Redundancy Mitigation in Cooperative Perception for Connected and Automated Vehicles

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Abstract— **Cooperative perception (or cooperative sensing or collective perception) enables connected and automated vehicles to exchange sensor data in order to improve their perception of the driving environment. ETSI is currently developing a standard for collective perception. The standard defines the message format and generation rules. These rules identify when a message should be transmitted and what information it should include. This study shows first that the current ETSI solution generates many redundant collective perception messages that increase the channel load and can compromise the networks' scalability. Unnecessary redundancy can reduce the reliability of V2X (Vehicle to Everything) communications and ultimately decrease the effectiveness of collective perception. This study proposes a modification of the current ETSI solution to control redundancy and avoid the transmission of unnecessary CPM data or messages. The evaluation shows that our proposal significantly reduces the redundancy and channel load and improves the reliability of V2X communications compared to current ETSI solution for collective perception. This is achieved while maintaining the perception achieved by ETSI for the safety-critical short and medium distances.**

Index Terms— Collective perception, cooperative perception, cooperative sensing, redundancy, message generation, connected automated vehicles, V2X, vehicular networks, ITS-G5, ETSI.

I. Introduction

Autonomous vehicles use onboard sensors to perceive the environment. The sensors´ perception capabilities are reduced under the presence of obstacles (including other vehicles) or adverse weather conditions. Vehicles can improve their perception using wireless communications to exchange sensor data with nearby vehicles and infrastructure. This is known as cooperative perception, collective perception or cooperative sensing. Previous studies have demonstrated that collective perception or cooperative sensing can improve the perception capabilities of vehicles even beyond their sensors' detection range [1]. The study in [1] analyzes the advantages and disadvantages of exchanging raw sensor data, processed metadata or compressed data. Exchanging raw sensor data would require significantly large bandwidths that cannot be provided by existing V2X (Vehicle to Everything) technologies such as DSRC, ITS-G5 or C-V2X. Recent studies (e.g. [2] and [3]) hence focused on the exchange of basic information about detected objects (e.g. their position, speed and size) to reduce the communication bandwidth required for collective perception. This approach has been adopted in Europe where ETSI (European Telecommunications Standards Institute) is currently defining the standard for the Collective Perception Service (CPS) [4]. The CPS draft standard defines the Collective Perception Message (CPM) format and the CPM generation rules. These rules establish when vehicles should generate a new CPM message and the information it should include. A CPM includes one common header and multiple containers with information about the vehicle that generates the CPM, the capabilities of its onboard sensors, and the detected objects (their position, speed, size, etc.). The authors analyzed in [5] the current CPS draft standard and demonstrated that current ETSI CPM generation rules result in the frequent transmission of CPMs that include information about a small number of detected objects. This can compromise the network's scalability since most of the transmitted data is headers rather than data about detected objects. The analysis also showed that current CPM generation rules result in significant redundancy. For example, the study showed that vehicles can receive as much as 25 to 50 times per second the same data about a detected object under the evaluated scenarios. This is the case because current CPM generation rules are exclusively based on changes of the detected objects' dynamics (position and speed). In this case, all vehicles in the vicinity of a detected object that detect a change in the objects' dynamics will generate a CPM with the same information about the detected object. Redundancy can be positive to confirm the accurate detection of objects or vehicles. However, an excessive redundancy can overload the V2X communications channel and compromise the network's scalability. It can also negatively impact the perception accuracy if an overloaded channel results in packet collisions. These collisions can reduce the probability of receiving CPM messages and ultimately impact the effectiveness of collective perception or cooperative sensing.

This paper proposes a modification of the current ETSI CPS solution in order to control the redundancy in the network without degrading the perception capabilities of Connected and Automated Vehicles (CAVs). The proposal controls redundancy by preventing vehicles to report about detected objects in CPMs if they have already received updates about

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the same object from other vehicles. Transmitting another CPM with the same detected object data will increase redundancy without a significant benefit to neighbor vehicles that have already received the same data from other vehicles. This proposal is aligned with the vision outlined in [6] where authors discuss the need to consider the value of the information about a detected object to decide whether it should be transmitted or not. This paper demonstrates that the proposed solution reduces significantly the redundancy in the network as well as the channel load and improves the V2X reliability. In addition, our proposal maintains the perception achieved with the current ETSI solution for short and medium distances (up to around 200m radius). These distances are critical for the safety of CAVs.

II. Collective Perception Standardization

Current ETSI developments to specify the CPS service are described in the Technical Report in [4] and will serve as baseline for the specification of CPS in ETSI TS 103 324. The Technical Report describes the CPM format and the CPM generation rules. CPM messages include an ITS (Intelligent Transport Systems) PDU (Protocol Data Unit) header and 4 types of containers: Management Container, Station Data Container, Sensor Information Containers (SICs) and Perceived Object Containers (POCs). The ITS PDU header includes Data Elements like the protocol version, the message ID and the Station ID. The Management Container is mandatory and provides basic information about the transmitting vehicle (e.g. its position). The position information is used by the receiver to reference the detected objects. The Station Data Container is optional and includes additional information about the transmitting vehicle (e.g. its speed, heading, or acceleration). In addition, the CPM can include up to ten SICs to describe the capabilities of the sensors embedded in the transmitting vehicle. Finally, the POCs provide information about the detected objects (e.g. the distance between the detected object and the transmitting vehicle), the speed and dimensions of the object, and the time at which these measurements were done. A single CPM can include up to 255 POCs.

The CPM generation rules define when a vehicle should generate and transmit a CPM and the information to be included in the CPM. Current ETSI CPM generation rules [4] establish that a vehicle has to check every *T_GenCpm* if a new CPM should be generated and transmitted. By default, *T_GenCpm* is set equal to 100ms although it can be equal to any multiple of 100ms in the range between 100ms and 1000ms. For every *T_GenCpm,* a vehicle should generate a new CPM if it has detected a new object, or if any of the following conditions are satisfied for any of the previously detected objects:

1. Its absolute position has changed by more than 4m since the last time its data was included in a CPM.
2. Its absolute speed has changed by more than 0.5m/s since the last time its data was included in a CPM.
3. The last time the detected object was included in a CPM was 1 (or more) seconds ago.

A vehicle includes in a new CPM all new detected objects and those objects that satisfy at least one of the previous conditions. The vehicle still generates a CPM every second even if none of the detected objects satisfy any of the previous conditions. The information about the onboard sensors is included in the CPM only once per second.

III. Motivation

This section evaluates the current ETSI CPS solution to motivate our proposal. In particular, the section evaluates the level of redundancy generated by the current ETSI CPS proposal. To this aim, we consider a 5km long six-lane (three per direction) highway scenario[1] that we simulate using the road mobility simulator SUMO following the conditions reported in Table I. We consider two traffic densities following the V2X simulation guidelines in [7]. The speed of vehicles at each lane is configured using statistics from the PeMS database for a typical 3-lane US highway [8].

TABLE I. Scenario

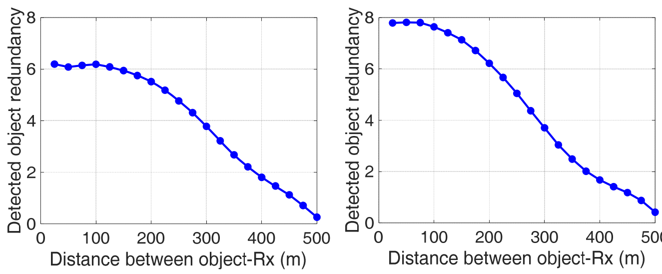
Traffic density	60 veh/km	120 veh/km
Speed per lane	140 km/h	70 km/h
	132 km/h	66 km/h
	118 km/h	59 km/h

V2X communications are simulated using the network simulator ns3 [9]. In our analysis, all vehicles communicate using ETSI's ITS-G5 standard (based on IEEE 802.11p) over the same channel. The propagation effects are modeled using the Winner+ B1 propagation model following [7]. The transmission power is set to 23dBm and the packet sensing threshold to -85dBm. All vehicles transmit using the 6Mbps data rate (i.e. they utilize QPSK modulation with ½ code rate). The ns3 simulator has been extended with a CPS component implemented by the authors. The component creates CPM messages based on the ETSI CPM message format [5]. CPM messages are generated following current ETSI´s solution (Section II) with *T_GenCpm*=0.1s. Vehicles are configured with two forward sensors following [4] and [5]. The first sensor has a 65m range and a FoV (Field of View) of ±40º. The second sensor has a 150m range and a ±5º FoV. The object detected by two sensors are assumed to be fused.

ETSI CPM generation rules include information about a vehicle in a CPM every 200ms and 300ms for the low and high traffic density scenarios respectively. For example, vehicles move at speeds between 32.7m/s and 38.8m/s in the low traffic density scenario. Vehicles then need 0.11s to 0.13s to move 4m. *T_GenCpm* is defined as a multiple of 100ms. Therefore, the information about a vehicle is included in a CPM every 200ms for low traffic densities. Similar calculations can be done for the high traffic density scenario. These calculations are important to select the adequate observation time window and correctly evaluate the performance and effectiveness of the collective perception service. We then consider observation time windows of 200ms and 300ms for the low and high traffic density scenarios, respectively. These values correspond to the time required by ETSI CPM generation rules for a vehicle to send an update about an object in a CPM for the two traffic densities.

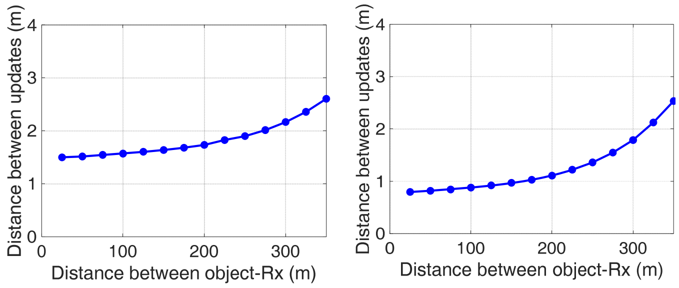
[1] Statistics are only collected for vehicles located in a 2km road segment around the middle of the scenario in order to avoid boundary effects.

Figure 1 plots the number of times a vehicle receives CPMs with data about the same object over the selected observation time windows. These CPMs come from different vehicles that detect the same object. The metric depicted in Figure 1 is referred to detected object redundancy. It is represented as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 1 highlights the redundancy levels resulting from current ETSI CPM generation rules. Rather than receiving a single object update per observation window, on average, vehicles receive more than 5 updates for low and more than 6 updates for high traffic densities respectively up to distances of around 200m. This results that the vehicles receive updates about objects more frequently than really necessary. This is illustrated in Figure 2 that plots the distance travelled by an object between two successive CPMs that include information about that object. Results are again plotted as a function of the distance between the object and the vehicle receiving the CPMs. This figure clearly shows that a vehicle receives updates about a detected object much more frequently than in fact intended by ETSI CPM generation rules. Figure 2 shows that on average a vehicle will receive an object update less than every 1.7m for low density and less than every 1.1m for high density up to distances of around 200m. This is in contrast to the 4m threshold established by the CPM generation rules to decide when an update should be transmitted. Sending frequent updates might be unnecessary from the perception point of view and can significantly increase the load on the communications channel. This can augment packet collisions and reduce the reliability of V2X communications which can ultimately decrease the perception capabilities of CAVs. We propose in the following section a modification of the current ETSI CPS to control the unnecessary detected object redundancy while minimizing the changes to the standards.



(a) Low density (b) High density

Figure 1. Object redundancy as a function of the distance between the detected object and the vehicle receiving the CPMs.



(a) Low density (b) High density

Figure 2. Average distance travelled by a detected object between two successive CPMs reporting about this object. Metric represented as a function of the distance between the object and the vehicle receiving the CPMs.

IV. PROPOSAL

The objective of our proposal is to reduce the redundancy in the transmission of CPMs without decreasing the perception capabilities of CAVs for short and medium distances since CPMs are critical for their safety. Our proposal is executed before the original ETSI CPM generation rules to filter out the detected objects that have been recently transmitted by a nearby vehicle. To this aim, the proposed algorithm analyses every *T_GenCpm* the change in the absolute position (ΔP_R) and speed (ΔS_R) of every detected object since the last time the object was received in a CPM from other vehicles. If $\Delta P_R \leq P_Threshold$m and $\Delta S \leq S_Threshold$m/s, the object will not be included in the CPM even if it complies with the original ETSI CPM generation rules' conditions, which are analyzed later. *P_Threshold* and *S_Threshold* threshold values must be equal or smaller than 4m and 0.5m/s respectively to reduce redundancy. The rationale for this proposal is that if a vehicle has recently received an update about the same object from other vehicles, there is no need for the vehicle to send another update about this object since neighbor vehicles will have already received the data from other vehicles. This reduces unnecessary redundancy. The pseudo-code of the proposed extension to the ETSI CPM generation rules is described in lines 1-5 of Algorithm I. Then, the algorithm follows the original ETSI CPM generation rules and computes for the remaining detected object the variation of absolute position (ΔP), the variation of speed (ΔS) and the time elapsed (ΔT) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the conditions specified in Section II is satisfied following the current ETSI CPM generation rules. If it is the case, the CPM should include the information about the detected objects that satisfy ΔP>4m or ΔS>0.5m/s or ΔT>1s and that were not omitted by our proposed redundancy reduction mechanism. The pseudo-code for this process is reported in lines 6-11 of Algorithm I.

ALGORITHM I.
Input: Detected Objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

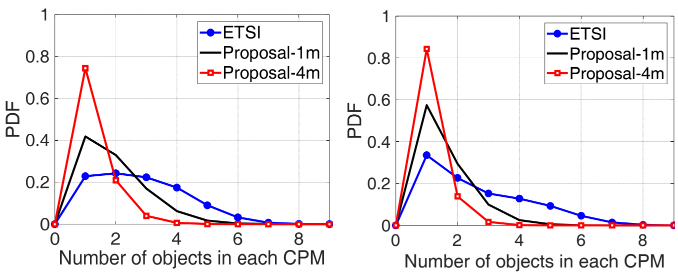
```
1.  For every detected object do
2.      Calculate ΔP_R and ΔS_R since last time received in a CPM
3.      If ΔP_R < P_Threshold && ΔS_R < S_Threshold then
4.          Continue
5.      Else
6.          Calculate ΔP, ΔS and ΔT since last time included in a CPM
7.          If ΔP>4m || ΔS>0.5m/s || ΔT>1s then
8.              Include object in current CPM
9.          End if
10.     End If
11. End For
```

V. EVALUATION

Our proposal is analyzed using the simulation set-up and conditions described in Section III. The proposed algorithm is implemented considering two threshold configurations: (*P_Threshold*=1m, *S_Threshold*=0.5m/s) and (*P_Threshold*=4m, *S_Threshold*=0.5m/s). These configurations are referred to as proposal-1m and proposal-4m in this evaluation.

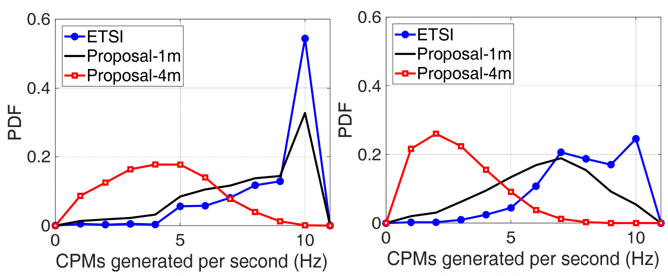
Figure 3 compares the PDF of the number of objects included in each CPM with the current ETSI generation rules and our proposal. Figure 3 shows that our proposal reduces the number of detected objects included per CPM under low and high traffic densities and for both configurations. The largest reductions are obtained with the proposal-4m configuration. Figure 3 also shows that our proposal reduces the number of objects included per CPM when augmenting the traffic density. This is because when the density increases there are many vehicles that transmit the same redundant data with the ETSI CPM generation rules. Our proposal reduces the redundancy and has then a higher impact when the traffic density increases. This is very interesting since higher densities can compromise the networks' scalability.

Our proposal also reduces the number of CPMs transmitted per second. This is visible in Figure 4 that compares the PDF of the number of CPMs generated per vehicle per second with the ETSI CPM generation rules and our proposal. The proposal-4m configuration achieves again the higher reduction levels. These results clearly show that our proposal generates less CPMs per second with smaller size than the current ETSI CPM generation rules. This reduces the channel load as illustrated in Table II. The channel load is estimated in terms of the average CBR (Channel Busy Ratio). The CBR is defined as the percentage of time that the channel is sensed as busy. Table II shows that our proposal significantly reduces the channel load as a consequence of the trends depicted in Figure 3 and Figure 4. In particular, the proposal-1m configuration reduces the CBR by 17%-26% and the proposal-4m configuration by 58%-68% when compared to the current ETSI solution. As expected, Table II shows that the CBR increases with the traffic density. However, lower increases are observed with our proposal following the trends observed in Figure 3 and Figure 4. This shows that the proposed algorithm can better cope with increases in the network load.



(a) Low density (b) High density

Figure 3. PDF of the number of objects included in each CPM.



(a) Low density (b) High density

Figure 4. PDF of the number of CPMs generated per second.

TABLE II. AVERAGE CBR (CHANNEL BUSY RATIO)

Policy	Traffic density	CBR
ETSI	Low	19.2 %
	High	31.8 %
Proposal-1m	Low	15.9 %
	High	23.4 %
Proposal-4m	Low	8.1 %
	High	10.1 %

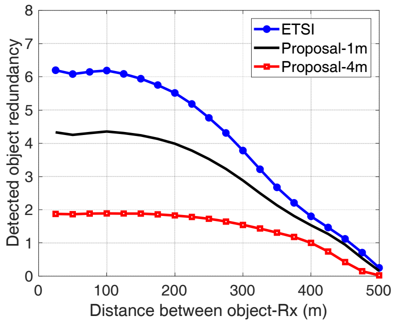
TABLE III. DISTANCE (METERS) WITH PDR $\geq$ 0.9

Policy	Traffic density	PDR
ETSI	Low	181m
	High	112m
Proposal-1m	Low	200m
	High	160m
Proposal-4m	Low	250m
	High	233m

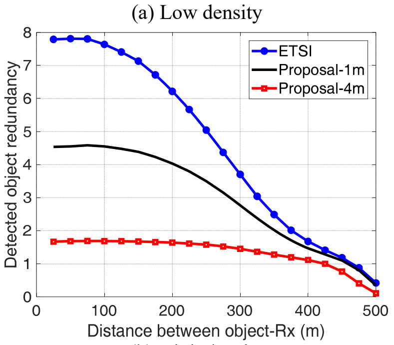
Reducing the CBR and channel load reduces the packet collisions and improves the PDR (Packet Delivery Ratio). This is actually shown in Table III that reports the distance up to which a PDR equal or higher than 0.9 is guaranteed[2]. Table III shows that our proposal increases this distance compared to the current ETSI solution. In particular, the proposal-1m configuration increases it by 10% and 42% in low and high traffic densities, and the proposal-4m configuration by 38% and 108% respectively. These results demonstrate that our proposal increases the reliability of V2X communications.

Figure 5 shows the effectiveness of our proposal to reduce the redundancy introduced by current ETSI's CPS solution. The figure depicts the object redundancy as a function of the distance between the object and the vehicle receiving the update or CPM. This metric represents the number of times a vehicle receives CPMs with an update about the same object over the observation time window. The object redundancy decreases with the distance due to the propagation effects that reduces the PDR. Figure 5 shows that our proposal effectively reduces the number of object updates compared to ETSI´s solution in order to control the channel load. This reduction is achieved without sacrificing the perception performance for short and medium distances that are critical for the safety of CAVs. This is illustrated in Figure 6 that compares the perception achieved with the current ETSI CPM generation rules and our proposal. The perception is estimated with the object perception ratio that is defined as the probability to detect an object (i.e. a vehicle in this study) within the observation time window. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the observation time window. Figure 6 also shows the perception achieved with an autonomous vehicle that only uses its sensors and does not implement V2X communications. In this case, we consider that a vehicle successfully detects an object if the sensors detect the object during the same time window. Figure 6 plots the average object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 6 shows that relying exclusively on the onboard sensors results in a very low perception performance. The perception is significantly improved when using

[2] This distance is considered a V2X performance reference by some standardization organizations such as the 3GPP [7].

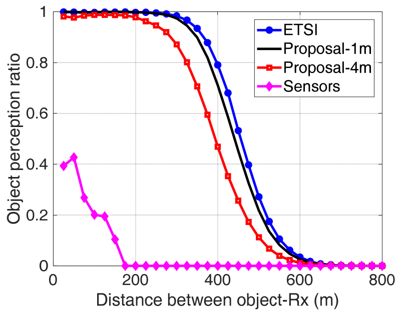


(a) Low density

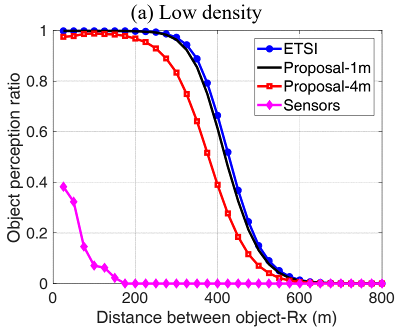


(b) High density

Figure 5. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.



(a) Low density



(b) High density

Figure 6. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs

collective perception or cooperative sensing. Figure 6 shows that our proposal achieves the same (or nearly the same) perception as ETSI´s current solution for the critical short and medium distances (up to around 200m) and both traffic densities. In particular, the perception performance is identical for the proposal-1m configuration. These results show that the proposed algorithm can reduce the redundancy without degrading the perception capabilities compared to current ETSI´s solution at the critical short and medium distances. It should be noted that the performance is evaluated considering only the transmission of CPM messages. Higher channel load levels resulting from the transmission of additional messages (e.g. CAM or MCM messages) could increase the load and degrade the perception achieved with current ETSI's solution. Our proposal would be more robust again such increase since Table II demonstrates that our proposal significantly reduces the CBR and hence increases the reliability (Table III). Figure 6 also shows that the performance degrades for higher distances. This is due to the propagation effects that impact more the proposal-4m configuration since it is the one that transmits less CPMs. This configuration is hence more sensitive to packet losses.

VI. Conclusions

Collective perception or cooperative sensing will enable connected and automated vehicles to exchange sensor information to improve their perception of the surrounding environment. ETSI is currently defining standards for collective perception message formats and rules to decide when these messages should be generated and what information they should contain. This study shows that the current ETSI solution for collective perception tends to generate significant redundancy in the network that can compromise its scalability without significantly improving the perception performance. This paper has proposed a modification to the ETSI CPM message generation rules to control the redundancy in the network. The evaluation has shown that our proposal significantly reduces the redundancy and channel load and improves the reliability of V2X communications. The proposal maintains the same perception performance (with significantly less messages) than current ETSI's solution for safety-critical short and medium distances, while improving the network scalability. Our proposal has been recently incorporated as part of the ETSI technical report draft as one of the potential solutions to mitigate redundancy in cooperative perception.

References

[1] S. Kim *et al.*, "Multivehicle Cooperative Driving Using Cooperative Perception: Design and Experimental Validation," *IEEE Transactions on ITS*, vol. 16, pp. 663-680, 2015.

[2] A. Rauch *et al.*, "Analysis of V2X communication parameters for the development of a fusion architecture for cooperative perception systems," *Proc. IEEE Intelligent Vehicles Symposium (IV)*, Baden-Baden, Germany, pp. 685-690, 2011.

[3] H. Günther *et al.*, "Realizing collective perception in a vehicle," *Proc. IEEE Vehicular Networking Conference (VNC)*, USA, pp. 1-8, 2016.

[4] ETSI ITS, "Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective - Perception Service (CPS) ", ETSI TR. 103 562 V0.0.16, June 2019.

[5] G. Thandavarayan *et al.*, "Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving", *Proc. IEEE Intelligent Vehicle Symposium*, Paris (France), June 2019.

[6] Giordani *et al.*, "Investigating Value of Information in Future Vehicular Communications", *Proc. IEEE 2nd Connected and Automated Vehicles Symposium (CAVS)*, Honolulu, Hawaii, USA, 22-23 September 2019.

[7] 3rd Generation Partnership Project (3GPP), Technical Specification Group Radio Access Network; "Study on LTE-based V2X Services,". 3GPP TR 36.885 V14.0.0, 2016.

[8] Caltrans Performance Measurement System (PeMS), California Department of Transportation data-set, U.S. State, Online, available at http://pems.dot.ca.gov/. Last accessed on: 2019-01-16.

[9] M. Rondinone *et al.*, "iTETRIS: A modular simulation platform for the large scale evaluation of cooperative ITS applications", *Simulation Modelling Practice and Theory*, vol. 34, pp. 99-125, May 2013.