Infrastructure Support for Cooperative Maneuvers in Connected and Automated Driving

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***Abstract*—Connected and automated vehicles can exploit V2X communications to coordinate their maneuvers and improve the traffic safety and efficiency. To support such coordination, ETSI is currently defining the Maneuver Coordination Service (MCS). The current approach is based on a distributed solution where vehicles coordinate their maneuvers using V2V (Vehicle-to-Vehicle) communications. This paper proposes to extend this concept by adding the possibility for the infrastructure to support cooperative maneuvers using V2I (Vehicle-to-Infrastructure) communications. To this aim, we propose a Maneuver Coordination Message (MCM) that can be used in cooperative maneuvers with or without road infrastructure support. First results show the gains that cooperative maneuvers can achieve thanks to the infrastructure support. This paper also analyses and discusses the need to define MCM generation rules that decide when MCM messages should be exchanged. These rules have an impact on the effectiveness of cooperative maneuvers and on the operation and scalability of the V2X network.**

Keywords— Maneuver coordination, cooperative maneuver, infrastructure, connected and automated vehicles, CAV, V2X, vehicular networks, C-ITS, cooperative ITS.

I. INTRODUCTION

The introduction of Autonomous Vehicles (AV) is expected to improve traffic safety, reduce fuel consumption and improve the traffic. AVs will make use of a number of on-board sensors (e.g. cameras, lidars or radars) to perceive their environment and drive autonomously. However, these sensors do not facilitate the dynamic interaction of vehicles, and AVs can only sense and (try to) infer what other AVs are doing. V2X (Vehicle to Everything) communications can facilitate the direct interaction of Connected and Automated Vehicles (CAVs). CAVs will be able to exchange wirelessly information about their driving intentions so that vehicles can coordinate their maneuvers. Maneuver coordination (or cooperative maneuvers) allows vehicles to quickly adapt their driving based on the dynamics of surrounding vehicles, avoid misunderstandings about driving intentions, and facilitate the coordination of maneuvers with other cooperative vehicles [1]. For example, a CAV entering a highway through an on-ramp lane can coordinate its maneuver with other CAVs on the highway in order to find a gap for merging without disrupting the traffic on the highway and on the on-ramp lane.

The European Telecommunications Standards Institute (ETSI) is currently defining the Maneuver Coordination Service (MCS). The standardization process is still at its early stages but the current approach (aligned with previous studies [2]-[5]) is based on a purely distributed solution where vehicles coordinate their maneuvers using V2V (Vehicle to Vehicle) communications. As part of the H2020 TransAID project[1], this work proposes to extend the maneuver coordination concept and include the possibility for the road infrastructure to support the coordination of maneuvers using V2I (Vehicle to Infrastructure) communications. Such support does not imply that the infrastructure will coordinate the maneuvers of vehicles, but instead it can provide advices, notifications or information that vehicles can utilize to coordinate their maneuvers (e.g. speed advices for a smooth coordination of maneuvers). Our proposal does not replace the current V2V-based MCS approach discussed at ETSI but rather complements it. In this context, this paper proposes a Maneuver Coordination Message (MCM) that can be transmitted by the vehicles and/or infrastructure nodes to coordinate a maneuver. First results presented in this paper show the traffic safety benefits that the support from the infrastructure can provide to the coordination of maneuvers. In addition, the paper discusses and analyses the need to define MCM generation rules that decide when MCM messages should be exchanged. Such rules have an impact on the effectiveness of cooperative maneuvers and on the operation of the V2X network.

The remainder of this paper is organized as follows. Section II reviews the state of the art and the status of the MCS standardization. Section III describes the TransAID proposal that complements the current MCS proposal by enabling the possibility for the road infrastructure to support the coordination of maneuvers. Section IV presents the MCM format that supports this proposal. Section V discusses the need to define MCM generation rules, and analyses their impact on the V2X network. Finally, Section VI presents the main conclusions and future directions.

II. STATE OF THE ART AND STANDARDIZATION

AVs are being designed to handle autonomously diverse traffic conditions and scenarios. However, automated driving might not always be possible (e.g. due to an unforeseen situation that the vehicle does not know how to handle) and a

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[1] https://www.transaid.eu/

Transition of Control (ToC) will be required [6]. A ToC is the handover of the control of the vehicle from the automation system to the driver or vice versa. If a ToC fails, a Minimum Risk Maneuver (MRM) is executed and the vehicles perform a controlled stop. Complex traffic situations with an elevated number of ToCs can negatively impact the traffic safety and efficiency [7]. Cooperative maneuvers can help reduce ToCs and hence mitigate their negative effects. A cooperative maneuver is defined as the coordination of the maneuvers of two or more vehicles for a safer and more efficient driving. The cooperative maneuvers defined so far are generally designed to solve specific traffic situations. For example, the AutoNET2030 project developed: 1) a cooperative lane change solution based on a relative road space reservation mechanism, and 2) an intersection coordination solution based on the vehicles prioritization [2]. Another proposal for cooperative lane change maneuvers is found in [3]. The solution is designed to minimize the induced overall braking of all the involved vehicles. [4] proposes a cooperative intersection passing maneuver based on the creation of virtual platoons of vehicles. All these solutions target specific traffic maneuvers and might not be directly applicable to other maneuvers. Lehmann et al. propose a completely different and innovative solution for cooperative maneuvers in [5]. In particular, they propose a solution that can be in principle applied to every type of maneuver. The solution is based on the exchange between vehicles of their planned and desired trajectories so that they can identify potential conflicts and coordinate their maneuvers.

The ETSI Technical Committee on ITS has recently started work to standardize a Maneuver Coordination Service (MCS) [8]. The scope is to create a common framework for the implementation of cooperative maneuvers. However, the work is at its early stages and an agreement has not yet been finalized on how vehicles should coordinate their maneuvers. A first approach is based on the proposal from Lehmann et al. [5]. The proposal is a fully distributed solution where vehicles coordinate their maneuvers by exchanging their planned and desired trajectories using V2V communications. The proposal is divided into three steps. First, the need to coordinate a maneuver is detected. Second, the type of coordination is agreed between the involved vehicles. Finally, the cooperative maneuver is executed.

The proposal requires all CAVs to continuously broadcast an MCM including their planned trajectories. This is done so that vehicles can detect the need to coordinate a maneuver without having to infer and predict the planned trajectories of other vehicles (which would be subject to errors). Let's now consider the example of Figure 1 where the grey CAV wants to overpass a slow truck. To overpass it, it would need to execute the desired trajectory. However, it needs first to detect whether this trajectory generates any traffic conflict. To do so, the CAV compares its desired trajectory with the planned trajectories received from neighbouring vehicles, and computes whether they intersect and the intersecting vehicle has the right of way. If it is the case, the desired trajectory cannot be executed without coordinating the maneuver of the two vehicles. This is exactly the case of the top subfigure of Figure 1 where the green vehicle has the right of way and intersects with the desired trajectory of the grey vehicle. When the grey vehicle detects this conflict, it also broadcasts within the MCM its desired trajectory. When the green vehicle receives the desired trajectory, it understands it as a request for coordination from the grey vehicle. If the green vehicle is willing to modify its planned trajectory so that the green vehicle can execute its desired trajectory and overpass the truck, it will modify its planned trajectory and broadcast it in the MCM. When the grey vehicle receives the new planned trajectory of the green vehicle, it checks whether it intersects with its desired trajectory. If it doesn't, the grey vehicle transforms its desired trajectory into its planned trajectory and starts the overtaking maneuver. The other vehicles will be notified since vehicles have to periodically and continuously broadcast their MCMs. The solution currently under discussion is governed by the right of way rules. The vehicle that possesses the right of way must agree to modify its planned trajectory. Otherwise, the negotiation is not successful and the grey vehicle in Fig. 1 has to discard its desired trajectory. Please note that this approach could generate a cascade process if a vehicle needs to start cooperative maneuver with a vehicle to allow the desired trajectory of a third vehicle.

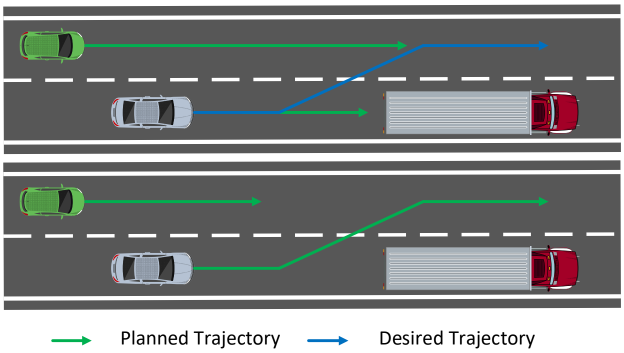

Figure 1. Example of cooperative maneuver.

III. Infrastructure Support For Maneuver Coordination

The maneuver coordination approach under discussion in ETSI is fully distributed and based on V2V communications. It can operate under a wide range of scenarios and conditions. We propose to extend the current MCS approach to also consider for the possibility to utilize road infrastructure to support the coordination of maneuvers under certain scenarios and conditions. This proposal exploits V2I communications, and is fully complementary to the current V2V-based approach. Some of the benefits of using the infrastructure to support maneuver coordination include:

1) Neutral coordination: Road infrastructure (or authorities) is currently utilized to support traffic management under particular conditions such as traffic jams, peak hours or under the presence of roadworks. Simultaneously managing multiple maneuvers in a small area can be a challenge for a fully distributed solution. CAVs could hence benefit from the support of the road infrastructure to coordinate maneuvers. Road Side Units (RSUs) deployed along the road could support vehicles in the maneuver coordination process by providing advices or suggestions so that vehicles can take better decisions. For example, when two lanes are merged into a single lane due to roadworks, the infrastructure could help coordinate in time and space the merging maneuvers in order to reduce traffic disruptions. Similarly, the infrastructure could also send suggestions to CAVs regarding lane change or speed advices. The support from the infrastructure could hence be considered as a natural evolution of current road traffic signalling systems.

2) Enhanced perception: The V2V distributed approach proposed to date for maneuver coordination needs to detect that the coordination of a maneuver is necessary in order to initiate the process. The detection capabilities are hence in principle limited to the V2V range. RSUs could be strategically located in specific areas with extended V2I range thanks to a higher elevation of the antennas and better propagation conditions. These nodes can gather information about the driving conditions through the Cooperative Awareness Message (CAM) [9] (beacons or BSMs) and Collective Perception Message (CPM) [10] messages received from vehicles. They can also fuse this data with other ITS sensors (e.g. cameras and inductive loops) to further improve the perception capabilities and increase the detection range. This increases the time and space in which vehicles can coordinate their maneuvers, and improves the traffic management. This is also particularly useful under mixed traffic scenarios where conventional, connected and automated vehicles coexist.

3) Coordination of multiple vehicles: Complex traffic situations could require the coordination of multiple vehicles. Coordinating multiple vehicles through a V2V distributed approach can require a pairwise and sequential coordination of the maneuvers. This can increase the time needed to coordinate all vehicles and hence impact the road traffic. Road infrastructure nodes could facilitate this coordination by acting as a common coordination entity that provides coordinated advices to multiple vehicles.

To illustrate the benefits of our proposed approach, we consider the scenario depicted in Figure 2. This scenario includes an area where automated driving is not possible and all approaching vehicles need to perform a ToC before entering the area. Our objective is to coordinate the maneuvers resulting from the multiple ToCs in the same area so that they don't negatively influence the traffic flow and safety. To this aim, we propose an infrastructure-based maneuver coordination process that distributes the ToCs over time and space. To do so, the infrastructure monitors the traffic upstream of the area where automated driving is not allowed. This can be done by combining the information of the CAM and CPM messages with the information of other road sensors (e.g. cameras or inductive loops). The infrastructure informs upcoming vehicles of the presence of this 'no automated driving' area using a DENM (Decentralized Environmental Notification Message) message that we have extended to include a new *causeCode* in the *eventType* field of the *Situation Container* [11]. The infrastructure identifies the vehicles that need to perform a ToC (i.e. CAVs approaching the area)[2] and computes the best time and location for each upcoming CAV to execute their ToC. The infrastructure disseminates these advices using the MCM defined in Section IV.

[2] TransAID (as well as other projects) proposes to extend the CAMs to include information specific for CAVs. In particular, we propose to add a new *AutomatedVehicleContainer* container that includes for example information about the current level of automation of a CAV.

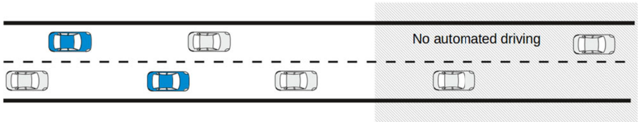

Figure 2. Scenario.

The proposed approach has been simulated in the microscopic traffic simulator SUMO [12]. We model a two-lane highway with a length of 5 Km and a maximum speed of 130 Km/h. The starting point of the 'no automated driving' area is situated at 2.5 Km from the start of the scenario. We assume a level of service C (i.e. 1617 vehicles/hour/lane). Different CAVs penetration rates have been simulated. Traffic mix 1 considers that 15% of vehicles are CAVs, 25% connected vehicles and 60% of conventional vehicles. Traffic mix 2 considers 25% of CAVs, 35% of connected vehicles and 40% of conventional vehicles. Traffic mix 3 considers 40% of CAVs, 50% of connected vehicles and 10% of conventional vehicles. Figure 3 represents the average number of times in which a vehicle experiences a Time To Collision (TTC) with any other neighbouring vehicle lower than three seconds (and hence there is a potential risk of collision). The baseline scenario corresponds to the scenario in which our proposed approach is not applied and the ToCs occur near the starting point of the 'no automated driving' area. The TransAID results correspond to the simulations in which our approach to distribute ToCs and coordinate maneuvers with the support from the infrastructure is applied. Figure 3 clearly shows that our proposed approach significantly improves the traffic safety as it drastically reduces the occasions in which vehicles are confronted with a TTC lower than 3 seconds. These results clearly illustrate the traffic advantages that the support from the infrastructure can bring to the maneuver coordination process. In this context, we propose to extend the existing MCS concept by including the possibility that the road infrastructure supports the coordination of maneuvers. To this aim, we define in the following section a new Maneuver Coordination Message that vehicles can use to coordinate their maneuvers, and that the road infrastructure can use to support such coordination.

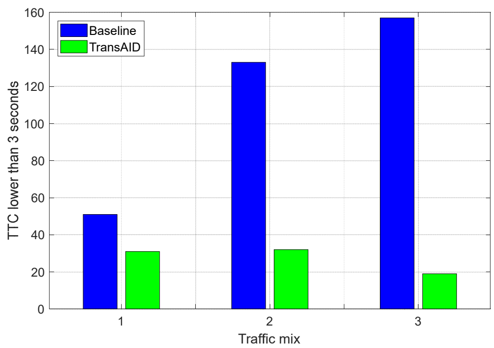

Figure 3. Average number of events with a Time to Collision (TTC) lower than 3 seconds considering a Level of Service C.

IV. MCM FORMAT

This paper proposes a Maneuver Coordination Message that supports the coordination of maneuvers between vehicles and also the participation of the road infrastructure if needed. Figure 4 shows the format of the proposed MCM. It includes the *ItsPduHeader* which is a common header for all ETSI standard messages that includes the information of the protocol version, the message type and the ID of the originating ITS station. The *GenerationDeltaTime* defines the time at which the MCM has been generated. The *BasicContainer* includes the latest position (*ReferencePosition*) and the type of the originating station (*StationType*); the station can be a vehicle or a RSU in our proposal. The *ManeuverContainer* can include a *VehicleManeuverContainer* if is transmitted by a vehicle or a *RSUSuggestedManeuverContainer* if it is transmitted by the road infrastructure. This approach is aligned with that followed by ETSI for other messages (e.g. CAMs) where there are different containers depending on the type of ITS station [9].

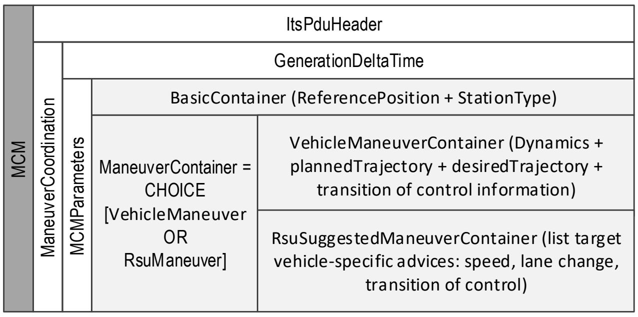

Figure 4. Proposed MCM format.

The *VehicleManeuverContainer* is transmitted by vehicles and includes the *planned trajectory* and the *desired trajectory*, as depicted in Figure 5. It can then implement the distributed V2V-based maneuver coordination approach currently under discussion in ETSI. The container also includes the *vehicle dynamics* object that includes information such as the heading, speed, acceleration or lane position. This information is transmitted on the MCM to avoid cooperative maneuvers to have to rely on the reception of CAMs. The *VehicleManeuverContainer* contains different data elements to inform nearby stations about ToCs and/or MRM maneuvers. For example, the *time of take-over request* field indicates the time at which a take-over request will be triggered when a ToC has been scheduled. The *target automation level* defines the automation level of the vehicle after a ToC, and the *trigger time of MRM* defines the time when an MRM will take place if the driver is unable to take control of the vehicle. The proposed MCM format allows RSUs to send notifications or advices to the vehicles. If a vehicle receives an advice from an RSU it will respond by including a bit string (*advice followed*) to inform the RSU (and nearby vehicles) of whether it has accepted the advice or not. The advice is identified with the *advice ID* field.

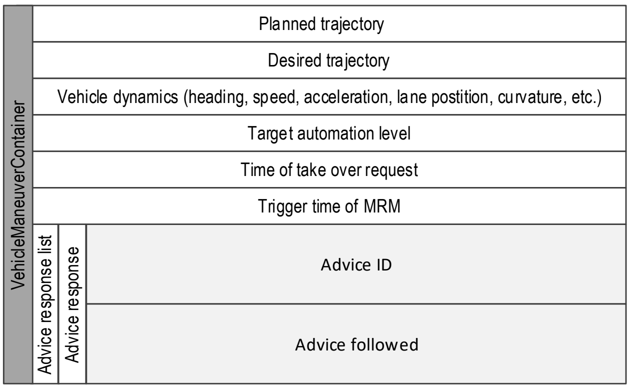

Figure 5. *VehicleManeuverContainer.*

The *RSUSuggestedManeuverContainer* is transmitted by RSUs and is depicted in Figure 6. This container includes different data elements so that RSUs can support the coordination of maneuvers. The *intersectionReferenceID* and the *roadSegmentReferenceID* are used as geographical references of the advices or notifications contained in the MCM. Any *lane ID* employed in the MCM will refer to this specific intersection or segment of the road. This container includes the *vehicle advice list* composed by a list of *vehicle advice* objects. Each *vehicle advice* is sent to a specific vehicle that is identified by the *Target Station ID;* this field defines the *Station ID* of the vehicle to which the advice is sent. Three types of advices are possible: lane advice, speed and gap advice, and ToC advice. Every advice contains a unique identifier (*Request ID*). The *lane advice* includes the *Target lane, Lane change position, Lane change time, Lane change speed* to inform vehicles of the target lane and the position, speed and time where the lane change shall be executed. It also includes the field *Triggering time of ToC* that specifies a point on the road where a take-over request shall be triggered if the lane change has not been executed. This is useful in situations where the infrastructure can foresee that the CAV will not be able to autonomously manage a specific traffic situation occurring in one lane. In this case, the infrastructure sends the lane change advice and specifies that if the lane change is not possible it is recommended to perform a ToC. The *speed and gap advice* object includes indications about the speed vehicles should follow or the gaps they should maintain with other vehicles. It specifies the lane ID (*advice lane ID*) and position (*Advice position*) where the advice shall be followed. The specific speed or gap advice is encoded in the *Target speed* field or the *Target gap* field. Finally, *ToC advice* contains information such as the reason for the ToC (*ToC advice reason*), the position and time to start the ToC (*Position to start ToC* and *Time to trigger ToC*) and the position to finish the ToC (*Position to end ToC*). It could be used by the road infrastructure to coordinate (e.g. to distribute in space and time) the ToC of multiple vehicles.

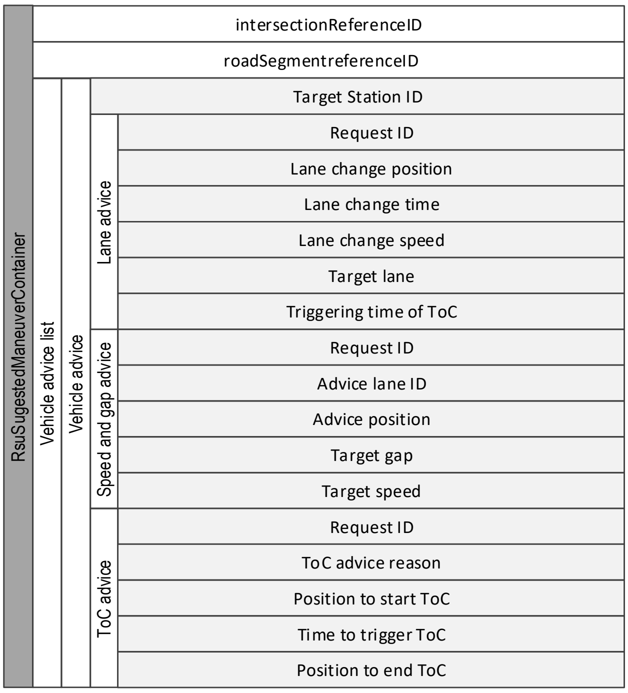

Figure 6. *RSUSuggestedManeuverContainer*.

V. MCM Generation Rules

The previous sections have demonstrated how a MCS supported by the infrastructure can improve the traffic safety, and have proposed a corresponding MCM format. The full design of a Maneuver Coordination Service requires also defining the message generation rules. These rules indicate which vehicles should transmit an MCM and when they should transmit it. The generation rules will have a significant impact on the traffic effectiveness of the maneuver coordination process. They can also influence the performance and scalability of the V2X network since MCM messages will increase the channel load. Such increase can be particularly challenging if MCMs have to be transmitted in the reference control channel together with other messages such as CAMs or CPMs. Increasing the channel load augments packet collisions and the communications latency, and reduces the V2X reliability. These effects can in turn degrade the effectiveness of the MCS.

This section analyses the impact on V2X networks of three possible message generation rules for different traffic densities. Two of them consider the periodic transmission of MCMs at 2Hz (i.e. every 0.5s) and 10Hz (i.e. every 0.1s). The third one is a dynamic policy where vehicles generate an MCM when their absolute position changes by more than 4m. This approach is aligned with the one currently considered at ETSI for the transmission of CAMs. The channel load created by the message generation rules is estimated analytically using the CBR (Channel Busy Ratio) metric following the method in [13]. The CBR is defined as the ratio of time that the channel is sensed as busy. It can be estimated by multiplying the traffic density (β, in vehicles/m), the message generation frequency (λ in Hz), the message duration (T, in seconds), and the spatial integral of the packet sensing ratio (PSR):

$$CBR = \beta \cdot \lambda \cdot T \cdot \int_d PSR(d) \qquad (1)$$

PSR is defined as the probability of sensing a packet at a given distance. This probability is computed as the probability that the transmission of a message produces a received signal power at the receiver higher than the carrier sense threshold. Equation (1) assumes that vehicles are uniformly distributed and there are no packet collisions. Packet collisions reduce the amount of time that the channel is sensed as busy compared to the CBR estimated with equation (1). The reduction factor can range between 10% and 20% when the CBR varies between 0.3 and 0.6 approximately according to previous studies such as [14] and [15].

Figure 7 plots the CBR as a function of the traffic density for the three message generation rules. The results are computed for a packet size of 300B, a straight road segment with 4 lanes and the Winner+ B1 propagation model [16]. The message generation frequency for the dynamic policy has been computed using the well-known Van Aerde model [17] that relates traffic intensity, traffic density and speed. This model has been used to obtain the relationship between the traffic density and the speed[3]. Figure 7 shows that the periodic message generation rules do not scale well with the density since the CBR linearly increases with the traffic density. The periodic policy at 10Hz generates the highest channel load while it is unclear whether generating an MCM every 0.5s (periodic policy at 2Hz) is sufficient for a safe and efficient coordination of the maneuvers. On the other hand, the dynamic policy adapts the message generation frequency to the vehicles' speed. This reduces the CBR as the traffic density increases because vehicles move slower.

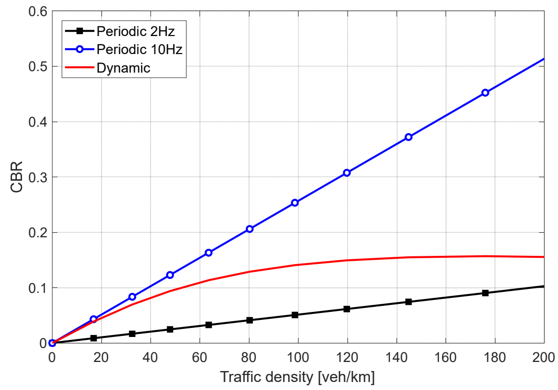

Figure 7. CBR (Channel Busy Ratio) as a function of the traffic density for three different MCM generation rules.

This result highlights the interest for dynamic message generation rules that take into account the vehicular context. However, further research is needed to define the message generation rules. For example, rather than continuously (with a fixed or dynamic frequency) generating MCMs, more advanced policies might also consider additional factors like the detection (through CAMs or CPMs) of a new vehicle (or

[3] To this aim, we consider a maximum road capacity of 2200 vehicles/hour/lane, a maximum speed of 140km/h, and a maximum density of 200 vehicles/km/lane.

object) or the anticipation of a required change of trajectory. In addition, it is also necessary to analyse whether MCMs should co-exist on the reference control channel with CAMs (or beacons) and other existing messages, or whether multi-channel schemes should be considered to reduce the risk of channel congestion.

VI. Conclusions

Cooperative maneuvers allow CAVs to coordinate their traffic maneuvers for a safer and more efficient driving. Current efforts to define cooperative maneuvers are mainly focused on a distributed approach where vehicles use V2V communications to exchange information about their planned and desired trajectories. This paper proposes to extend this approach by including the possibility for the road infrastructure to support the coordination of maneuvers. The paper demonstrates with a use case how such support can improve the traffic safety. In addition, we propose a format for the Maneuver Coordination Message (MCM), and discuss and analyse the impact that different MCM generation rules may have on the performance and stability of V2X networks. The discussion opens future research directions for an efficient implementation of cooperative maneuvers from a communications perspective.

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