NR-V2X for Cooperative Adaptive Cruise Control

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Short summary

The introduction of vehicular communications has long been advocated as a compelling tool to improve platooning safety and stability performances. However, wirelessly linking the vehicles opens up a set of potential shortcomings including vulnerability to cyber-attacks and communication breakdowns. This manuscript introduces a simulation module that replicates the communication dynamics and the transmission impairments in a homogeneous Cooperative Adaptive Cruise Control platoon of vehicles. A stand-out feature of the work is the message broadcasting latency characterization based on the actual conflicts in accessing the radio channel, in an attempt to move beyond the fixed-latency assumption. In a realistic communication environment, the cooperative scheme proved to be feasible: the platoon achieves weak string stability even when simultaneously affected by severe communication outages and significant traffic perturbations. The paper further elaborates on the possibility of lowering the time-gap policy and the vehicles' energy expenditure when leveraging radio communications to transmit information.
Keywords: Connected and Automated Driving, Communication Network Modeling, Traffic flow.

1 Introduction

Cooperative Adaptive Cruise Control (CACC) is an approach to the automation of vehicle longitudinal dynamics that has been mainly envisaged for highway scenarios. Evolving from Adaptive Cruise Control (ACC), CACC aims at enabling shorter inter-vehicle spacing than ACC while together improving the platoon's stability Shladover et al. (2018). Such improvements are attributed to the additional perception capabilities that communication empowers. Namely: lower latency in relative speed estimation and leader(s)'s acceleration information broadcasting.
Whereas the distance and the speed of the preceding vehicle can be obtained through the follower's onboard sensors' measurements in the ACC platoon, in the case of CACC the leader(s) acceleration, as well as the speed and distance of non-contiguous vehicles can be transmitted relying on a specific Vehicle-to-Vehicle (V2V) radio technology, such as the IEEE 802.11p or the 5G-based New Radio Vehicle-to-Everything (NR-V2X) Association et al. (2019) that allows followers to anticipate their reaction to traffic perturbations.
CACCs are currently envisioned as SAE J3016 Committee (2021) Level 1 or Level 2 systems. In practice, the systems would enable driving assistance by automating the longitudinal dynamics only (Level 1) or additionally automating the steering action when coupled with lane-centering capabilities (Level 2). However, the driver, at all times, remains in charge of supervising the system.
Despite higher automation systems where the driver is no longer responsible for the driving task are approaching the market Donà et al. (2022), driving assistance is a very important subject of research due to the potential detrimental effect it can have on the transportation network if not properly designed Ciuffo et al. (2021) and the large penetration rate potentially achievable.
Since vehicular communications enable followers to exchange information, several CACC topologies have been suggested in the literature, schematically shown in Fig. 1. More accurately, CACC solutions can be classified as follows according to the survey works considered Z. Wang et al. (2018); Basiri et al. (2020): Predecessor-Follower (PF), Predecessor-Leader Follower (PLF), Two Predecessors-Follower (TPF) and Two Predecessors-Leader Follower (TPLF).

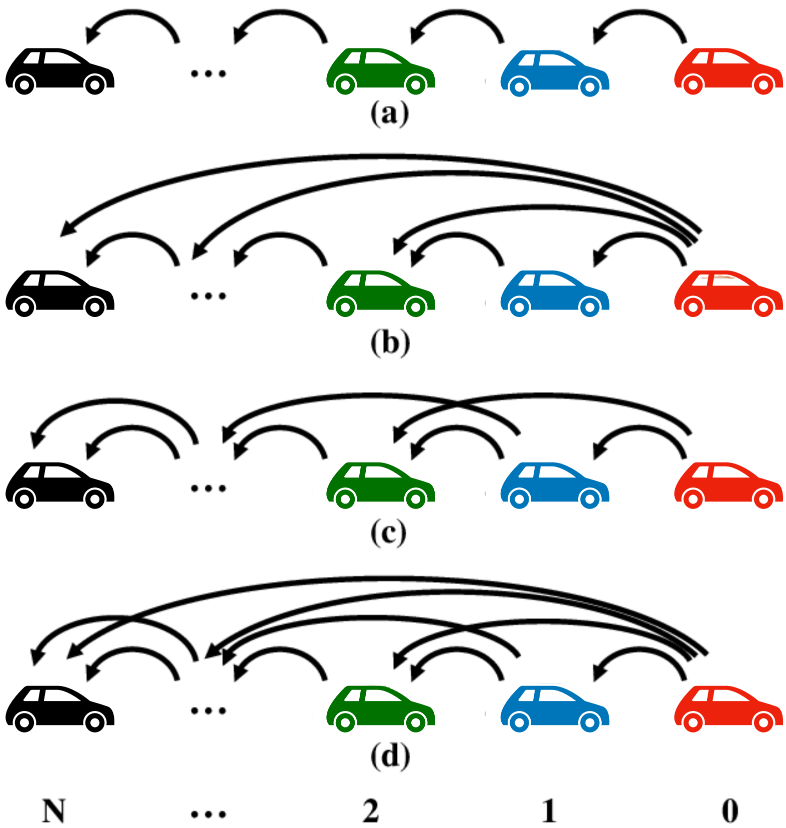


Figure 1: CACC schemes: (a) PF, (b) PLF, (c) TPF, and (d) TPLF.

Without loss of generality, the methodological analysis of this paper embraces the CACC-PF solution: such a choice is motivated by simplicity and the need to focus on the role played by communications in maintaining a stable platoon. However, the analysis can be easily extended to other CACC configurations. In a CACC-PF platoon, each follower is provided with the acceleration of the vehicle immediately preceding it, which is transmitted through the wireless channel, as exemplified in Fig. 2.

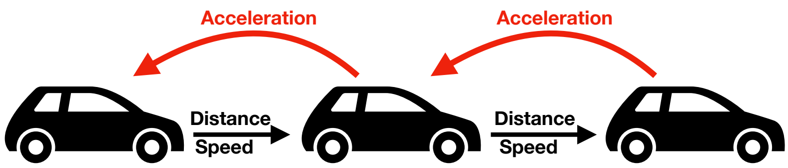


Figure 2: The examined CACC-PF scheme.

Concerning car-follow simulation artifacts to replicate the CACC dynamics, there are several well-studied approaches in the literature ranging from Intelligent Driver Model (IDM)-inspired solutions to asymmetrical linear controllers with saturation or Model Predictive Controller (MPC) which are effectively summarized in the recent survey works by He et al. and Dey et al. He et al. (2019); Dey et al. (2015).
However, despite the substantial research effort on CACC, some of which also embrace a dedicated treatment for the communication layer C. Wang et al. (2020), several open issues remain unaddressed. In particular, when it comes to assessing how communication failures affect the stability and safety of a CACC platoon. Indeed, for the CACC automation scheme to provide tangible transportation benefits, penetration rates beyond 50% are required Donà et al. (2023); Mattas et al. (2018) which might stress the network infrastructure to a point where communication is no longer reliable. This work tries to address such a research gap by combining a vehicular network simulator developed by the University of Modena and Reggio Emilia Lusvarghi & Merani (2021) with existing tools to abstract the CACC functioning already presented in Donà et al. (2022).

2 Methodology

CACC Modeling

In the following, a linear controller model has been adopted to replicate the CACC-equipped vehicle car-following control law:

$$u_{CACC-PF}(t) = k_d(v_L(t-T) - v(t)) + k_p(s(t-T) - t_g v(t) - \eta) + k_a a_L(t - T_C), \tag{1}$$

where $s(\cdot)$ represents the distance between the leader and the ego follower, $v_L(\cdot)$ the leader's speed, $v(\cdot)$ the ego's speed, $a_L(\cdot)$ the leader's longitudinal acceleration, and $u(\cdot)$ the commanded control action. Moreover, k_d and k_p are the controller's gains, t_g the desired time-gap, T is the estimation delay which accounts for the RADAR signal gathering and processing (e.g., filtering of noisy measurements), η is the standstill spacing, k_a is the feed-forward leader's acceleration gain, and T_C the communication latency. The CACC-PF platoon adopts the constant time gap policy (CTG) where the reference spacing between vehicles is proportional to the follower's speed.
The traffic participant is assumed to transition to a *free-flow* regime whenever the reference free-flow acceleration

$$u_{FF}(t) = k_d(v_{FF} - v(t)), \tag{2}$$

is lower than the acceleration predicted by Eq.(1).
The target acceleration, $\min\{u_{CACC-PF}, u_{FF}\}$, is then forwarded to a double integrator with mechanical actuation latency τ_a to replicate the vehicle dynamics

$$\begin{cases} \dot{x}(t) = v(t) \\ \dot{v}(t) = a(t) \\ \dot{a}(t) = \dfrac{u(t) - a(t)}{\tau_a}. \end{cases} \tag{3}$$

Table 1 reports the calibrated parameters of the present study, whose values are within the intervals derived from real-world characterizations of ACC models as of He et al. (2022); Shi & Li (2021); Gunter et al. (2020).

Table 1: Vehicle platoon simulation parameters.

$\boldsymbol{k_p}$ (s^2)	$\boldsymbol{k_d}$ (s)	$\boldsymbol{k_a}$ ($-$)	$\boldsymbol{t_g}$ (s)	$\boldsymbol{\tau_a}$ (s)	$\boldsymbol{T}$ (s)	$\boldsymbol{\eta}$ (m)
0.1	0.5	1.0	1.5	0.3	0.2	2.5

The constant communication latency T_C assumption commonly postulated in the literature is here disregarded in favor of a more realistic approach, where the delay results from the accurate modeling of the vehicular communications. As a matter of fact, T_C may vary due to packet losses, eventually resulting in prolonged silence periods, during which communication inside the platoon is missing.

Simulation Scenario

The microscopic simulation environment relies on a 5000 m-long highway segment having six lanes, three for each direction, every lane being 4 m wide. The first lane accommodates the CACC platoon, which is made of 10 followers plus the leader, whereas in the remaining five lanes, passive simulated vehicles travel at a constant velocity set to 110 km/h with a vehicular density of 100 vehicles/km while broadcasting packets over the radio channel. A schematic bird view is shown in Fig. 3.
Every car is equipped with a transceiver that supports direct Vehicle-to-Vehicle (V2V) communications. The passive vehicles navigating the non-CACC lane contribute to the background traffic, increasing the load on the radio channel and therefore affecting the CACC's operation. The high vehicular density which is assumed guarantees that a worst-case, demanding scenario is examined.
The simulation setup is such that, starting from a steady car-follow status, at $t = 5$ s the CACC leader introduces the perturbation displayed in Fig. 4, forcing the followers to react to its deceleration effort before gradually recovering a new equilibrium speed.
Since passenger cars are considered, the longitudinal acceleration is further bounded within the $[-4.5, 2]$ $\mathrm{m/s}^2$, an interval representative of the human-driving behavior Bokare & Maurya (2017) and acceleration and deceleration policies of commercial ACCs Ciuffo et al. (2021).

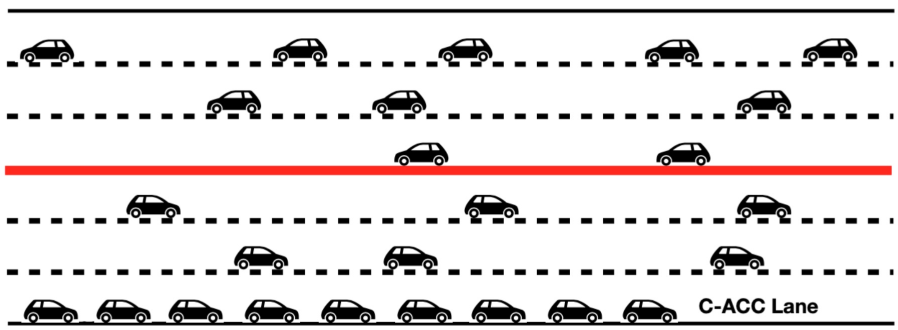


Figure 3: Schematic view of the simulated scenario.

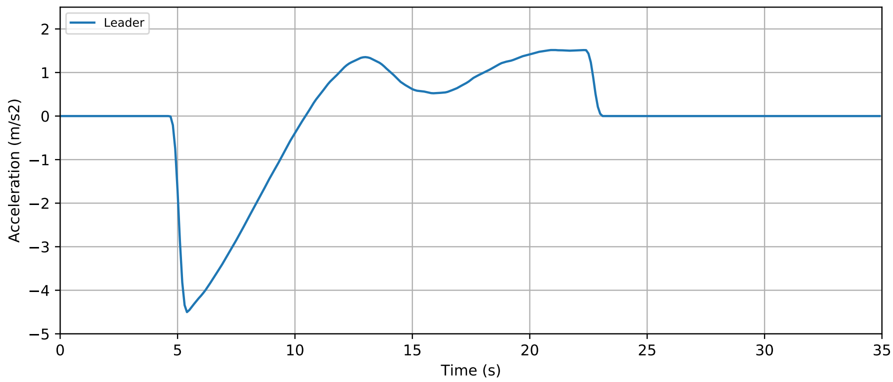


Figure 4: The leader's acceleration over time.

Communication Modeling

This paper assumes that the NR-V2X cellular standard is the wireless solution adopted by each vehicle to exchange information, and more accurately, to broadcast the current value of its acceleration, which is necessary to enable the CACC-PF scheme.

NR-V2X supports direct V2V communications and rules the radio resource allocation via two operating modes, termed Mode 1 and Mode 2. The former relies on the central orchestration of the cellular infrastructure to coordinate the assignment of transmission grants to vehicles under network coverage. The latter is a distributed resource allocation mode that does not require the support of the cellular network and, therefore, can also be employed by vehicles in out-of-coverage conditions. Among the two, Mode 2 has been selected in the present study, as communications inside the platoon have to be safely guaranteed regardless of cellular coverage.

In Mode 2, two alternative radio resource assignment schemes have been standardized: Semi Persistent Scheduling (SPS) and Dynamic Scheduling (DS). When adopting the SPS strategy, vehicles periodically and autonomously perform reservations of the radio resources in a proper time window W based on the activity they heard on the channel during the previous sensing interval S. When the DS scheme is employed, vehicles select resources in W to perform one-shot transmissions, without any resource reservation.

As communication among vehicles is not ideal, the packets conveying the information about the vehicle's acceleration are subject to losses while crossing the wireless medium. Packet collisions, transmission impairments, and half-duplex limitations of the radio transceivers are responsible for such losses, in both the SPS and DS schemes.

In this work, the simulation of NR-V2X Mode 2 communications relies on the MoReV2X simulator Lusvarghi & Merani (2021) (available at `https://github.com/LLusvarghi/MoReV2X` under the GNU-GPL license), a dedicated NR-V2X system-level simulator built on top of ns-3 Riley & Henderson (2010) and further adapted to CACC-platoon applications in Chelli (2023) by enabling the possibility of interacting with the microscopic vehicular traffic simulator described in Section 2.

Employing the MoReV2X simulator, we analyzed both the SPS and DS strategies, assuming that 200 bytes packets are broadcasted with a periodicity equal to 100 ms by the vehicles inside the platoon, as well as by the cars traveling on the remaining lanes. The considered channel model is the Highway LOS/NLOSv channel model defined by 3GPP in 3GPP (2019). The main physical (PHY) and Medium Access Control (MAC) sublayer choices employed in the simulations are reported in Table 2.

Table 2: Main PHY and MAC sublayer parameter settings.

Parameter	**Setting**
Center frequency	5.9 GHz
Available bandwidth	20 MHz
Subcarrier spacing	30 kHz
Subchannel size	12 RBs
Modulation and Coding Scheme	16 QAM – 0.49
Transmission power	23 dBm
Receiver sensitivity	−103.5 dBm
Noise PSD	−174 dBm/Hz
RSRP threshold	−128 dBm
Keep probability	0

Metrics for assessment

Transport metrics

The first transport-related KPI is the string stability, which in the present work translates into the looser weak string stability w_{SS} Monteil et al. (2019), as only bounded perturbations are applied to the CACC-PF platoon. Its expression is given by

$$w_{SS} = \frac{v_{leader,free-flow} - \min(v_{lastfollower})}{v_{leader,free-flow} - \min(v_{leader})}, \tag{4}$$

where $v_{leader,free-flow}$ is the free-flow velocity of the leader before the perturbation occurs, $\min(v_{lastfollower})$ is the minimum velocity recorded for the last follower, and $\min(v_{leader})$ is the minimum velocity recorded for the leader. The condition $w_{SS} > 1$ indicates that the platoon exhibits weak string instability, whereas $w_{SS} \leq 1$ corresponds to a weak string stable system. The choice of computing the string stability w_{SS} of the last follower is due to the string instability effect, as the last follower experiences the largest speed variations.
A further figure of merit is the average traffic flow per lane q, which is determined as

$$q = k \cdot \bar{u}_s, \tag{5}$$

where k is the platoon's density in (vehicles/km) and $\bar{u}_s$ is the harmonic mean of the speed in (km/h). Thus q is expressed in (vehicle/h), and a baseline theoretical maximum flow of ≈ 2400 vehicle/h per lane as of the mean time-gap assumed. In the following, q will be calculated over the whole simulation time.
An additional KPI considered in this paper is the Root Mean Square (RMS) value of the longitudinal acceleration:

$$a_{x,RMS} = \sqrt{\frac{1}{N}\sum_{i}^{N} a_x(i)^2}, \tag{6}$$

where $a_x(i)$ is the value of the longitudinal acceleration at the time instant i, $i = 1, 2, ..., N$, covering the entire simulation time window. $a_{x,RMS}$ represents a proxy for driving comfort and fuel efficiency objectives.
Additional transport-related KPIs are the number of simulated crashes, N_{crash}, the mean percentage of time spent by a vehicle in car-following mode, % of CF-mode, and the consumed energy per vehicle, E_{veh}, given in kWh/100km. They are representative of the CACC-PF safety, platoon's stability, and environmental sustainability impact, respectively.

Communication KPIs

In a real environment it is crucial to understand how long the lack of communication may last as if excessively prolonged, it will negatively impact the CACC-PF performance. To this aim, the

Packet Inter-Reception (PIR) is the performance metric to examine on the communication side, useful for all those use cases that require high reliability, such as CACC platooning. For a given distance D, the PIR is defined as the time between two consecutive successful receptions of packets belonging to the same application flow, when the distance between the transmitting and receiving vehicle is within the $(0, D]$ range at the reception time of the two packets.
In this work, the further notion of PIR outage probability P_{out} is introduced. This is defined as the probability that the PIR exceeds a given threshold x_{thres},

$$P_{out} = Pr\{PIR \geq x_{thres}\}, \tag{7}$$

and therefore coincides with the PIR Complementary Cumulative Distribution Function (CCDF) evaluated at x_{thres}.

3 Results

CACC Ideal Behavior

To set a useful term of comparison, it is initially assumed that the communications among the vehicles of the CACC platoon are ideal, i.e., they are not affected by any packet losses, and only a fixed latency $T_C = 100$ ms is introduced by the communication process.
Fig. 5 reports the acceleration (top), speed (middle), and spacing (bottom) between consecutive CACC-controlled vehicles as a function of time, for the leader and the following 10 vehicles of the platoon, termed F_i, $i = 1, 2, \ldots, 10$, in the legend.
The figure reveals that the system reaction is string stable. Enlarging the observation window from 35 to 100 s, the simulation further indicates that the time gap converges to $t_g = 1.5$ s, which is the desired value, for all pairs of consecutive vehicles.
Table 3 displays the values of the transport KPIs introduced in Section 2, namely, the w_{SS}, the mean vehicular flow q, the RMS of the longitudinal acceleration, as well as the average time spent in CCC mode, the number of crashes, and the used energy per vehicle. Regarding the last parameter, its evaluation takes into account the speed and acceleration profile of each vehicle in the platoon, along with its mass, set to 1500 kg.

Table 3: Transport KPIs in case of ideal communications.

$\boldsymbol{w_{SS}}$	$\boldsymbol{q}$ (veh/h)	$\boldsymbol{a_{x,RMS}}$(m/s^2)	**Mean CF** (%)	$\boldsymbol{N_{crash}}$	$\boldsymbol{E_{veh}}$(kWh/100 km)
0.482	1935	1.029	100	0	19.29

It is worth observing that under the same perturbation, and for the same value of time gap $t_g = 1.5$ s, the simpler ACC scheme cannot achieve the weak string stability condition and 6 crashes would occur in the simulation.

CACC Behavior in the Real Communication Environment

Next, it is assumed that the communications among the vehicles take place in a real propagation environment, affected by packet losses. In this setting, the Complementary Cumulative Distribution Function (CCDF) of the PIR is reported in Fig. 6 for the two different radio resource assignment modes standardized in NR-V2X Mode 2, the SPS and the DS schemes. The PIR has been computed considering a radius of $D = 50$ m around the transmitting vehicle. This choice provides a pessimistic estimate, as in reality, the pairs of communicating vehicles in the platoon are much closer. Nevertheless, it is a useful approach that leads to a conservative estimate of the performance the platoon achieves. Incidentally, it turns out that the CCDF is almost exclusively affected by packet collisions, while packet losses due to poor propagation conditions are rare, given the modest D value.
In what follows, different values of the outage probability P_{out} are considered, namely, 10^{-3}, 10^{-4}, and 10^{-5}. The corresponding PIR thresholds x_{thres} are reported in Table 4, as derived from Fig. 6. The figure and the table reveal that persisting outages are infrequent and in the majority of the cases the DS strategy is by far better performing than the SPS alternative. This is the case since the SPS strategy, due to its periodic reservation of resources, is characterized by persistent packet collisions. However, in what follows the worst condition is deliberately explored, corresponding

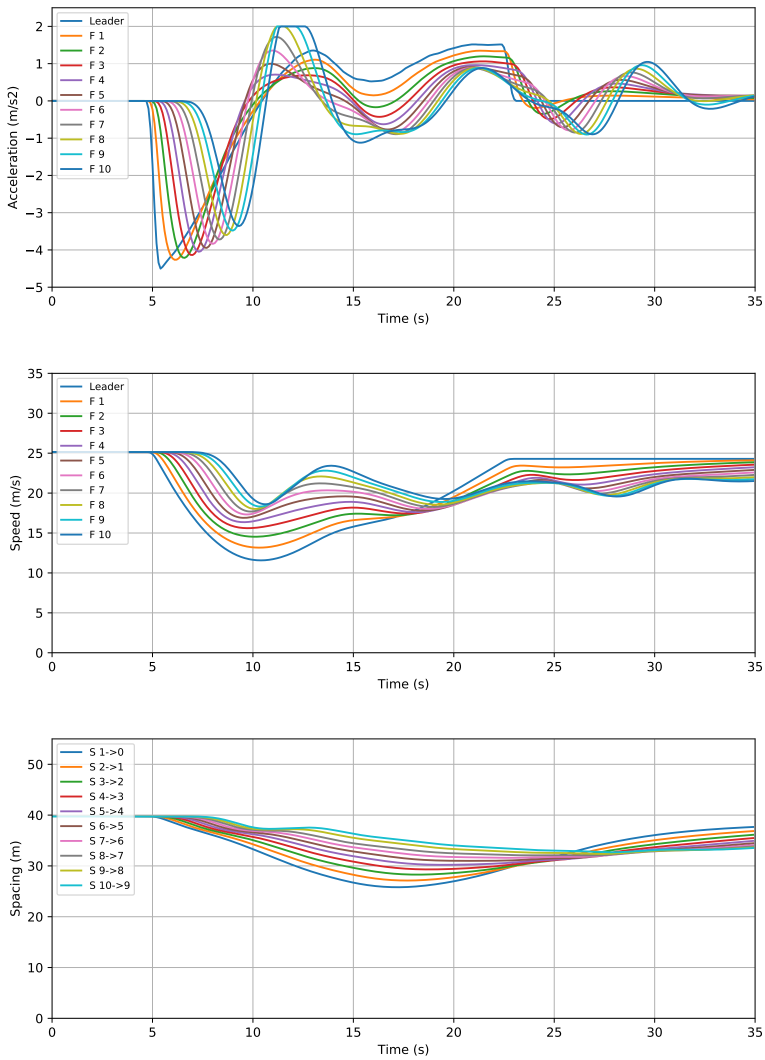


Figure 5: acceleration (top), speed (middle), spacing (bottom) between consecutive CACC-controlled vehicles. Ideal communication with a fixed latency of 100 ms.

to the highest communication outage among those examined, experienced by SPS and lasting $x_{thres} = 1350$ ms.

Table 4: PIR thresholds x_{thres}.

		Outage Probability		
		$\mathbf{10^{-3}}$	$\mathbf{10^{-4}}$	$\mathbf{10^{-5}}$
Resource Allocation Scheme	**SPS**	210 ms	1130 ms	1350 ms
	DS	260 ms	310 ms	350 ms

Several simulations are then run introducing the following concurrent disturbances in the platoon:

- the perturbation of Fig. 4 is applied to the leader's acceleration;
- a deterministic breakdown in the communication between the leader and its first follower is assumed, that lasts for 1350 ms and begins at the worst possible time, i.e., when the derivative of the leader's perturbation reaches its maximum, at time $t = 5$ s.

In this new scenario, Fig. 7 reports the acceleration, speed, spacing, and the t_g between consecutive vehicles as a function of time, disclosing that the system successfully absorbs the perturbation. Moreover, the transport KPIs in Table 5 reveal that string stability is still ensured and no crashes have occurred. The comparison against the ideal communication case indicates a w_{SS} worsening by a 28% factor and an increase of energy consumption of $\approx 14\%$.

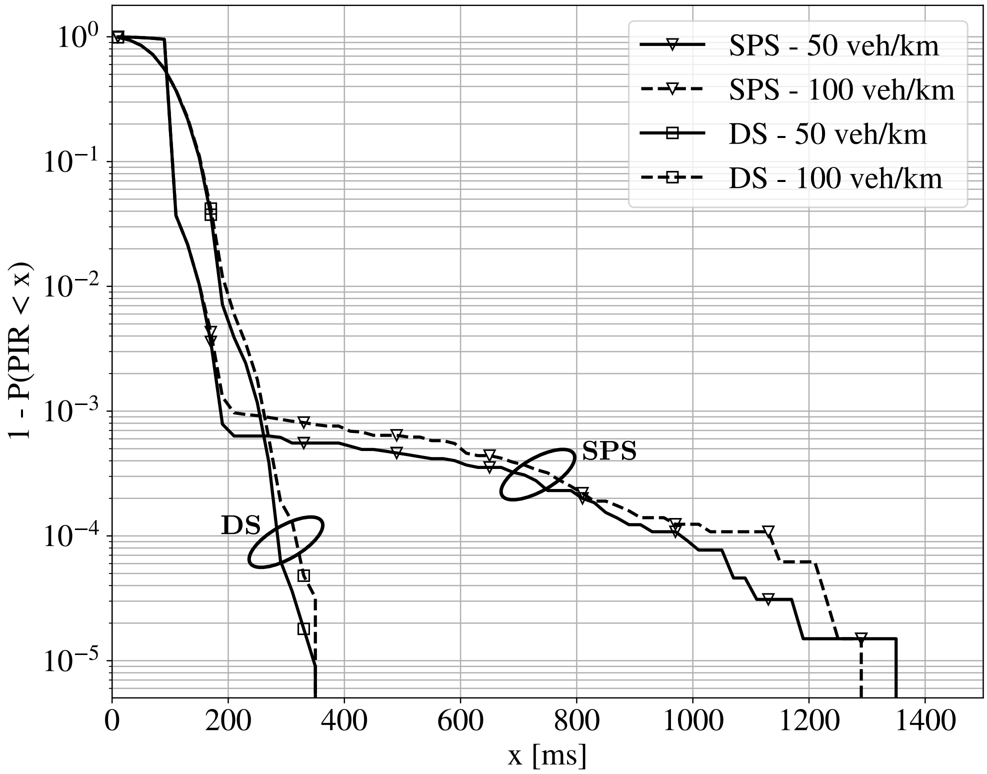


Figure 6: PIR CCDF for different vehicular densities and different resource allocation techniques.

Table 5: Transport KPIs in case of modeled communications.

w_{SS}	q (veh/h)	$a_{x,RMS}$(m/s^2)	**Mean CF** (%)	N_{crash}	E_{veh}(kWh/100 km)
0.617	1935	1.219	100	0	21.94

A further analysis this work pursued addresses the following question: what happens if the desired time gap t_g takes on values lower than 1.5 s when the better performing DS scheme is in place? Fig. 8 answers the question, displaying the w_{SS}, the RMS value of the longitudinal acceleration $a_{x,RMS}$, and the number of crashes N_{crash} as a function of t_g. The chart uncovers that the weak stability property is maintained as long as $t_g \geq 0.8$ s. Moreover, for $t_g = 0.8$ s the percentage of time spent by the platoon's vehicles in the car-following mode is still 100%, $w_{SS} = 0.973$, and $a_{x,RMS} = 1.416$ m/s^2. In parallel, the mean flow increases to $q = 3108$ vehicles/h and the energy consumption raises up to $E_{veh} = 25.26$ kWh/100 km.

4 Discussion and Conclusion

This paper coupled an accurate modeling tool for vehicular communications with a simple car-following simulation environment, to characterize the effects of communication failures on the safety and stability of CACC operation.
The two different strategies for radio resource assignment envisioned by the NR-V2X standard, namely, SPS and DS, were investigated, and it was shown that SPS, despite being more poorly performing, still guarantees CACC safety in the most harmful setting among those considered in this study.
After the CACC characterization in the reference scenario of ideal communications, the present work investigated the effects on CACC performance of the worst predicted outage, meant as the longest-lasting lack of communication, at the beginning of the leader's perturbation. The CACC proved robust to the prolonged sequence of packet losses and was able to maintain string stability, exhibiting only a marginal reduction in comfort/energy efficiency and a reduced capability of dampening the perturbation.

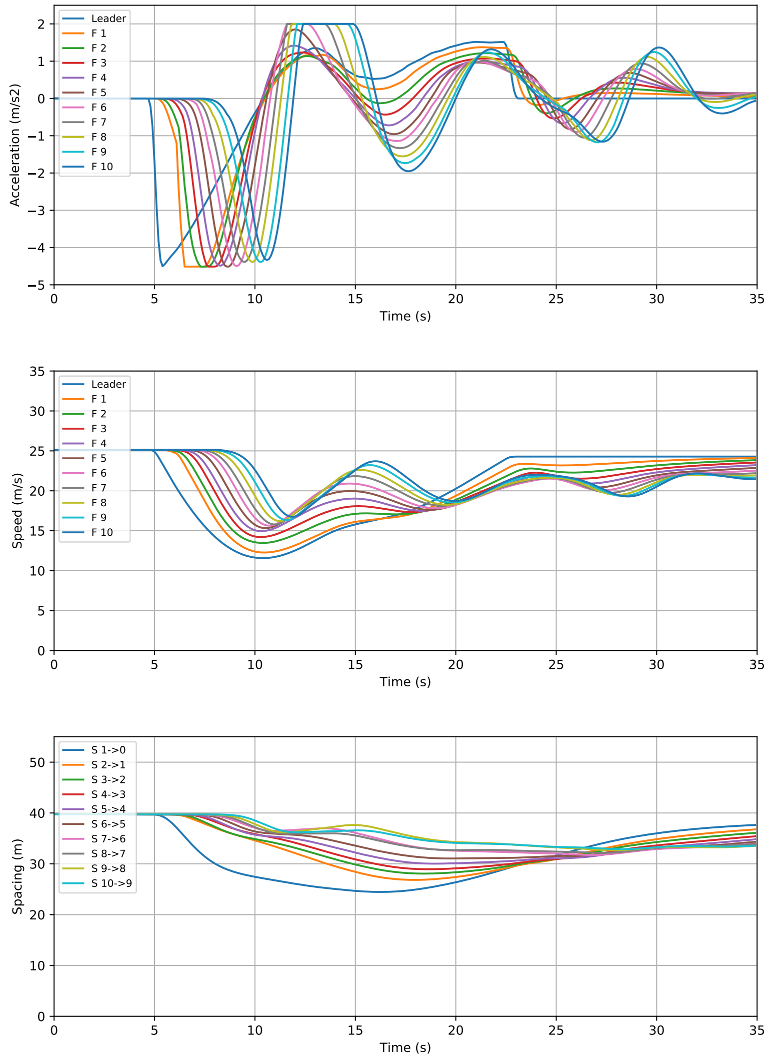
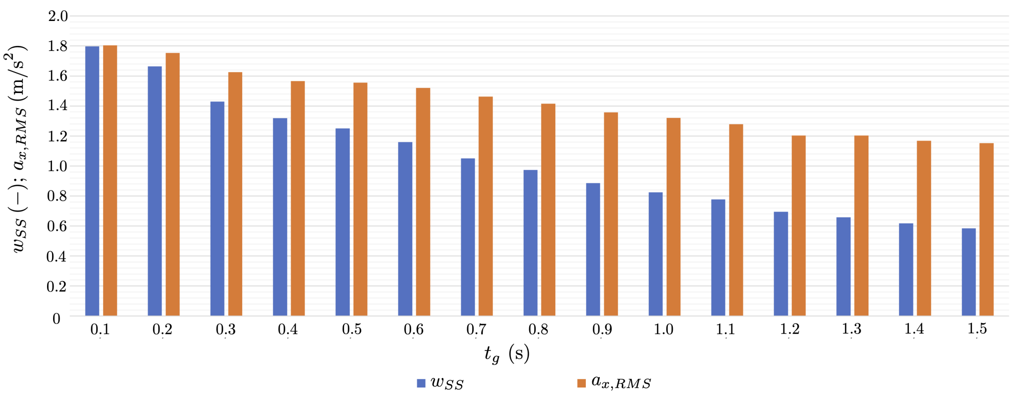


Figure 7: (a) acceleration, (b) speed, and (c) spacing between consecutive CACC-controlled vehicles. Worst-case communication failure scenario.



N_{crash}	8	4	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 8: w_{SS}, $a_{x,RMS}$ and N_{crash} as a function of t_g.

Furthermore, when the better performing DS strategy was considered and the same perturbation was applied to the platoon, the CACC was demonstrated to remain weak string stable up to a time-gap as low as 0.8 s.

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