V2X COMMUNICATIONS FOR MANEUVER COORDINATION IN CONNECTED AUTOMATED DRIVING

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Message Generation Rules

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Connected automated vehicles (CAVs) can use vehicle-to-everything (V2X) communications to exchange their driving intentions and coordinate their maneuvers. Message generation rules are necessary to decide when and how maneuver coordination messages (MCMs) should be generated. The design of these generation rules must consider the critical nature of maneuver coordination and the limited bandwidth available for V2X communications. This study proposes the first two sets of V2X message generation rules for maneuver coordination between CAVs. The *Risk* proposal increases the rate at which vehicles generate MCMs when vehicles detect a potential safety risk. With the *Tracking Trajectories* proposal, vehicles generate a new maneuver coordination message when they significantly modify their planned trajectory. For both proposals, the messages include the planned and possible desired trajectories of the ego vehicle. The evaluation shows that the proposed generation rules efficiently support maneuver coordination and offer a balance between more frequent updates of the driving intentions of CAVs and lower

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THIS STUDY PROPOSES THE FIRST TWO SETS OF V2X MESSAGE GENERATION RULES FOR MANEUVER COORDINATION BETWEEN CAVs.

coordination time and better control of the V2X communications channel load. This study also reveals that congestion control protocols can significantly impact maneuver coordination.

CAVs use V2X communications to exchange information (e.g., position and speed) for safety awareness and traffic management services. CAVs can also use V2X communications to coordinate their maneuvers. Maneuver coordination allows CAVs to exchange information about their intentions and coordinate their driving and is thus key to improving traffic flow and safety [1], [2], [3]. The European Telecommunications Standards Institute (ETSI) and Society of Automotive Engineers (SAE) have launched standardization activities to define maneuver coordination (ETSI TR 103578) and maneuver sharing and coordinating (SAE J3186) services, respectively, but the work is still in the early stages.

The implementation of maneuver coordination requires generation rules for vehicles to decide when and how they should generate MCMs. These messages are referred to as *MCMs* by ETSI and *maneuver sharing and coordination messages* (*MSCMs*) by SAE. In this article, we will refer to the message as *MCMs*, but MSCMs are valid likewise. A frequent transmission of messages would provide updated information about other vehicles' driving intentions but risks saturating the communications channel. The design of generation rules should hence guarantee safe and smooth maneuver coordinations while efficiently using the limited bandwidth.

Previous studies generate MCMs at fixed rates [3], [4]. This study advances the state of the art with the first two sets of message generation rules for maneuver coordination. The *Risk* proposal augments the rate at which vehicles generate MCMs when they detect a potential safety risk. The *Tracking Trajectories* proposal increases the MCM generation rate when the transmitting vehicle significantly modifies its trajectory. Our evaluation shows that both proposals support maneuver coordination and offer a balance between more frequent updates of the driving intentions and a lower load on the communications channel. The load can also be managed using congestion control protocols. However, this study reveals that these protocols can significantly impact maneuver coordination, and their interaction should be carefully designed.

The State of the Art

The first studies on maneuver coordination presented specific protocols for concrete maneuvers. For example, Hobert et al. [4] design a cooperative lane change solution where vehicles use V2X communications to reserve a space on the road. Englund et al. [5] propose virtual platoons to organize how vehicles should cross an intersection and a cooperative maneuver for merging platoons. Heß et al. [6] propose negotiation techniques for CAVs to cooperate during lane changes. Chou et al. [7] propose a specific solution for coordinating lane merges. All these studies design specific protocols and sequences of V2X messages for coordinating concrete maneuvers, and their solutions might not be applicable to other maneuvers. This approach challenges the scalability of maneuver coordination as it requires a solution for each type of maneuver.

Lehmann et al. [8] present an alternative approach and propose a generic solution for maneuver coordination that is valid for any type of maneuver and driving scenario. This approach [8] is an implicit maneuver coordination framework since vehicles request and negotiate maneuver coordinations implicitly by exchanging planned and desired trajectories. Vehicles could also explicitly negotiate cooperative maneuvers [9]. However, explicit approaches require specific and explicit messages for requesting, accepting, and confirming a coordinated maneuver.

To the best of the authors' knowledge, none of the existing proposals (whether maneuver specific or generic) specify message generation rules for MCMs. Some of them generate messages for coordinating a maneuver, and all of them assume that vehicles generate additional messages at a constant and predefined rate to provide information about their driving intentions in addition to event-based generated messages. The periodic generation of messages could unnecessarily overload the communications channel and prevent important messages from being received. It is then necessary to design message generation rules that allow for maneuver coordination while efficiently utilizing the communications channel. This article advances the state of the art by presenting, to the authors' knowledge, the first two sets of message generation rules for maneuver coordination. We implement and test the rules over the proposal from [8] given the advantages of using a solution that can be applied to any type of maneuver. Our evaluations focus only on communications among vehicles.

Maneuver Coordination

Vehicles using the maneuver coordination approach presented in [8] exchange their planned and desired trajectories to implicitly coordinate maneuvers. The planned trajectory represents the driving intentions of a vehicle in the short term (i.e., the next few seconds). The desired trajectory is the trajectory that a vehicle would like to follow but cannot follow because it overlaps with the planned trajectory of another vehicle that has the right of way. Vehicles broadcast their planned trajectories using MCMs. The vehicles use the trajectories received in MCMs to identify potential traffic conflicts with nearby vehicles. If a vehicle without the right of way wants to initiate a maneuver with a target vehicle, it requests the maneuver coordination by transmitting its desired trajectory together with the planned trajectory in an MCM. The vehicle that has the right of way may accept or reject the request. If the vehicle with the right of way accepts the request, it modifies its planned trajectory so that the initiating vehicle can execute its desired trajectory without collision.

This is illustrated in Figure 1 for a lane change maneuver example. The vehicles in the scenario broadcast their planned trajectory. At t_1, the initiating vehicle (V_{init}) wants to change lanes as it is approaching a low-speed truck. However, it detects that its desired trajectory collides with the planned trajectory of the target vehicle (V_{target}) that has the right of way. V_{init} should then not initiate the maneuver unless V_{target} modifies its planned trajectory to allow the lane change. To request the maneuver coordination, V_{init} broadcasts its desired trajectory together with its planned trajectory in the following MCMs. If V_{target} is willing to let V_{init} change lanes, it modifies its planned trajectory (e.g., reducing its speed to create a gap) and transmits it on the following MCMs. When V_{init} detects that the new planned trajectory of V_{target} does not collide with its desired trajectory, its desired trajectory becomes its planned trajectory (at t_2 in Figure 1), and V_{init} can change the lane. If V_{target} does not modify its planned trajectory, V_{init} understands that V_{target} declines the coordination request, and the maneuver is not executed.

Message Generation Rules

This article proposes two sets of generation rules (*Risk* and *Tracking Trajectories*) to decide when and how vehicles should generate MCMs. Like in [8], we consider that vehicles regularly broadcast their planned trajectories so that the neighboring vehicles can be aware of their driving intentions and detect the possible need for maneuver coordination. However, our generation rules do not transmit MCMs at fixed rates but adapt the time interval between MCMs. Both strategies establish a minimum rate for regular broadcasting of MCMs. Each strategy then defines different conditions under which such a

THIS ARTICLE PROPOSES TWO SETS OF GENERATION RULES (RISK AND TRACKING TRAJECTORIES) TO DECIDE WHEN AND HOW VEHICLES SHOULD GENERATE MCMS.

rate should be increased. The *Risk* strategy increases this rate when a vehicle detects that it is at risk with at least one nearby vehicle (*Risk* condition). For example, two vehicles that are close to each other could represent a safety risk since a collision could occur if one of the two modifies its trajectory. If there are no safety risks, vehicles broadcast MCMs at the minimal rate to reduce the channel load.

With *Tracking Trajectories*, vehicles also generate MCMs at the minimal rate unless they detect that their planned trajectory has significantly changed with respect to their planned trajectory included in the previous MCM (*Tracking Trajectories* condition). The rationale for the *Tracking Trajectories* strategy is that vehicles do not need to frequently broadcast their trajectory if nearby vehicles are already aware of their driving intentions and if these intentions have not significantly changed.

We define a minimum and a maximum time interval between consecutive MCMs for the two proposed generation rules. The maximum time interval (T_{max}) guarantees that vehicles will inform nearby vehicles of their driving intentions with a minimum MCM generation rate. The minimum time interval (T_{min}) limits the maximum MCM generation rate to avoid overloading the channel. Vehicles check every T_{check} seconds whether they should generate a new MCM following Figure 2, with T_{check} lower or equal to T_{min} and considering that T_{max} is a multiple of T_{check}. An ego vehicle generates a new MCM if its last MCM was generated at least T_{min} seconds ago and if at least one of the following conditions is satisfied:

1) The ego vehicle wants to initiate a maneuver coordination and include a desired trajectory in the next message.
2) The ego vehicle has received a desired trajectory in conflict with its current planned trajectory from a vehicle that wants to coordinate a maneuver.

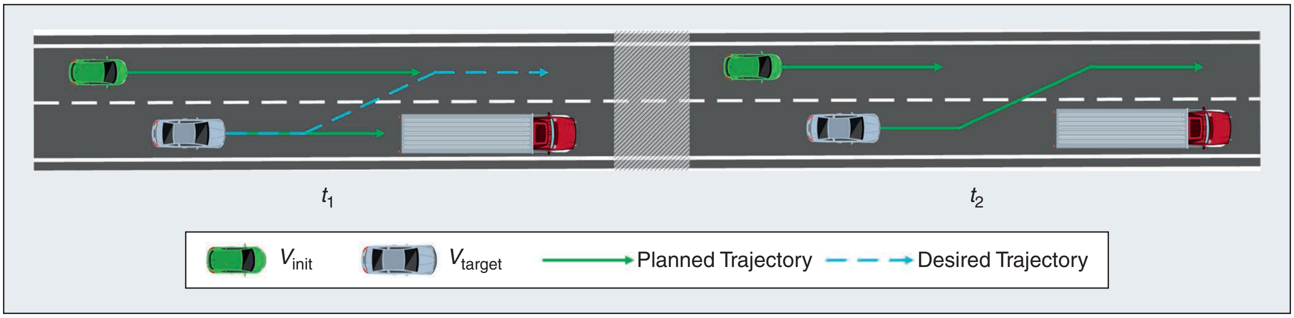

FIGURE 1 Maneuver coordination in a lane change.

3) The time elapsed since the last message generated by the ego vehicle is equal to or greater than T_{max}.
4) *Risk* or *Tracking Trajectories* conditions are satisfied when using the *Risk* or *Tracking Trajectories* generation rules, respectively.

The first two conditions deal with negotiation for a cooperative maneuver (known as *agreement seeking* following the ETSI and SAE terminology), and we establish them to reduce the maneuver coordination time. The coordination time is the time elapsed between the generation of the first MCM with a desired trajectory to request a coordination and the reception of the MCM with an updated planned trajectory from the vehicle that accepts the request for coordination. The request for coordination could be accepted or not by the ego vehicle, but in both cases, the ego vehicle generates a new MCM following the second condition to indicate its decision to the initiating vehicle as soon as possible (Figure 2). The last two conditions deal with what is known as *intent sharing* (following the terminology of ETSI and SAE), with the third one established to guarantee a minimum rate for the generation of MCMs. The difference between the two proposed generation rules lies in the fourth condition (*Risk* and *Tracking Trajectories* conditions), i.e., on the message generation for intent sharing.

The *Risk* condition relies on the time-to-risk (*TTR*) metric that we define as the time left for two vehicles in the same or adjacent lanes to reach the same longitudinal position considering their planned trajectories. *TTR* is an extension of the time-to-collision (*TTC*) metric [10]. *TTC* is the time left for two vehicles in the same lane to collide if they maintain their speed. *TTR* extends *TTC* to consider that vehicles in adjacent lanes could also pose a risk when approaching each other since a change in their driving intentions could result in a collision. Another difference with *TTC* is that *TTR* considers the planned trajectories of the two vehicles (i.e., their future positions and speeds), while *TTC* considers only their current position and speed.

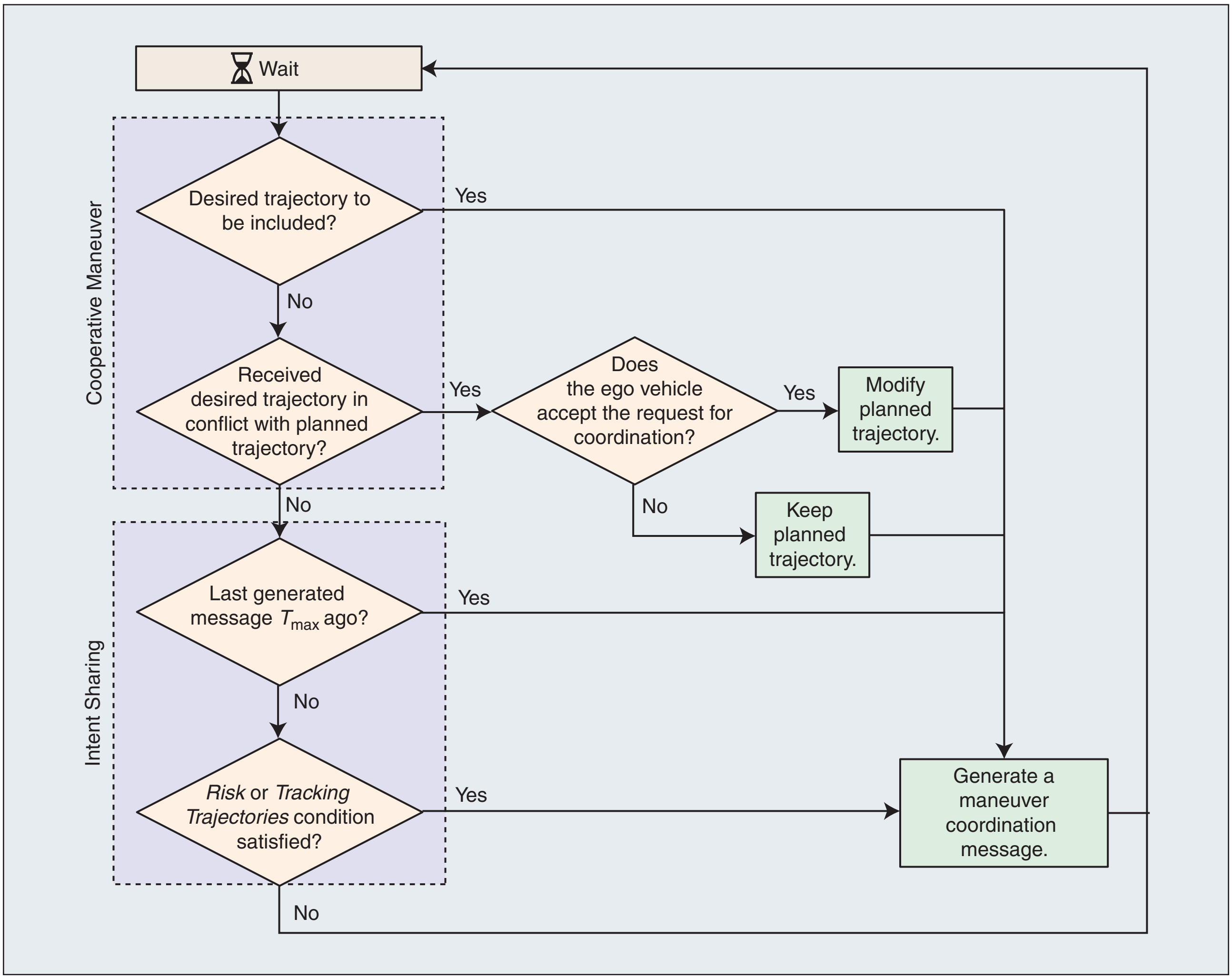

FIGURE 2 *Risk* and *Tracking Trajectories* generation rules for MCMs.

We consider that a planned trajectory Z is a sequence of points uniformly distributed in time over the duration of the trajectory. We denote a planned trajectory as $Z=[z_1, z_2, \ldots, z_N]$, where N is the number of points z_i in the trajectory. z_i is defined as $z_i=(p_i, v_i, t_i)$, where $p_i=(x_i, y_i)$ is the position of the vehicle on the road, v_i is its velocity, and t_i is the time at point z_i. (x_i is the longitudinal position along the road and y_i is the lateral position. To simplify the notation, we use the road as the reference coordinate system, and thus, the lateral position on the road changes only when the vehicle changes the lane.) The first point of the trajectory $[z_1=(p_1, v_1, t_1)]$ includes the current position and velocity of the vehicle and the current time t_1. We compute the *TTR* between two vehicles A and B with trajectories Z^{A} and Z^{B} at t_1 as

$$TTR(Z^{\mathrm{A}}, Z^{\mathrm{B}}) = \min_i \left(T(z_i^{\mathrm{A}}, z_i^{\mathrm{B}}) + \Delta t_i\right) \tag{1}$$

where $T(z_i^{\mathrm{A}}, z_i^{\mathrm{B}})$ is the time from t_i that it will take the two vehicles to reach the same longitudinal position at the same time. We compute $T(z_i^{\mathrm{A}}, z_i^{\mathrm{B}})$ as

$$T(z_i^{\mathrm{A}}, z_i^{\mathrm{B}}) = \begin{cases} \dfrac{DL(p_i^{\mathrm{A}}, p_i^{\mathrm{B}})}{v_i^{\mathrm{B}} - v_i^{\mathrm{A}}} & \text{if } v_i^{\mathrm{B}} > v_i^{\mathrm{A}} \text{ and } x_i^{\mathrm{B}} < x_i^{\mathrm{A}} \\ \dfrac{DL(p_i^{\mathrm{A}}, p_i^{\mathrm{B}})}{v_i^{\mathrm{A}} - v_i^{\mathrm{B}}} & \text{if } v_i^{\mathrm{A}} > v_i^{\mathrm{B}} \text{ and } x_i^{\mathrm{A}} < x_i^{\mathrm{B}} \\ 0 & \text{if } x_i^{\mathrm{A}} = x_i^{\mathrm{B}} \\ \infty & \text{otherwise} \end{cases} \tag{2}$$

where $DL(p_i^{\mathrm{A}}, p_i^{\mathrm{B}})$ is the longitudinal distance (i.e., along the lanes) between both vehicles at t_i. Equation (2) considers whether the two vehicles are approaching each other (the first two equations) or not (the third and fourth equations). In the fourth one, $T(z_i^{\mathrm{A}}, z_i^{\mathrm{B}})$ is set to infinity since the two vehicles are moving away from each other. Equation (1) includes the term $\Delta t_i = t_i - t_1$ to estimate the *TTR* because the ego vehicle computes the *TTR* at t_1, and the two vehicles will still need Δt_i s to reach the positions p_i^{A} and p_i^{B} used in the estimation of $T(z_i^{\mathrm{A}}, z_i^{\mathrm{B}})$. The ego vehicle then estimates the *TTR* in (1) as the minimum value computed along all the points of the planned trajectories of the two vehicles. To evaluate the *Risk* condition, an ego vehicle computes its *TTR* with all its neighboring vehicles. The *Risk* condition is fulfilled when the minimum *TTR* experienced by the ego vehicle with any of its neighboring vehicles is lower than a threshold TTR_{th}. The configuration of the threshold should ensure that the ego vehicle can frequently inform neighboring vehicles about its driving intentions when it detects a risk situation.

The *Tracking Trajectories* condition establishes that a vehicle should transmit a new MCM if its planned trajectory has significantly changed with respect to the planned trajectory included in its previous MCM. To compute the difference between the new planned trajectory (Z^{new}) and the previous one (Z^{pre}), we define the metric distance between trajectories (*DBT*). To calculate *DBT*, we consider that the first point of the previous trajectory Z^{pre} corresponds to time t_1^{pre} and the last point to t_N^{pre}. The first point of the new trajectory Z^{new} corresponds to t_1^{new} and the last point to t_N^{new}. We should note that t_1^{pre} is lower than t_1^{new}, and t_N^{pre} is lower than t_N^{new} since the new trajectory is generated more recently than the previous one. To calculate *DBT*, we use the new trajectory as a reference and modify the previous trajectory so that it is defined within the time limits of the new trajectory ($[t_1^{\mathrm{new}}, t_N^{\mathrm{new}}]$).

To this aim, we discard the ρ points p_i of the previous trajectory that satisfy the condition that t_i^{pre} is lower or equal than t_1^{new}. The modified previous trajectory Z^{mod} includes then the $N-\rho$ points of the previous trajectory that satisfy such conditions (i.e., $z_1^{\mathrm{mod}} = z_{\rho+1}^{\mathrm{pre}}$, $z_2^{\mathrm{mod}} = z_{\rho+2}^{\mathrm{pre}}, \ldots, z_{N-\rho}^{\mathrm{mod}} = z_N^{\mathrm{pre}}$). We then complete the modified previous trajectory Z^{mod} with ρ points ($z_{N-\rho+1}^{\mathrm{mod}}$ to z_N^{mod}) using trajectory prediction techniques. In particular, we compute the position of each of these ρ points through linear interpolation assuming that the speed of the last point of the previous trajectory (v_N^{pre}) is maintained. This approach is sufficiently accurate for the considered scenario since vehicles normally do not significantly vary their speed. A more accurate prediction would reduce the number of MCMs generated and thus the channel load. The *DBT* is then the maximum distance between the positions of the new and modified previous trajectories

$$DBT(Z^{\mathrm{mod}}, Z^{\mathrm{new}}) = \max_i DG(p_i^{\mathrm{mod}}, p_i^{\mathrm{new}}) \tag{3}$$

where $DG(p_i^{\mathrm{mod}}, p_i^{\mathrm{new}})$ is the geographical distance between p_i^{mod} and p_i^{new}. We consider the maximum *DBT* in the *DBT* definition to capture both sudden and significant changes in trajectory.

The *Tracking Trajectories* condition establishes that the ego vehicle should generate a new MCM when the planned trajectory has significantly changed with respect to its previous planned trajectory. In particular, the *Tracking Trajectories* condition generates a new MCM when $DBT(Z^{\mathrm{mod}}, Z^{\mathrm{new}})$ is higher than DBT_{th}. DBT_{th} should be configured to generate a new MCM when it includes a lane change or a relevant longitudinal change. For example, a value of $DBT_{\mathrm{th}} = 1.5$ m ensures that all lane changes represent a substantial change in trajectory (considering a typical lane with a width of 3.5 m).

Evaluation Platform and Scenario

We have evaluated the proposed message generation rules for maneuver coordination using the simulation platform described in [3]. The platform simulates maneuver coordination by integrating ns-3 with the vehicular

WE ILLUSTRATE THE OPERATION OF THE PROPOSED GENERATION RULES IN A HIGHWAY SCENARIO WITH COORDINATED LANE CHANGE MANEUVERS.

ad hoc network (VANET) highway mobility module [11]. This module uses the intelligent driver model for the longitudinal control of vehicles and the MOBIL lane change model for lane change decisions [12]. The simulator includes a maneuver coordination component to manage the coordination process that includes the proposed MCM generation rules. The simulator also includes a trajectory planner component to estimate the planned and desired trajectories of vehicles.

We illustrate the operation of the proposed generation rules in a highway scenario with coordinated lane change maneuvers. In this scenario, vehicles can coordinate their lane changes following the approach described in the "Maneuver Coordination" section and the implementation of trajectories and lane changes of [3]. Vehicles generate MCMs following the *Risk* or *Tracking Trajectories* generation rules at the facilities layer. For both rules, T_{check} and T_{min} are set equal to 0.1 s, corresponding to a maximum rate of 10 Hz. We run simulations with T_{max} equal to 1 s or 9 s. We consider $T_{max} = 1$ s because this is the maximum time between generated messages usually considered for basic V2X services (e.g., Cooperative Awareness Messages). We also consider $T_{max} = 9$ s since the planned and desired trajectories are 10 s long in this study, and vehicles may not need to transmit updates of their trajectory often if their trajectories do not change.

The threshold of the *Risk* condition is set to $TTR_{th} = 3$ s. (This threshold is commonly used to identify a risk situation for vehicles in the same lane using the *TTC* metric, so we adopt this threshold for the *TTR* [10].) The threshold of the *Tracking Trajectories* condition is set to $DBT_{th} = 1.5$ m. (This value ensures that a new MCM is generated when the new trajectory includes a lane change since the width of lanes is 3.5 m.) We compare the proposed generation rules with a baseline scheme that constantly generates 10 MCMs per second [3]. All the messages generated by the baseline scheme include the planned trajectory, and vehicles include only the desired trajectory when they detect the need for coordination (i.e., when the desired trajectory of a vehicle collides with the planned trajectory of another vehicle). We assume that maneuver coordination requests are always accepted independently of the generation rules. The size of MCMs is equal to 329 B when they include only the planned trajectory and 608 B when they include both the planned and desired trajectories [13]. The transmitted trajectories have 30 points.

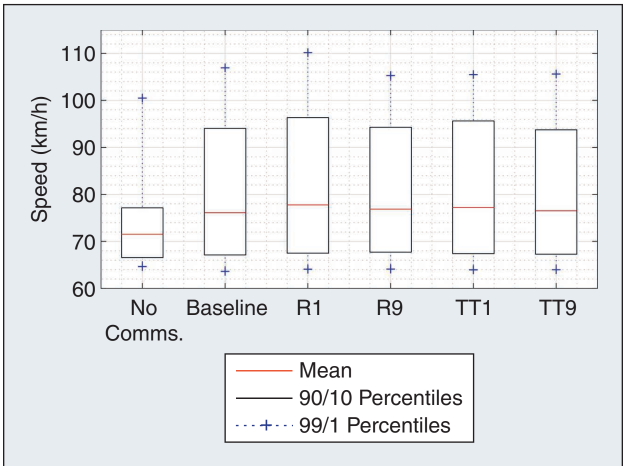

FIGURE 3 The speed of vehicles that initiate a maneuver coordination in a time window of 20 s for 30 vehicles/km/lane. Comms.: communications.

The highway is 5 km long and has three lanes in each direction. We have simulated four different densities (10, 20, 30, and 40 vehicles/km/lane) to observe the behavior of the proposed generation rules when the scenario gets congested. The scenario has periodic boundary conditions, i.e., the two edges of the scenario are connected, and vehicles reaching one edge appear on the opposite edge traveling with the same speed and heading and in the same lane. The scenario models passenger cars and trucks, with trucks representing 20% of the total number of vehicles. The desired speed of vehicles follows a random uniform distribution (120 km/h ± 20% for cars and 80 km/h ± 20% for trucks).

All vehicles have an IEEE 802.11p transceiver and transmit at 6 Mb/s with 23 dBm. At the access layer, we implement the reactive and adaptive decentralized congestion control (DCC) schemes defined by ETSI TS 102 687 to control the channel busy ratio (CBR). The CBR is the percentage of time that the channel is sensed as busy. Reactive DCC uses a state machine to select the message transmission rate; each state is mapped to a range of CBR values and a message rate. Adaptive DCC uses a linear control process so that vehicles adapt their message rate to achieve a target CBR of 68%. However, the CBR converges in practice to a lower value that depends on the number of neighboring vehicles. Reactive DCC reduces the channel load more aggressively than adaptive DCC [14]. For each combination of generation rules, density, and DCC configuration, we performed 15 simulation runs, each of them with a 600-s simulation time.

Evaluation

Figure 3 shows an example of how maneuver coordinations can benefit traffic for a density of 30 vehicles/km/lane. The figure compares the speed of vehicles initiating a maneuver with and without maneuver coordination. The figure compares the baseline scheme that generates

MCMs at 10 Hz and the *Risk* and Tracking Trajectory proposals with $T_{\max} = 1$ s and 9 s (Rx = *Risk* with $T_{\max} = x$, and TTx = *Tracking Trajectories* with $T_{\max} = x$). Figure 3 shows that maneuver coordination increases the speed of vehicles. It also shows that our proposed generation rules do not degrade the speed compared to the baseline scheme despite reducing the rate at which MCMs are generated.

This is visible in Figure 4, which plots the probability density function (PDF) of the number of MCMs generated by each vehicle per second. We measure this number in intervals of 1 s, so it is possible that no message is generated in a 1-s interval when $T_{\max} = 9$ s. Figure 4 shows that the proposed generation rules significantly decrease the number of messages generated per second compared to the baseline scheme. Specifically, the *Tracking Trajectories* proposal generates only one message per second 95% of the time when $T_{\max} = 1$ s; this number further decreases when $T_{\max} = 9$ s since the time between consecutive messages increases up to 9 s if there are no significant changes in the trajectories. *Tracking Trajectories* generates the least number of MCMs in the evaluated scenario. Simulations conducted for the other traffic densities show that the number of messages generated per second by *Tracking Trajectories* reduces as traffic density increases. This is because vehicles have fewer options to change lanes (and hence, there are no significant trajectory updates) when there are more vehicles on the road.

Figure 4 also shows that the *Risk* proposal generates either one or 10 MCMs per second depending on whether the vehicle detects a potential risk with at least one neighboring vehicle or not. Figure 4 shows that this trend is independent of $T_{\max}$. The percentage of time that the *Risk* proposal generates 10 MCMs per second increases with the traffic density since vehicles detect more potential risks (TTR lower than TTR_{th}) when there are more vehicles on the road.

The number of messages generated per second has a direct impact on the channel load. Table 1 reports the CBR experienced with the different generation rules and traffic densities. The results obtained without DCC show that the baseline scheme generates the highest CBR (up to 66%) and that the CBR measured with the two proposed generation rules decreases as $T_{\max}$ increases. *Tracking Trajectories* produces the lowest CBR because it operates most of the time with the lowest generation rate (maximum time interval $T_{\max}$), and hence, generates the minimum number of messages per second (Figure 4). Table 1 also shows that *Risk* generates a CBR between the baseline and *Tracking Trajectories*. Table 1 shows that DCC has a negligible impact on the CBR (and the transmission of messages) under low traffic densities.

However, DCC reduces the CBR of the *Risk* and baseline schemes as the density increases. This is the case because these two schemes generate the highest number of messages per second, and DCC starts dropping messages to control the channel load. Reactive DCC produces higher reductions in CBR since it is designed to limit the channel load to lower CBR levels than adaptive DCC [14]; adaptive DCC has a certain impact only under the highest traffic density. DCC does not affect *Tracking Trajectories* at all densities evaluated since it generates significantly fewer messages per second than the other two schemes (Figure 4) and reduces the CBR (Table 1).

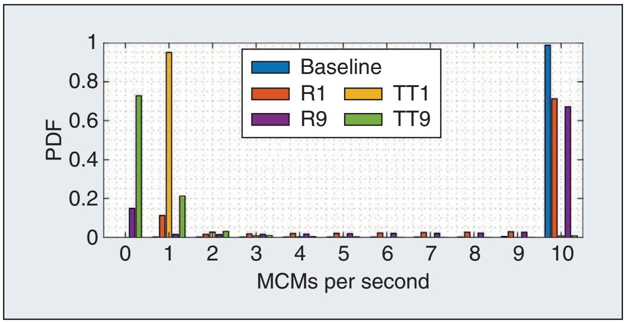

FIGURE 4 A probability density function (PDF) of the number of MCMs generated per vehicle per second for 30 vehicles/km/lane. This number is measured in intervals of 1 s.

TABLE 1 ***Average CBR.***

		Average CBR (%)		
Vehicles/ km/lane	***Generation rules***	***Without DCC***	***Reactive DCC***	***Adaptive DCC***
10	Baseline	28.5	28.3	28.3
	R1	14.3	14.2	14.2
	R9	11.7	11.5	12
	TT1	4.7	4.7	4.7
	TT9	2.8	2.8	2.9
20	Baseline	50	36.5	49.4
	R1	38.4	34.2	38.4
	R9	36	33	35.9
	TT1	7.9	8	8.1
	TT9	4.1	4.2	4.1
30	Baseline	61.5	36.5	59.5
	R1	55.9	36.5	55.1
	R9	53.4	36.7	51.8
	TT1	10.2	10.2	10.2
	TT9	4.2	4	3.9
40	Baseline	66.6	36.5	61
	R1	63.7	36.7	60.5
	R9	58.3	37.1	60
	TT1	11.9	11.8	12
	TT9	2.9	2.6	2.6

The channel load increases interference and can result in message losses (due to packet collisions) that negatively impact the reliability of V2X communications. Figure 5 plots the packet delivery ratio (PDR) experienced for 30 vehicles/km/lane to show this effect. The PDR is measured above the access layer so that it can account for all possible types of packet losses, including packets generated but dropped (and hence, not transmitted) by the access layer (in our case by DCC access). The PDR provides information on the communication range, and hence, on the distance at which vehicles could start coordinating their maneuvers. Figure 5 shows that *Tracking Trajectories* achieves the highest PDR since it reduces the CBR (Table 1), and hence, the probability of packet collisions. The increase in CBR with the baseline and *Risk* schemes results in a higher probability of packet collisions and the degradation of the PDR. Figure 5 also shows that DCC does not impact the PDR when using *Tracking Trajectories* since this scheme maintains low CBR levels.

On the other hand, reactive DCC severely degrades the PDR of the baseline and *Risk* schemes since it drops more than 40% of the messages to control the channel load. The impact of adaptive DCC on the PDR of *Risk* is small for this density since the CBR is not sufficiently high to activate adaptive DCC. The baseline technique follows a similar trend to *Risk* but with lower PDR values. We obtained similar trends for different values of $T_{\max}$.

The number of messages generated per second (Figure 4) and the V2X communications performance (Figure 5) impact the capability of each vehicle to maintain updated information about the driving intentions of surrounding vehicles. This is visible in Figure 6, which compares the mean of the maximum age of information per packet for 30 vehicles/km/lane. This metric is defined as the time elapsed between the generation time of a message received from a specific vehicle and the reception time of the next message received from the same vehicle. Figure 6 shows that *Tracking Trajectories* results in the highest age of information despite its better PDR and lower channel load. This is due to the lower number of messages it generates per second (Figure 4). Figure 6 shows that baseline and *Risk* achieve similar performance, although the baseline scheme generates more messages per second (Figure 4). This is because the baseline scheme loses more messages due to the higher CBR. *Tracking Trajectories* reduces the number of generated messages when $T_{\max}$ increases (Figure 4), and this increases the maximum age of information per packet. This is not observed for *Risk* because the duration of situations without risk that do not trigger a new MCM is significantly lower than 9 s. Figure 6 also shows that DCC increases the age of information since it drops messages to control the channel load.

The number of MCMs generated per second during coordinations and the PDR impact the execution of maneuver coordinations. We analyze such execution by estimating the maneuver coordination time. Figure 7 depicts the average maneuver coordination time for 30 vehicles/km/lane with and without DCC. We measure the coordination time only during coordinations, i.e., when all techniques transmit at 10 Hz. Losing a message during the coordination process increases the maneuver coordination time. Therefore, the coordination time depends then on the probability of packet reception (and consequently, the channel load and packet collisions). The figure shows that the *Risk* and baseline schemes increase the average maneuver coordination time compared to *Tracking Trajectories* when DCC is disabled. *Tracking Trajectories* achieves the lowest coordination time because it reduces the channel load and therefore increases the PDR, despite its higher age of information (Figure 6).

Figure 7 also shows that DCC significantly increases the maneuver coordination time of the baseline and *Risk* schemes, especially when using reactive DCC. This is the

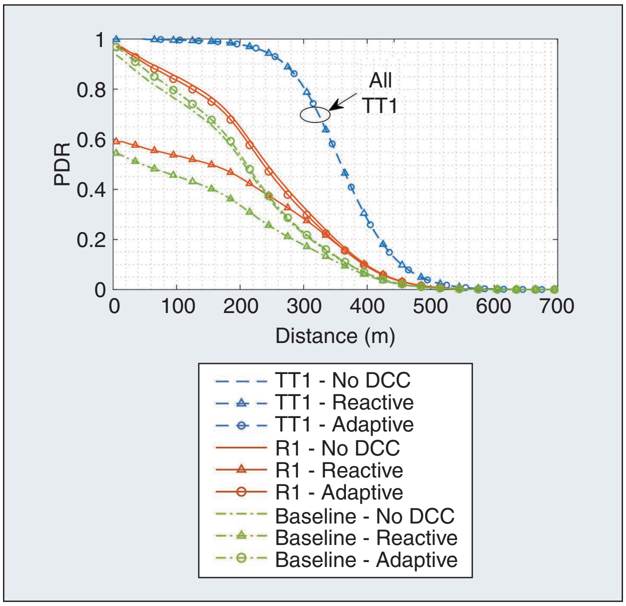

FIGURE 5 A packet delivery ratio (PDR) for 30 vehicles/km/lane.

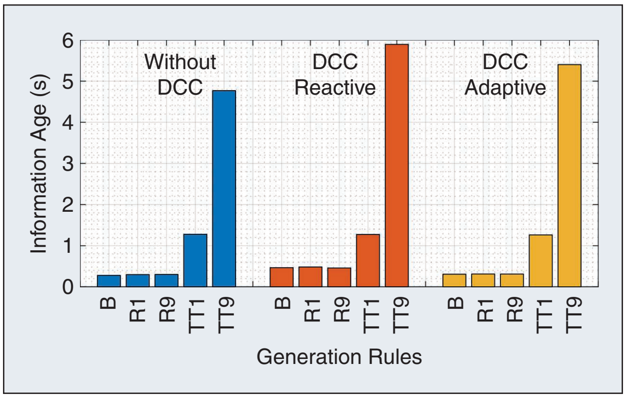

FIGURE 6 The mean of the maximum age of information per packet for 30 vehicles/km/lane.

case because reactive DCC can drop a high percentage of messages to control the load. The figure also shows that DCC does not significantly affect *Tracking Trajectories*. We have observed similar trends for other densities. For 10 vehicles/km/lane, all schemes reach an average coordination time of approximately 100 ms. However, the average maneuver coordination time increases with the traffic density for the baseline and *Risk* schemes. Without DCC, the coordination time increases by 19.5% and 11.9% when the density increases from 10 to 40 vehicles/km/lane for baseline and *Risk* schemes, respectively. With reactive DCC, these increases are 172.3% and 171.4%, and with adaptive DCC, they are 54.4% and 39.5%. However, the average coordination time does not increase with *Tracking Trajectories*. The channel load increases with the traffic density, and such an increase has a higher impact on maneuver coordination when using rules that generate more messages.

The obtained results demonstrate that *Risk* and *Tracking Trajectories* can successfully support maneuver coordinations and outperform a baseline implementation based on a periodic generation of messages. *Risk* ensures more frequent updates of the driving intentions compared to *Tracking Trajectories* but augments the channel load and the coordination time due to a lower transmission reliability. On the other hand, *Tracking Trajectories* increases the age of information as it decreases the message generation rate. However, this does not negatively affect maneuver coordinations as it reduces the coordination time. This reduction is achieved because it reduces the channel load and increases the probability of correctly receiving the transmitted messages, including those with implicit maneuver coordination requests or negotiations, which are key for coordinations. In this case, *Tracking Trajectories* can be considered more effective in the given scenario and conditions as it reduces the channel load compared to *Risk*.

Discussion and Conclusion

This article presents the first two sets of message generation rules specifically designed for maneuver coordination in

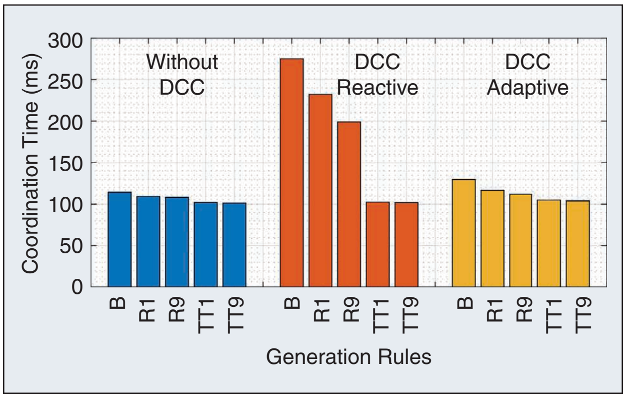

FIGURE 7 The average maneuver coordination time for 30 vehicles/km/lane density.

IN FACT, THE STUDY HAS SHOWN THAT TRANSMITTING MORE MESSAGES DOES NOT NECESSARILY RESULT IN THE BETTER EXECUTION OF V2X SERVICES.

connected and automated driving. The *Risk* proposal increases the rate at which the ego vehicle generates MCMs when it detects a potential risk. This results in more frequent updates about the driving intentions of the surrounding vehicles and a lower information age. With *Tracking Trajectories*, an ego vehicle generates a new message only when it significantly changes its trajectory or driving intentions. This reduces the number of MCMs and the channel load and improves the reliability of V2X communications. This is achieved at the cost of a higher age of information. However, the higher age of information does not negatively impact maneuver coordinations with *Tracking Trajectories* as it achieves the lowest coordination time.

Both proposals can efficiently support maneuver coordination while reducing the channel load and the number of messages generated compared to a baseline scheme with a fixed message generation rate. The conducted study has also shown that congestion control can negatively impact the execution of maneuver coordination for the baseline and *Risk* approaches since they increase the channel load and congestion control impacts the transmission of messages. However, congestion control does not impact *Tracking Trajectories* under the considered conditions since it significantly reduces the channel load. Different maneuvers or scenarios can impact the number of messages generated by each technique and may require the fine-tuning of some of their parameters, which is out of the scope of this study. However, they would not impact the behavior of the techniques and the trends observed in this study since the proposed generation rules have been designed independently of the type of maneuvers or driving scenarios.

Our study shows the need to design congestion control protocols that consider the context, needs, and characteristics of maneuver coordination services as well as other V2X services. The impact of such protocols on the overall efficiency of V2X services can be conditioned by the possible coexistence of multiple V2X services on the same channel. Such coexistence would require V2X services to more carefully control the generation of messages to guarantee the scalability of the V2X network. In fact, the study has shown that transmitting more messages does not necessarily result in the better execution of V2X services, and this clearly calls for further research on the design of V2X services that carefully curate the information transmitted based on their estimated value.

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