Performance Assessment of Intent Sharing in Infrastructure-assisted Cooperative Perception Services

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***Abstract*—In traditional cooperative awareness (CA) and cooperative perception (CP), connected vehicles exchange periodic messages containing their current status and perceived objects. This paper investigates the concept of intent sharing-based cooperative perception (IBCP) for connected vehicles. IBCP introduces a more interactive framework wherein an ego vehicle communicates its intent (i.e., future trajectory), while other connected road users and infrastructure share alerts concerning potential conflicts with the ego vehicle. We compare and analyze the performance of the IBCP protocol in contrast to the existing CA and CP systems. We use experimental data and simulated scenarios to assess the manifold benefits that IBCP brings to a platoon of vehicles executing a left turn at an intersection. Our evaluation parameters encompass safety improvements, enhanced situational awareness, heightened comfort levels, and the mitigation of disruptions within the vehicular platoon.**

***Index Terms*—cooperative perception, intent sharing, vehicle-to-everything, vehicle-to-vehicle, vehicle-to-infrastructure**

I. Introduction

Cooperative maneuvering has recently been a focal point of extensive research and standardization efforts [1], [2]. It encompasses various strategies such as (i) intent-sharing cooperation in which connected vehicles share their intended future trajectories, and (ii) agreement-seeking cooperation in which connected vehicles negotiate to reach mutual agreements on right-of-way. This aspect significantly enhances the coordination among connected vehicles (CVs) in traffic. Protocol architecture, application protocols, and use cases for intent sharing and maneuver coordination are summarized in [3].

In parallel, cooperative perception stands out as a cornerstone in enhancing the efficacy of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, even at low market penetrations. It facilitates the sharing of object detection information among CVs, enabling them to be aware not only of nearby CVs but also unconnected vehicles, cyclists, pedestrians, and other road users. The ongoing standardization by SAE [4] and ETSI [5], coupled with active research efforts, underscores the potential and importance of cooperative perception [6], [7]. These efforts address various aspects, including the advantages in awareness, wireless bandwidth requirements, and methods to optimize the efficiency of cooperative perception services [8]–[10].

Recognizing the potential in combining cooperative perception with maneuvering technologies is pivotal. One significant outcome resulting from this synergy is intent sharing-based cooperative perception (IBCP) [11]. In IBCP, a connected ego vehicle shares its planned trajectory with surrounding CVs (referred to as remote vehicles) and connected infrastructure. These remote vehicles and infrastructure then detect and analyze the motion of nearby road users, predicting potential conflicts with the ego vehicle along its planned trajectory. Road users that are predicted to have a conflict with the ego vehicle are referred to as *critical road users*. Subsequently, the remote vehicles or infrastructure send notifications to the ego vehicle, containing details about the predicted time-to-conflict, state and projected trajectory of the critical road user, and recommended actions to avoid the conflict. IBCP empowers CVs to anticipate conflicts proactively and take preemptive measures to avert them. It can be seen as a complementary approach to traditional cooperative perception, functioning as an on-demand service that focuses on predicted conflicts rather than relying solely on periodic transmissions of detected objects.

This paper compares the performance of IBCP with traditional cooperative awareness (CA) and cooperative perception (CP) protocols. It demonstrates, by focusing on a platoon of vehicles making a left turn in an intersection scenario, the added value of intent sharing in enhancing awareness and comfort. Furthermore, the paper presents a comprehensive evaluation of the IBCP protocol, highlighting its advantages in utilizing intent sharing not only for the ego vehicle but also for other road participants such as the following vehicles in the platoon. The benefits outlined are (i) safety improvement and enhanced awareness to anticipate conflicts and protect critical road users, (ii) comfort by avoiding sudden braking to ensure a controlled and smooth maneuver through the intersection, and (iii) coordination with following vehicles in the platoon by signaling the need to delay or adjust the left turn to minimize disruptions among the platoon members. Overall, the paper offers a comprehensive analysis of the IBCP protocol, demonstrating its benefits in enhancing cooperative perception and its potential in improving safety, maneuvering, and platoon coordination within connected vehicle systems.

The paper is structured as follows. Section II introduces the IBCP protocol. Section III details the traffic scenario. In Section IV, we conduct a comparative analysis, assessing the performance of the IBCP protocol in relation to both traditional CA and CP protocols. Finally, Section V summarizes the key findings and insights presented in the work.

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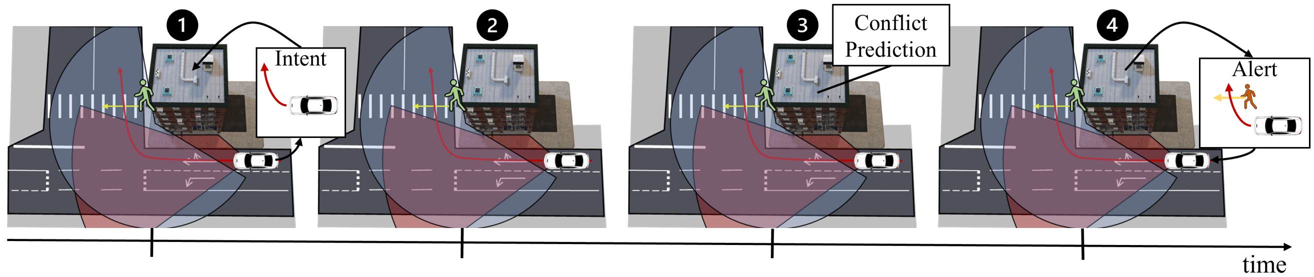

Fig. 1. IBCP protocol with an example of an occluded pedestrian detection.

II. IBCP Protocol

We illustrate the steps of the IBCP protocol in Fig. 1 in an intersection scenario where the ego vehicle in the right street is planning to make a right turn. There is also a (green) pedestrian (i.e., a critical road user) crossing the top street. The ego vehicle is connected and equipped with perception sensors (e.g., radars and cameras). Note that the field of view of the ego vehicle is obstructed and cannot detect the pedestrian. This obstruction implies that neither the ego vehicle nor the pedestrian can initially see each other, potentially leading to a conflict if they remain unaware of each other's presence. There is also a connected roadside infrastructure unit equipped with a perception sensor array to detect objects in the intersection.

The IBCP protocol serves to address such hazardous situations. In contrast to traditional CP, where vehicles transmit information about detected road users periodically, the IBCP protocol specifically targets road users posing a risk of conflict to connected vehicles. This targeted approach enhances conflict anticipation at a minimal cost to the wireless channel. Illustrated in Fig. 1, the IBCP protocol consists of four stages:

1) Intent Sharing: The ego vehicle shares its future trajectory via the intent message that may also include its kinematic properties such as speed and acceleration.
2) Detection: The infrastructure, with a wide field-of-view and minimal obstructions, detects all road users in the intersection using its sensors.
3) Determining Critical Road Users: The roadside infrastructure uses the ego vehicle's intent in addition to information about the detected objects from the previous step to assess potential conflicts between the detected road users and the ego vehicle. Specifically, in Fig. 1 a conflict is predicted between the ego vehicle and the green pedestrian crossing the street. In this scenario the pedestrian is referred to as a *critical road user*.
4) Sending Notifications: If a conflict is predicted, an alert message containing details about the conflict and the *critical road user* is generated and broadcasted and subsequently received by the ego vehicle.

Similar to [2], [12], the intent message details the future lane position, speed, and acceleration limits of a connected vehicle within some time horizon $\tau_{\max}$. That is, for a connected vehicle with a speed profile $v_{\mathrm{E}}(t)$ and acceleration profile $a_{\mathrm{E}}(t)$, the shared parameters are constrained within defined limits: $\underline{v}_{\mathrm{E}} = \min_t v_{\mathrm{E}}(t)$, $\bar{v}_{\mathrm{E}} = \max_t v_{\mathrm{E}}(t)$, $\underline{a}_{\mathrm{E}} = \min_t a_{\mathrm{E}}(t)$, and $\bar{a}_{\mathrm{E}} = \max_\tau a_{\mathrm{E}}(t)$.

III. Scenario Description

To assess the benefits of the IBCP, we employ the FKA InD dataset [13]. This dataset captures the trajectories of vehicles, cyclists, and pedestrians within an urban intersection in Aachen, Germany, using a drone with a rate of 25 frames/s, cf. Fig. 2. Notably, this intersection features a construction zone causing occlusions among road users, making it a pertinent case for this study. Within dataset 13 of the FKA InD dataset, depicted in Fig. 2, our focus lies on platoons of vehicles (i.e., red vehicles) executing left turns as a group from a main street onto a side street. Throughout the remainder of this paper, the vehicle leading the platoon executing this left turn will be referred to as the ego vehicle. The blue vehicle parked in the side street is a connected remote vehicle that transmits CAMs, CPMs, or Alerts based on the considered protocol.

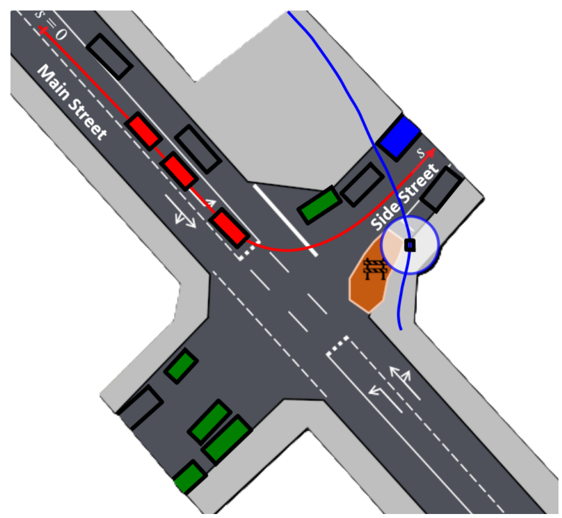

Fig. 2. A left-turn scenario involving an occlusion due to a construction zone captured in the Aachen Dataset [13]. The positions of left-turning vehicles is determined within the coordinate system along their path (red line). The platoon of vehicles might encounter conflicts with pedestrians crossing the side street (blue line).

A. Motion of Critical Road Users

We focus on pedestrians crossing the side street from behind the construction zone in Fig. 2. Road user 1 from dataset 13 represents such a pedestrian in this scenario. By applying various time offsets to this trajectory, we simulate potential conflicts between the pedestrian and the platoon, offering diverse initial conditions that influence reactions and conflict severity. Our assumption is that pedestrian movement remains independent of surrounding vehicle activity, simulating scenarios where pedestrians might be inattentive or obscured by a construction zone, hindering their visibility.

B. Actuation and Control of the Platoon

In this context, a conflict between the platoon and the pedestrian is defined as the event when the time-to-conflict $T_{\mathrm{c}}(t)$ between the lead vehicle and the pedestrian is lower than a predefined threshold T_{th}. Note that the time-to-conflict is predicted over a future time horizon $\tau_{\max}$ such that

$$T_{\mathrm{c}}(t) = \min_{\tau \in [0, \tau_{\max}]} \frac{s_{\mathrm{P}}(t+\tau) - s_{\mathrm{E}}(t+\tau) - r_{\text{conflict}}}{v_{\mathrm{E}}(t+\tau)} \tag{1}$$

where $s_{\mathrm{P}}(t+\tau)$ and $s_{\mathrm{E}}(t+\tau)$ are the predicted positions of the pedestrian and ego vehicle at time $t+\tau$ projected on the platoon path (i.e., red line in Fig. 2), respectively. We define a circular conflict zone centered at the pedestrian with a radius r_{conflict} to protect that pedestrian. That is, (1) is used to calculate TTC only when the predicted position of the ego vehicle over $[t, t+\tau_{\max}]$ is within the conflict zone, otherwise, $T_c(t) > T_{\mathrm{th}}$. In addition, $v_{\mathrm{E}}(t+\tau)$ is the predicted longitudinal velocity of the ego vehicle, respectively, assuming that $v_{\mathrm{E}}(t)$ is greater than $v_{\mathrm{P}}(t)$, the velocity of the pedestrian, for all t.

Note that the predicted position and velocity of the ego vehicle rely on the speed and acceleration boundaries and the coordinates of the left-turn path. Predictions for the pedestrian's position and velocity adopt a constant-velocity model. This approach allows us to compute an instantaneous time-to-conflict, as described in (1), at any point along the trajectory to assess the safety of the left turn maneuver.

Once the ego vehicle identifies a critical road user (detected via sensors, a CPM, or an alert), it initiates a braking maneuver to prevent the conflict. The controller determines a deceleration rate allowing the vehicle to stop based on the distance to the predicted conflict point, the current speed, and position of the ego vehicle. Subsequent vehicles respond to speed adjustments of their lead vehicle as well. A major advantage of IBCP is that the alert messages are received by all vehicles in the platoon, ensuring synchronized reactions to anticipated conflicts. Conversely, in CA and CP, subsequent vehicles in the platoon only react upon detecting velocity changes in their preceding vehicle. This results in increased reaction times for the following vehicles.

Priority is given to stopping at the intersection in the main street rather than in front of the pedestrian in the side street, if feasible. This prioritization considers pedestrian safety and avoids platoon disruption. The minimum deceleration required to stop at a specific distance s is determined by the equation:

$$a_{\mathrm{brake}}(s) = \frac{v_{\mathrm{E}}(t)^2}{2(s - s_{\mathrm{E}}(t) - \sigma v_{\mathrm{E}}(t))} \tag{2}$$

where σ denotes the actuation latency for the vehicle, representing the time to process information and generate required brake torque to stop. If $s = s_{\mathrm{M}}$, denoting the stopping line of the intersection, the minimum deceleration to stop at this point is computed. This decision process is shown in Fig. 1.

Algorithm 1 Actuation and Control of the Platoon

if a critical road user is detected **then**
  Use $a_{\mathrm{brake}}(s)$ to calculate deceleration to stop at s
  if a_{brake}(intersection) $\leq a_{\text{comfort}}$ **then**
    Initiate braking to stop before intersection
  else if a_{brake}(pedestrian/preceding vehicle) $\leq a_{\min}$ **then**
    Initiate braking to stop at pedestrian/preceding vehicle
  else
    Initiate braking to stop using $a_{\min}$
  end if
end if

When a conflict is detected, each vehicle in the platoon adjusts s to stop before the intersection, or the pedestrian or preceding vehicle, whichever is closer. Additionally, a_{comfort} is defined as a more comfortable deceleration compared to the maximum deceleration $a_{\min}$. For example, if the ego vehicle cannot stop before the intersection comfortably (i.e., $a_{\mathrm{brake}}(s_{\mathrm{M}}) \leq a_{\text{comfort}}$), it aims to stop before the conflict area, e.g., the pedestrian crossing, employing the smallest magnitude deceleration for safety (i.e., $a_{\mathrm{brake}}(s_{\mathrm{P}}(t) - r_{\text{conflict}})$). If the braking distance is insufficient, an emergency braking maneuver with $a_{\min}$ is executed to minimize the speed of impact. To prevent impractically small deceleration values, if (2) yields a deceleration below 1 [m/s^2], the vehicle coasts at a constant speed and then decelerates to 1 [m/s^2] for stopping.

C. Wireless Communication

As stated earlier, we investigate three different protocols, based on the different messages sent over the wireless communication channel: CA, traditional CP, and IBCP. The set of messages transmitted in each case is summarized in Table I. In the IBCP protocol, the ego vehicle broadcasts its intent message at a rate of 1 Hz and the infrastructure/remote vehicles broadcast the alerts at a rate of 10 Hz only when a conflict is detected until it is resolved.

TABLE I
PROTOCOLS AND CORRESPONDING MESSAGE SETS

Protocol	**CAM** [14]	**CPM** [15]	**Intent**
CA	1-10 Hz ETSI Rules	None	None
CP	1-10 Hz ETSI Rules	1-10 Hz ETSI Rules	None
IBCP	1-10 Hz ETSI Rules	1-10 Hz ETSI Rules	1 Hz Intent 10 Hz Alerts

IV. PERFORMANCE IN AN UNPROTECTED LEFT TURN

In this section, we conduct a performance evaluation of a platoon of three vehicles executing an unprotected left turn under three distinct protocols. Initially, we examine the CA protocol, where the ego (lead) vehicle solely relies on sensors and CAM messages. Then, we assess the CP protocol when connected vehicles and infrastructure exchange CPMs in addition to CAMs. Finally, we contrast these findings with the scenario where the ego vehicle incorporates the IBCP protocol. Our analysis centers on three vehicles, vehicle 21, 31, and 40, selected from the InD dataset to serve as the ego vehicle and two followers, cf. Fig. 2. The three vehicles are initially at a standstill at time step 2485. For our simulation, we adopt a reaction/actuation time of 0.6 [s] and minimum acceleration (i.e., maximum deceleration) of $a_{\min} = -8$ [m/s^2].

All vehicles are equipped with sensors with a range of 150 [m] and a field of view of 360 degrees. The dataset is used to determine the intent bounds of the ego vehicle which are $v_{\mathrm{E}} \in [0, 9.38]$ [m/s] and $a_{\mathrm{E}} \in [-2.79, 1.54]$. Note that the acceleration bounds shown are smaller in magnitude than $a_{\min}$, since $a_{\min}$ pertains to emergency braking. In general, we can leverage historical data for a given maneuver to determine these bounds.

A. Performance Metrics

To assess the three vehicle's emergency braking system performance, we use the instantaneous time-to-conflict (TTC) and minimum time-to-conflict ($\mathrm{TTC}_{\min}$) as the safety metrics. The $\mathrm{TTC}_{\min}$ denotes the smallest observed value of TTC in (1) during the whole maneuver. Notably, higher values of both metrics indicate a safer maneuver. A $\mathrm{TTC}_{\min}$ value of 0 [s] signifies an impact between the ego vehicle and the pedestrian, occasionally resulting in the vehicle continuing its motion post-impact. In such scenarios, the maximum impact speed is also determined, with higher values indicating poorer ego vehicle performance.

Additionally, the evaluation encompasses deceleration experienced during braking. Smaller deceleration magnitudes are preferable for driver comfort. The decision-making process prioritizes a safe stop while minimizing deceleration. The assessment also reports the ego vehicle's end condition. If conflict anticipation occurs before the left turn, the vehicle may stop in the main street. However, if anticipation happens later, the vehicle must stop in the side street to avoid impact. Each vehicle in the sequence must avoid collisions, with the ego vehicle steering clear of the pedestrian and the subsequent vehicles preventing collisions with their preceding counterparts. Therefore, stopping before the intersection signifies a higher level of anticipation compared to stopping in the side street.

B. Awareness and Comfort

In the first scenario, a pedestrian trajectory offset of 980 frames was applied which placed the pedestrian behind the construction zone. The connected remote vehicle and the platoon are initially unaware of the presence of the pedestrian.

Two key visualizations, Figs. 3 and 4, showcase the speed of vehicles 21 (ego), 31 (follower 1), and 41 (follower 2) across different protocols. In CA, the ego vehicle detects the pedestrian at timestep 107.2 [s] (denoted by a red star), with a 0.61 [s] TTC. Despite emergency braking of 8 [m/s^2] initiated after 0.6 [s] (due to the reaction time) at 107.8 [s] with a 0.01 [s] TTC, a collision becomes unavoidable with an impact speed of 0.9 [m/s]. Subsequent vehicles also decelerate and due to the sudden stop of the ego vehicle and cumulative reaction times, TTC diminishes significantly. Note that TTC of following vehicles is calculated with respect to the corresponding preceding vehicle.

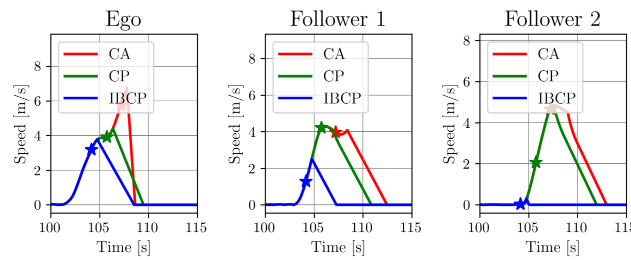

Fig. 3. Scenario 1: Speed profiles vs. time for CA, CP, and IBCP protocols.

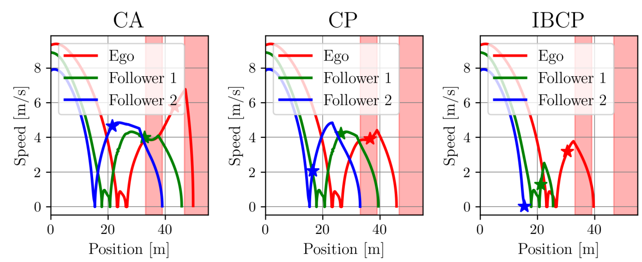

Fig. 4. Scenario 1: Speed profiles vs. position for CA, CP, and IBCP protocols.

In CP, the ego vehicle receives a CPM from the connected remote vehicle at timestep 105.76 [s] (illustrated by a green star) when the TTC is over 4 [s]. Commencing braking at 106.36 [s] with a deceleration of 1.41 [m/s^2], the vehicle safely halts before reaching the pedestrian. The $\mathrm{TTC}_{\min}$ over the whole trajectory of the lead vehicle is at 1.16 [s], highlighting the lower deceleration needed for safety compared to the CA case. Note also that the deceleration required to stop safely for all vehicles is lower (i.e., more comfortable) compared to the CA case.

In IBCP, the (blue) connected remote vehicle obtains the lead vehicle's intent message. Utilizing this information, it assesses the potential conflict between the platoon and other road users within its detection range. This evaluation determines if a road user qualifies as a critical road user, employing a defined TTC threshold of 3 seconds (i.e., $T_{\mathrm{th}} = 3$). Upon identifying a road user meeting this criterion, the remote vehicle transmits an alert to the platoon, signaling the anticipated conflict as elaborated earlier in the process. This proactive alert system forms a crucial element in the IBCP, ensuring timely notifications to mitigate potential conflicts on the road.

In this case, the ego vehicle receives an alert from the connected remote vehicle at timestep 104.16 [s] (highlighted by a blue star) with a TTC exceeding 4 [s]. This alert, earlier by 3.04 [s] compared to the CA case and 2.2 [s] compared to the CP case, allows the three vehicles to start braking at 104.76 [s]. That is, all vehicles in the platoon can react simultaneously which reduces the overall reaction time compared to the other protocols. A deceleration of only 0.6 [m/s^2] is applied at the ego vehicle to stop before reaching the pedestrian. The $\mathrm{TTC}_{\min}$ extends to 6.01 [s]. Fig. 3 also shows that the declarations for the following vehicles are also lower compared to the CA and CP cases.

Fig. 4 illustrates the speed profile of the vehicles along the

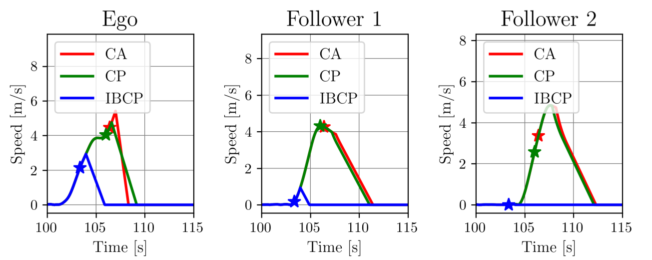

Fig. 5. Scenario 2: Speed profiles vs. time for CA, CP, and IBCP protocols.

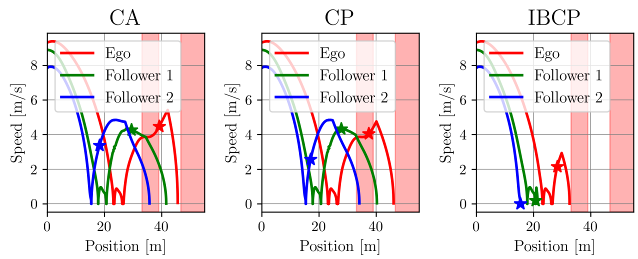

Fig. 6. Scenario 2: Speed profiles vs. position for CA, CP, and IBCP protocols.

platoon's path in all protocols. The shaded areas denote the range of positions deemed unsafe for halting, such as stopping in the middle of the intersection or within the conflict zone of the pedestrian. In the CA and CP, the ego vehicle detects the pedestrian after both the lead and some of its following vehicles pass the point where stopping before the intersection is feasible. Consequently, the ego vehicle stops in the side street after the intersection, causing its followers to stop behind the ego vehicle. This potentially creates an unsafe situation for follower vehicles and oncoming traffic. Conversely, in the IBCP protocol, although the alert was issued shortly before the ego vehicle crosses the intersection line, follower 1 and 2 managed to stop before entering the intersection, avoiding potential conflicts with oncoming traffic.

C. Platoon Coordination and Disruptions

In the second scenario, the offset of the pedestrian trajectory is set to 960 frames, which is 0.8 [s] earlier compared to the first scenario. This pedestrian is initially occluded by the construction zone. Comparable advantages are evident in Fig. 5, highlighting the superiority of IBCP over NC and CP. For example, the lead vehicle's minimum required deceleration to avoid a conflict with the pedestrian is 4.06 [m/s^2] in NC, 1.85 [m/s^2] in CP, and notably reduced to 1.52 [m/s^2] in IBCP. Moreover, the $\mathrm{TTC}_{\mathrm{min}}$ measured for the ego vehicle is significantly extended, spanning 0.73 [s] in NC, 0.83 [s] in CP, and exceeding 8 [s] in IBCP. These metrics clearly underscore the safety and comfort advantages offered by IBCP protocol.

Furthermore, Fig. 6 demonstrates another pivotal benefit of IBCP. In this case, all three vehicles in the platoon can stop before reaching the intersection, minimizing disruptions within the platoon. In CA and CP, the platoon is split where some vehicles (including the ego vehicle) proceed through the intersection before stopping at the pedestrian while other vehicles wait before entering the intersection until the traffic clears. This is because the delay in detecting the pedestrian resulting from the late anticipation of the conflict, with the first conflict detection at timestep 106.4 [s] in CA, 106.0 [s] in CP, and happening notably later in IBCP at 103.36 [s].

V. Conclusions and Future Work

In this paper we assessed the merits of the intent sharing-based cooperative perception (IBCP) protocol for platoons of connected vehicles. In IBCP, an ego vehicle shares its intent and future trajectory while surrounding connected road users provide the ego vehicle with information concerning critical objects that may conflict with the ego vehicle. We have shown that for a left turning platoon of connected vehicles with limited visibility, IBCP improves safety, situational awareness, and comfort compared to systems with traditional cooperative awareness and perception. Future work will focus on evaluating channel load in large-scale simulations encompassing various traffic environments.

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