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Traffic congestion detection in large-scale scenarios using vehicle-to-vehicle communications

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ABSTRACT

Cooperative vehicular systems are currently being investigated to design innovative ITS (*Intelligent Transportation Systems*) solutions for road traffic management and safety. Through the wireless exchange of information between vehicles, and between vehicles and infrastructure nodes, cooperative systems can support novel decentralized strategies for ubiquitous and more cost-attractive traffic monitoring. In this context, this paper presents and evaluates CoTEC (*COperative Traffic congestion detECtion*), a novel cooperative technique based on Vehicle-to-Vehicle (V2V) communications designed to detect road traffic congestion. CoTEC is evaluated under large-scale highway scenarios using iTETRIS, a unique open source simulation platform created to investigate the impact of cooperative vehicular systems. The obtained results demonstrate CoTEC's capability to accurately detect and characterize road traffic congestion conditions under different traffic scenarios and V2V penetration rates. In particular, CoTEC results in congestion detection probabilities higher than 90%. These results are obtained without overloading the cooperative communications channel. In fact, CoTEC reduces the communications overhead needed to detect road traffic congestions compared to related techniques by 88%.

1. Introduction

Cooperative vehicular communications represent a promising technology to improve road traffic safety and efficiency. Through the continuous exchange of messages between vehicles (Vehicle-to-Vehicle or V2V communications), and between vehicles and infrastructure nodes (Vehicle-to-Infrastructure or V2I communications), real-time information about the current road traffic conditions can be cooperatively collected and shared. In particular, vehicles can estimate their surrounding traffic conditions by overhearing the beacon or heartbeat messages, also known as CAMs (*Cooperative Awareness Messages*), periodically broadcasted by neighboring vehicles; these messages include important information about the vehicle's position and speed. In contrast to conventional infrastructure-based monitoring solutions (e.g. inductive loops or video cameras) that can only detect traffic conditions at the locations where the sensors are deployed, cooperative vehicular systems could be able to monitor any road segment through its V2V-based monitoring capabilities. Despite their potential, the lack of quantifiable performance indicators in large-scale scenarios demonstrating their beneficial impact may hinder the eventual take-up and establishment of cooperative vehicular systems. In this context, this paper presents CoTEC (*COperative Traffic congestion detECtion*), a novel technique designed to efficiently detect and characterize road traffic congestion using V2V communications. The proposed technique is capable of providing valuable information to road traffic managers about the characteristics of the detected congestion conditions, for example, its location, length and intensity. To demonstrate its benefits, CoTEC is evaluated under large-scale highway scenarios using the iTETRIS platform (*an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions*, http://www.ict-itetris.eu/). The obtained results demonstrate that CoTEC can accurately detect road traffic congestion conditions without deploying any infrastructure sensors and requiring significant communications overhead. This capability is demonstrated under different traffic and deployment scenarios, including varying V2V penetration rates.

The rest of the paper is organized as follows. Section 2 reviews the different V2V-based traffic monitoring solutions that have been reported to date in the literature. The techniques are reviewed based on their capability to detect congestion, and the type of traffic information they can provide. Based on the identified need for more precise and efficient V2V-based traffic monitoring solutions, Section 3 presents CoTEC and details its operation. Section 4 introduces the iTETRIS simulation platform, and describes how to implement and

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integrate into the platform an external traffic management application such as CoTEC. Section 5 analyzes CoTEC's capability to accurately and efficiently detect road traffic congestion conditions. This analysis includes the comparison of CoTEC against another state-of-the-art V2V-based traffic monitoring solution and an infrastructure-based detection mechanism. Finally, Section 6 summarizes CoTEC's main benefits and capabilities to efficiently and accurately detect road traffic congestion conditions using V2V communications.

2. V2V-based traffic monitoring

The potential of cooperative vehicular communications has fostered the design of innovative V2V-based traffic monitoring solutions. For example, (Fukumoto et al., 2007) presents the COC (*Contents Oriented Communications*) proposal where vehicles estimate road traffic density from received beacon messages, and periodically transmit this information to other vehicles. Vehicles can then detect traffic congestion conditions by comparing the exchanged traffic density estimates with average density values for the road segments under evaluation. This capability is obtained at the expense of overloading the communications channel through the continuous exchange of traffic density estimates. To limit the communications load, TrafficView (Nadeem et al., 2004) employs an aggregation method that combines data from different vehicles located close to each other. Other techniques also propose to efficiently combine the information generated by multiple vehicles using digital road maps. For example, the SOTIS technique reported in (Wischhof et al., 2005) proposes vehicles to generate and exchange traffic information about the road segment they are currently located in, and other road segments for which they have traffic information. This information can be generated by the vehicles themselves or received from other vehicles. Differently from SOTIS, the technique reported in (Miller, 2008) proposes that only one vehicle in each road segment is in charge of collecting and aggregating road traffic data. This information is then transmitted to adjacent road segments. However, the selection of the vehicle responsible for the data aggregation usually generates additional signaling overhead. The techniques previously described require the periodic exchange of packets different from the beacon messages already included in the IEEE802.11p/WAVE or ITSG5A standards (ETSI, 2011). To reduce the overhead generated by these messages, StreetSmart (Dornbush and Joshi, 2007) limits the exchange of traffic information to only situations of unexpected or abnormal traffic conditions, e.g. traffic jams. The mechanism reported in (Vaqar and Basir, 2009) by Vaqar and Basir reduces the risk of communications overload by only estimating traffic congestion locally at each vehicle using pattern recognition techniques that exploit the beacon messages received from nearby vehicles. However, the lack of mechanisms to validate or correlate the traffic congestion estimates among various vehicles may lead to unreliable detections. This limitation is partially overcome in (Lin and Osafune, 2008), where Lin and Osafune propose a voting procedure so that neighboring vehicles exchange their traffic estimates and try to reach a consensus decision. The work reported in (Farazy-Fahmy and Ranasinghe, 2008) also proposes a cooperative detection process that calculates the number of vehicles in a traffic jam using a tree-based counting algorithm. However, the formation and management of the tree requires the exchange of a large number of packets, with the consequent risk of overloading the communications channel.

To summarize, Table 1 reviews the existing V2V-based traffic monitoring techniques based on their detection capabilities and the type of traffic information they provide. *Congestion detection* indicates the capability of the technique to monitor traffic conditions and detect congestion situations. *Detection correlation* refers to whether individual congestion estimates are correlated or not among several vehicles to reach a consensus decision. *Congestion level* and *Traffic jam length* refer to the technique's capability to classify the detected traffic jam's congestion level (or intensity) and quantify its length. *Limited overhead* indicates whether the technique is capable to limit the generation of communications overhead to only situations of abnormal traffic conditions (e.g. traffic jam). Finally, *Dissemination* indicates whether the technique includes the capacity to select the vehicle that will be in charge of disseminating the detected traffic congestion conditions to approaching vehicles or road authorities (e.g. through nearby road side units or cellular links). This capacity would avoid the possibility that multiple vehicles detecting the same traffic congestion conditions generate redundant messages that could overload the communications channel.

The conducted review has shown that good progress has been made so far towards designing innovative V2V-based traffic monitoring solutions. However, there is currently no technique capable of providing all the features summarized in Table 1, and further research is needed to accurately monitor traffic conditions while addressing the existing trade-off between accurate traffic congestion estimation and efficient use of the scarce communication resources. In this context, this paper presents CoTEC, a novel V2V-based traffic congestion detection technique that efficiently uses the communications channel. To this aim, vehicles only exchange traffic information messages when potential road traffic congestion has been detected. Vehicles implementing CoTEC continuously monitor their surrounding traffic conditions. When a congestion condition is detected, the vehicles launch a cooperative procedure to correlate their individual estimates and increase the congestion detection accuracy. In addition, an important novelty of CoTEC is that it can provide a valuable set of indicators

Table 1
V2V-based traffic monitoring techniques.

Technique	Congestion detection	Detection correlation	Congestion level	Traffic jam length	Limited overhead	Dissemination
COC (Fukumoto et al., 2007)	Yes	Yes	Yes[a]	Yes	No	No
TrafficView (Nadeem et al., 2004)	Yes[b]	Yes	Yes[a]	Yes	No	No
SOTIS (Wischhof et al., 2005)	Yes[b]	Yes	Yes[a]	Yes	No	No
Miller (Miller, 2008)	Yes[b]	Yes	Yes[a]	Yes	No	No
StreetSmart (Dornbush and Joshi, 2007)	Yes	Yes	Yes[a]	Yes	Yes	No
Vaqar (Vaqar and Basir, 2009)	Yes	No	Yes	No	Yes	No
Lin & Osafune (Lin and Osafune, 2008)	Yes	Yes[c]	No	No[d]	Yes	Yes

[a] The technique provides traffic information such as the vehicles' speed and/or traffic density. However, it does not classify the congestion level based on the collected traffic measurements.
[b] The technique has been designed to monitor road traffic conditions, but is currently not able to explicitly detect congestion situations.
[c] The detection correlation is based on a voting process carried out among vehicles located in the one-hop neighborhood; no multi-hop correlation is applied.
[d] The technique does not explicitly provide the traffic jam length. Such length could be indirectly inferred from the locations of the jam header and tail, but this would require an evolution of the original proposal.

characterizing traffic congestion conditions. In particular, CoTEC can provide information about the length, intensity, location and start time of the traffic jam. This information can be very valuable to road traffic operators in order to adopt effective actions to mitigate a detected road traffic congestion situation.

3. Methods of congestion detection

CoTEC implements a fuzzy-logic-based mechanism to locally detect traffic congestion conditions using the beacon messages received from surrounding vehicles. If a traffic congestion condition is locally detected, CoTEC activates a cooperative process that shares and correlates the individual estimations made by different vehicles to accurately sense and characterize the traffic congestion.

3.1. Local traffic congestion detection

Detecting traffic congestion is not a trivial task, and several metrics have been proposed in the literature. This paper is based on the process developed by Skycomp to classify and characterize road traffic congestion (Major highway performance ratings and bottleneck inventory - State of Maryland – Spring, 2009). By analyzing the traffic data collected through aerial surveys of different freeways, Skycomp provides their associated Level-Of-Service (LOS). This metric represents a quality measure to describe the operational conditions within a traffic stream, as defined by the Highway Capacity Manual (HCM) (Highway capacity manual - HCM 2000, 2000). Six different levels of service are defined, with LOS A representing free-flow conditions and LOS F describing breakdowns in vehicular flow. The HCM LOS system does not distinguish between different levels of traffic congestion for the LOS F category. However, Skycomp's proposal extends the HCM LOS F rating to differentiate distinct levels of traffic congestion. Since CoTEC is targeted at detecting and classifying traffic congestion, this work has adopted Skyscomp's extended HCM LOS F rating (Major highway performance ratings and bottleneck inventory - State of Maryland – Spring, 2009) reported in Table 2.

To classify the level of congestion, CoTEC proposes a traffic congestion quantification process based on fuzzy theory. As reported in (Binglei et al., 2008), mechanisms based on fuzzy logic are especially suitable for addressing complex non-deterministic decision problems such as the identification of traffic congestion. The CoTEC fuzzy-based detection mechanism takes the traffic density estimate and the vehicle's speed as input parameters, and provides the traffic congestion level as output parameter. The traffic density is locally estimated by each vehicle using the received beacon messages from neighboring vehicles. Each vehicle maintains a neighbor table that keeps record of the vehicles from which at least one beacon message has been recently received; their positioning data is also stored in the table. Every time a beacon message is received, the transmitting vehicle's entry in the neighbor table is updated. To avoid outdated information, information in the table is removed after a given timeout interval CAM_{Tout}. The traffic density can then be calculated using the information stored in the neighbor's table:

$$Density\ Estimation = \frac{NDN}{(d_{NeighFront} + d_{NeighBack}) \cdot NL} \quad (1)$$

where NDN is the Number of Detected Neighboring vehicles, $d_{NeighFront}$ and $d_{NeighBack}$ are the distance between the vehicle estimating the traffic density and the furthest detected vehicles located in front of and behind the estimating vehicle, and NL is the Number of Lanes of the road. CoTEC employs a moving average algorithm to avoid false congestion detection alarms due to transitory variations in the traffic flow. The algorithm averages the speed and density estimates before being passed to the congestion detection process. The *MAW* (Moving Average Window) parameter defines the time interval over which the estimates are averaged.

The input variables are classified into different categories or fuzzy sets. The defined fuzzy sets for the speed are *very slow, slow, medium* and *fast*, and for traffic density, *low, medium, high* and *very high*. A fuzzy set can contain elements with partial degree of membership, and consequently, an input value can belong to several fuzzy sets at the same time. To account for this possibility, CoTEC defines the membership functions depicted in Fig. 1, and that have been implemented following Skycomp's congestion rating system. Output fuzzy sets representing the different road traffic categories have also been defined according to Skycomp's congestion classification: *free-flow*$=0$, *slight congestion*$=1/3$, *moderate congestion*$=2/3$ and *severe congestion*$=1$. Finally, fuzzy rules relating the input (speed and density) and output fuzzy sets (congestion levels) have been established (Table 3). As Fig. 1(c) illustrates, the quantification output is a continuous value indicating the level of congestion, with 0 representing free flow conditions, and 1 representing severe traffic congestion conditions.

Wireless communications are characterized by large and fast variations of the received signal level as a result of multipath fading. This variability can negatively impact the accuracy of CoTEC's traffic density estimates obtained from Eq. (1). This is the case because the signal variability can result in sporadically detecting neighboring vehicles located at large distance, thereby increasing the $d_{NeighFront}$ and $d_{NeighBack}$ values. Since such detections are sporadic, not all vehicles located at distances below $d_{NeighFront}$ and $d_{NeighBack}$ will be detected, thereby resulting in inaccurate traffic density estimates. To illustrate the impact of the wireless signal variability, Table 4 compares the traffic density estimates obtained when only the pathloss propagation effect is reproduced (*Simplified* scenario), and when the pathloss, shadowing and multipath fading propagation effects are considered (*Complete* scenario). The data reported in Table 4 corresponds to a highway scenario with a constant traffic density of 48 veh/km/lane. The obtained results show that the signal variability characteristic of wireless communications significantly increases the maximum distance at which neighboring vehicles can be detected, and thereby the average number of detected vehicles. However, the traffic density is underestimated since distant vehicles are detected with a lower probability, as reported in Fig. 2.

CoTEC implements an additional optimization process to minimize the impact of sporadic detections of distant vehicles on traffic density estimates. Fig. 3 depicts the Cumulative Distribution Function (CDF) of the density estimation error when all the detected vehicles are taken into account to estimate the traffic density (*Without Optimization*). The figure also shows this error when the traffic density is estimated considering only the 50%, 60%, 70%, 80% and 90% closest detected vehicles. The density estimation error is computed as the difference between CoTEC's traffic density estimation and the correct traffic density measured from SUMO traces. As illustrated in Fig. 3, the traffic density is underestimated if the optimization process is not applied. When such process is applied, the underestimation is reduced as the percentage of selected vehicles diminishes. However, the results

Table 2
Skyscomp Levels of Congestion.

	Level of congestion	Density (veh/km/lane)	Speed (km/h)
LOS F	Slight	[29–37]	[48–81]
	Moderate	[37–50]	[24–64]
	Severe	Above 50	Below 40

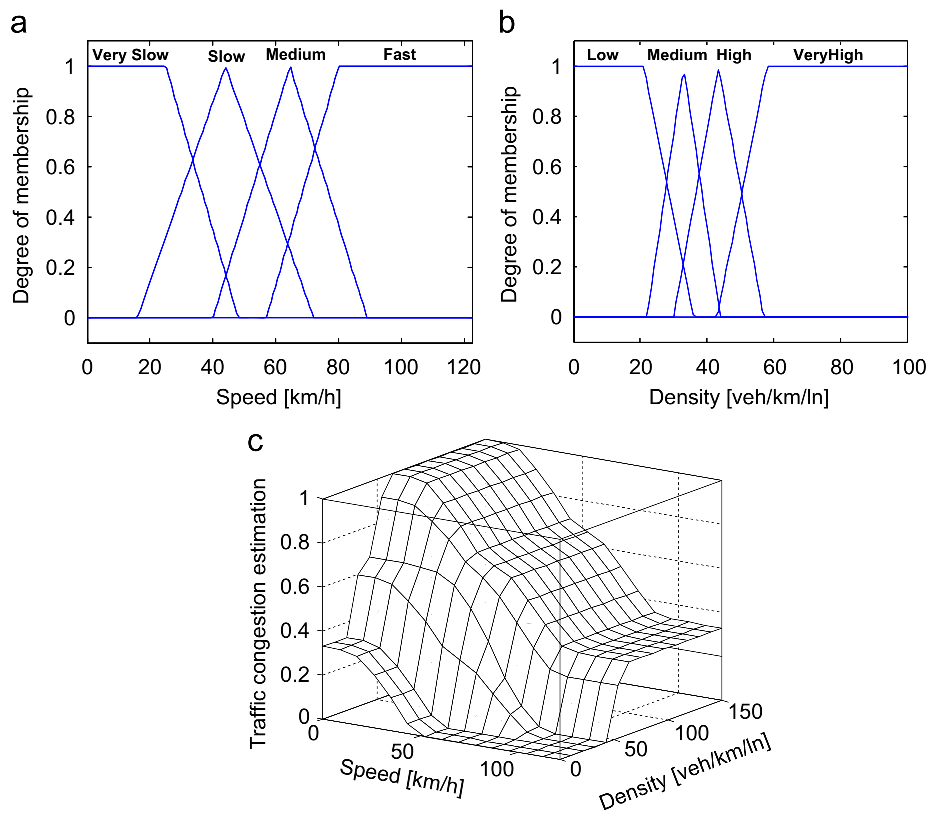

Fig. 1. CoTEC fuzzy-based congestion detection mechanism. (a) Speed membership functions. (b) Traffic density membership functions. (c) Level of congestion.

Table 3
CoTEC Fuzzy Rules.

		Traffic density			
		Low	Medium	High	Very High
Speed	Very Slow	Slight	Moderate	Moderate	Severe
	Slow	Free	Slight	Moderate	Moderate
	Medium	Free	Slight	Slight	Moderate
	Fast	Free	Free	Free	Slight

Table 4
Impact of Signal Variability on Traffic Density Estimation.

	Simplified	Complete
Max. detection distance [m]	287	589
Num. of detected neighbors	49	75
Density estimation [veh/km/lane]	45	35

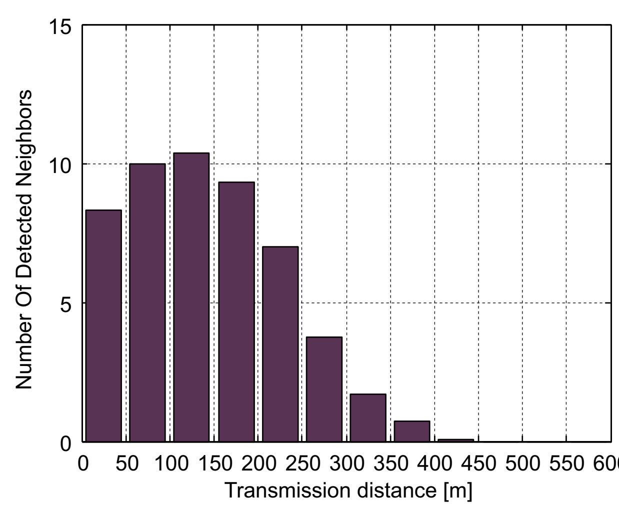

Fig. 2. Number of detected vehicles as a function of the distance (Complete scenario).

depicted in Fig. 3 show that reducing this percentage below 60% results in an overestimation of the traffic density. Based on these observations, CoTEC finally estimates the traffic density considering only the 60% closest detected vehicles.[1]

3.2. Cooperative traffic congestion detection

Every vehicle implementing CoTEC continuously monitors the road traffic conditions, and estimates through the fuzzy-based detection mechanism the current level of road congestion. When such level exceeds a predefined congestion threshold *Cth*,[2] vehicles activate a cooperative procedure based on multi-hop communications to achieve a consensus decision. This procedure allows collaboratively evaluating the individual estimations that different vehicles make locally, thereby improving the congestion detection accuracy. It is worth stressing that CoTEC does not generate any additional communications overhead with normal

[1] The selected percentage has been validated following a large set of simulations for the highway scenario described in Section 5. The scenario included thousands of vehicles, and considered various traffic densities and vehicular speeds.

[2] Cth corresponds to the minimum congestion level to be monitored, and its value can be varied depending on traffic management policies.

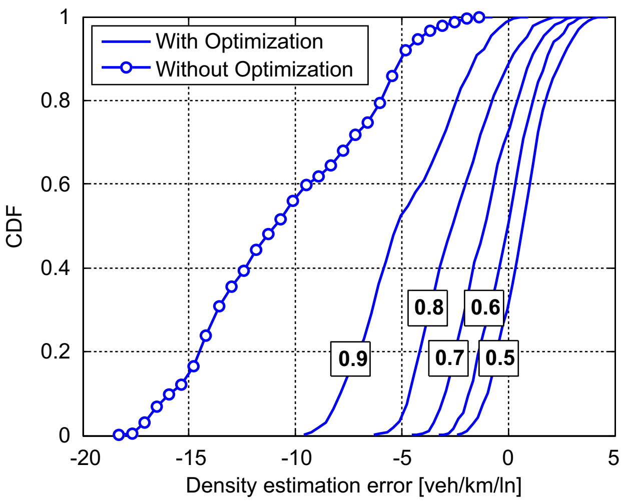

Fig. 3. CDF of the density estimation error.

traffic conditions, since the cooperative procedure is only launched when a congestion condition is locally detected.

CoTEC's cooperative detection mechanism is based on the exchange of CTE (*Cooperative Traffic Estimation*) messages; the exchange is launched when congestion is detected. These messages are employed to collect local traffic estimations made by different vehicles, and cooperatively correlate them to achieve a coherent and reliable detection. In addition, the exchange of CTE messages allows quantifying the level of congestion and its length. To this aim, vehicles located close to the front end of the traffic jam are responsible for the periodic generation of CTE messages which are multi-hop forwarded towards the rear end of the jam. Every vehicle relaying a CTE message updates the traffic information included in the message based on its own traffic estimation. Finally, vehicles situated in the rear end of the traffic jam that receive CTE messages will get a global and complete vision of the road congestion level, and will stop the forwarding process. In order to determine the location and length of the traffic jam, the CTE message includes the position of the first relaying vehicle within the traffic congestion.

CoTEC's successful operation requires accurately identifying the vehicles close to the front end of the traffic jam that will generate the CTE messages. To this aim, CoTEC defines a procedure by which vehicles that have recently left the traffic jam, and are therefore close to its front end, will be responsible for generating the CTE messages. To this aim, every vehicle evaluates its local traffic estimation for a certain period of time. The vehicle is considered to have recently left the traffic jam if its previous local estimations sustainably reported LOS F congestion level, and this level is not reported in its recent measurements. The vehicles at the front end of the traffic jam will periodically generate CTE messages at a selectable rate that will determine the periodicity of the traffic information updates. The procedure to identify the vehicles close to the front end of the traffic jam is fully configurable through three different parameters:

- *OI* (Observation Interval): time interval during which the reported congestion level is evaluated.
- *MCI* (Minimum Congestion Interval): a vehicle estimates to have been in the traffic jam if during *OI* it has reported LOS F congestion level for a time interval longer than *MCI*.
- *MFFI (*Minimum Free-Flow Interval): a vehicle estimates to have left the traffic jam if it has reported free-flow conditions for a time interval longer than *MFFI*.

Based on these configurable time intervals, a vehicle will generate a CTE message if it has detected LOS F condition for a time interval longer than *MCI* during *OI*, and has recently reported free-flow conditions for a time period longer than *MFFI*. CoTEC also implements an alternative method that is activated whenever vehicles are completely stopped in a traffic jam for a time interval longer than *VHI* (Vehicle Halted Interval). In this case, vehicles start monitoring the beacons transmitted by their neighbors to identify whether they are located at the front end of the traffic jam, and should therefore generate a CTE message. A vehicle estimates to be at the front end of the traffic jam, if 90% of received beacon messages come from vehicles located behind.

The delivery of CTE messages from the front end of the jam to its rear end is performed through a multi-hop information-centric forwarding protocol. In particular, CoTEC implements a contention-based scheme for the selection of forwarding nodes similar to CBF (Contention Based Forwarding) (Fussler et al., 2003), but adapted to operate at the application layer. When a vehicle wants to forward a CTE message, it single-hop broadcasts the packet to its neighbors. Vehicles receiving the message schedule the re-transmission of the message by activating a contention timer T_{Cont} with a duration inversely proportional to the distance to the previous forwarder (distant vehicles wait shorter times before re-transmitting the message). Vehicles receiving a CTE message from a vehicle behind will not attempt to retransmit the packet; as a result, the CTE message is only propagated backwards (in opposite direction to the traffic flow). T_{Cont} is computed as:

$$T_{Cont} = \begin{cases} T_{Max}\left(1-\frac{dist(c,p)}{Txon\ Range_{Max}}\right) & \text{if } dist(c,p) \le Txon\ Range_{Max} \\ 0 & \text{Otherwise} \end{cases} \quad (2)$$

where T_{Max} is the maximum forwarding delay, *dist(c,p)* is the distance between the vehicle currently attempting to transmit the CTE message and the previous forwarder, and $TxonRange_{Max}$ is the maximum expected communications range for a given transmission power. CoTEC employs a suppression mechanism by which vehicles that overhear the broadcast transmission of the scheduled CTE message from other neighbors will cancel their own re-transmission attempts. As a result, CoTEC limits the communications overhead by preventing that once a vehicle transmits a CTE message, other close-by vehicles generate additional and redundant CTE messages. The forwarding of a CTE message ends as soon as it reaches an area where vehicles do not detect congestion. If a vehicle receives a CTE message and has not locally detected traffic congestion, it would be considered to be located outside the traffic jam. This vehicle could then inform other approaching vehicles or traffic management authorities of the detected traffic congestion (this process is out of the scope of this paper).

While CTE messages are forwarded, the individual traffic congestion estimates are cooperatively processed to improve the congestion detection accuracy. Four different methodologies to cooperatively compute the congestion level were implemented and evaluated in (Bauza et al., 2010). The results showed that the technique based on the median statistic provides the best detection accuracy. This technique computes the median statistic of the congestion estimates based on grouped frequency distributions. The range of congestion levels to be monitored $[C_{th}, 1]$ is divided into intervals of equal width (0.1 in this work). The CTE message includes as many data fields as congestion intervals. Every time a vehicle forwards a CTE message, the frequency of the interval in which the vehicle's congestion estimation lies within is increased by the number of neighbors the forwarding vehicle has detected. This approach takes advantage of the fact that estimations made by vehicles geographically close to each other are relatively similar. As a result, a more accurate statistic can be obtained by considering all the neighboring vehicles that may have equivalent estimations. When the CTE message reaches the rear end of the

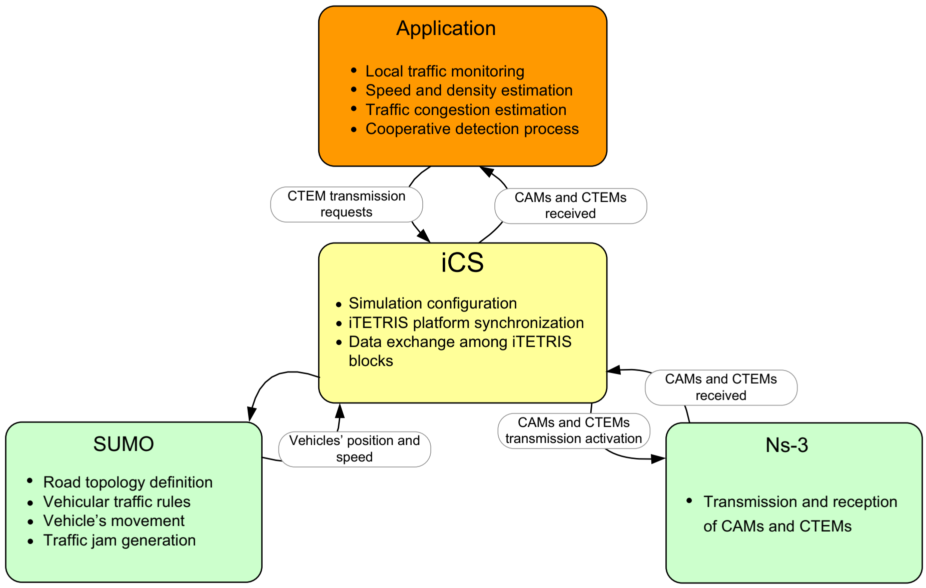

Fig. 4. iTETRIS architecture and integration of CoTEC into the iTETRIS platform.

traffic jam, the median of the traffic congestion estimations is computed based on the frequency intervals (Ott and Longnecker, 2010):

$$Median = L + \frac{w}{f_m}\left(\frac{n}{2} - cf_b\right) \quad (3)$$

where n is the total number of frequencies, L is the lower limit of the median congestion interval,[3] w is the width of the median congestion interval, f_m is the frequency of the median congestion interval, and cf_b is the cumulative frequency of the class preceding the median congestion interval.

4. iTETRIS simulation platform

The future deployment of cooperative vehicular communication solutions requires their extensive testing under large-scale scenarios. To this aim, CoTEC has been evaluated using the iTETRIS simulation platform that integrates two widely used open source platforms (SUMO and ns-3) to realistically investigate cooperative multi-technology vehicular systems in large-scale scenarios.

4.1. iTETRIS simulation platform

The iTETRIS platform is an open source, modular and computationally-efficient simulation tool capable of realistically simulating large-scale cooperative vehicular systems. Its architecture is shown in Fig. 4. The SUMO and ns-3 blocks are devoted to model and simulate traffic mobility and wireless communications respectively. The iCS (*iTETRIS Control System*) is a middleware module coordinating all the functional blocks involved in the simulation process. The *Applications* module is language-agnostic, and is implemented externally to facilitate the development and implementation of cooperative applications and traffic management strategies. This module interacts with the rest of the platform through the assistance of the iCS. The resulting iTETRIS architecture allows grouping in separate blocks the functionalities and simulation models related to transportation engineering, wireless communications and networking, and traffic management applications. Compared to tightly coupling and integrating these functionalities into a unique simulator, the adopted approach facilitates the use of iTETRIS by the different type of experts involved in the design, implementation and testing of cooperative vehicular solutions. iTETRIS implements a set of flexible and efficient interfaces based on IP sockets for the interaction and exchange of information among the different simulation blocks. The information is exchanged to and from the iCS following a client/server architecture, where the iCS is the client controlling and synchronizing the communication process, and the rest of blocks are servers that respond and act upon iCS requests.

The iTETRIS cooperative vehicular communications implementation is compliant with the European ITS communications architecture defined by the ETSI Technical Committee on ITS (ETSI, 2010a). The platform includes the ITS-G5A (ETSI, 2010b) (a European adaptation of the IEEE 802.11p/WAVE standards), UMTS, WiMAX and DVB-H access technologies (Bauza et al., 2009), and the ITS and IP transport and networking protocol stacks. The ITS stack facilitates multi-hop communications through the inclusion of geo-networking protocols. The ns3 iTETRIS module also includes the facilities' functions specified in the European ITS communications architecture that are related to communications (e.g. message management, service management and addressing mode), while the remaining facilities (e.g. relevance check, location referencing, station positioning, mobile station dynamics and LDM support) have been included in the iCS block for reducing the message exchange in the iTETRIS platform.

iTETRIS adopted the city of Bologna as its testing scenario, and the simulation platform includes different large-scale areas of the city where cooperative technologies could have a significant impact. In particular, the selected traffic scenarios include: an inner city area prone to traffic disruptions caused by football matches, and that is also close to the city cemetery and hospital; an inner city ring-way connected to an important city road with significant public transportation traffic; and an orbital road interconnected and running besides a highway that allows traffic movement across the two road infrastructures. The selected scenarios have been microscopically reproduced in SUMO based on real data obtained from the Bologna traffic database. The SUMO platform has also been extensively evolved within the iTETRIS project, and now incorporates valuable performance indicators such as pollutant and noise emission levels that allow precisely quantifying the effectiveness of cooperative traffic management policies from an environmental viewpoint.

[3] The median congestion interval is the class corresponding to cumulative frequency just $\geq n/2$.

4.2. Implementation of CoTEC

CoTEC has been implemented in C++ as an external traffic application (*Applications* module). Its integration in iTETRIS has been undertaken through the subscriptions system provided by the iCS. By means of subscriptions, external applications are able to request traffic information from the iTETRIS platform. Accordingly, the iCS periodically provides the applications with the requested traffic information, for example, information about the position and speed of the vehicles present in the scenario. In addition, the applications can employ the communications-related subscriptions to request the wireless transmission of cooperative messages in ns-3 (e.g. CTE messages), and collect the messages that have been successfully received through V2V communications. Fig. 4 summarizes the integration of CoTEC in iTETRIS, and illustrates the interaction and information exchanged between the different iTETRIS blocks. SUMO periodically calculates the position and speed of all the vehicles present in the scenario. ns-3 employs this information (obtained through the iCS) to simulate the wireless exchange of information between vehicles. As described in Section 3, CoTEC is able to locally detect traffic congestion by analyzing the beacon (or CAM) messages received from neighboring vehicles. ns-3 simulates the transmission of beacon messages, and returns the set of messages that have been successfully received by each vehicle. This information is delivered to the CoTEC application through the iCS. Based on the received messages, CoTEC first estimates the speed and traffic density in each vehicle's local neighborhood, and then decides whether to generate a CTE message if traffic congestion has been detected locally. If a CTE message is necessary, its ns3 transmission is activated by CoTEC through the iCS module. The iCS also informs the CoTEC application about the CTE messages that have been successfully exchanged. When CoTEC detects that a vehicle located outside the traffic jam has received a CTE message, it estimates the traffic congestion level through the cooperative process and the median metric described in Section 3.2.

5. CoTEC performance

CoTEC's performance has been evaluated in the iTETRIS highway scenario depicted in Fig. 5, and covering an area of 50 km × 20 km. The highway has two directions and two lanes per direction, and the maximum speed is limited to 130 km/h. The performance evaluation has conducted under three scenarios characterized by different vehicle traffic densities under free-flow conditions (i.e. before the traffic jam takes place): scenario A (5 veh/km/lane), scenario B (10 veh/km/lane) and scenario C (15 veh/km/lane). Each conducted simulation corresponds to more than 2 hours of real road traffic, and several simulations have been executed for each scenario to guarantee the statistical validity of the obtained results. The relative error of the observed mean values was kept below 0.05 in all cases using 95% confidence intervals. The maximum number of vehicles in the highway at a given point in time during each simulation run was 4500 vehicles. Traffic congestion has been generated over a two-lane highway segment by gradually reducing the maximum speed limit from 130 km/h to 10 km/h, which varies the traffic density throughout the simulations between 5 veh/km/lane and 70 veh/km/lane.

To evaluate CoTEC's capability to accurately detect and characterize road traffic congestion conditions, its performance is compared against that obtained with the technique proposed by Lin and Osafune, and an infrastructure-based monitoring solution using inductive loops. Lin and Osafune technique (Lin and Osafune 2008) has been selected as it is the only available V2V-based solution that it is able to trigger traffic congestion notifications based solely on traffic measurements collected through beacon or CAM messages (thereby limiting the communications overhead). In addition, Lin and Osafune technique also correlates congestion estimates between one-hop neighbors through a voting procedure. The infrastructure-based monitoring solution considers the deployment of inductive loops along the highway; several separation distances between loops (from 100 m to 1000 m) have been simulated. Each inductive loop provides traffic statistics about the number of sensed vehicles (flow) and their average speed every 10 seconds. The traffic density estimated by the inductive loops is obtained as the ratio between the traffic flow and the average speed. The traffic density and speed estimates are then used as input parameters to the fuzzy-based detection process. The congestion level estimated using the infrastructure-based monitoring solution is finally obtained by averaging the individual estimations made by the different loops deployed along the road segment where the traffic congestion is detected. This process is followed to conduct a fair comparison with CoTEC's congestion estimation.

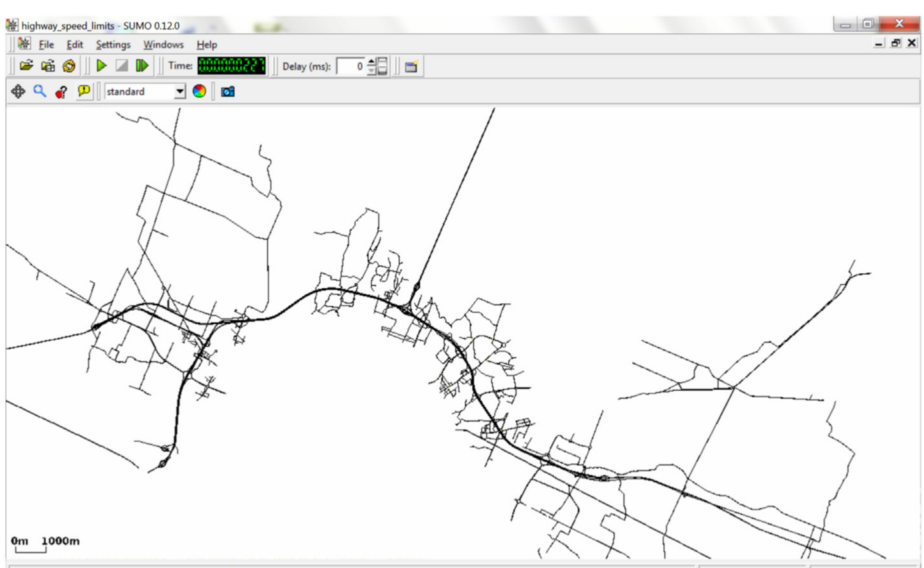

Fig. 5. Snapshot of the simulated SUMO highway scenario.

5.1. Lin and Osafune congestion detection technique

The work reported by Lin and Osafune in (Lin and Osafune, 2008) considers that vehicles periodically exchange data (mainly speed and position information) between one-hop neighbors. Based on the collected data, each vehicle can estimate the traffic condition in its neighborhood. Traffic congestion can be detected based on two different speed parameters computed over a time window *MAW*: (a) the average speed of the estimating vehicle, and (b) the average relative speed between the estimating vehicle and its neighbors. If the first average speed is lower than a predetermined threshold AST_1 (First Average Speed Threshold), the vehicle estimates to be in a traffic jam. Additionally, when the second average speed is below a predetermined threshold AST_2 (Second Average Speed Threshold), the detection technique considers that the estimating vehicle and the neighboring vehicles are traveling at a similar speed and/or subject to the same traffic condition. The proposal reported in (Lin and Osafune, 2008) also implements a voting process among one-hop neighbors to confirm a detected traffic congestion condition, and identify the beginning and end positions of the traffic jam. Once a vehicle locally detects traffic congestion, it broadcasts a voting message to request neighboring vehicles to transmit their own traffic condition estimates. If the percentage of neighboring vehicles that also report a congestion condition is above *NDT* (Neighbor Detection Threshold), the traffic congestion is considered to be confirmed. Based on the relation between the number of downstream and upstream vehicles that have also detected traffic congestion, a vehicle can determine its position within the traffic congestion. If this difference is above *HTDT* (Header and Tail Detection Threshold), the vehicle estimates being located at the

Table 5
Simulation Parameters.

Wireless communications	
Communications Channel	Control Channel - CCH
CAM Frequency	2 Hz
CAM_{Tout}	5 s
Propagation Model	Cheng Highway model (Cheng et al., July 2008)
Transmission Power	10 dBm, 15 dBm, 20 dBm
V2V Penetration Rate	100%, 75%, 50%
CoTEC	
MAW	10 s
Congestion Threshold C_{th}	1/6
OI	5 s
MCI	4 s
MFFI	1 s
T_{max}	1 s
$TxonRange_{Max}$	700m
Lin and Osafune	
MAW	10 s
AST_1	40 km/h
AST_2	10 km/h
NDT	70%
HTDT	30%

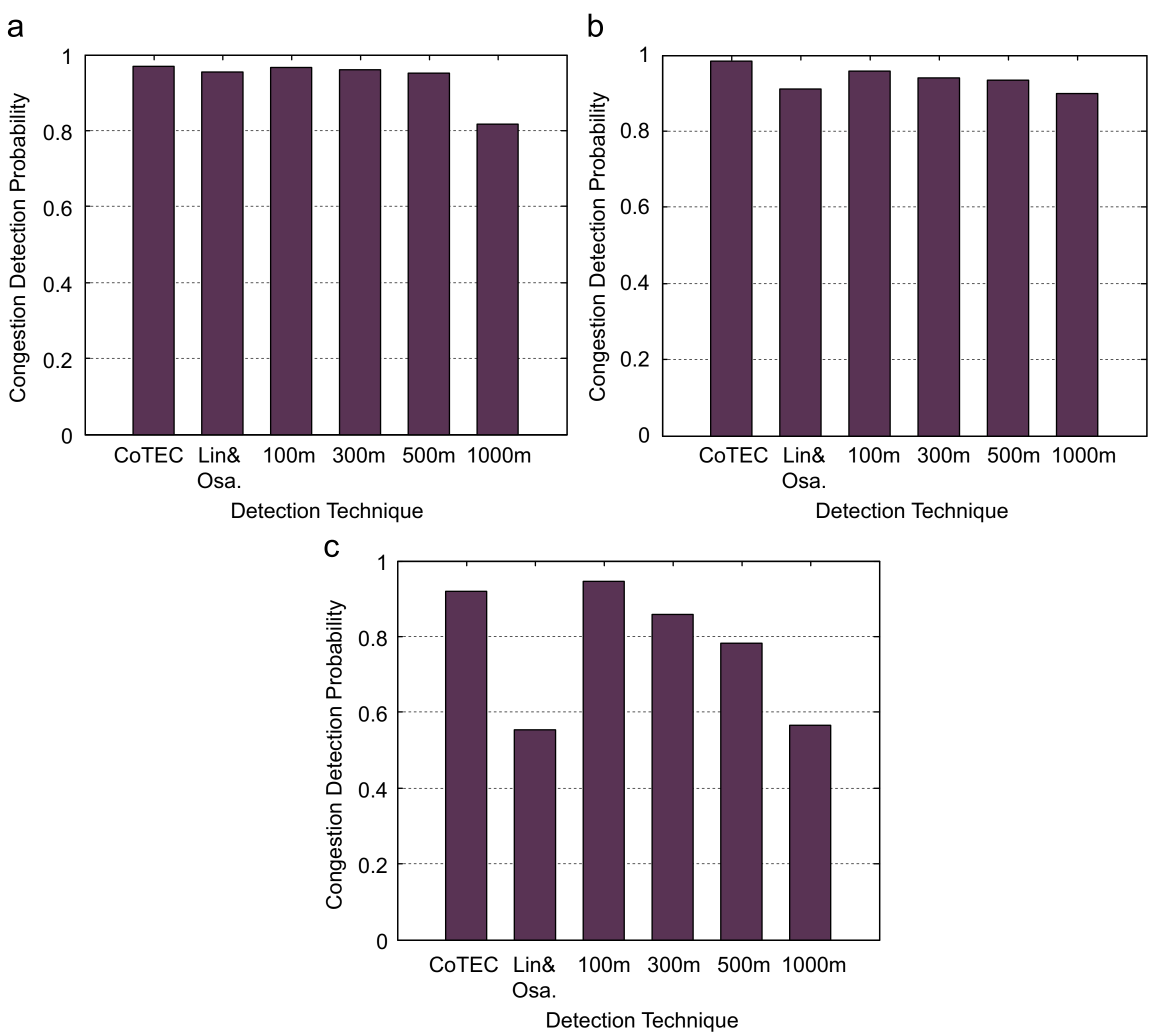

Fig. 6. Congestion detection probability. (a) Scenario A, (b) Scenario B and (c) Scenario C.

rear end of the traffic jam. It is important to note that Lin and Osafune technique is not capable to indicate the length or intensity of the traffic congestion.

5.2. Simulation results

Table 5 summarizes the 802.11p/ITS-G5A V2V communication parameters, radio propagation model, and configuration parameters for the CoTEC and Lin and Osafune techniques. The configuration parameters for both V2V detection techniques have been selected following a simulation-based optimization process, with the results presented here corresponding to those parameters offering the best performance for each V2V detection technique.

Fig. 6 depicts the congestion detection probability, i.e. the probability of successfully detecting a congestion event, for the three detection techniques. The obtained results show that under scenarios A and B (characterized by low and medium traffic densities in the absence of traffic congestion) all three techniques are able to detect traffic congestion with a probability higher than 80%. However, for scenarios with more dense traffic conditions (scenario C), Lin and Osafune's congestion detection capability is seriously deteriorated. This is due to the fact that Lin and Osafune technique only bases its congestion estimation on the collected vehicles' speed, while CoTEC also considers traffic density estimates. Considering both speed and traffic density provides CoTEC with the capability to detect road traffic congestions irrespectively of the traffic scenario. Fig. 6 also shows that the use of inductive loops with a low separation distance results in a congestion detection probability similar to that obtained with CoTEC. However, increasing the separation distance between inductive loops reduces the number of locations where traffic information is collected, and thereby seriously degrades the congestion detection probability. This trend emphasizes the existing trade-off between detection accuracy and deployment cost of inductive loops, and the opportunities resulting from the use of V2V-based detection techniques such as CoTEC.

To evaluate the detection's accuracy, the traffic congestion estimates obtained with the evaluated detection techniques are compared against those obtained using an idealistic monitoring solution that would have full access to all the traffic information for the congested road segment (this solution is referred to as Centralized solution). The idealistic approach obtains the vehicles' speed and traffic densities in the congested road segment directly from SUMO traces. Fig. 7 illustrates the congestion estimation error (mean and 95th percentile) comparing the CoTEC and inductive loops congestion estimates against that obtained with the Centralized solution; the figure includes results for several separation distances between inductive loops. The estimation error is computed as the difference in the congestion level estimates obtained by the Centralized approach, and the CoTEC and inductive loops detection techniques. The negative sign of the estimation error indicates that the congestion is underestimated. It is convenient to note that Lin and Osafune technique has not been included in this analysis since the technique cannot provide information about the intensity of traffic congestion. The results depicted in Fig. 7 show that the congestion estimation error increases with the separation distance between inductive loops for all traffic scenarios. This is due to the fact that as the separation distance increases, the traffic information available to estimate the traffic congestion decreases. The results depicted in Fig. 7 demonstrate that CoTEC's mean congestion estimation error

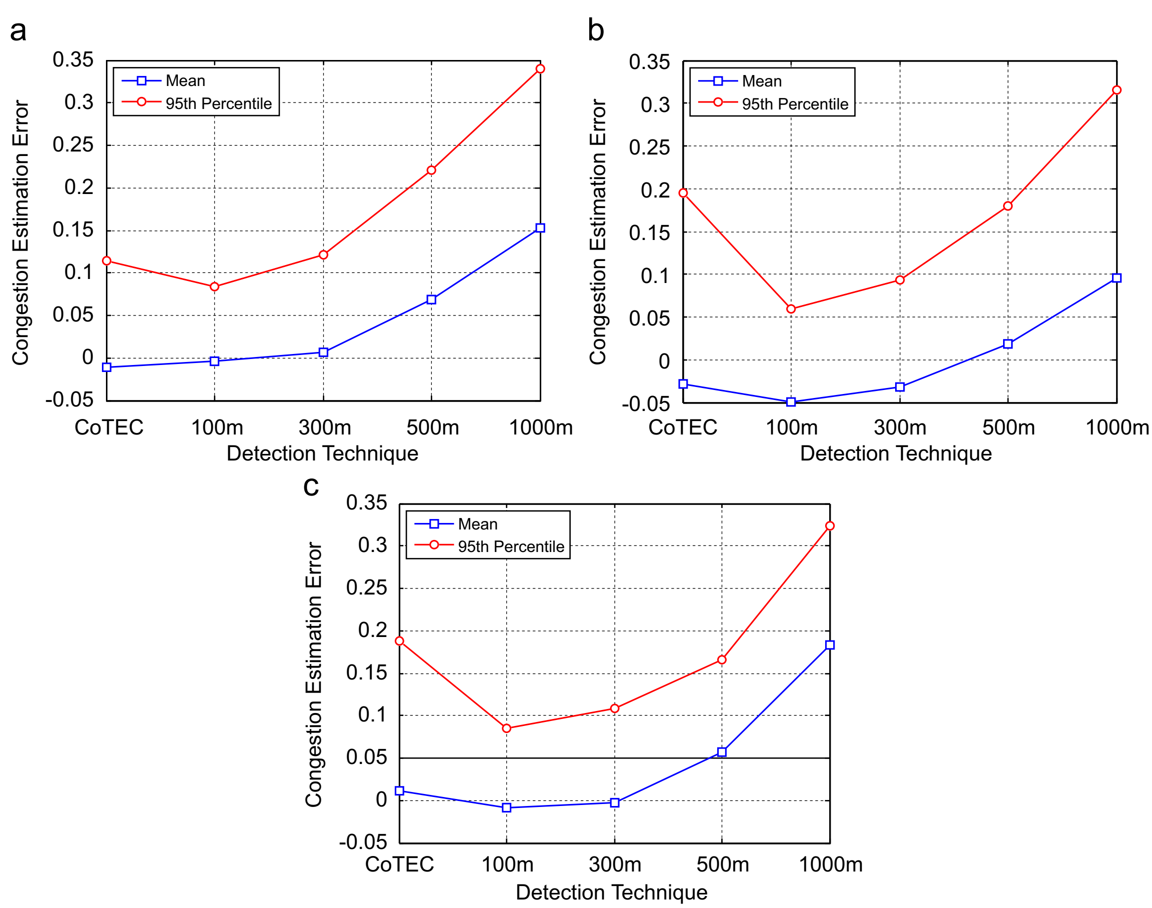

Fig. 7. Congestion estimation error. (a) Scenario A, (b) Scenario B and (c) Scenario C.

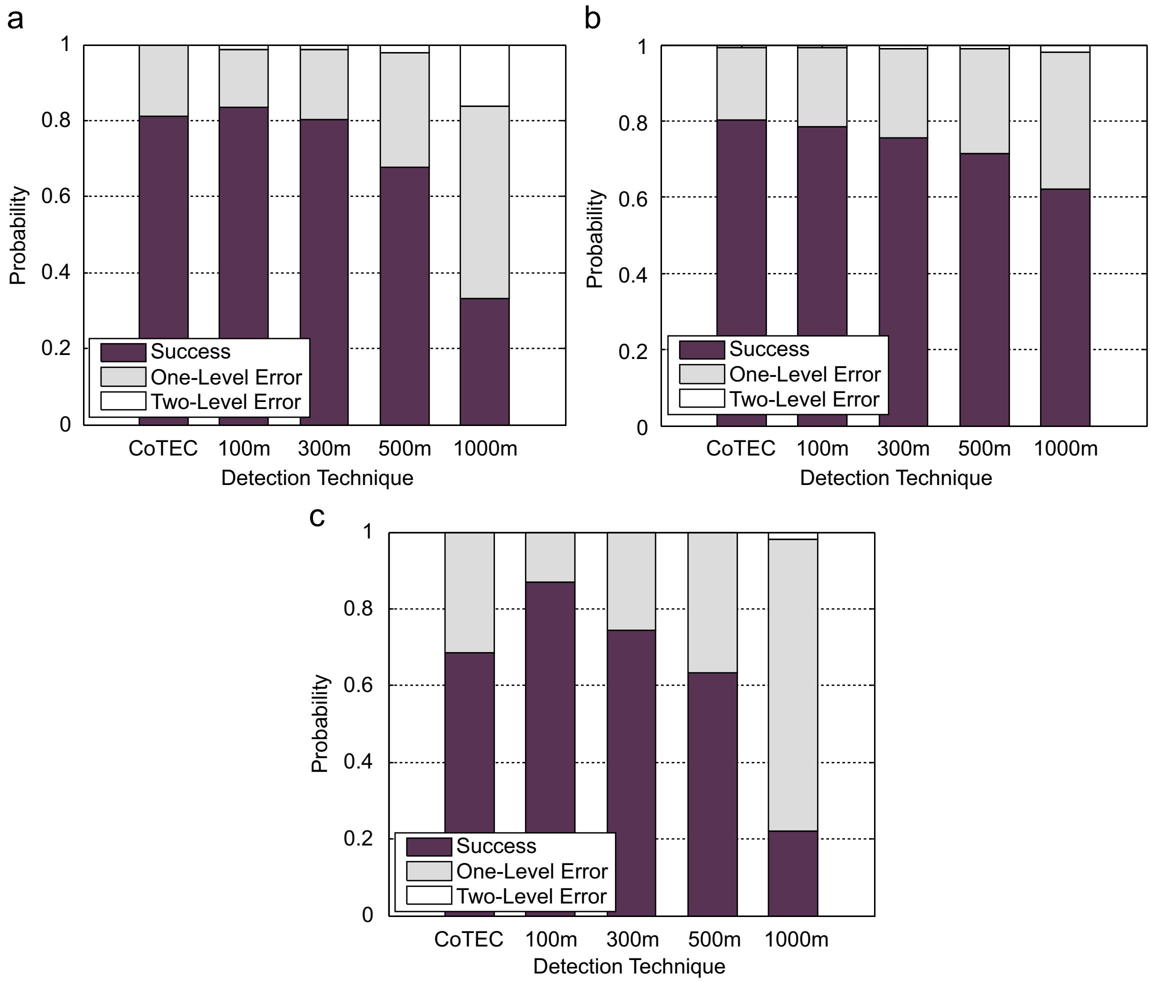

Fig. 8. Congestion level classification success and error rates. (a) Scenario A, (b) Scenario B and (c) Scenario C.

is low and close to the one obtained by an infrastructure-based monitoring solution with inductive loops placed every 100 m. It is important to remember that CoTEC is a fully distributed and V2V-based solution that does not require any infrastructure nodes for estimating the traffic congestion level. CoTEC's performance is slightly degraded when analyzing the 95th percentile, although it still achieves an accuracy level greater than that obtained with inductive loops placed every 1000 m.

The response to any road traffic congestion event may vary depending on its characteristics (e.g. intensity and length). As a result, it is important that congestion detection mechanisms are capable to successfully classify and characterize traffic congestions. Fig. 8 analyses this capability for the CoTEC and inductive loops detection techniques based on Skycomp's classification system. The figure reports the percentage of occasions in which the techniques detect the same level of congestion as the Centralized approach (*Success*), and the percentage of occasions in which the congestion level is wrongly estimated by a difference of one or two levels. The obtained results demonstrate that CoTEC provides a high congestion classification success rate (around 80% for scenarios A and B), close to that obtained with inductive loops placed every 100 m. In addition, CoTEC's congestion error never exceeds one congestion level, which could be the case with inductive loops with large separation distances.

The previous analysis can be complemented through the evaluation of the percentage of correct and incorrect detections per congestion level. These percentages are reported in Table 6 when applying CoTEC or using inductive loops deployed every 100 m, 300 m or 1000 m. The correct detections parameter represents the percentage of occasions in which a technique has correctly detected a given congestion level.[4] The incorrect detections parameter represents the percentage of occasions in which a technique erroneously estimates a given congestion level.[5] To better illustrate these two parameters, let's consider an example where 100 severe congestion level events took place. Let's consider that a given technique reported severe congestion in 80 occasions, with 40 of them being correctly estimated. In this case, the *Correct Severe Detections* parameter would be equal to 40%, whereas *Incorrect Severe Detections* would be equal to 50%. The obtained results show that CoTEC achieves a high percentage of correct detections under all scenarios and for all congestion levels. Its performance is close to that obtained with inductive loops deployed every 300 m, except for severe congestion levels. In the latter case, CoTEC outperforms the detection using inductive loops, in particular for scenarios A and C. Inductive loops improve their capacity to correctly detect severe congestion events when the distance between loops increases. This is due to the fact that when a lower number of loops are deployed, the technique using inductive loops tends to overestimate the congestion level. This results in a higher percentage of correct severe congestion detections, but also a higher percentage of incorrect

[4] This parameter is computed considering the number of occasions in which each congestion level occurs.

[5] This parameter is computed considering the number of congestion level estimates made by the technique.

severe congestion detections, and a lower percentage of moderate and slight correct congestion detections.

A key feature differentiating CoTEC from existing V2V detection solutions (including Lin and Osafune technique) is its ability to provide information about the characteristics of the detected traffic congestion. The forwarding of CTE messages towards the rear end of the traffic jam allows quantifying the length of the jam. Fig. 9 illustrates the mean and standard deviation of the traffic jam length estimation error using CoTEC and inductive loops; the error is again estimated taking into account the length measured through the Centralized approach. The length of the detected traffic jam using inductive loops is computed as the distance between the first and last loop detecting congestion. A negative sign in the estimation error indicates that the length of the jam is underestimated. The obtained results for all traffic scenarios show that CoTEC achieves a mean length detection error lower than using inductive loops deployed every 300 m.

Table 6
Correct and Incorrect detections.

Congestion Level Detections	CoTEC (%)	Loops 100 m (%)	Loops 300 m (%)	Loops 1000 m (%)
Scenario A				
Correct Severe Detections	64	6	8	17
Incorrect Severe Detections	45	50	76	94
Correct Moderate Detections	87	96	91	31
Incorrect Moderate Detections	14	18	19	50
Correct Slight Detections	78	88	85	43
Incorrect Slight Detections	7	1	3	9
Scenario B				
Correct Severe Detections	90	76	76	99
Incorrect Severe Detections	13	2	7	33
Correct Moderate Detections	73	86	84	35
Incorrect Moderate Detections	24	30	32	29
Correct Slight Detections	71	73	62	29
Incorrect Slight Detections	21	20	14	18
Scenario C				
Correct Severe Detections	59	38	21	100
Incorrect Severe Detections	61	23	57	83
Correct Moderate Detections	80	96	90	29
Incorrect Moderate Detections	28	11	14	21
Correct Slight Detections	59	85	67	5
Incorrect Slight Detections	11	3	9	0

Another interesting feature of any traffic congestion detection technique would be how quickly it can detect a congestion situation. Table 7 shows the mean and the 10th and 90th percentiles of the time needed to detect a congestion level using CoTEC, Lin and Osafune, and inductive loops with separation distance of 100 m. The obtained results show that deploying a large number of inductive loops reduces the mean detection time, but can also generate congestion alarms before a traffic jam ever happens (negative values of the time to detection). CoTEC's longer time to detection is caused by the use of the moving average algorithm, and the consensus detection process carried out as CTE messages are forwarded towards the rear end of the traffic jam (Section 3). Lin and Osafune's technique significantly increases the time to detection for scenario C (highest traffic density) as a result of its detection process being based only on the vehicles' speed.

Guaranteeing the scalability of cooperative V2X systems requires limiting the load on the communications channel as a

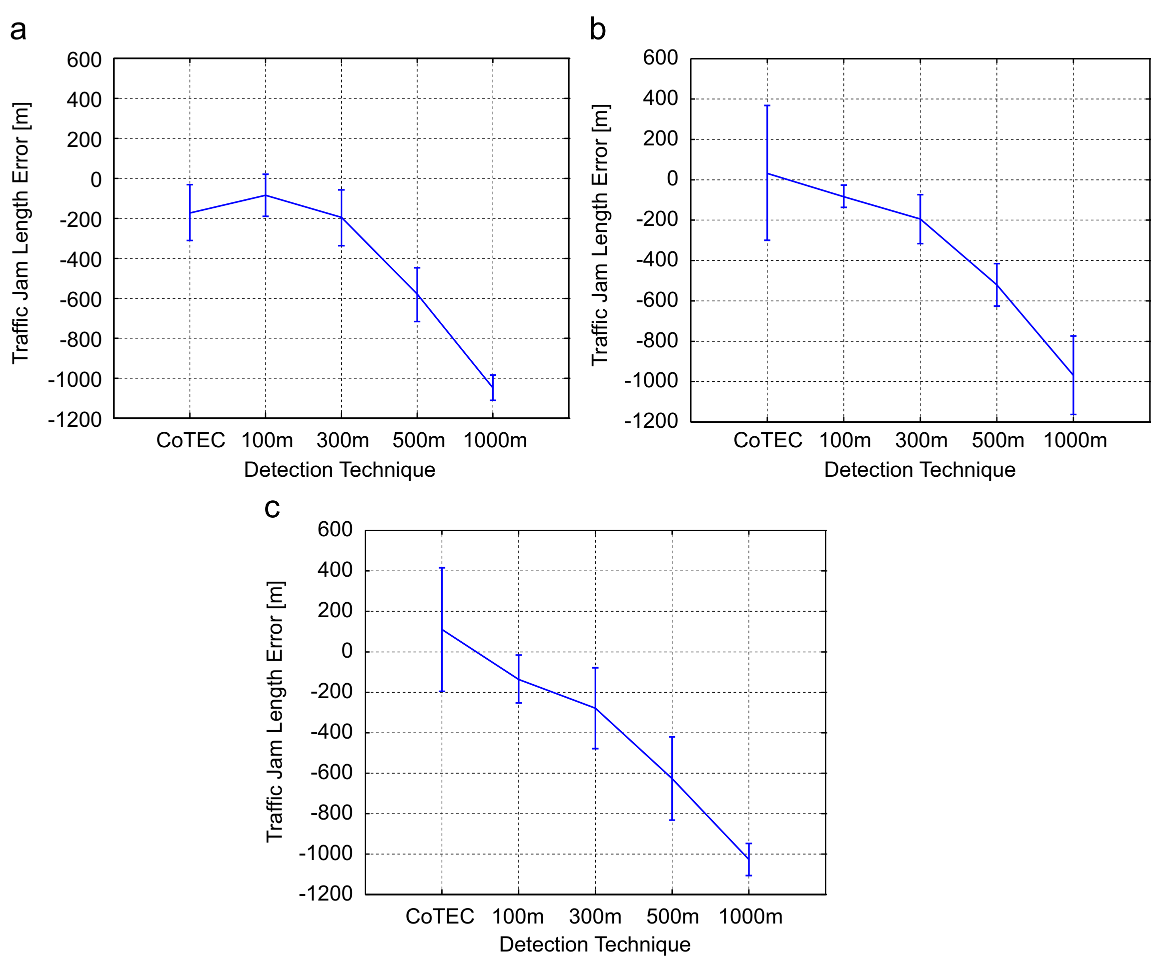

Fig. 9. Traffic jam length estimation error. (a) Scenario A, (b) Scenario B and (c) Scenario C.

Table 7
Time to detection.

Detection Technique	Mean (s)	10th percentile (s)	90th percentile (s)
Scenario A			
Inductive loops	−9	−33	4
CoTEC	18	12	31
Lin and Osafune	−21	−37	−1
Scenario B			
Inductive loops	−60	−102	−8
CoTEC	−14	−82	26
Lin and Osafune	18	−10	43
Scenario C			
Inductive loops	−29	−63	−7
CoTEC	19	−45	60
Lin and Osafune	106	84	139

Table 8
Congestion Detection Overhead.

Detection Technique	Txons/ detection	Overhead/ detection (KB)	Overhead/ load (%)
Scenario A			
CoTEC	13	2.3	0.6
Lin and Osafune	76	10.7	5.2
Scenario B			
CoTEC	14	2.4	0.5
Lin and Osafune	106	15.0	3.5
Scenario C			
CoTEC	14	2.4	0.4
Lin and Osafune	114	16.1	1.3

result of the use of a CSMA (Carrier Sense Multiple Access) medium access technique. It is therefore important that V2V-based congestion detection techniques limit the overhead they require to successfully detect and characterize road traffic congestions. To estimate such overhead, Table 8 presents the average number of packet transmissions required by each technique to successfully detect a congestion condition (Txons/Detection), i.e. the number of transmitted packets is divided by the number of detected congestion events. The number of transmitted packets corresponds to the voting request and reply messages for Lin and Osafune's technique, and CTE messages for CoTEC (i.e. beacon or CAM messages are not taking into account in the Txons/Detection parameter). The obtained results show that CoTEC always generates significantly less overhead than Lin and Osafune. The observed differences are explained by the techniques' distinct voting procedures. While CoTEC only needs to forward the CTE messages to the rear end of the traffic jam, Lin and Osafune requires that every time a voting request message is transmitted, all the neighboring vehicles respond with a voting reply message.

Table 8 also reports the overhead (in kilobytes) generated per congestion detection event, and the ratio between the overhead generated by the detection techniques and the total communications load (i.e. the sum of the techniques' overhead and the load resulting from the mandatory and periodic transmission of CAM messages). The size of CTE messages required by CoTEC to detect road traffic congestions is higher than the size of the packets used by Lin and Osafune (171 bytes versus 141 bytes). However, the results depicted in Table 8 show that the overhead generated by Lin and Osafune per congestion detection event is always higher than that produced by CoTEC. In addition, it is important to note that while the overhead generated by CoTEC represents less than 0.6% of the total communications load, this percentage can increase to up to 5.2% when considering Lin and Osafune. Overall, the results reported in Table 8 clearly show that CoTEC reduces the overhead required to detect road traffic congestions, and makes a more efficient use of the cooperative vehicular communications channel. Making an efficient use of the communications channel is a key priority in the community to guarantee the bandwidth requirements of the demanding traffic safety applications while securing the system's stability as the technology is gradually adopted and new applications are introduced.

The previous results were obtained considering a V2V transmission power equal to 10 dBm. Future cooperative systems could rely on the use of adaptive transmission power control. As a result, it is relevant to analyze the impact of the transmission power on CoTEC's congestion detection capability and efficiency. The results depicted in Table 9 show that the success detection rate decreases with the transmission power. This is due to two main reasons. With a high transmission power, vehicles that have recently entered the traffic jam take longer to report congestion since they still detect neighboring vehicles outside the traffic jam. This effect results in an increase of the traffic jam length estimation error as reported in Table 9. The use of a low transmission power also requires a larger number of relays (hops) to forward a CTE message from the header of the jam towards its rear end (Table 9). Since every vehicle participating in the forwarding process includes its congestion estimation in the CTE message, the number of individual estimates used to compute the congestion level increases for low transmission power levels. This effect increases the detection's accuracy and success rate. It is important to stress that cooperative systems will adapt the vehicles' transmission power based on the detected road traffic context. It can therefore be expected that vehicles will need to decrease their transmission power under high vehicular densities to avoid overloading the communications channel. In this context, the fact that CoTEC improves its performance and accuracy when vehicles transmit at low power levels is a positive feature that further ensures its capability to efficiently monitor road traffic congestion conditions.

Table 9
Impact of transmission power on CoTEC congestion detection.

Tx Power	Success rate (%)	Jam length estimation error (m)	Relays per CTE
10 dBm	78	229	8.4
15 dBm	73	304	6.3
20 dBm	61	354	4.6

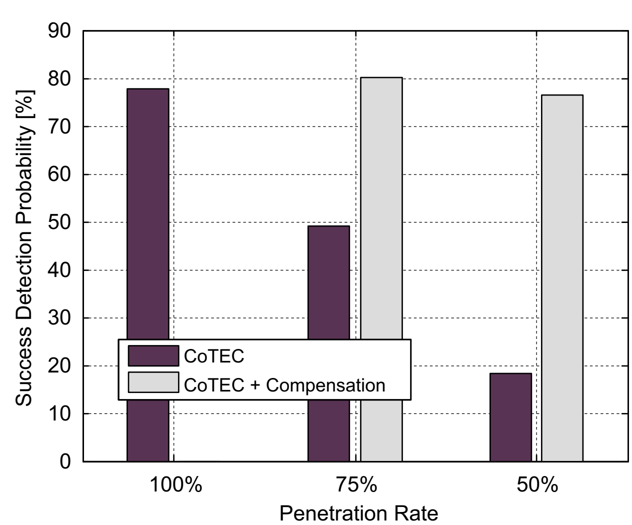

Fig. 10. Success classification rate versus 802.11p/ITS-G5A penetration rate.

Several studies have shown that the capabilities and performance of cooperative vehicular systems can be significantly degraded under low market penetration rates of cooperative technologies. The previous results considered that all vehicles were equipped with V2V communication technologies. The results depicted in Fig. 10 show that CoTEC's traffic congestion detection capability is significantly degraded under low V2V penetration rates. This degradation is due to a decrease in the detection of neighboring vehicles (only vehicles equipped with 802.11p/ITS-G5A) that results in an underestimation of the traffic density. To overcome CoTEC's degradation under low V2V penetration rates, a simple yet effective compensation mechanism is here implemented. The mechanism assumes the knowledge of the general penetration rate through market statistics, and scales the detected number of neighbors based on these statistics. For example, if only 5 vehicles have been detected when the 802.11p/ITS-G5A penetration rate is 50%, the compensation mechanism will estimate the number of detected neighboring vehicles to be equal to 10. This new estimate is then used to compute the traffic density. The results depicted in Fig. 10 show that this simple compensation methodology is able to recover CoTEC's detection performance to a level of accuracy close to that obtained with a 100% 802.11p/ITS-G5A penetration rate.

6. Conclusions and future work

Cooperative vehicular communications open new possibilities to develop advanced traffic monitoring solutions in next-generation ITS systems. In this context, this paper has presented CoTEC, a novel distributed technique using V2V communications to detect and characterize traffic congestion. The proposed technique includes mechanisms to compensate the impact of radio propagation on the accurate estimation of traffic density, and to account for the gradual market introduction of cooperative vehicular communications. CoTEC has been evaluated in a large scale highway scenario using the iTETRIS simulation platform, and its performance has been compared to V2V and infrastructure-based detection solutions. The obtained results demonstrate that CoTEC can successfully and accurately detect congestion conditions. In addition, CoTEC can accurately characterize such conditions, in particular the length and intensity of a traffic jam, without requiring the deployment of any infrastructure nodes. CoTEC and V2V communications can hence represent an efficient and cost-attractive solution for road management authorities to detect and characterize road traffic congestion conditions.

The authors are currently investigating efficient communication mechanisms to disseminate CoTEC's road traffic congestion information to vehicles approaching the congested area. Using this information, vehicles would be able to modify their route, and select alternative ones that avoid the congested area. An interesting research area would then be to investigate how to efficiently couple V2V-based road traffic monitoring mechanisms with cooperative traffic management strategies. Such coupling should be studied in large scale scenarios in order to better understand the impact on road traffic conditions, and the capability of cooperative systems to efficiently distribute road traffic flows.

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