows Dijkstra to find the shortest path. In our case, *the weight represents the updated traffic condition of the segment* (i.e., how long a vehicle is expected to be on the road segment based on the information that it managed to collect via the network).

The problem of estimating a link's traffic condition based on the collected samples is not trivial for the following reasons:

First, *noise in the observations*: Although traffic conditions do not rapidly change over time (traffic jam's dynamics are relatively slow), sample delays can be quite noisy. Distinct vehicles may drive through the same street segment at the same time but at a different pace. Some vehicles may stop at a traffic light, at a pedestrian crossing, or to pick up a passenger, whereas other vehicles rush through the street segment. The result is that samples may significantly vary, although collected close in time.

Second, *sample rate variation*: There is no guarantee that a link's traffic samples will be received at a fixed rate. (It depends on traffic and the dissemination strategy.) For example, a vehicle may receive multiple old samples and just a few fresh samples. One key problem is how to weigh this information (age of samples) to calculate the best possible estimation of the current conditions.

Finally, *absence of information*: No recent information may be received for some road sections. The two possible choices are to use weights that represent either historical data (e.g., typical average speed at that time on that road segment) or speed limits. However, we need to identify how quickly the information is considered as obsolete.

To answer these questions, we tested a number of solutions to interpret the collected samples to provide an accurate estimation of the current traffic conditions.

- 1) **Default**: A link's weight is computed by dividing its length by its speed limit

$$W_{\text{linkID}} = \frac{\text{LinkLength}}{\text{SpeedLimit}}. \quad (1)$$

CATE sets this as the default weight when no information is known about a link.

- 2) **Most recent estimate**: For each link, CATE selects the most recent sample in terms of timeStamp (not the time this vehicle received it)

$$W_{\text{linkID}} = \text{Delay}_{\text{linkID,mostRecentSample}}. \quad (2)$$

This is the simplest algorithm as it discards all the samples that were collected earlier. However, a link's weight

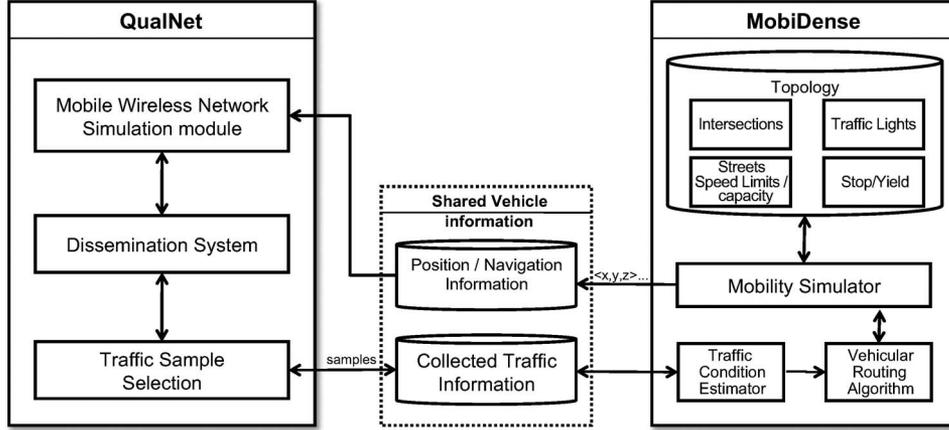


Fig. 2. MobiDense and QualNet interactions.

can heavily fluctuate since samples can rapidly vary. Surprisingly, the results illustrated in Section V show that this approach achieves a satisfactory performance. From a theoretical viewpoint, this is justified by observing that end-to-end times on road segments follow a bimodal distribution [32]. If the distribution that models the low congested state and the distribution that models the highly congested state are not very spread, considering that it takes some time to transit from one state to the other, any recent traversal time sample can correctly represent the current state of the link.

- 3) *Bayes' estimate*: We use a simple Bayesian estimator to predict the current traffic conditions by using a large number of samples taken at different times

$$W_{\text{linkID}} = (1 - \alpha) * \text{Delay}_{\text{NewSample}} + \alpha * \text{CurrentWeight}_{\text{LinkID}} \quad (3)$$

where α is a parameter tuned by the sample's age (so that older samples do not excessively weight).

- 4) *Bayes with aging estimate*: This is the same as before, but the absence of information moves the weight back to the default value given by the free flow traversal time

$$W_{\text{linkID}} = (1 - c) * \text{BayesWeight}_{\text{linkID}} + c * \text{DefaultWeight}_{\text{LinkID}}. \quad (4)$$

c is an aging factor computed as

$$c = \frac{\text{Min}(\text{curTime} - \text{recentSampleTime}, \text{maxAge})}{\text{maxAge}}. \quad (5)$$

This approach differs from [10], where information is always assumed to be known, in interpreting no information as no congestion and, therefore, accordingly dropping link weights.

V. EVALUATION PLATFORM

To evaluate CATE, we designed and implemented a tool that simulates both dynamic vehicular navigation (mobility) and

the VANET dissemination. Solutions that couple a mobility simulator and a telecommunications network simulator can be found in [12] and [33]–[35]. Differently from previous work, we integrate QualNet [36], which is a communications network simulator specifically designed for wireless networks, and MobiDense [37], which is a mobility simulator that we designed and implemented. These two simulators constantly interact: *Future mobility decisions are influenced by the network dissemination (e.g., collected information), and the network dissemination is influenced by the mobility patterns (location of the vehicles)*. A depiction of the interactions between the two tools is shown in Fig. 2.

A. MobiDense

MobiDense [37] is a mobility simulator that combines topology and traffic flow information to generate a mobility trace. We chose MobiDense as it allows us to dynamically modify the road weights and because it can directly plug into QualNet. It is able to simulate vehicular mobility on real road-network topologies that are extracted from digital maps. Moreover, we use detailed information about the type of street segments (i.e., two-way or one-way roads, speed limits, and number of lanes), the probability of stopping at an intersection, traffic light locations, traffic light timings, and phases. When no additional information is provided with the digital map, the street segment capacities are used to estimate the enforcing speed limits and to adapt intersection stop probabilities and red/green time phases of traffic lights. Consequently, queues may build up at intersections and propagate backward. Aside from topological information, MobiDense also requires a traffic flow model: the starting point and time and the destination of all vehicles to be simulated. Intermediate routing decisions are individually taken by each vehicle's routing module based on the topology and the street weights that are used.

In terms of interaction with QualNet, at each time-in step t for each vehicle v that is now at location $v\langle x_t, y_t \rangle$, MobiDense calculates its position for the next time step $v\langle x_{t+1}, y_{t+1} \rangle$. To perform this task, MobiDense simulates v 's mobility based on the route that it selected to reach its final destination, the road topology, and the other vehicles in the simulation (e.g., traffic queues, speed limits, traffic lights, and car-following models).

However, periodically, MobiDense recalculates v 's route to its final destination based on the traffic samples collected via the network. (The samples collected per vehicle are placed in the "Collected Traffic Information" database that shown in Fig. 2.) Furthermore, since each vehicle acts as a traffic sensor, MobiDense also adds samples to the database: when a vehicle exits a road segment, a sample for this link is added in the database. Later, this sample will be disseminated via the network (initially to v 's neighbors and later further away).

In conclusion, MobiDense takes the role of the following:

- 1) a smart navigation system that can dynamically route each vehicle based on the estimated traffic conditions that were received via the network;
- 2) a traffic sample sensor; and
- 3) a mobility simulator that moves the vehicles based on the topology and the real traffic.

B. QualNet

The wireless network dissemination modules are implemented in QualNet [36], which is a well-known network simulator that is particularly suited for the simulation of wireless networks.

First, at each instance t , the vehicles are placed at the locations that were instructed by MobiDense. Since we are using short-range radio, these locations will determine connectivity.

To disseminate information, each vehicle periodically broadcasts samples that are found in the "Collected Traffic Information" database (a shared buffer between the two simulators). As described in the previous sections, these broadcasts contain only a subset of the samples that are in the database. Similarly, when a vehicle receives a message from the network, it adds the newly received samples to the database. MobiDense will later use them to dynamically reroute the vehicle, and QualNet will further disseminate them.

Notice that QualNet and MobiDense continually exchange information. (They synchronize once every second.) MobiDense provides the vehicles' positions and the streets' traversal times to QualNet, whereas QualNet is used to gossip the information.

VI. STUDYING THE IMPACT OF VEHICULAR AD HOC NETWORK DISSEMINATION ON TRAFFIC

We will now move to our main contribution: the evaluation of the impact of the system presented in Section IV. The goal of this work is to establish whether a distributed (ad hoc) system such as CATE, when used by all vehicles, can reduce traffic congestion. The main performance metric is the vehicle's total trip time, but other aspects should also be considered. First, we will study how performance improvements, if any, are distributed among vehicles. Second, we will measure how quickly the information is disseminated. Finally, we will quantify the amount of communication traffic that is produced.

For our evaluation, we use a scenario based on downtown area of Portland, OR. The area is approximately $4 \text{ km} \times 7 \text{ km}$, and a map is shown in Fig. 5. The area includes 4968 streets and 3429 intersections. About 16 500 vehicles are involved in the simulation. Each vehicle's journey information (start

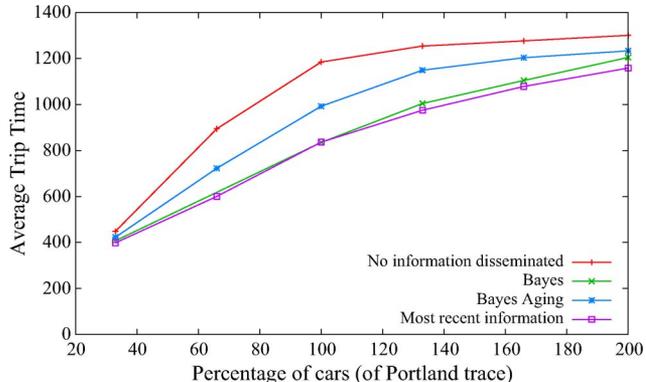


Fig. 3. Trip times for different information handling strategies (in seconds).

time and location and end point) is extracted from large-scale surveys on the population of Portland. This information is extremely valuable as it is very important to have realistic traffic flows that follow a certain spatio-temporal distribution. Origin–destination pairs are then plugged into our coupled mobility-telecommunication simulator.

We use the same source to extract information such as traffic light positions and delays, intersection stop probabilities, speed limits, and road capacities. MobiDense produces traces, in the absence of information dissemination between vehicles, which reproduce in terms of flows the original survey observations.

A. Traffic Information Evaluation

Each vehicle stores traffic samples, grouped by linkID, in a local buffer. In case no information is known about a link, all the strategies we implement assume that there is no traffic on such link. (We assume that vehicles traverse the link at free flow speed.) We now compare the three different traffic estimation algorithms described in Section IV: 1) *most recent estimate*; 2) *Bayes*; and 3) *Bayes with aging*. We additionally compare these strategies to the case where no information is disseminated.

Traffic flows are adjusted from 33% of the traffic that is found in the original survey to double the actual flow values. For example, if an average of 100 vehicles per hour enter the map from a certain intersection in the original survey, we begin the simulation with a flow of 33 vehicle/h. Therefore, we simulate the network observing its behavior with low densities, and we then gradually increase traffic to reach typical morning traffic volumes.

As we see in Fig. 3, in the absence of information feedback, when density increases, overall trip times quickly rise from 400 s (about 7 min) to 1200 s (about 20 min), on average. When CATE is used, trip times drop. A higher absolute improvement is observed under normal traffic congestion, but the gain is surprisingly less when we have higher than normal traffic conditions. This result radically differs from what is found in [7]–[9] and [38]. An intuitive explanation may be found by observing Fig. 5. As we can see in Fig. 5(a), traffic is mainly localized on the freeways and on the bridges that traverse the river. However, traffic is not all generated by vehicles that traverse the river or that take a freeway. Many vehicles could reach their destinations through alternate routes, but they do not. In

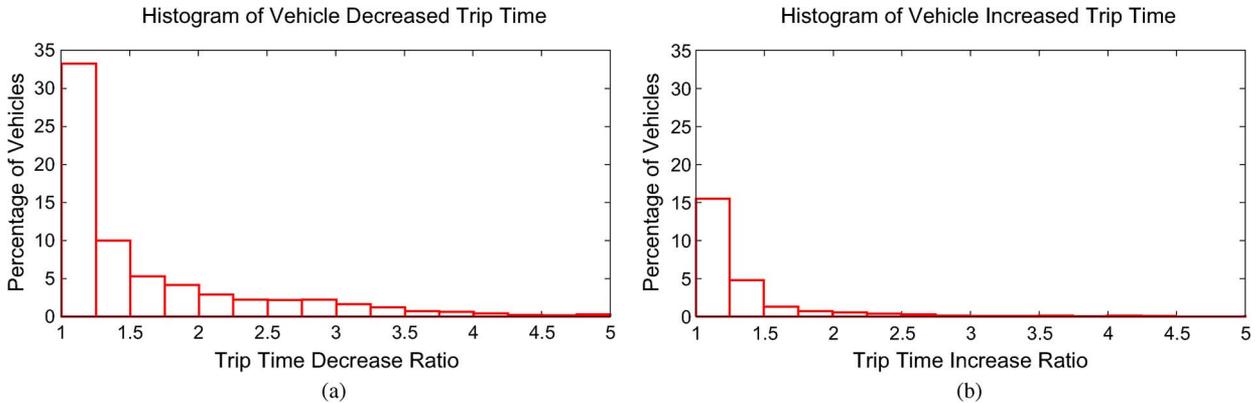


Fig. 4. Histogram of trip-time loss/gain. (a) Improvement (decreased trip time). (b) Deterioration (increased trip time).



Fig. 5. Map of speed. Green streets are not congested. Yellow areas show an average speed that is slightly lower than speed limit. In red street segments, the average speed is much lower than the speed limit. (a) No information. (b) CATE.

Fig. 5(b), we see the result of using CATE. Many more yellow links (i.e., slightly congested links) and fewer red links (i.e., heavily congested) are present. In fact, heavily congested links are substituted by a number of slightly congested (yellow) links in Fig. 5(b). This indicates that, when vehicles collected the traffic information, they were diverted from heavily congested areas to areas that were previously not congested, creating some minor congestion.

The space for improvement is high because the topology we are here analyzing is realistic, and more than one path is usually available to reach a location. At the center of the map, in the Manhattan-like section, we can see an increase in yellow links when using CATE. Under normal morning traffic conditions, the average trip time is 29% lower, which is a significant improvement.

In terms of weight calculation algorithms, we observe that the most recent information and Bayes strategies provide the best results in this simulated scenario. This happens because, if there is traffic on a link, end-to-end times considerably increase, whereas they otherwise slightly oscillate above the free flow delay time. Bayes with aging still improves but not as much as the other two methods since traffic conditions are not rapidly changing.

It is important to understand how travel time improvements are distributed. Fig. 4 shows a histogram of the trip times gain/loss for normal traffic conditions when dissemination is used. More specifically, gain ratio [see Fig. 4(a)] is defined as $ratio = oldtime/newtime$. For example, a ratio of 2 means that the vehicle halved its trip time, a ratio of 3 means that

it needed one third, etc. Similarly, deterioration time [see Fig. 4(b)] is defined as $ratio = newtime/oldtime$ (a ratio of 2 means the vehicle doubled its trip time). As we observe, a large number of vehicles, i.e., 34%, saved 20% of the time (ratio 1.25 means the new time is $1/1.25$ of the old time). There were also luckier vehicles that were able to avoid big traffic queues and complete their journey two or three times faster (ratios 2 and 3). In total, 64% of the vehicles saved time. However, at the same time, we see that some of the drivers required more time when our application was used. This is due to some of the traffic being diverted into smaller roads that, consequently, become busier. However, we can observe that far fewer drivers have their time increased rather than decreased, and their trip times are no more than two times longer. Finally, 23% of vehicles were not really affected ($\pm 10\%$ trip time).

Finally, in terms of penetration ratio, we experimented with a range of 10%–100%. As expected, when less vehicles are equipped with CATE, the system's performance is slightly worse. However, in our experiments, we noticed that, when only 34% of the vehicles are equipped with CATE, the performance is comparable with higher penetration ratios.

B. Traffic Information Dissemination Quality

We also want to understand how well CATE disseminates traffic information, giving a close representation of real traffic conditions to each vehicle. In fact, the results that we presented in Fig. 3 may derive from an unfair dissemination of information. We should remember that, in simple scenarios

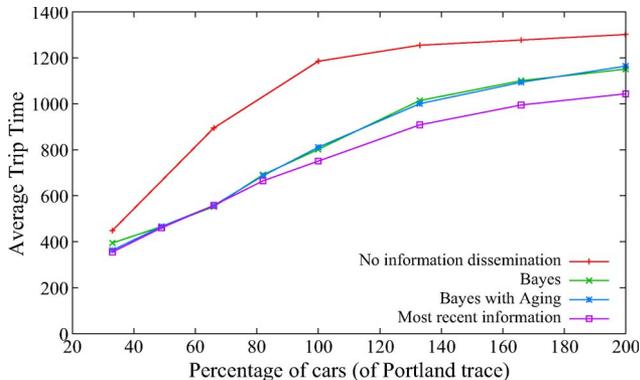


Fig. 6. Trip times (in seconds) when full knowledge is instantly available to all the vehicles (best information dissemination case).

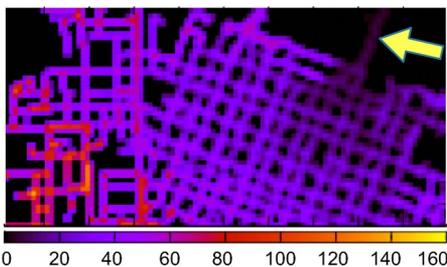


Fig. 7. Two-dimensional Heatmap of age of received information (in seconds) about the link highlighted by the arrow (bridge). Vehicles away from the bridge receive older traffic information.

[7]–[9], [38], it has been shown that a fully informed traffic network can deteriorate traffic performance. Therefore, random inconsistencies in traffic information dissemination may be inducing a better traffic behavior.

To estimate the impact of the dissemination protocol on the system’s performance, we compute the overall average travel time when all traffic information is immediately available at all vehicles. This is the infinite bandwidth/zero delay scenario, i.e., a full-knowledge scenario where all vehicles know all possible information in real time. We then observe the variation in aggregated average traffic trip time between a fleet of vehicles that gossip information and a fleet of vehicles that immediately receive all the available information. Note that this mode would not be possible in reality, and we just use it to compare with full-knowledge scenario.

Fig. 6 shows the results for the same traffic estimation methods used before, yet now information is not collected with the dissemination protocol (i.e., gossip). All the collected information is instantly available when a vehicle requires running its routing algorithm. We observe that the same trends appear as when CATE is used. The comparison with Fig. 3 reveals that trip times are slightly smaller. This result is very interesting as we can conclude that informed vehicles can reduce the overall average trip time and that CATE is performing well, giving an updated picture of the network to each vehicle.

To better understand how recent information is received at a vehicle, we analyze the information propagation speed on the map. Fig. 7 shows a zoomed area of the map (near the central section, between Burnside Bridge and Morrison Bridge). In this graph, we plot the average age of information about the bridge

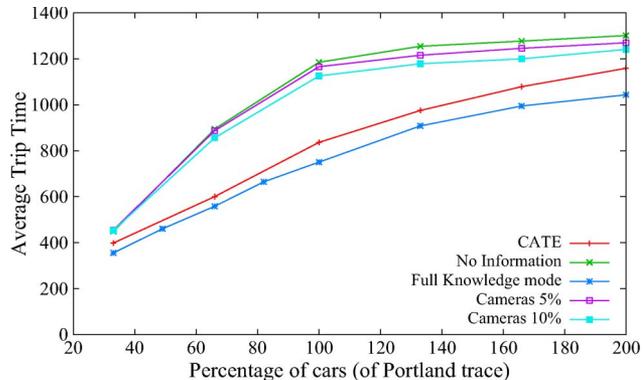


Fig. 8. Infrastructure versus CATE. Average trip time (in seconds).

pointed by the arrow: Morrison Bridge. In nearby areas, this information is, on average, less than 1 min old. In areas that are about 2 km away, information is, on average, about 3 min old. In fact, in the whole 4-km \times 7-km simulation area, we could rarely find vehicles that were using information older than 15 min. This explains why the results shown in Figs. 3 and 6 are so close: CATE performs close to full knowledge since traffic trends (i.e., as congestion build up) are slower than information dissemination, thus giving vehicles enough time to react.

C. Infrastructure Versus Infrastructure-Less Probing

We here compare CATE to state-of-the-art solutions that monitor selected street segments using video cameras or induction loops, and disseminate traffic information using cellular networks (e.g., 3G) or frequency-modulation stations. With such systems, all vehicles can instantly access the same updated and accurate information about the instrumented roads. In CATE, we have the opposite situation, i.e., information is collected by all the vehicles (and, thus, on almost all street segments), but information is not as recent due to dissemination delay. Additionally, with CATE, distinct vehicles are likely to have a different perspective of the traffic situation.

For our comparison, we monitor 5% and 10% of the streets of downtown Portland. These streets are not randomly chosen, and we chose the most congested 5%–10%. Therefore, the delay information about the most congested streets is instantly delivered to all the vehicles.

Fig. 8 shows the total average trip times as traffic flows increase. The infrastructure-based solution is outperformed due to its lack of flexibility. When a vehicle learns that a monitored street is congested, it clearly avoids it. However, as a result, vehicles may congest streets with no traffic monitoring capabilities. On the other hand, CATE collects information about all streets using each vehicle as a mobile sensor. Therefore, the build up of new congestion points is reported. Information might be delayed, but it is recent enough to avoid congestion hotspots.

D. Studying the Impact of Misbehaving Nodes

Furthermore, although trust and security protocols can be used to ensure that the vehicles cooperate and are accountable for the information that they share (e.g., [18]–[22]), we were

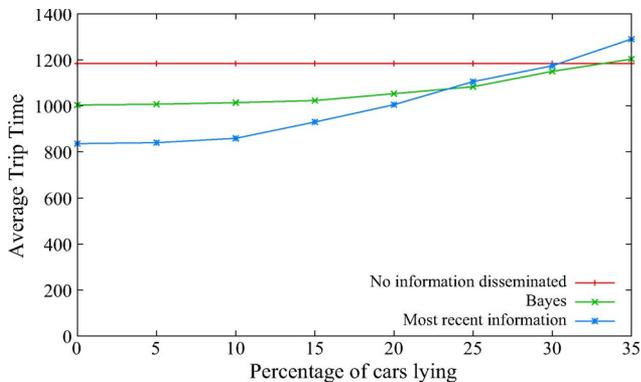


Fig. 9. Performance when a percentage of nodes are misbehaving.

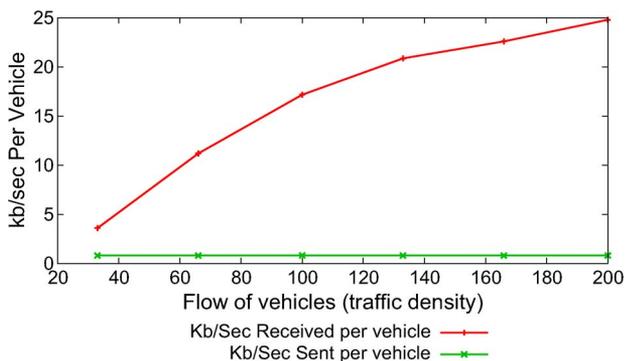


Fig. 10. Network data rates.

also interested in identifying the impact of misbehaving nodes on the traffic conditions.

In our scenario, misbehaving nodes are nodes that intentionally spread wrong information about a pre-agreed selection of road segments. More specifically, in our simulation, we would like to identify the worse-case scenario: All the misbehaving nodes will advertise that all the bridges are fully congested apart from one: I405 (the leftmost bridge in Fig. 5). If a large percentage of nodes spread this information, this will force a large number of vehicles to use highway I405.

In Fig. 9, we plot how different numbers of misbehaving nodes affect trip times (0% is the reference point). Clearly, a small percentage ($< 10\%$) does not affect our system. As the percentage of malicious nodes increases to a significant size ($> 22\%$), we observe that Bayes achieves better performance than using the most recent estimate. This happens because Bayes is averaging multiple samples to create a more accurate estimation. In any case, we observe that it requires an unrealistically large amount of misbehaving nodes ($> 30\%$) to impact worse driving times than the scenarios that do not use our system.

E. Gossip Network Overhead

We measured the dissemination protocol network overhead to estimate the communication's network congestion. In all simulations, we used a 10-s gossip interval and a 2000-byte sending buffer. Fig. 10 shows the transfer rates experienced by each node. As it can be observed, plenty of space is available for more data. Vehicles only receive data at 16 kb/s during normal

morning traffic conditions, whereas devices compliant to the 802.11p [39] standard are expected to provide transmission rates on the order of tens of megabits.

VII. ON THE ROAD

Finally, we were interested in examining whether such a system is feasible. There are many technical challenges in building a system like CATE. First, vehicles should be able to accurately identify and collect samples using their GPS and maps. Furthermore, there are computationally demanding tasks (e.g., traffic estimation based on received samples, rerouting, etc.). Finally, real performance problems such as radio range and radio propagation speed can be evaluated. Therefore, we implemented a fully working prototype of CATE. This prototype allows us to further understand the challenges in such a system.

Fig. 11 shows our implementation's graphical user interface coded in C# and using Microsoft MapPoint as our navigation system API. The prototype, which was for experimentation, enables a user to manually tune parameters such as the route recomputation interval, the dissemination interval, the sample selection, and the weight calculation algorithms.

We here assess the practicality of deploying CATE by implementing its main components and performing a set of connectivity experiments. Unfortunately, a more interesting set of experiments that involve traffic information gathering and dissemination and vehicular navigation is unfeasible.

We use the UCLA Campus Vehicular Testbed (C-VeT) [40]. C-VeT offers both vehicle-to-vehicle and vehicle-to-infrastructure connectivity, a virtualized shared environment, and a number of tools to record a system's behavior and performance.

A. Experimental Setup

During the experiments, each vehicle carries a personal computer equipped with a Zyxel AG-225 H card (IEEE 802.11 a/b/g compliant) and a SIRF-STAR-III-based GPS receiver. The hosts were assigned a static Internet Protocol address and a predefined service set identifier. A high-gain omnidirectional antenna was installed on each vehicle's rooftop, and the line-of-sight range was approximately 250 m.

We designed two classes of experiments to study the feasibility of CATE. First, we performed connectivity experiments to evaluate the amount of traffic samples that can be transmitted between two vehicles that are directed in opposite directions. Second, we tested CATE's basic communication features, i.e., its neighborhood discovery scheme and its dissemination scheme. Eight vehicles were involved in this second test.

B. Experiments

We performed a number of experiments using our prototype implementation, aiming to examine the feasibility of such a system.

1) *Connectivity*: To assess the connectivity between two nodes surrounded by traffic, we performed two experiments. First, we measured the throughput achieved between two static

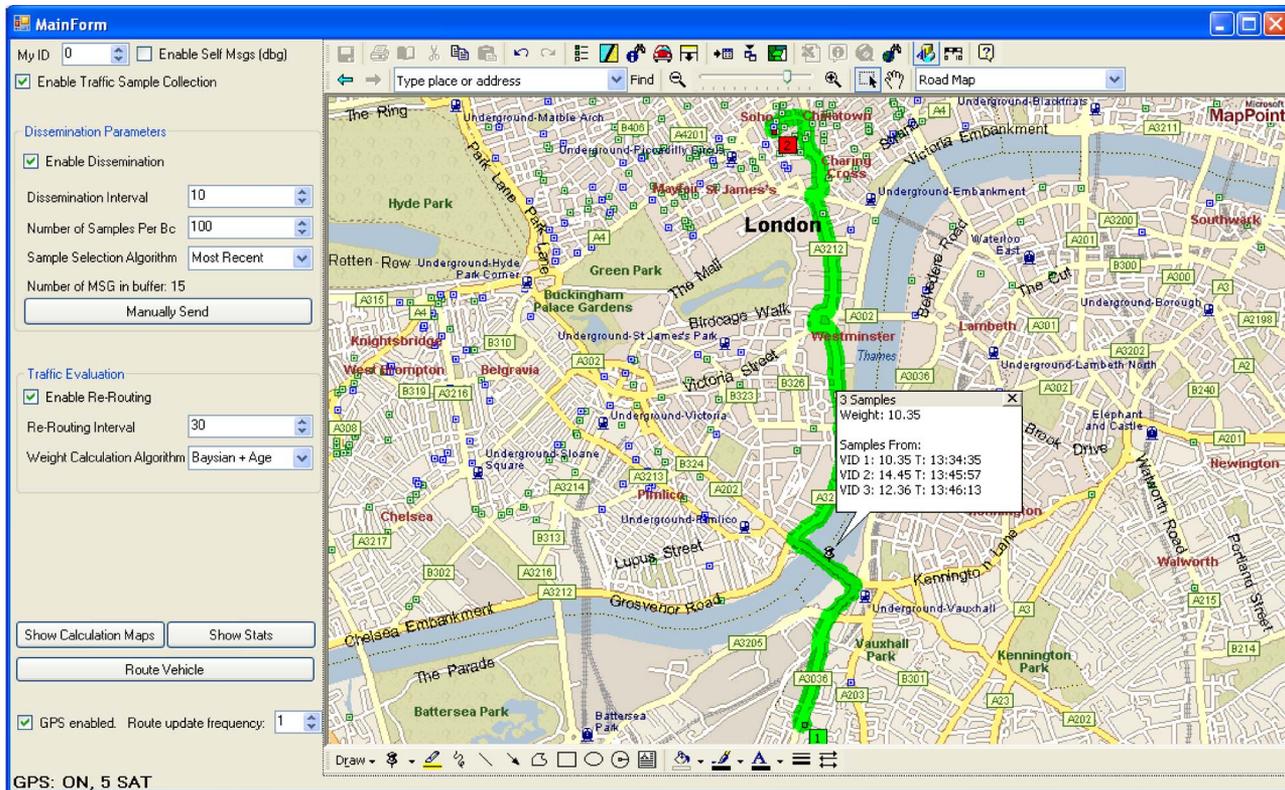


Fig. 11. Our implementation prototype.

vehicles. In this way, we define the best case. Second, we measured how much traffic samples could be disseminated between two cars traveling in opposite directions at 30 mi/h (or 13.4 m/s). Each experiment was repeated ten times.

In the static case, at the UDP layer, the average throughput is 30.004 Mb/s, the peak throughput is 30.3 Mb/s, and the minimum throughput is 28 Mb/s. Two vehicles were driven, following normal traffic, and never exceeded the speed of 30 mi/h. Once they were in radio range, a stream of UDP packets flowed from the first to the second vehicle. We measured the amount of data transferred during each contact. On average, β received 7.24 MB during an average contact time of 15 s.

2) *Dissemination*: CATE was deployed on C-VeT and tested in its basic features. In fact, we tested the neighborhood discovery protocol and the dissemination protocol. Experiments were performed using eight vehicles moving in UCLA's campus.

The neighborhood discovery protocol transmitted hello packets at 1 Mb/s with no acknowledgements, whereas gossip packets were transmitted at the nominal rate of 54 Mb/s.

We performed two tests. *One-hop gossiping*: In this experiment, each vehicle gossiped information to all other vehicles in range. We measured the average amount of traffic samples transferred during a contact among vehicles; on average, 2.35 MB was transferred (about 125 000 traffic samples). This value is lower than the experiment with two cars because (a) the channel load is higher (each car is transmitting to two to three neighbors on average), and (b) the mobility pattern created a long tail distribution of contact times ranging from 3 to 30 s. We observed a peak data transfer of 3.35 MB and a minimum value of 1.76 MB. *2-MB traffic-sample dissemination*: In the

second test, only one car behaved as a source of a 2-MB traffic-update chunk that represents a full map update. We here aimed at estimating the average delay experienced when transferring a big amount of traffic samples from this vehicle to all the others. In this experiment, we used CATE's dissemination scheme, setting the dissemination interval to 1 s. On average, the 2-MB samples reached all other vehicles in 125 s. On average, the first vehicle received the entire amount of data in less than 20 s, the majority of the other vehicles (five out of eight) received the data in 72.5 s, and the last two vehicles received the data in 118 and 125 s, respectively.

While the experiments described in this section are far from realistic since they do not consider vehicular rerouting based on traffic estimations, the experiments show the feasibility of the proposed application. In fact, CATE is easy to deploy with off-the-shelf equipment and the computation power available in any navigation system or personal-digital-assistant device. Moreover, the bandwidth provided by available wireless technologies is more than sufficient to support the low data rates that an ad hoc ITS requires.

VIII. CONCLUSION

In this paper, we have quantified the effects of deploying a decentralized traffic-based navigation system in downtown Portland, OR. Moreover, we have analyzed the effects that full knowledge and partial monitoring would have on traffic congestion. First, our results show that a decentralized approach can reduce traffic congestion in a realistic scenario. This result is not trivial since there are a number of previous works that point in the opposite direction. Second, our results show that a

gossip scheme performs very well, both in terms of vehicular traffic and telecommunications traffic overhead. In fact, when nodes are provided with full information about traffic with no delay, the average travel time only slightly decreases. Third, we show that monitoring only a subset of streets, even when these are the most congested streets, can lead to unsatisfactory results. In terms of future work, we are interested in studying the joint optimization of information dissemination and vehicle's trip times. Moreover, smart distribution techniques of traffic information could avoid the buildup of secondary congestion generated by the dissemination of identical information (e.g., avoiding a closed road can congest the obvious second best road). In conclusion, smart navigation represents a powerful and cost-efficient tool, which, together with others (e.g., use of public transportation, etc.), can combat the increase in traffic congestion in urban areas.

REFERENCES

- [1] F. Calabrese, M. Colonna, P. Lovisolo, D. Parata, and C. Ratti, "Real-time urban monitoring using cell phones: A case study in Rome," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 1, pp. 141–151, Mar. 2011.
- [2] R. G. Herrtwich, "Communicating vehicles—communicating roadways: New approaches to driver information and road safety," in *Proc. 11th Annu. ACM Int. Conf. Mobile Comput. Netw.—Invited Talk*, 2005.
- [3] R. Resendes, "The new grand challenge—Deploying vehicle communications," in *Proc. ACM Int. Workshop Veh. Inter-Netw.—Keynote Address*, 2008.
- [4] Y. Yang and R. Bagrodia, "Evaluation of VANET-based advanced intelligent transportation systems," in *Proc. 6th ACM Int. Workshop Veh. Inter-Netw.*, 2009, pp. 3–12.
- [5] S. Eubank, H. Guclu, V. Kumar, M. Marathe, A. Srinivasan, Z. Toroczkai, and N. Wang, "Modelling disease outbreaks in realistic urban social networks," *Nature*, vol. 429, no. 6988, pp. 180–184, May 2004.
- [6] M. Beckmann, C. B. McGuire, and B. Winsten, *Studies in the Economics of Transportation*. New Haven, CT: Yale Univ. Press, 1955.
- [7] R. Jayakrishnan, H. Mahmassani, and T. Y. Hu, "An evaluation tool for advanced traffic information and management systems in urban networks," *Transp. Res. Part C: Emerging Technol.*, vol. 2, pp. 126–147, Sep. 1994.
- [8] R. Arnott, A. de Palma, and R. Linsdey, "Does providing information to drivers reduce traffic congestion?" *Transp. Res. Part A: Gen.*, vol. 25, no. 5, pp. 309–318, Sep. 1991.
- [9] H. M. Al-Deek, A. J. Khattak, and P. Thananjeyan, "A combined traveler behavior and system performance model with advanced traveler information systems," *Transp. Res. Part A: Policy Pract.*, vol. 32, no. 7, pp. 479–493, Sep. 1998.
- [10] T. Nadeem, S. Dashtinezhad, C. Liao, and L. Iftode, "TrafficView: Traffic data dissemination using car-to-car communication," *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 8, no. 3, pp. 6–19, Jul. 2004.
- [11] L. Wischhof, A. Ebner, and H. Rohling, "Information dissemination in self-organizing intervehicle networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 6, no. 1, pp. 90–101, Mar. 2005.
- [12] C. Sommer, R. German, and F. Dressler, "Bidirectionally coupled network and road traffic simulation for improved IVC analysis," *IEEE Trans. Mobile Comput.*, vol. 10, no. 1, pp. 3–15, Jan. 2011.
- [13] F. Soriguera and F. Robuste, "Requiem for freeway travel time estimation methods based on blind speed interpolations between point measurements," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 1, pp. 291–297, Mar. 2011.
- [14] M. Westerman, R. Litjens, and J. Linnartz, "Integration of probe vehicle and induction loop data: Estimation of travel times and automatic incident detection," Univ. California, Berkeley, CA, Tech. Rep. UCB-ITS-PRR-96-13, 1996.
- [15] K. Sampiget, L. Huang, M. Li, R. Poovendran, K. Matsuura, and K. Sezaki, "CARAVAN: Providing location privacy for VANET," in *Proc. Embedded Sec. Cars*, 2005, pp. 1–5.
- [16] M. Gerlach, "Assessing and improving privacy in VANETs," in *Proc. Embedded Sec. Cars*, 2006, pp. 19–28.
- [17] M. Gerlach and F. Guttler, "Privacy in VANETs using changing pseudonyms—Ideal and real," in *Proc. 65th Veh. Technol. Conf.—Spring*, 2007, pp. 2521–2525.
- [18] J. Serna, J. Luna, and M. Medina, "Geolocation-based trust for VANET's privacy," in *Proc. Int. Symp. Inf. Assur. Security*, 2008, pp. 287–290.
- [19] M. Gerlach, "Trust for vehicular applications," in *Proc. 8th Int. Symp. Auton. Decentralized Syst.*, 2007, pp. 295–304.
- [20] Z. Wang and C. Chigan, "Cooperation enhancement for message transmission in VANETs," *Wireless Pers. Commun.*, vol. 43, no. 1, pp. 141–156, Oct. 2007.
- [21] P. Papadim, L. Buttyan, T. Holczer, E. Schoch, J. Freudiger, M. Raya, Z. Ma, F. Kargl, A. Kung, and J. P. Hubaux, "Secure vehicular communications: Design and architecture," *IEEE Commun. Mag.*, vol. 46, no. 11, pp. 100–109, Nov. 2008.
- [22] J. J. Haas, Y. C. Hu, and K. P. Laberteaux, "Design and analysis of a lightweight certificate revocation mechanism for VANET," in *Proc. 6th ACM Int. Workshop Veh. Internetworking*, 2009, pp. 89–98.
- [23] [Online]. Available: <http://tiger.census.gov/>
- [24] F. Bai, N. Sadagopan, and A. Helmy, "The important framework for analyzing the impact of mobility on performance of routing for ad hoc networks," *Ad Hoc Netw.*, vol. 1, no. 4, pp. 383–403, Nov. 2003.
- [25] G. Marfia, G. Pau, E. De Sena, E. Giordano, and M. Gerla, "Evaluating vehicle network strategies for downtown Portland: Opportunistic infrastructure and the importance of realistic mobility models," in *Proc. 1st MobiSys Int. Workshop Mobile Opportunistic Netw.*, 2007, pp. 47–51.
- [26] I. Leontiadis and C. Mascolo, "Opportunistic spatio-temporal dissemination system for vehicular networks," in *Proc. 1st Int. MobiSys Workshop Mobile Opportunistic Netw.*, 2007, pp. 39–46.
- [27] I. Leontiadis, P. Costa, and C. Mascolo, "A hybrid approach for content-based publish/subscribe in vehicular networks," *Pervasive Mobile Comput.*, vol. 5, no. 6, pp. 697–713, Dec. 2009.
- [28] C. E. Palazzi, M. Rocchetti, and S. Ferretti, "An inter-vehicular communication architecture for safety and entertainment," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 1, pp. 90–99, Mar. 2010.
- [29] Z. J. Haas, J. Y. Halpern, and L. Li, "Gossip-based ad hoc routing," *IEEE/ACM Trans. Netw.*, vol. 14, no. 3, pp. 479–491, Jun. 2006.
- [30] R. Sedgewick and J. S. Vitter, "Shortest paths in Euclidean graphs," *Algorithmica*, vol. 1, no. 1, pp. 31–48, Jan. 1986.
- [31] Q. Song and X. Wang, "Efficient routing on large road networks using hierarchical communities," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 1, pp. 132–140, Mar. 2011.
- [32] S. Tepley and G. D. Evans, "Evaluation of the quality of signal progression by delay distributions," *Transp. Res. Board, Transp. Res. Rec.*, no. 1225, pp. 1–7, 1989.
- [33] C. Lochert, A. Barthels, A. Cervantes, M. Mauve, and M. Caliskan, "Multiple simulator interlinking environment for IVC," in *Proc. 2nd ACM Int. Workshop Veh. Ad Hoc Netw.*, 2005, pp. 87–88.
- [34] S. Y. Wang, C. L. Chou, Y. H. Chiu, Y. S. Tseng, M. S. Hsu, Y. W. Cheng, W. L. Liu, and T. W. Ho, "An integrated simulation platform for vehicular traffic communication and network researches," in *Proc. 1st IEEE Int. Symp. Wireless Veh. Commun.*, 2007, pp. 2081–2085.
- [35] Y. Pigne', G. Danoy, and P. Bouvry, "A platform for realistic online vehicular network management," in *Proc. 2nd IEEE Int. Workshop Manage. Emerging Netw. Services*, 2010, pp. 615–619.
- [36] [Online]. Available: <http://www.scalable-networks.com/>
- [37] G. Marfia, P. Lutterotti, and G. Pau, "MobiTools: An integrated toolchain for mobile Ad Hoc networks," Univ. California, Los Angeles, CA, Tech. Rep. 070019, 2007.
- [38] K. Kobayashi, "Information and rational expectations and network equilibria—An analytical perspective for route guidance systems," *Springer Ann. Regional Sci.*, vol. 28, no. 4, pp. 369–393, Dec. 1994.
- [39] [Online]. Available: http://grouper.ieee.org/groups/802/11/Reports/tgp_update.htm
- [40] [Online]. Available: <http://vehicular.cs.ucla.edu/>



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