Road Traffic Congestion Detection through Cooperative Vehicle-to-Vehicle Communications

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***Abstract*—Cooperative vehicular systems are being developed to improve traffic safety and management. Reducing road traffic congestion can be achieved through effective management strategies. In this sense, mechanisms for its rapid and accurate detection that allow evaluating the road network performance are crucial. Current Intelligent Transportation Systems (ITS) require the deployment of infrastructure sensors to monitor traffic conditions. Their installation is often expensive and their capability to provide accurate traffic information is limited. In this context, this paper proposes CoTEC (COperative Traffic congestion detECtion), a novel cooperative technique based on Vehicle-to-Vehicle (V2V) communications and fuzzy logic to detect road traffic congestion without the need to deploy infrastructure sensors. The proposed technique is also capable to accurately detect the traffic congestion intensity and length.**

Keywords-component; cooperative vehicular communications, vehicle-to-vehicle (V2V) communications, traffic congestion detection

I. Introduction

Road traffic congestions result in important economical and productivity losses, as well as an increasing environmental impact. To reduce their negative effects, novel Intelligent Transportation Systems (ITS) are currently being investigated. One of the critical aspects that will enable the design of efficient traffic management policies will be the capacity to effectively monitor the traffic conditions and rapidly detect traffic congestion. Conventional traffic monitoring solutions based on infrastructure sensors include inductance loops, video and image processing, and microwave radars. These types of detectors provide fixed-point or short-section traffic information that is extracted from vehicles passing the detection zone. They generally report data about the vehicles' volume and lane occupancy, that combined, can be used to estimate the vehicles' speed. One of the main limitations of point detection technologies is that the traffic estimates are based on measurements taken at a specific location that might not provide an accurate representation of the traffic conditions over larger road segments. The design of point-based traffic monitoring solutions is therefore characterized by a trade-off between the traffic estimates accuracy and the number of deployed infrastructure sensors.

Cooperative vehicular communication systems have been identified as one of the ITS technologies that offers a higher potential to improve traffic safety and efficiency through the continuous exchange of information between vehicles (Vehicle-to-Vehicle or V2V communications) and between vehicles and infrastructure nodes (Vehicle-to-Infrastructure or V2I communications). In this context, cooperative vehicles would become very valuable mobile sensors from which infrastructure elements deployed along the road network would extract traffic information. In addition, the continuous exchange of messages between vehicles that include information about their locations and speed could also represent a very powerful tool for each vehicle to continuously monitor its local road traffic conditions in a distributed manner and without requiring the deployment of a large number of infrastructure sensors or nodes. In this context, this paper presents and evaluates CoTEC (COperative Traffic congestion detECtion), a novel technique to efficiently detect road traffic congestion using V2V communications. The proposed technique is able to control the communications overhead required for such detection. In addition, and to the authors' knowledge, it is the first technique that is also capable of providing valuable information to road traffic managers about the characteristics of the detected congestion conditions, for example, its location, length and intensity.

II. Background on Congestion Detection Mechanisms Based on V2V Communications

Several studies that exploit cooperative V2V communications to monitor the road traffic conditions have recently been published. In cooperative V2V communication systems, vehicles periodically transmit broadcast beacons, also known as CAMs (Cooperative Awareness Messages), in order to announce their presence to neighboring nodes providing information about their speed and location. Many of the proposed techniques rely on the periodic exchange of specific packets (distinct from beacons or CAMs), that are not initially considered within cooperative standards, and that are transmitted to estimate road traffic conditions beyond each vehicle's transmission range. The transmission of these packets should be carefully considered in order not to overload the cooperative communications channel. An example of these techniques is the COC (Contents Oriented Communications)

[1] proposal. With this technique, vehicles estimate the road traffic density from the received broadcast beacons or CAMs, and periodically transmit this information to other vehicles. As a result, vehicles obtain traffic density information for different locations, and can detect congestion situations by comparing these road traffic density estimates with average traffic density values for the road segments under evaluation. The capacity of the COC technique to detect traffic congestion through V2V communications is obtained at the expense of an additional communications load that could saturate the cooperative wireless channel. To limit the communications load generated by V2V protocols that detect road traffic conditions, TrafficView [2] 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, in SOTIS [3], vehicles 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. To avoid the communications overload that could be generated by neighboring vehicles, [3] additionally proposes the use of an adaptive broadcast algorithm. Differently from SOTIS, in [4], only a single vehicle in each road segment is in charge of collecting and aggregating road traffic data. Once aggregated, the information is transmitted to adjacent road segments. In this approach, each road segment can be considered as a cluster of vehicles where only the cluster head is able to collect traffic data and transmit it to other clusters. The drawback of this approach is that the selection of the cluster head usually generates additional signaling overhead. In addition, it is important to emphasize that the definition of road segments is usually challenging. In fact, many techniques define road segments based on the vehicle's transmission range, but this might significantly vary, in particular when applying transmit power and congestion control protocols.

The techniques previously described have been designed to monitor and estimate road traffic conditions through V2V communications, and broadcast this information to neighboring vehicles. To reduce the communications overhead that these techniques continuously generate, StreetSmart [5] has been designed. This mechanism limits the exchange of traffic information to only those situations of unexpected or abnormal traffic conditions, such as traffic jams. A different approach is presented in [6], where each vehicle continuously estimates a congestion index for the road section it is currently located in. This index is estimated considering the current travel time, and the travel time that should be expected without traffic congestion. The technique defines a request-response procedure for vehicles to demand traffic congestion information for a given area. Since all vehicles in that area reply to every congestion information request, the communications overhead and risk to saturate the cooperative channel is potentially high. The mechanism reported in [7] reduces the risk of communications overload by only making traffic congestion estimates locally at each vehicle using pattern recognition techniques that exploit the information received from nearby vehicles through their CAMs. The fact that the traffic congestion estimates are not validated or correlated among various vehicles may lead to unreliable detections. This limitation is overcome in [8], where a voting procedure is employed through which nearby vehicles exchange their traffic estimates and try to reach a consensus decision.

The reviewed techniques have clearly highlighted the potential of cooperative V2V technologies to distributedly monitor road traffic conditions and detect congestion without deploying additional infrastructure nodes. However, there are inefficiencies and trade-offs (e.g. efficient use of the communications channel versus accurate traffic conditions estimation and congestion detection) that still need further research. In this context, this paper proposes CoTEC, a novel traffic congestion detection technique based on cooperative V2V communications. CoTEC continuously monitors traffic conditions at the vehicle level, and only when a congestion situation is locally detected, activates a cooperative procedure that correlates individual decisions for a more accurate congestion detection. Additionally, CoTEC is able to provide valuable information for road traffic managers about the characteristics of the detected traffic congestion, for example, its location, length and intensity. This information will help traffic managers better decide on the actions to overcome the detected traffic congestion.

III. CoTEC

CoTEC uses the CAM or beacon messages that vehicles periodically broadcast, mainly for safety purposes, to monitor the road traffic conditions. These conditions are monitored locally by every vehicle. CoTEC uses fuzzy logic to locally detect a potential road traffic congestion condition. When a congestion situation is detected, CoTEC will share the individual estimations made locally by different vehicles to collaboratively and accurately detect and characterize the road traffic congestion.

A. Traffic congestion local estimation

As previously said, CoTEC uses the CAM or broadcast beacons messages to monitor road traffic conditions and detect congestion. However, the detection of road traffic congestion is not a trivial task, and several metrics for its estimation and characterization have been proposed in the literature. In this context, this paper considers the system to classify and characterize road traffic congestion developed by Skycomp [9] through different campaigns conducted in several US cities. 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) [10]. Six different levels of service are defined, with LOS A representing free-flow conditions and LOS F describing breakdowns in vehicular flow. It is important to note that the HCM LOS system does not distinguish between different levels of traffic congestion for the LOS F category. On the other hand, Skycomp's system 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 the Skyscomp's extended HCM LOS F rating [11] reported in Table I.

TABLE I. LEVELS OF CONGESTION IN COTEC

	Level of congestion	Traffic density	Vehicles' speed
LOS F	Slight	[46-60] veh/mi/ln or [29-37] veh/km/ln	[30-50] mi/h or [48-81] km/h
	Moderate	[60-80] veh/mi/ln or [37-50] veh/km/ln	[15-40] mi/h or [24-64] km/h
	Severe	Above 80 veh/mi/ln or 50 veh/km/ln	Below 25 mi/h or 40 km/h

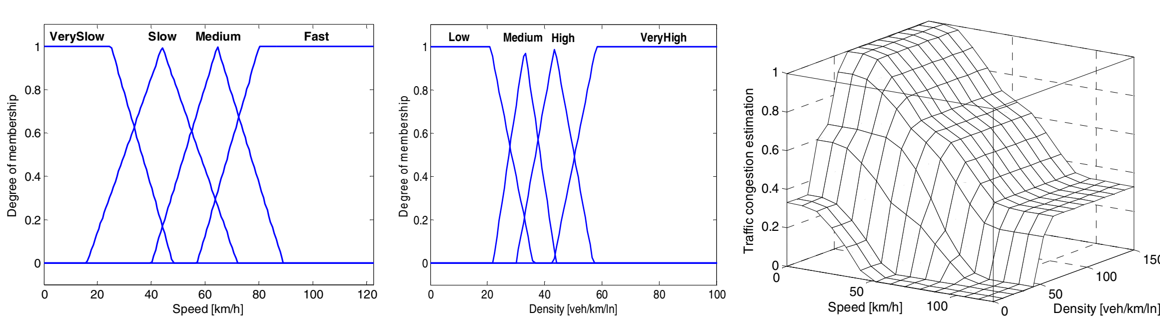
Given a set of speed and traffic density estimates, a logical and intuitive approach to categorize the level of congestion would be to directly map those values into one of the traffic congestion categories reported in Table I. However, as pointed out in [12], the use of definite boundaries between traffic categories may lead to high error rates when operating near the categories' boundaries. This is due to the intrinsic nature of the traffic flows whose variations (e.g. from free flow to traffic jam) follow a continuous process [13], and consequently no clear boundaries exist between the distinct traffic flow statuses. In fact, the Skycomp's classification reported in Table I shows that a given speed value can indicate two distinct congestion categories based on the associated traffic density. This uncertainty in the definition of the boundaries between different categories makes fuzzy-logic-based systems especially suitable for addressing complex non-deterministic decision problems such as the identification of traffic congestion. Taking this into account, CoTEC proposes a traffic congestion quantification system based on fuzzy theory. The fuzzy-based proposal takes the traffic density and vehicle speed as input parameters and provides the corresponding traffic congestion level or traffic jam intensity as output parameter.

As previously explained, each vehicle implementing CoTEC estimates its local traffic conditions based on its vehicular speed and surrounding traffic density. The vehicle's speed can be easily obtained from the CAN bus of the vehicle or from a GPS device. The local traffic density can be estimated through the reception of CAM messages from neighboring vehicles. In particular, the traffic density is calculated based on the number of detected neighboring vehicles, their distance to the vehicle estimating the traffic density, and the number of lanes of the road. Therefore, each vehicle can estimate its local traffic conditions in terms of vehicular speed and traffic density, and then feeds these values into the congestion detection system.

As in any fuzzy-based decision system, the input variables are first classified into different categories or fuzzy sets. The possible fuzzy sets for the speed are *very slow, slow, medium* and *fast*. For traffic density, the defined fuzzy sets are *low, medium, high* and *very high*. One of the main particularities of fuzzy logic is that 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. For instance, a speed value of 25 km/h could be member, with a different degree of membership, of both *very slow* and *slow* speed fuzzy sets. In order to determine the degree of membership of the input values to each of the fuzzy sets, membership functions are employed. The membership functions used in CoTEC, which have been implemented based on the Skycomp's congestion rating system, are illustrated in Figure 1a) and Figure 1b). In addition, output fuzzy sets corresponding to the different road traffic categories have also been defined according to Skycomp's congestion classification, with *free-flow*=0, *slight congestion*=1/3, *moderate congestion*=2/3 and *severe congestion*=1. To finalize the definition of the CoTEC fuzzy-based congestion detection system, fuzzy rules that relate the input (speed and density) and the output fuzzy sets (congestion levels) have been established and are displayed in Table II. The fuzzy rules have been designed based on the speed, traffic density and road congestion categories considered in the Skycomp's system. As Figure 1c) illustrates, the output of the traffic jam quantification system is a continuous value within the interval [0, 1] indicating the level of congestion (traffic jam intensity), with 0 representing free flow and 1 severe traffic congestion.

TABLE II. COTEC FUZZY RULES RELATING INPUT SPEED AND DENSITY SETS WITH OUTPUT CONGESTION LEVELS

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



a) Speed membership functions *b) Traffic density membership functions* *c) Level of congestion provided by the detection system*

Figure 1. CoTEC fuzzy-based congestion detection system.

B. *Cooperative traffic congestion detection*

CoTEC proposes a cooperative procedure based on multi-hop communications to achieve a consensus decision on the traffic congestion situation. The proposed approach allows collaboratively evaluating the individual estimations that different participating vehicles make locally. As described in the previous section, every vehicle in CoTEC continuously monitors the road traffic conditions, and estimates through the fuzzy-based detection system the current level of road congestion. Only when the traffic estimation exceeds a predefined congestion threshold C_{th}, vehicles activate the cooperative traffic information exchange mechanism. C_{th} corresponds to the minimum congestion level to be monitored and its value can be varied depending on traffic management policies. It is worth stressing that CoTEC does not generate any additional communications overhead when traffic conditions are normal, since the cooperative procedure is only launched when a traffic congestion condition is locally detected.

The CoTEC cooperative detection mechanism is based on CTE (*Cooperative Traffic Estimation*) messages which are exchanged when a traffic congestion situation has been 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, and as novelty with respect to other proposals, the CTE message is also exchanged to quantify 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 packet 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 level of road congestion. In order to determine the location and length of the traffic jam, the CTE message includes, as data field, the position of the first relaying vehicle within the traffic congestion (*front end location).* Vehicles at the rear end of the traffic jam will derive the length of the traffic congestion by simply analyzing the *front end location* field in the CTE message.

A key aspect in CoTEC is to identify the vehicles close to the front end of the traffic jam that will generate the CTE messages. CoTEC defines a procedure, that is open for further optimizations, 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 such 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 configurable frequency rate which allows selecting the periodicity of the traffic information updates.

The delivery of CTE messages from the front end of the jam to its rear end is performed through an information-centric forwarding protocol making use of multi-hop communications. With information-centric forwarding the responsibility of routing the information resides on the application itself, instead of on the network layer as it occurs in packet-centric forwarding. When a vehicle wants to forward a message, it single-hop broadcasts a packet. A vehicle that receives this message will deliver the message directly to the correspondent application. Then, the application merges the new information with the (locally-stored) information and decides about further forwarding procedures. The forwarding mechanism that CoTEC employs is an adaptation of the Contention-Based Forwarding (CBF) protocol [14] with modifications to take the forwarding decisions at the application layer. CoTEC implements a contention-based scheme for the selection of forwarding nodes. A relaying vehicle broadcasts the CTE message to all its neighbors. Vehicles receiving the message schedule the re-transmission of the message by activating a timer whose duration is inversely proportional to their distance to the previous forwarder (distant vehicles wait shorter times before re-transmitting the message). Vehicles receiving a message from behind will not attempt to retransmit the packet. Therefore, the message is only propagated backwards (in opposite direction to the traffic flow). On the other hand, vehicles that overhear the broadcast transmission of the scheduled CTE message from other neighbors will cancel their own re-transmission attempts (in ideal conditions, only one vehicle forwards the packet). As a result, the CoTEC protocol prevents that once a vehicle at the front end of a traffic jam generates a CTE message, other close-by vehicles generate additional and redundant CTE messages that would overflow the communications channel. It is worth stressing that the forwarding of CTE messages is finalized as soon as it reaches a zone where vehicles do not detect congestion. Vehicles whose traffic estimations are lower than the congestion threshold C_{th} will not further forward the CTE message. This way, vehicles that receive a CTE message and have not detected traffic congestion will consider themselves to be located outside the traffic jam. In addition, if a false or inaccurate traffic congestion situation is detected, the multi-hop forwarding of CTE messages will be immediately prevented by vehicles that do not agree with the detected congestion situation. The vehicles located outside the traffic jam that have received a CTE message will be in charge of disseminating compact and summarized information on the traffic congestion to distant vehicles approaching the traffic jam or delivering it to traffic management centers through deployed road side units. It is convenient to mention that the procedures to efficiently disseminate the traffic congestion information to approaching vehicles are not addressed in this work that focuses on the cooperative traffic congestion detection through V2V communications.

Once the mechanism to exchange the traffic congestion information among vehicles by means of CTE messages has been explained, how this information is processed to achieve a cooperative and coherent congestion detection is described. The final aim of this cooperative mechanism is to accurately detect traffic congestion conditions and to be able to quantify their intensity. This will allow traffic managers to better decide the counter-measures to adopt for a detected traffic congestion situation. This work has implemented and evaluated four different methodologies to compute the overall level of congestion based on the local estimations from different vehicles[1]:

- *Mean-based cooperative estimation (Mean)*: as the CTE message is forwarded towards the rear end of the traffic jam, the mean of the individual congestion estimations is computed in every hop. A relaying vehicle calculates the mean based on its own estimation (*VehicleEstimation*), the number of previous forwarding vehicles or hops (*n-1*) and the mean congestion estimation computed by the last forwarder ($Mean_{n-1}$):

$$Mean_n = \frac{VehicleEstimation + (n-1)\cdot Mean_{n-1}}{n}$$

where n indicates that the computation is made by the *n-th* vehicle updating this value. As it can be observed, only two additional data fields need to be transmitted in the CTE message: the mean estimation computed by the last forwarder ($Mean_{n-1}$) and the number of previous hops (*n-1*).

- *Median-based cooperative estimation (Median)*: each vehicle relaying a CTE message includes its own traffic estimation in the packet. The vehicle located outside the traffic jam, which is in charge of disseminating the detected traffic congestion to approaching vehicles or to the road managers, computes the median based on the individual estimations of the set of relaying nodes. It is worth noting that, as the CTE message travels towards the rear end of the traffic jam, the size of the packet increases (a new estimation is aggregated in every hop).

- *Cooperative estimation based on frequency intervals (Median intervals)*: this method is also based on the median statistic, but carries out a different estimation process. Instead of calculating the median through raw data (individual estimations of relaying vehicles), it is computed based on grouped frequency distributions. The range of congestion levels to be monitored [C_{th}, 1] is divided into intervals of equal size (e.g. 0.1). The CTE message includes as many data fields as congestion intervals. In each congestion interval field in the CTE message, the frequency of the forwarders' estimations (number of vehicles detecting a congestion level) is recorded. Every time a vehicle forwards a CTE message, the frequency of the interval in which the vehicle's estimation lies within is increased by 1. For example, if C_{th} is set to 0.4 and the congestion range [0.4, 1] is divided into 6 intervals of the same size, a forwarding vehicle estimating a congestion level of 0.56 will increase the frequency of the congestion interval [0.5, 0.6] by 1. When the CTE message reaches the rear end of the traffic jam, the median of the traffic congestion estimations is calculated based on the received frequency intervals. One advantage of this method is that the size of the CTE message is always fixed, independently from the number of relaying vehicles and the length of the traffic congestion.

- *Cooperative estimation based on frequency intervals and number of neighbors (Median intervals neighbors)*: in this case, the median is also calculated based on frequency intervals. However, in this technique, when a forwarding vehicle updates the congestion frequency intervals in the CTE message, it increases the corresponding interval by the number of neighbors the vehicle has detected. For example, if a vehicle has detected 24 neighbors in its surroundings, it will increase the corresponding congestion interval in the CTE message by 24. This approach takes advantage of the fact that the estimations made by vehicles geographically close to each other are relatively similar, and thus a more accurate statistic can be obtained by considering all the neighboring vehicles that may have equivalent estimations.

IV. CoTEC EVALUATION IN FREEWAY SCENARIOS

To evaluate the potential of CoTEC to detect and monitor traffic congestion through the use of distributed and cooperative V2V communications, this work has conducted a simulation study which focused on the analysis of the techniques for the cooperative processing of traffic information estimations. Although CoTEC could work in different traffic scenarios (urban, rural, highways, etc.), this paper evaluates the mechanism in a freeway environment. To this aim, realistic vehicular movement traces have been produced using the traffic simulator SUMO [15]. A freeway segment with 2 lanes per direction and a length of 3.5km has been reproduced. Furthermore, a traffic jam of varying congestion intensity and duration of 8min has been simulated in an 800m portion of the road segment. The traffic jam has been artificially generated with SUMO by gradually reducing the maximum speed limit from 120km/h to 22km/h. V2V communications with a fixed 300m transmission range are assumed; currently, more realistic propagation conditions are being introduced. In the simulation study, vehicles periodically transmit CAM messages with a 1Hz periodicity indicating their location and speed.

A. Traffic congestion local estimation

Figure 2 plots the mean speed and traffic density values for the 800m freeway segment affected by congestion. As it can be observed, there is a gradual decrease in the vehicles' speed down to 22 km/h, which results in an increase in the traffic density up to a maximum value of 62 veh/km/ln. As it can be observed, for t=550s, the traffic conditions start gradually recovering. The colored bar in the upper part of the figure indicates the traffic status obtained from the fuzzy-based detection system. It is convenient to remark that vehicular communications have not been considered to obtain the results presented in Figure 2. On the contrary, it has been assumed that the traffic information for the congested segment (speed of all the vehicles in the segment and the associated traffic density) is fully available and processed in a centralized fashion to obtain the congestion levels. This has been done to produce benchmark traffic estimations against which to compare those obtained through the V2V-based CoTEC proposal. The mapping between the level of congestion provided by the fuzzy system and the traffic status has been performed based on the membership functions employed for the output fuzzy sets (*free-flow*, *slight congestion*, *moderate congestion* and *severe congestion*).

[1] These vehicles are those selected by the CoTEC forwarding protocol to route the CTE messages towards the rear end of the traffic jam.

On the other hand, Figure 3 shows congestion estimations based on information gathered through V2V communications. This figure depicts the surface plot of the levels of congestion that the vehicles in the scenario detect by continuously monitoring their close surroundings. These congestion levels are shown as a function of time and the position of the vehicle providing the congestion level estimation with respect to the start of the road segment under evaluation. As explained, the local traffic monitoring conducted by each vehicle is achieved through the reception of beacons or CAM messages transmitted by neighboring vehicles. Each vehicle estimates the traffic congestion through the fuzzy-based detection system, which takes the vehicle speed and the traffic density as input parameters. The figure allows appreciating how the traffic jam evolves in space and time.

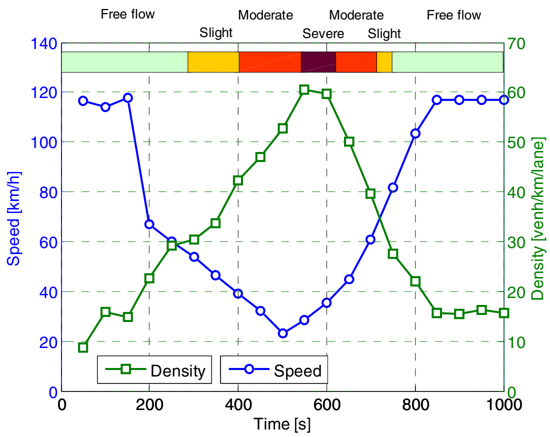


Figure 2. Mean traffic density and speed in the congested segment.

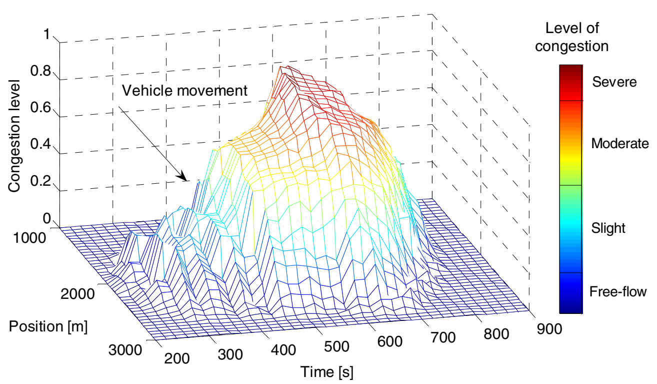


Figure 3. Traffic congestion local estimation based on V2V communications.

B. *Cooperative traffic congestion detection*

As it has been explained, CoTEC employs a multi-hop communication mechanism for the exchange of traffic information among vehicles when a traffic congestion situation has been locally detected. The individual estimations collected through the multi-hop mechanism are statistically processed to compute a cooperative and accurate estimation on the level of congestion (or traffic jam intensity). Four different techniques to estimate such level of congestion have been proposed. To evaluate the accuracy of these cooperative V2V congestion detection techniques, their performance is compared against the case in which the congestion estimation is made in a centralized fashion; this will be referred as *Centralized*. Figure 4 illustrates the congestion estimation provided by each of the cooperative detection techniques based on distributed V2V communications, and that estimated through the centralized approach. The results in Figure 4 have been obtained considering a CTE message generation period of 30s and correspond to exactly the same traffic conditions as reported in the previous section. As it can be appreciated, the method *Median Intervals Neighbors* is capable to closely follow the estimation obtained through the centralized approach. By contrast, the technique based on the mean statistic significantly underestimates the level of congestion. This is partially due to the statistical effect that the (low value) estimations made by vehicles located in the front and rear ends of the traffic jam have in the mean value. This is also evidenced in Figure 5, which shows the CDF of the congestion estimation error for each of the cooperative detection methods. The estimation error is computed as the difference in the congestion level estimates obtained by the centralized approach and one of the CoTEC detection techniques. In this respect, the estimation error obtained with the technique *Median Intervals Neighbors* is significantly lower than the error provided by the rest of the techniques. Finally, it is interesting to emphasize that although the *Median* approach provides a better performance than the *Median intervals* technique, the difference is not very significant. On the other hand, the *Median* approach can result in a notable communications overhead as the traffic congestion length increases.

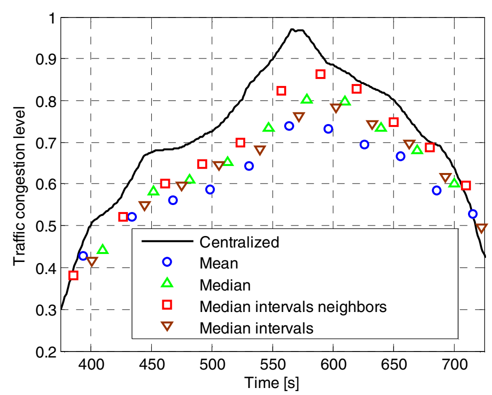


Figure 4. Traffic congestion estimation obtained through the CoTEC cooperative detection techniques.

To investigate the influence of the number of vehicles participating in the cooperative detection process on the accuracy of the congestion estimation, different distances between forwarding vehicles (*relaying distance*), varying from 100m to 300m, have been considered. As a consequence of reducing the relaying distance, the number of participating vehicles, and consequently, the number of local traffic estimates to cooperatively detect and quantify the congestion level increases[2]. Figure 6 illustrates the Root Mean Squared of

[2] It is important to note that this distance is not equivalent to the transmission range which has been maintained at 300 meters. This means that a vehicle would still be able to detect neighboring vehicles located at 300m, but only vehicles located at the varied *relaying distance* can be selected to forward a CTE message.

the estimated Error (RMSE) achieved by all the cooperative detection techniques for an increasing relaying distance. In addition, the figure also depicts the number of vehicles participating in the forwarding of CTE messages from the front to the rear end of a traffic jam. Since the forwarding vehicles are also the vehicles participating in the cooperative estimation of the congestion, this number is also equivalent to the number of traffic local estimates used to compute the congestion levels. First of all, it is worth stressing that independently of the relaying distance, the *Median Intervals Neighbors* technique always achieves the lowest RMSE, and therefore provides a more accurate traffic congestion estimation. Although the *Median* technique also exhibits good performance, this is achieved at the expense of a higher CTE message size (higher communications overhead) as the number of hops or length of the traffic jam increases. As it could be expected, the results of Figure 6 also show that the number of vehicles needed to relay a CTE messages increases as the relaying distance decreases. Since the higher the number of relaying vehicles, the higher the number of local traffic estimates used to cooperatively estimate the congestion level, the RMSE achieved by all the techniques diminishes as the number of participating vehicles increases.

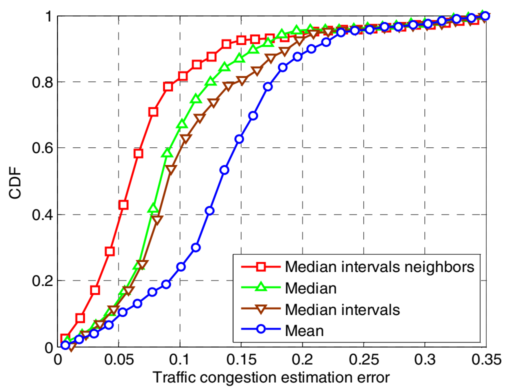


Figure 5. CDF of congestion estimation error for the cooperative estimation techniques.

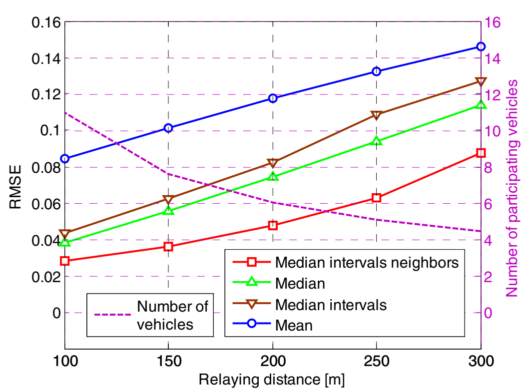


Figure 6. RMSE for increasing relaying distance and different cooperative techniques.

V. CONCLUSIONS

Cooperative vehicular communications systems offer new capabilities to develop innovative and advanced solutions for traffic monitoring and management. In this context, this paper has introduced and evaluated CoTEC, a novel cooperative and distributed V2V mechanism to efficiently detect traffic congestion. The initial investigations have demonstrated the capacity of the proposed mechanism to accurately quantify the traffic congestion level, while efficiently using the cooperative communications channel. The proposed technique could then provide valuable real-time information for road traffic managers. In addition, if coupled with data dissemination protocols, it could also warn approaching vehicles of the presence of a traffic congestion situation so that they can adopt decisions to counteract their negative effects.

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