On the Impact of V2X-based Maneuver Coordination on the Traffic

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***Abstract*—Connected and automated vehicles (CAVs) are expected to make use of Vehicle-to-Everything (V2X) communication to exchange sensor and trajectory data. Using this data, CAVs can coordinate their maneuvers for safer and more efficient driving. ETSI and SAE are currently working to define standards for maneuver coordination and cooperative driving. The current approach at ETSI is based on a distributed solution where vehicles use Vehicle-to-Vehicle (V2V) communication to exchange their planned and desired trajectories. This study evaluates the potential benefits of the ETSI Maneuver Coordination Service to improve the traffic speed using a unique simulation tool. To do so, we first evaluate the impact of maneuver coordination on the vehicles involved in a coordination process. We also evaluate the effects of maneuver coordination on the overall traffic compared to scenarios without coordination. Our study shows that maneuver coordination can yield significant benefits to traffic mobility, however these improvements are intimately linked to the surrounding traffic environment and the specifications of the coordinated maneuver. This highlights the need for more detailed studies on the design of maneuver coordination protocols that should consider the vehicular context when executing and configuring the coordination process.**

Keywords—maneuver coordination, maneuver sharing, intent sharing, cooperative driving, connected and automated vehicles, CAV, V2X communication, V2V, MCM, vehicular networks.

I. INTRODUCTION

Autonomous vehicles use on-board sensors to detect the surrounding traffic and environment. However, existing sensors present certain limitations that can reduce their sensing range (e.g. due to the presence of obstacles or adverse weather conditions) and their capacity to accurately infer the driving intentions of neighboring vehicles. These limitations can be addressed using Vehicle-to-Everything (V2X) communication, which enables vehicles to wirelessly exchange sensor data and driving intentions. This exchange allows Connected and Automated Vehicles (CAVs) to cooperate and adapt their driving based on the dynamics and driving intentions of nearby vehicles. Two or more vehicles can agree on the execution of a specific maneuver for increasing the safety and/or driving efficiency. This is referred to as maneuver coordination or cooperative driving.

In recent years, there has been an increasing interest in the development of protocols for maneuver coordination. Many of the studies conducted to date focus on coordination for specific maneuvers and/or scenarios. For example, the authors in [1] designed a cooperative lane change mechanism that minimizes the induced overall braking of all the involved vehicles. In [2], the authors present four use cases for cooperative driving (including convoy driving, cooperative lane change, and cooperative intersection management), and analyze the V2X communication requirements for those cases. More examples can be found in [3], where authors survey maneuver coordination algorithms for intersections and highway on-ramps. The ubiquitous deployment of maneuver coordination will require the capability to operate in a wide set of scenarios and driving environments. The difficulties associated with the design of cooperation algorithms for all possible maneuvers has shifted current research and standardization efforts towards the design of general maneuver coordination algorithms that can be applied in multiple scenarios. For example, Lehmann et al. presented in [4] a general coordination algorithm based on the regular V2X exchange of planned and desired trajectories between vehicles. The objective is that vehicles can use their own trajectories and those of surrounding vehicles to identify potential driving conflicts and coordinate their maneuvers when necessary. The study in [5] extends the concept in [4] by considering aspects related to contradictory decisions between negotiating vehicles. The IMAGinE project in [6] extends the number of trajectories exchanged, where each trajectory has a weight based on its driving cost. Additionally, vehicles can also offer different cooperation options to surrounding vehicles. The H2020 TransAID project in [7] introduces the possibility for the road infrastructure to support maneuver coordination by providing recommendations and information (e.g. speed or lane change advices) that vehicles can use to coordinate their maneuvers.

The relevance of cooperative driving or maneuver coordination has also triggered standardization efforts worldwide. For example, SAE (Society of Automotive Engineers) has recently standardized cooperation classes for V2X messages and related these classes to the SAE automation levels [8]. ETSI (European Telecommunications Standards Institute) is currently defining the Maneuver Coordination Service (MCS) [9]. Given the early stage of the standardization process, the performance and efficiency of current V2X-based maneuver coordination approaches are yet to be extensively evaluated.

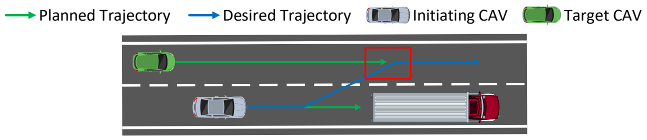
This study progresses the state-of-the-art by evaluating the impact of V2X-based maneuver coordination on the traffic. Our study considers the current MCS framework at ETSI and implements a simulation platform that allows for the realistic evaluation of maneuver coordination based on the exchange of trajectories among vehicles. The simulation platform is based on ns-3 and the VANET Highway Mobility module [10]. We implement additional functionalities to estimate the planned and desired trajectories and control the mobility of vehicles based on the exchange of these trajectories. This allows for a realistic simulation of V2X-based maneuver coordination which in turn enables us to evaluate the benefits of maneuver coordination. Our current approach is a solution based on the exchange of planned and desired trajectories that is aligned with previous studies [4]-[7]. Our analysis shows the potential of maneuver coordination for the improvement of the traffic flow, but also the need for a careful design and configuration of future maneuver coordination protocols.

II. MANEUVER COORDINATION SERVICE

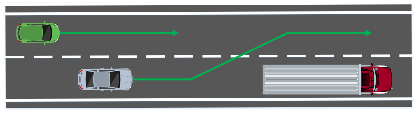
Currently, ETSI is developing specifications to define a Maneuver Coordination Service for maneuver coordination based on V2X communications [9]. The work is still at its early stages and there is not a final agreement yet on how CAVs should coordinate their maneuvers. The current candidate for standardization is based on [4] which considers that CAVs exchange planned and desired trajectories using Maneuver Coordination Messages (MCMs). Planned trajectories represent the short-term (next seconds) driving intentions of the ego CAV and are conflict-free with the planned trajectories of surrounding remote CAVs. Desired trajectories represent the trajectory that CAVs would like to follow but cannot do so due to a conflict with another CAV's planned trajectory. Desired trajectories thus collide with the planned trajectory of at least one surrounding CAV. The transmission of a desired trajectory is an implicit request for coordination from the transmitting CAV to the potentially colliding CAV.

The current ETSI MCS approach requires CAVs to continuously broadcast MCMs with their planned trajectories. If a CAV wants to change its trajectory, it can use the planned trajectories from surrounding CAVs (received in the MCMs) to detect if its new trajectory would collide with any of the surrounding CAVs, and hence coordination is necessary. This approach allows CAVs to detect the need for coordination without having to estimate the driving intentions of other CAVs. When a CAV detects the need for coordination, it transmits its desired trajectory along with the planned trajectory in an MCM. We will refer to this CAV that triggers the coordination as the *initiating CAV*. This desired trajectory is in conflict with the planned trajectory of another CAV, which will be referred to as the *target CAV,* and cannot be executed unless vehicles agree to coordinate their maneuvers. The coordination is agreed upon when the target CAV updates its planned trajectory so that it is not in conflict anymore with the desired trajectory of the initiating CAV. When this happens, the initiating CAV can convert its desired trajectory into its planned trajectory. On the other hand, the target CAV can reject the initiating CAV's request to cooperate by not updating their planned trajectories to resolve the conflict. In such a scenario the initiating CAV would have to stick to its default planned trajectory until it initiates another cooperation.

This process is illustrated with the example in Fig. 1, which is supported by the timeline shown in Fig. 2. In this example, the gray CAV is the initiating CAV and wants to change the lane to overpass a slow truck. Fig. 1a shows how the desired trajectory of the gray CAV conflicts with the planned trajectory of the green CAV which has the right of way. The green CAV is the target CAV in this example. The desired trajectory of the gray CAV includes the lane change and can only be executed if the green and gray CAVs coordinate their driving. Once the gray CAV detects the conflict, it requests coordination with the green CAV by transmitting an MCM that includes its planned and desired trajectories. Once the green CAV receives the desired trajectory from the gray CAV, it becomes aware of the conflict and the request for coordination from the gray CAV. Then, the green CAV compares the received desired trajectory with its planned trajectory and decides if it is willing to accept the coordination. If so, it will update its planned trajectory so that it is not in conflict anymore with the desired trajectory of the gray CAV and transmits a new MCM with the new conflict-free planned trajectory. When the gray CAV receives this MCM, it detects that the coordination has been accepted since the new planned trajectory of the green CAV is not in conflict anymore with the initiating/gray CAV's desired trajectory. Then, the gray CAV transforms its desired trajectory into its planned trajectory, transmits this new planned trajectory (see Fig. 1b) in the next MCM, and starts the lane change. It is important to highlight that the maneuver coordination proposal is governed by the right of way rules. This implies that the CAV that has the right of way is the one that must accept modifying its trajectory to accept the initiating CAV's trajectory. In case the target CAV does not accept the cooperation request, it does not modify its planned trajectory in a way to accommodate the desired trajectory of the initiating CAV. This way the target CAV does not relinquish its right-of-way.



(a) Transmission of desired trajectory



(b) Updated planned trajectories

Fig. 1. Maneuver coordination using MCM for a lane change example

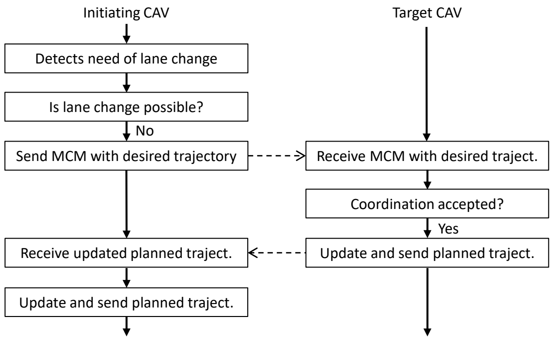


Fig. 2. Timeline of maneuver coordination for a lane change example

III. SIMULATION PLATFORM

We develop a unique simulation platform to realistically simulate V2X-based maneuver coordination following the proposal in Section II. The platform tightly couples the simulation of traffic and V2X communications so that maneuvers are driven by the information received from MCMs. The simulation platform also includes a new module to estimate planned and desired trajectories. The module predicts the future trajectories of vehicles based on the current traffic conditions. There are different simulators that can couple the simulation of traffic and V2X communications (e.g. iTETRIS [11]). However, to our knowledge, there is no simulation platform available that can also estimate the planned and desired trajectories of vehicles, and hence realistically analyze and evaluate V2X-based maneuver coordination. This study fills this gap by implementing a new simulation platform that models V2X-based maneuver coordination using planned and desired trajectories. Fig. 3 represents the architecture of the implemented simulator.

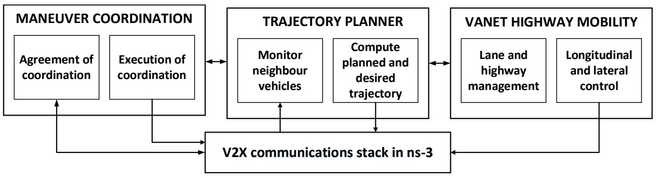


Fig. 3. Architecture of the simulation platform

The developed simulator uses ns-3 and the VANET Highway Mobility module [10]. This module manages the movement of vehicles in ns-3 based on well-known traffic mobility models, which allows ns-3 to perform tightly coupled traffic and communication simulations. The module creates a driving structure of highways that are divided in lanes that contain vehicles. A control submodule monitors the movement of vehicles inside lanes, between lanes and between highways. The behavior of vehicles is modeled using the Intelligent Driver Model (IDM) [12] for the longitudinal control and the MOBIL lane change model [13] for the lane change decisions. The module also provides an interface for the external control of the behavior of vehicles from the ns-3 user application. The developed simulation platform includes two new modules to estimate trajectories and implement maneuver coordination. The Trajectory Planner module dynamically computes the planned and desired trajectories of vehicles. The Maneuver Coordination module implements the maneuver coordination approach based on [4] and described in Section II, but it could be extended to implement other approaches.

A trajectory is implemented as a sequence of timestamped geographic positions. These positions are uniformly distributed over the trajectory duration, T. The first position in the trajectory is the current position of the vehicle, and successive positions are the estimated future positions of the vehicle. The time difference between consecutive positions within a trajectory is assumed constant and equal to a predefined time step, ΔT. To calculate the planned trajectory of a CAV, the Trajectory Planner module uses the future positions of its neighboring CAVs at each time step and applies the IDM and MOBIL algorithms accordingly to calculate the future lateral and longitudinal movement of the CAV. The trajectory is obtained by applying a series of lateral and longitudinal translations to the current position of the CAV. The desired trajectory is only computed when a CAV detects the need for coordination. A coordination will be needed if the following conditions are fulfilled:

a) the CAV that initiates the coordination wants to execute a given maneuver,
b) the maneuver cannot be executed by the initiating CAV due to the right of way rules, and
c) it is physically possible for the target CAV to modify its planned maneuver to allow the coordination.

These conditions are continuously monitored by the Maneuver Coordination module. An initiating CAV computes the desired trajectory if all conditions are fulfilled. In this study, we focus on cooperative lane change, but the implemented platform can be easily extended for other maneuvers. That is, the desired trajectory includes a lane change that satisfies the previous conditions. In this case, the desired trajectory is computed using the IDM model for the longitudinal control on the current lane, then a lane change is added at a specific pre-determined time. The rest of the trajectory is computed using the IDM in the destination lane.

The Maneuver Coordination module is in charge of detecting the need for coordination, triggering the exchange of V2X messages, and executing the corresponding driving maneuver using a state machine. It implements the current ETSI solution for maneuver coordination based on [4]. The process starts with the Maneuver Coordination identifying whether a CAV is interested in performing a lane change. A CAV will want to perform a lane change whenever the acceleration gain obtained as a result of the lane change exceeds a given threshold. Following the example in Fig. 1, the initiating CAV (gray color) detects the slow truck ahead in its lane and decides that a lane change is desirable because it would avoid reducing its speed if it changes the lane. When the initiating CAV decides to perform a lane change, the Maneuver Coordination module checks if the lane change can be performed without cooperation. To do so, it estimates the planned trajectory of the initiating CAV and checks at each time step if the lane change is possible without cooperation according to the MOBIL algorithm (i.e. there is no other vehicle obstructing the lane change). If the lane change is possible, it will simply change its planned trajectory to include the lane change, because no cooperation is needed. If the lane change is not possible without cooperation, the initiating CAV needs to compute its desired trajectory to start the cooperation. This case is illustrated in Fig. 1a since the lane change is not possible without cooperation because there is a CAV in the left lane which has the right of way. To obtain the desired trajectory, the Maneuver Coordination module checks if it is possible for the target CAV to create the gap necessary for letting the initiating CAV execute the lane change. In the example in Fig. 1, this means checking if the green CAV can decelerate safely and sufficiently to create a gap for the lane change. Then, the Maneuver Coordination module makes a request to the Trajectory Planner module to compute the desired trajectory that includes the lane change at the first timestep at which the gap can be created. If the gap cannot be created, the desired trajectory is not computed, and the coordination is not started. In any case, it is worth noting that even if the gap can be created by the target CAV, the lane change is not executed if the target CAV does not modify its planned trajectory to allow for the desired trajectory of the initiating CAV. The request for cooperation is context- and implementation-dependent whether the target CAV agrees to coordinate or not. The initiating CAV would detect whether the target CAV modifies its planned trajectory through the exchanged MCMs.

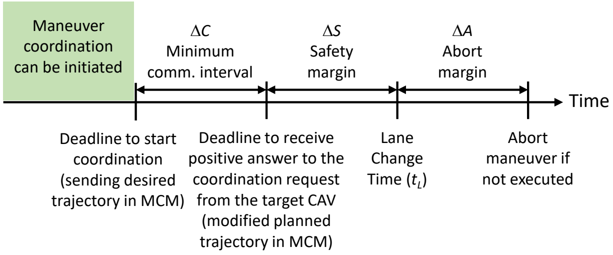


Fig. 4. Time sequence and thresholds for maneuver coordination

The state machine of the Maneuver Coordination module includes certain thresholds to manage the coordination process and ensure a safe and efficient coordination. These thresholds are shown in Fig. 4. The module computes the lane change time t_L once it detects that a coordination is necessary. The lane change time is the time at which the initiating CAV wants to start executing the lane change. For safety reasons, the maneuver coordination must be initiated at least ΔS

seconds before the lane change time where ΔS is a safety margin. The exchange of MCMs between the initiating and the target CAVs requires some additional time. Therefore, we define ΔC as the minimum communication interval for the exchange of MCMs to avoid initiating a maneuver coordination too close to the safety margin. The initiating CAV will then not launch a request for coordination if the remaining time to the lane change is lower than $\Delta C+\Delta S$. Finally, the Maneuver Coordination module aborts a coordination that has been agreed between the initiating and target CAVs, if the lane change is not executed before $t_L+\Delta A$. This is done to stop a coordination that has been agreed between initiating and target CAVs if: 1) the vehicles no longer need the lane change at the time it should be executed, or 2) the lane change is not possible anymore due to a change in traffic conditions.

IV. EVALUATION

In this section we evaluate the impact of maneuver coordination on the traffic flow. The evaluation is done considering the ETSI approach for maneuver coordination based on [4] (Section II) and the simulation platform described in Section III. We consider a 5 km long highway scenario with 6 lanes (3 in each direction) and periodic boundary conditions as in [14]. In this case, the number of vehicles in the scenario is constant and vehicles that reach one edge are inserted in the other edge with the same speed in the same lane. This boundary condition allows us to observe traffic at different densities for a relatively low number of vehicles in the simulation. The scenario includes passenger vehicles and trucks, with trucks representing 20% of all vehicles in the scenario. Trucks can only move along the right and middle lanes. The average desired speeds of passenger vehicles and trucks are 120 km/h and 80 km/h, respectively. The desired speed of each vehicle is randomly chosen from a uniform distribution centered at the average desired speed and with a deviation of ±20% around this average speed. This is done to generate a heterogeneous driving scenario [12]. We model the behavior of vehicles with the IDM and MOBIL parameters listed in Table I. The comfortable deceleration of vehicles is -2 m/s^2. This deceleration is also used to create a gap during a maneuver coordination. To create a gap, the target vehicle decelerates with the comfortable deceleration up to a period of 1 second. We first simulate a scenario where coordination between vehicles is disabled (referred to as *NoCoord*). We then simulate the same scenario with maneuver coordination enabled (referred to as *Coord*). In this scenario, vehicles transmit MCMs with a rate of 10 Hz, and we evaluate the performance considering a trajectory duration of T=10 s. Table I summarizes the most important simulation parameters.

We first analyze the behavior of vehicles during a coordination. Fig. 5 shows an example of the speed profile (in *Coord* simulations) of two vehicles that successfully execute a maneuver coordination. The blue curve represents the CAV that starts the coordination (i.e. the initiating CAV) and wants to change the lane. Note that the speed of the initiating CAV is limited in its current lane due to a slow leader vehicle. The red curve represents the target CAV that cooperates with the initiating CAV for executing the lane change. The figure shows that after the lane change time, the initiating CAV increases its speed up to its desired speed. Before this time, its speed was limited due to the presence of another vehicle ahead. The figure also shows that the speed of the target CAV slightly decreases before the lane change time to create the gap for the initiating CAV. However, it quickly recovers and increases again to the desired speed after the lane change. If coordinations were disabled (i.e. *NoCoord* simulations), the initiating CAV could not increase its speed up to its desired speed and perform the desired lane change in time.

TABLE I. PARAMETERS USED FOR IDM AND MOBIL MODELS

	Trucks	Cars
Time headway	1 s	0.8 s
Minimum gap	2 m	2 m
Maximum acceleration	1.5 m/s²	1.5 m/s²
Comfortable deceleration	2 m/s²	2 m/s²
Politeness factor	1	1
Max. safe deceleration	4 m/s²	4 m/s²
Lane change threshold	0.03 m/s²	0.03 m/s²
Bias to the right lane	0 m/s²	0 m/s²

TABLE II. SCENARIO PARAMETERS

Scenario	5 km highway
Number of lanes	6 (3 in each direction)
Lane width	3.7 m
Vehicle density	10, 20, 30 and 40 vehicles/km/lane
Passenger vehicles desired speed	120 km/h ±20%
Trucks desired speed	80 km/h ±20%
Truck penetration rate	20%
Trajectory duration (T)	10 s
Gap creation deceleration	-2 m/s^2
Gap creation time	1 s
ΔS	ΔS > gap creation time
ΔC and ΔA	1 s
Simulation time	600 seconds (statistics from 180 s)
Seeds	15

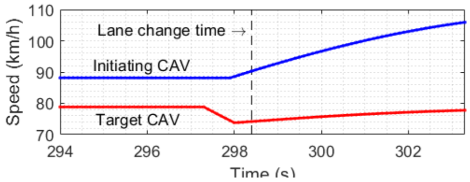
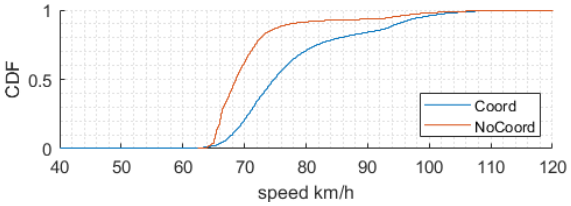


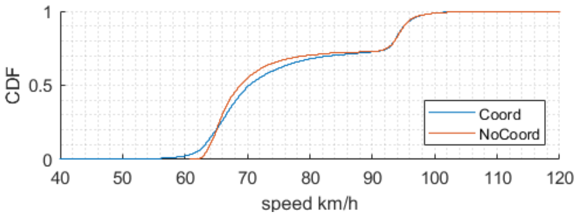
Fig. 5. Speed profile of two vehicles during a maneuver coordination

Fig. 6 and Fig. 7 depict the cumulative distribution function (CDF) of the speed of vehicles for the *NoCoord* and *Coord* simulations, for densities of 30 and 40 vehicles per kilometer per lane, respectively. We have not included the results for 10 and 20 vehicles/km/lane because they do not show any significant difference between the *Coord* and *NoCoord* simulations. This is because vehicles can freely change lanes without triggering a coordination when the traffic density is very low. Fig. 6a and Fig. 7a plot the CDF of the speed of only the vehicles that initiate a coordination for *Coord* simulations. The speed is measured during a time window that starts 10 seconds before the coordination is complement (i.e. when the vehicle that initiates the coordination changes lane) and ends 10 seconds after the coordination is finished. For *NoCoord* simulations, Fig. 6a and Fig. 7a we plot the CDF of the speed of the vehicles that could have initiated a coordination if this option was available. The speed is also measured in a time window analogous to that used for *Coord* simulations for comparison purposes. Fig. 6a and Fig. 7a clearly show that coordinations significantly improve the speed of vehicles that initiate a coordination for both densities. These gains are obtained without coordinations negatively impacting the traffic flow when the density is 30 vehicles/kilometer/lane. This is visible in Fig. 6b that plots the CDF of the speed of all vehicles in the scenario. The figure shows that the speed of all vehicles is quite similar when coordinations are enabled (*Coord*) or disabled (*NoCoord*).

We note that at higher densities, coordinations might have a negative impact on traffic flow if not properly designed. This is visible in Fig. 7b that shows the CDF of the speed of all vehicles in the scenario with a density of 40 vehicles/kilometer/lane. In this case, maneuver coordination can reduce the speed of certain vehicles (speeds below 60 km/h) as a consequence of the traffic disturbances generated by the vehicles that create the gaps during the maneuver coordination. The traffic flow is more sensitive to these disturbances at higher traffic densities since the inter-vehicle spacing is lower. These results highlight the need for optimizing the behavior of vehicles during maneuver coordinations. This can include, for example, adapting the deceleration and time used to create the gap based on the traffic density and context (speed, inter-vehicle spacing, etc.) of vehicles involved in a maneuver. Another possibility is involving more coordinating vehicles.

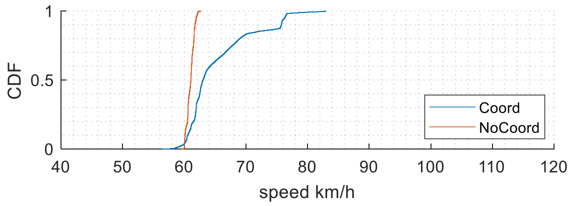


(a) Only vehicles that initiate a maneuver coordination

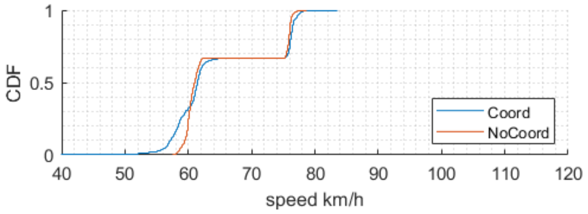


(b) All vehicles in the scenario

Fig. 6. CDF of the speed of vehicles with a density of 30 vehicles/km/lane.



(a) Only vehicles that initiate a maneuver coordination



(b) All vehicles in the scenario

Fig. 7. CDF of the speed of vehicles with a density of 40 vehicles/km/lane.

V. CONCLUSIONS

Maneuver coordination or cooperative driving is expected to improve the safety and driving efficiency of connected and automated vehicles. Standardization efforts are underway worldwide to define and specify protocols for maneuver coordination. In particular, ETSI is currently developing specifications to define a Maneuver Coordination Service that enables CAVs to coordinate their maneuvers by exchanging planned and desired trajectories using V2X communications. This study evaluates the impact of the ETSI maneuver coordination approach on the traffic. To this aim, we have implemented a novel simulation platform based on ns-3 that integrates traffic and communication models. The platform includes new modules for estimating the planned and desired trajectories of vehicles and for controlling and executing the maneuver coordination among vehicles based on the exchanged V2X messages. This is critical for an accurate evaluation of the impact of maneuver coordination on traffic. Our results demonstrate the potential of maneuver coordination to increase the speed of vehicles that initiate a coordination without degrading the overall traffic flow. However, the results obtained also reveal that maneuver coordination needs to be adequately configured and executed to avoid creating disturbances that negatively affect the traffic flow. This is particularly critical as the traffic density increases. Further studies will be therefore needed for an optimized and context-aware design and configuration of maneuver coordination protocols that adapt to the traffic and vehicular context.

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