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Deployment of a fully distributed system for improving urban traffic flows: A simulation-based performance analysis

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A B S T R A C T

Distributed, cooperative systems dedicated to road traffic self-organization are very attractive, but present some drawbacks. In particular, their cooperative nature makes them fairly inefficient when working with a reduced number of partners. This situation typically corresponds to the deployment stage, during which only a few vehicles cooperate. This time period cannot be avoided when pushing a new system to the market. We are interested in two features that are important for this kind of system: traffic jam detection and traffic alert transmission. For the first feature, we present a theoretical model that anticipates the proportion of equipped vehicles that allows an acceptable level of traffic jam detection, and we validate this model by simulation. For the second feature, we examine two ways to improve the system behaviour when the proportion of equipped vehicles is very low; their efficiency is tested through simulation. This study is innovative because the simulation platform we developed can take into account the directional behaviour of wireless communications in urban context for a low computational cost.

1. Introduction

The development of urban, suburban or inter-urban transportation generates many traffic jams arising from structural reasons or unexpected events. One possible means of combating these traffic jams is to use a Personal Navigation Assistant (PNA). To allow the users to reorganize their trips, these PNA must be able to perform a dynamic routing based on up-to-date data provided by a Traffic Information System (TIS). Such systems have already been proposed. Most of them are academic projects (e.g., Notice [1], SaveTime [2], Street Smart [3], TraffCon [4], SOTIS [5], Cartel [6]); a few others are commercial products (e.g., TMC [7], Dash Express [8] or TomTom HD Traffic [9]).

Whatever the approach, up-to-date traffic data must be provided to vehicles. Thus, it is necessary to measure the current state of traffic (*measurement*), construct a synthetic picture of this state (*aggregation*), and send this information to the vehicles concerned by dynamic routing (*diffusion*). Each of these three functions can be either *centralized* (i.e., performed by a common equipment) or *distributed* (i.e., performed by the vehicles). In this article, we suppose that all the above functions are distributed, leading to the definition of Distributed Traffic Information Systems (DTISs).

DTIS are inherently cooperative, which means that they cannot be effective when used by too few vehicles. This feature makes introducing these systems on the market difficult because their early users might gain no advantage. This situation typically arises during the deployment stage, which cannot be avoided. In addition, too little research has been done to address this major problem affecting DTIS. The aim of this article is to study the efficiency of DTIS when they are used by a low

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proportion of road users, and examine the ways to make them efficient enough in this situation. We focus here on the measurement and diffusion tasks because they provide key data for the DTIS and they are directly impacted by a low number of cooperative contributors.

2. Survey of traffic information systems

Historically, Traffic Information Systems (TISs) were based on Traffic Information Centers (TICs). In this approach, traffic data are collected by various sensors, either attached to the road network (e.g., Notice [1,7], TraffCon [4]), or carried by the vehicles (e.g., [9], Save Time [2]). Some systems (e.g., Dash Express [8]), may use both information sources. Raw traffic data are then sent to a TIC, where they are processed. Compiled data and/or advice about traffic are sent to the relevant vehicles, so that users may change their itinerary. The media used for this purpose may be an FM radio, using the Radio Data System (RDS) protocol in the Traffic Message Channel (TMC) system, or the cellular phone network.

Because the TIC approach is based on a global view, it allows a proactive management of the traffic. On the other hand, the disadvantages are numerous:

- Hawasa et al. [10] emphasize the computational power needed to implement a TIC.
- The deployment of fixed sensors is expensive so equipping the whole road network is impossible; for this reason, this approach is not scalable [11].
- When the sensors are attached to vehicles, cell phone networks are generally used to transport information; this network use is invoiced by the network providers [11].
- Sending traffic information from the TIC to the vehicles may be costly for the end user when using cell phone networks or inaccurate when using the TMC system.
- These systems are not very responsive, with a minimum latency delay of about 10 min.

For these reasons, research has been oriented toward another approach in which the various functions are distributed.

In DTIS, each vehicle helps to evaluate of the traffic quality. Information is exchanged directly among the vehicles on a wireless short-range medium. This architecture is very scalable, since each vehicle provides its own resources. It can be implemented everywhere, without infrastructure or operating costs. Because traffic data is directly transferred from vehicle to vehicle, this approach delivers extremely quick responses: less than a few seconds in case of short- or medium-range traffic (i.e., urban or suburban conditions). However, DTIS are difficult to set up because of their distributed nature. For this reason, commercial applications are not yet available, and this DTIS approach is still an open research topic. For example, it has been proposed by Yang and Recker [12], Wischoff et al. [5], Dornbush and Joshi [3] and Gibaud et al. [13].

The smooth functioning of a DTIS can be perturbed by several specific problems, for example:

- *Data storms*: A piece of information is first emitted, then forwarded by numerous vehicles, which may cause a saturation of the media [14]. This phenomenon is annoying because it could hide significant but minority information. It can also interfere with other activities when the medium is not reserved for traffic information.
- *Lack of data*: In areas with low density of equipped vehicles, data may not be generated (i.e., *sampling problem* [15,16]), or forwarded (i.e., *communication problem* [17,18]). In this case, data may be missing, lost or outdated before it is used.

Data storms cannot take place during the system's deployment, which is characterized by a low density of equipped vehicles. In contrast, lack of data is likely to occur during this deployment, whose duration is hard to estimate. A key subject is providing a significant gain to equipped vehicles during the deployment, thus making DTIS successful (i.e., accepted by their potential users) [19,20].

Most articles on this subject (e.g., [21,22]), do not address the problem of deployment on its own, but as a special case of sparsely connected Vehicular Ad-hoc NETwork (VANET). According to this approach, a poor connectivity may result from several causes, such as a low amount of traffic or vehicles clustering, which are not immediately related to a low penetration rate. Although this approach generally gives interesting results (e.g., suitable communication protocols), it does not specifically take into account the problem of generating traffic alerts.

For example, Zang et al. [23] present a system to avoid pile-ups on the highway and study the efficiency of messages diffusion, in terms of the system's penetration rate. However, an important aspect is not taken into account: in order to generate the crash alert, the first crashed vehicle must be equipped. From a general perspective, detecting perturbations is still ignored and remains a real issue for the development of DTIS.

3. A cooperation model for DTIS: the FORESEE approach

The way in which the vehicles cooperate may have a great influence on the traffic. This is the reason why we proposed the FORESEE cooperation model, which we used for our experiments. The model was described in more detail in Gibaud et al. [13]. This model is based on a fully distributed system composed of a set of agents that are physically installed in each vehicle. Each agent is a driving assistant that evaluates the surrounding traffic conditions from data sent by the other agents on a