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Negotiation: effective cooperative maneuvering strategy for connected automated vehicles

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Abstract

In this study, a novel negotiation-based cooperative maneuvering strategy is proposed to help vehicles avoid conflicts while maximizing the traffic efficiency in various traffic scenarios. We demonstrate how conflict charts can be utilized to determine the necessity of negotiation based on the status and intent shared by other vehicles. We also introduce a response rule and a control strategy to realize the negotiation protocol by means of a request-response mechanism. Meanwhile, simulations of an unsignalized intersection are used to demonstrate the effectiveness of the proposed method under different initial conditions.

Keywords:

Connectivity, Cooperation, Conflict analysis, Negotiation

1. Introduction

Conflicts may happen in various traffic scenarios, such as unsignalized intersections, merging scenarios, and roundabouts, where vehicles intend to use the same road resources at the same time. Effective conflict management plays an important role in ensuring safety and enhancing time efficiency [1]. With the advancements in automotive technologies, connected automated vehicles (CAVs) have received increasing attention for conflict resolution, as their ability to share status and intent via vehicle-to-everything (V2X) communication can be leveraged to improve the performance of decision-making [2-3], planning [4-5], and control [6-7] of vehicles.

In this study, we focus on the conflicts involving two vehicles, where cooperation of vehicles with various communication strategies can be leveraged to resolve conflicts, as shown in Fig. 1 Cooperation of vehicles may be achieved without communication as in Fig. 1(a), where Automated Vehicles (AVs) resolve conflicts based on their own perception [8]. However, the possible uncertainties in the information gathered through perception can lead to conservative actions. To address this, vehicles may cooperate utilizing communication technologies, as depicted in Fig. 1(b), where CAVs cooperate to resolve conflicts while utilizing the shared status and intent information [9-10]. However, their actions are expected to be passive, which means that a vehicle cannot disapprove an unfavorable maneuver plan of another vehicle. Compared to status and intent sharing strategies, negotiation-based cooperation opens up new opportunities for CAVs to resolve conflicts effectively as illustrated in Fig. 1(c). Through negotiation, vehicles can actively request future road resources and respond to such requests accordingly.

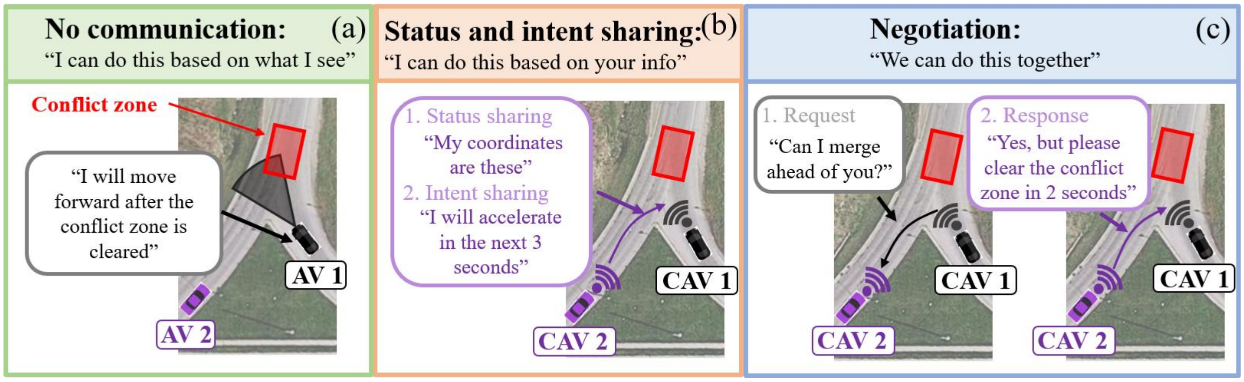

Fig. 1. – Three different strategies used for conflict resolution. (a) Without communication, vehicles make decisions based on what they perceive using sensors. (b) Through communication, vehicles make decisions based on status and intent information shared from other vehicles. (c) With negotiation, vehicles cooperate to resolve conflicts through a request-response mechanism.

In this study, a negotiation-based cooperative maneuvering strategy is proposed to resolve conflict under various traffic scenarios involving 2 vehicles. To avoid conflict, two vehicles must not exist in the conflict zone at the same time. We assume that both vehicles are connected automated vehicles and can share their status, intent, and other information via V2X communications by using existing coordination standards such as [11]. Based on the shared information, a request-response mechanism is utilized for agreement-seeking in conflict scenarios. Additionally, a strategy is proposed to individually control the vehicle motion for conflict resolution.

The rest of the study are organized as follows. In Section 2, the vehicle model is introduced. In Section 3, a conflict chart is constructed to determine the necessity of sending negotiation request. In Section 4, the details of the request-response protocol and the corresponding control strategy are presented. In Section 5, numerical simulations are utilized to determine the effectiveness of the proposed method at an unsignalized intersection. In Section 6, we conclude the study and identify future research directions

2. Modelling vehicle dynamics

Traffic conflicts may occur at unsignalized intersections (Fig. 2(a)) and merging scenarios (Fig. 2(b)) when vehicle 1 intends to merge while vehicle 2 is approaching along the main road. Note that in both scenarios, vehicle 2 has the right of way. To realize the negotiation protocol, the real-world conflict scenarios can be described by using the model in Fig. 2(c), where the conflict zone is illustrated by a red rectangle of length L. The variables r_1 and r_2 denote the distance between the vehicles and the conflict zone, while v_1 and v_2 denote the velocities of the vehicles. a_1 and a_2 denote the control inputs for vehicles, and l_1 and l_2 denote the lengths of the vehicles. The equations of motion for the CAVs are

$$\dot{r}_1 = -v_1, \dot{v}_1 = a_1, \dot{r}_2 = -v_2, \dot{v}_2 = a_2. \tag{1}$$

The velocities and accelerations are constrained within the bounds $v_1 \in [v_1^{\min}, v_1^{\max}]$, $v_2 \in [v_2^{\min}, v_2^{\max}]$, $a_1 \in [a_1^{\min}, a_1^{\max}]$, $a_2 \in [a_2^{\min}, a_2^{\max}]$. The negative signs in equation (1) indicate that the vehicles are moving towards the negative direction. For simplicity, we neglect the air resistance, rolling resistance, and the lateral dynamics of the vehicles.

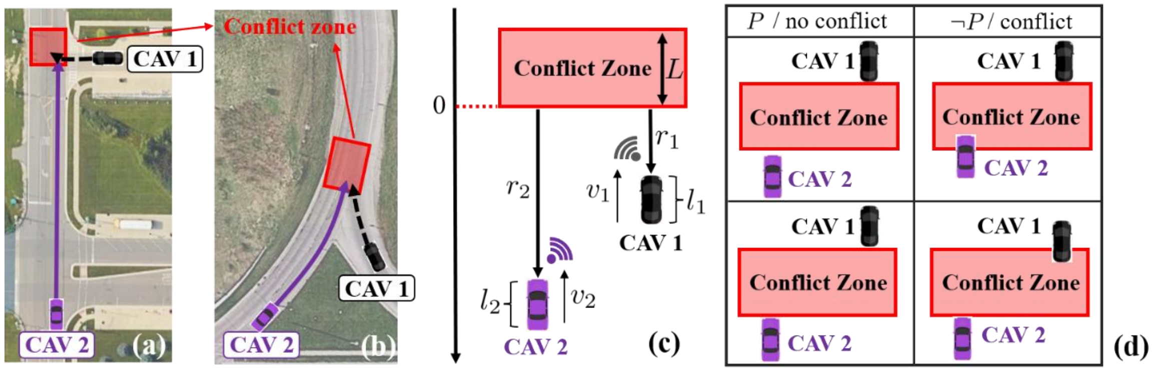

Fig. 2. -Modelling conflict in different traffic scenarios. (a) Unsignalized intersection. (b) Merging scenario. (c) Simplified model. (d) Examples where Proposition P is satisfied or not satisfied.

Our goal is to design a feasible and efficient negotiation framework that enables vehicles to avoid conflict while improving the time efficiency of the system. We assume that vehicles share their status (position and velocity) and intent (bounds for future velocity and acceleration [1]) with 10 Hz. For simplicity, the bounds of acceleration and velocity are constant during the merging process. However, our method can also apply to scenarios when the bounds are time varying. The acceleration and speed limits can vary across different vehicles and driving scenarios. The parameters used specifically in this study are shown in Table I.

Table 1 – Parameters setting in this paper

L	l_1	l_2	$a_1^{\min}$	$a_1^{\max}$	$a_2^{\min}$	$a_2^{\max}$	$v_1^{\min}$	$v_1^{\max}$	$v_2^{\min}$	$v_2^{\max}$
20 [m]	5 [m]	5 [m]	-4 [m/s²]	4 [m/s²]	-4 [m/s²]	3[m/s²]	0.1[m/s]	35[m/s]	0.1 [m/s]	35 [m/s]

3. Negotiation using conflict charts

Vehicles can predict potential conflicts when sharing their status and intent information with other vehicles. When a conflict is predicted, a request-response protocol can be implemented to resolve it. In this protocol, Vehicle 1 (requester) sends a negotiation request to Vehicle 2 (responder), and Vehicle 2 responds to Vehicle 1 by accepting or rejecting the request. In some cases, vehicle 2 may provide suggestions to the requester. The timing of sending a negotiation request plays a significant role in the resolution of conflict scenarios. An early negotiation request can lead to a waste of communication resources, while a delayed negotiation request can make conflict resolution challenging, or even infeasible. In this paper, we use the concept of conflict chart [1] to help vehicles determine the necessity of negotiation.

We start by defining a conflict chart for the scenario where vehicle 1 aims to pass the conflict zone before vehicle 2. We normalize this by proposition P:

$$P \coloneqq \{\exists t, r_1(t) = -(L + l_1) \wedge r_2(t) > 0\}, \tag{2}$$

where $\wedge$ denotes the logical conjunction "AND". Proposition P describes the situation when vehicle 1 has exited the conflict zone while vehicle 2 has not yet entered the conflict zone. We can prove that if proposition P is satisfied, then vehicle 1 can always merge ahead of vehicle 2 without conflict. Scenarios where Proposition P is satisfied/not satisfied are illustrated in Figs. 2(d).

From the perspective of vehicle 1, we can distinguish four different cases in terms of proposition P:

(i) Case 1: Proposition P is satisfied independent of the motions of vehicle 1 and vehicle 2, which means that there is no conflict in the traffic scenario;

(ii) Case 2: Proposition P may be satisfied depending on the motion of vehicle 1, which means that there exists a control strategy for vehicle 1 to resolve the conflict without the cooperation of vehicle 2;

(iii) Case 3: Proposition P may not be satisfied depending on the motion of vehicle 1 and vehicle 2, which means that the conflict-free maneuver is not guaranteed since vehicle 2 is uncontrollable from the perspective of vehicle 1;

(iv) Case 4: Proposition P is not satisfied independent of the motion of vehicle 1 and vehicle 2, which means that conflict is unavoidable.

It is worth noting that the cases described above can also be formulated from the perspective of vehicle 2 by simply swapping "vehicle 1" and "vehicle 2" in (ii) and (iii) to "vehicle 2" and "vehicle 1", respectively.

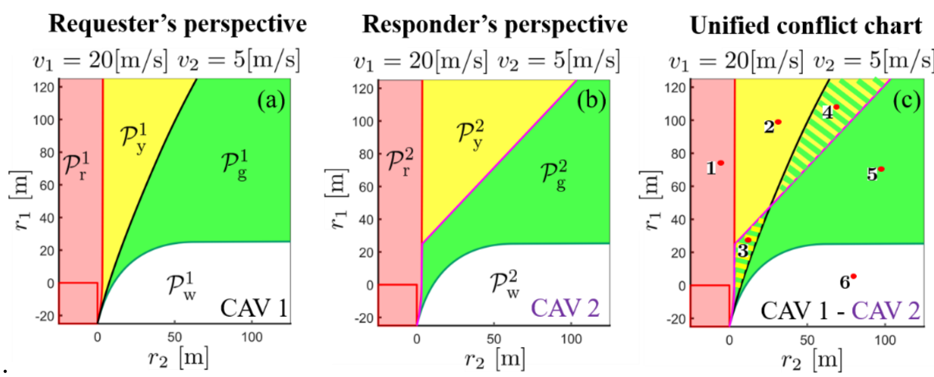

Fig. 3. - Conflict charts in the (r_1, r_2)-plane corresponding to traffic scenarios in Fig. 2(c) for $v_1 = 20$ [m/s] and $v_2 = 5$ [m/s]. (a) conflict chart designed from the perspective of vehicle 1, (b) conflict chart designed from the perspective of vehicle 2, and (c) unified conflict chart. The striped regions denote the overlap of yellow and green regions.

The four cases from perspectives of vehicle 1 and vehicle 2 mentioned above can be visualized as four disjoint regions using different colors in Fig. 3(a) and (b), respectively. The red square in each conflict chart denotes the conflict zone. White ($\mathcal{P}_{\rm w}^{\rm i}$), green ($\mathcal{P}_{\rm g}^{\rm i}$), yellow ($\mathcal{P}_{\rm y}^{\rm i}$), and red ($\mathcal{P}_{\rm r}^{\rm vi}$) regions represent the cases 1 to 4, respectively, from the perspective of vehicle i. It is worth noting that, in comparison to the conflict charts in [12], we added a new white region ($\mathcal{P}_{\rm w}^{\rm i}$) in the conflict chart to help vehicles avoiding unnecessary action on the (r_1, r_2)-plane. To provide an overview of the conflict scenarios, a unified conflict chart is constructed by combining the conflict charts of vehicles 1 and 2, as shown in Fig. 3(c), where the (r_1, r_2)-plane is partitioned into six regions by four curves. The striped regions denote that the region is yellow from one vehicle's perspective and green from the other vehicle's perspective.

Vehicles can use the conflict charts to determine when to initiate negotiation. Usually, the vehicle without the right-of-way should send a negotiation request to the vehicle with the right-of-way [13]. For example, in the unsignalized intersection depicted in Fig. 2(a), vehicle 1 may need to send a negotiation request to vehicle 2. If the state of vehicles is located in regions 1 or 6, negotiation is unnecessary: in region 1, conflict is inevitable, while in region 6, conflict is impossible independent of the motion of the vehicles. If the state of vehicles is located in regions 4 or 5, we can prove that there exists a control strategy for vehicle 1 to merge ahead without causing a conflict for any possible motion of vehicle 2. Therefore, in regions 4 and 5, vehicle 1 can merge ahead without negotiation. If the state of vehicles is located in regions 2 or 3, we can prove that negotiation is required to avoid conflict when vehicle 1 merges ahead of vehicle 2. Thus, if the state of the vehicles is in regions 2 or 3, vehicle 1 needs to send a negotiation request to vehicle 2.

4. Coordination and controller design

In this section, we aim to formulate a coordination protocol and a controller to realize the negotiation protocol in the scenario depicted in Fig. 2, where vehicle 1 wants to merge ahead at an unsignalized intersection while vehicle 2 is approaching. According to the analysis in Section 3, vehicle 1 needs to send a negotiation request to vehicle 2 in the regions 2 and 3 of the unified conflict chart to seek for cooperation. In regions 4 and 5, negotiation is not needed, and one can prove that vehicle 1 can avoid conflict individually by selecting the maximum feasible acceleration as the control input.

4.1 Design of response messages

Conflicts can be resolved using a negotiation-based cooperation method with a request-response mechanism when the state of vehicles is in regions 2 or 3 of the unified conflict chart, as illustrated in Fig. 4(a). When vehicle 1 sends a negotiation request to vehicle 2, vehicle 2 needs to send a response back to vehicle 1 to reach an agreement on the merging. Here, we propose a response message that can help vehicles avoid conflict while improving the time efficiency of the whole system.

In Fig. 4(b), $t_{2,\mathrm{in}}$ and $t_{1,\mathrm{out}}$ denote the times when vehicle 2 enters and vehicle 1 exits the conflict zone, respectively. Moreover, $T_{2,\mathrm{in}}^{\min}$ and $T_{2,\mathrm{in}}^{\max}$ denote the minimum and maximum times when vehicle 2 may enter the conflict zone if it has accelerations $a_2^{\max}$ and $a_2^{\min}$, respectively, and $T_{1,\mathrm{out}}^{\min}$ and $T_{1,\mathrm{out}}^{\max}$ denote the minimum and maximum times when vehicle 1 exits the conflict zone if it has $a_1^{\max}$ and $a_1^{\min}$, respectively. To prevent conflict, the following inequality must hold:

$$t_{2,\mathrm{in}} \geq t_{1,\mathrm{out}}\,. \tag{3}$$

This inequality states that once the vehicle 1 exits the conflict zone, the vehicle 2 has not yet entered, preventing both from being in the zone at the same time. When the state of the system is located in regions 2 or 3, if we only consider the conflict resolution, then various control strategies can be applied to satisfy the inequality (3). For instance, in Fig. 4(c), if a specific time $t_{1,\mathrm{out}} = t_{1,\mathrm{out}}^{*}$, highlighted as a green line within the range of $t_{1,\mathrm{out}}$, is selected for the exit time of vehicle 1, then all enter times of vehicle 2 $t_{2,\mathrm{in}} = t_{2,\mathrm{in}}^{*}$ within the green area of $t_{2,\mathrm{in}}$ in Fig. 4(c) satisfy the inequality (3), since $t_{2,\mathrm{in}}^{*} \geq t_{1,\mathrm{out}}^{*}$ always holds. Therefore, additional criteria, such as passenger comfort, energy consumption, and time efficiency can be considered to optimize the conflict-free maneuver. In this study, we focus on the time efficiency. Based on the analysis mentioned above, we can prove that $T_{1,\mathrm{out}}^{\min}$, which is the lower bound of $t_{1,\mathrm{out}}$ in Fig .4(c), can be chosen as a feasible control target for both vehicles to avoid conflict while maximizing time efficiency. Then, the control targets can be set as follows:

$$t_{2,\mathrm{in}} = t_{1,\mathrm{out}} = T_{1,\mathrm{out}}^{\min}. \tag{4}$$

$T_{1,\mathrm{out}}^{\min}$ can be selected as the response sent from vehicle 2 to the vehicle 1 suggesting that vehicle 1 should pass through the conflict zone by the time $t_{1,\mathrm{out}} = T_{1,\mathrm{out}}^{\min}$. It is worth mentioning that the response $T_{1,\mathrm{out}}^{\min}$ can be incorporated in the current negotiation messages by using the temporal characteristics of the target road resources standardized by SAE J3186 [11].

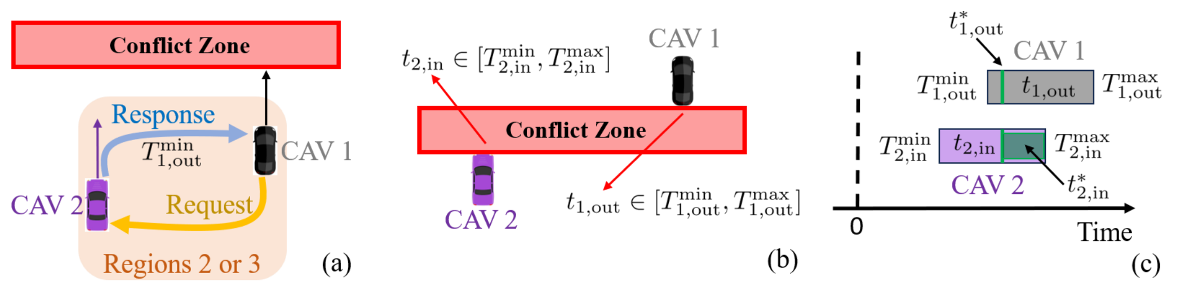

Fig. 4. - (a) The request-response mechanism used in the negotiation protocol. (b)The exit time ($t_{1,\text{out}}$) and enter time ($t_{2,\text{in}}$) of vehicles 1 and 2, respectively. (c) Range of the times when vehicles have passed or entered the conflict zone.

4.2 Controller design

To avoid conflict while improving time efficiency. $T_{1,\text{out}}^{\min}$ can be selected as the feasible control target for both vehicles. For vehicle 1, the control input can be set to $a_1^{\max}$, as the target $T_{1,\text{out}}^{\min}$ can be achieved by applying the control input upper bound $u_1(t) = a_1^{\max}$. However, the control input of vehicle 2 remains unknown since we do not know the mapping between $T_{1,\text{out}}^{\min}$ and the control input $u_2(t)$. Here, a simple method to calculate $u_2(t)$ analytically based on the control target $t_{2,\text{in}} = T_{1,\text{out}}^{\min}$ is shown in Appendix.
It is worth mentioning that various control strategies can be applied to vehicle 2 to achieve control target (4). However, the controller for vehicles 1 and 2 in Appendix offers the advantage of quicker processing time, as the analytical form of the controller can be derived.

5. Simulations and results analysis

In this section, we demonstrate the effectiveness of the proposed negotiation protocol through numerical simulations at an unsignalized intersection, as shown in Fig. 2(a). In this scenario, vehicle 1 intends to merge ahead with an initial position of $r_1(0) = 10$ [m] and an initial speed of $v_1 = 0.1$ [m/s], moving slowly as it nears the conflict zone. Meanwhile, vehicle 2, traveling on the main road, approaches with an initial position of $r_1(0) = 110$ [m] and an initial speed of 17.9 [m/s]. We assume that CAVs can share their status and intent with 10 Hz.
The times at which vehicles 1 and 2 exit the conflict zone are represented by magenta ($t_{1,\text{out}}$) and black ($t_{2,\text{out}}$) crosses, respectively, in the (r_1, r_2)-plane of Fig. 5. To evaluate the time efficiency of the system involving two vehicles, the time of the last vehicle exists conflict zone, $\max(t_{1,\text{out}}, t_{2,\text{out}})$, is selected as the metric. Without communication, a typical solution for vehicles to resolve the conflict at an unsignalized intersection can be summarized as 2 steps:
(1) vehicle 1 waits before vehicle 2 passes through the conflict zone.
(2) vehicle 1 accelerates after vehicle 2 clears the conflict zone.

Note that the case described above, where vehicle 2 merges ahead of vehicle 1, differs from proposition P (2), which states that vehicle 1 merges ahead of vehicle 2. The simulation results are shown in Fig. 5(a)-(c). Although the conflict can be resolved by the method mentioned above, the time efficiency of the whole system remains relatively low due to the conservativeness of vehicle 1's strategy. In particular, it takes 11.7 [s] until all vehicles clear the conflict zone. According to Sections 3 and 4, our negotiation protocol enables vehicles to resolve conflicts while maximizing the time efficiency. In Fig. 5(d)-(f), the negotiation protocol performs well when the system initiate negotiation in regions 3 (marked as a blue circle) of the unified conflict chart, taking 6.43 [s] for the whole system to pass through the conflict zone. In Fig. 5(g)-(i), vehicles initiate negotiation when the state is located in region 2 (marked as a blue circle), taking 9.13 [s] for the system to clear the conflict zone. It is observed that the earlier initiation of negotiation in regions 3 and 2 leads to greater improvements in time efficiency. It is worth to note that, vehicles can also utilize status and intent sharing without negotiation in region 3 or region 2. However, according to the definition of regions 3 and 2, the cooperation of vehicle 2 is required for vehicle 1 to merge ahead. Therefore, relying only on shared status and intent information is insufficient for vehicle 1 to merge ahead without conflict. In this situation, without negotiation, vehicle 1 still has to wait until vehicle 2 clears the conflict zone, resulting in low time efficiency.

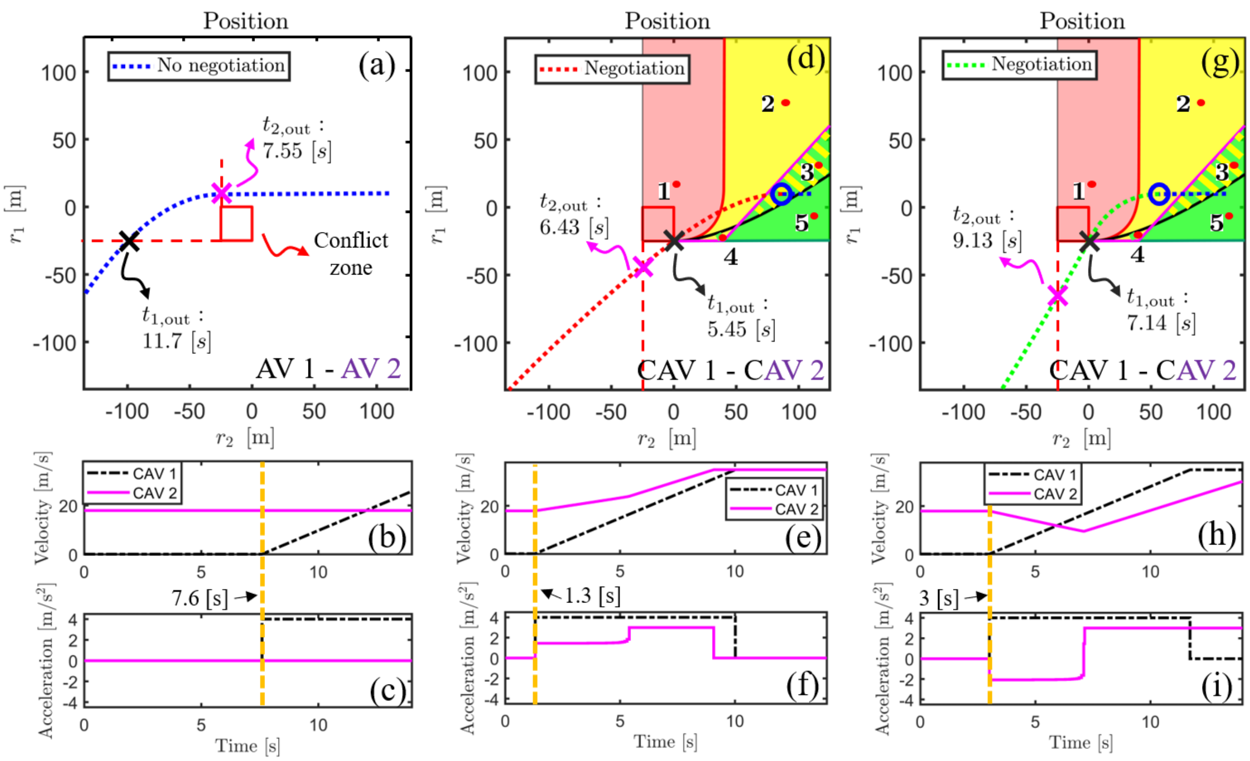

Fig. 5. - Simulation results of vehicles 1 and 2 merge at different regions of the conflict chart at different levels of cooperation. (a)-(c) A typical solution of the conflict when there is no negotiation between CAVs. (d)-(f) Vehicle 1 initiates negotiation in region 3 at 1.3 [s] (blue circle). (g)-(i) Vehicle 1 initiates negotiation in region 2 at 3 [s] (blue circle) in the merging process.

The time efficiency, shown by the times the vehicles exit the conflict zone for the above simulations are shown in the Fig. 6(a). Compared to the case without communication (baseline), the overall exit time of the system was reduced from 11.7 [s] to 6.43 [s] and 9.13 [s], when vehicles start to negotiate at the time $t = 1.3$ [s] and $t = 3$ [s], respectively. Recall that vehicle 1 will initiate negotiation in regions 3 and 2 and use status and intent sharing only in region 5. We consider 3 cases with different initial speed for vehicle 2 (case A: $v_2 = 8.9$ [m/s]; case B: $v_2 = 13.4$ [m/s]; case C: $v_2 = 17.9$ [m/s]) to comprehensively evaluate the performance of the proposed negotiation protocol at the unsignalized intersection. The exit times of vehicles for different initiation times are shown in Fig. 6(b). In Fig. 6(b), the x-axis of each figure denotes the time to start communication or negotiation during the conflict process. The first, second, and third rows denotes the exit time of vehicle 1, vehicle 2, and the whole system, respectively. As shown in Fig. 6(b), (e), and (h), the exit time of vehicle 1 is always reduced compared to the baseline, since vehicle 1 passes through first at the unsignalized intersection. In Fig. 6(c), (f), and (i), when vehicles start status and intent sharing in region 5, the exit time of vehicle 2 is the same as the exit time of the baseline since the motion of vehicle 2 is not altered in region 5. However, by applying the negotiation protocol in regions 3 and 2, the exit time of vehicle 2 is reduced when the vehicle 2 was far from the conflict zone and increased when the vehicle 2 was close to the conflict zone. This demonstrates that, sometimes, vehicle 2 needs to adjust its actions for the overall benefit of the system. Fig. 6(d), (g), and (j) show that the method proposed in this study can always help the system to improve the overall time efficiency.

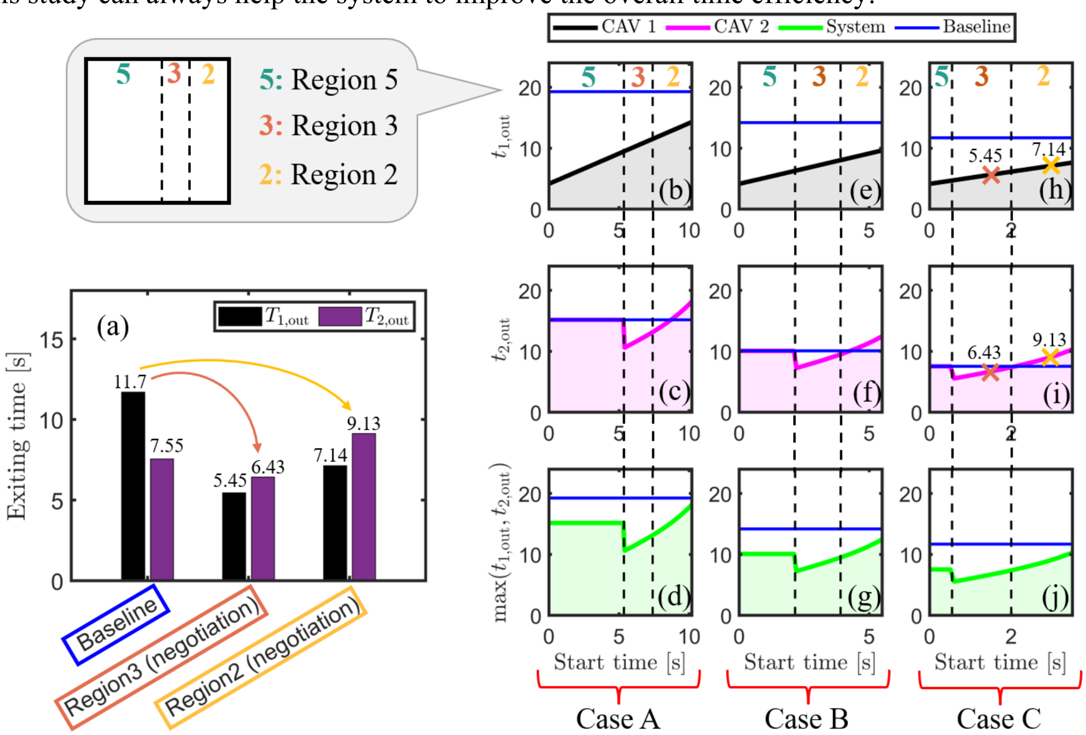

Fig. 6. - Simulation results in terms of time efficiency. (a) The exit times of vehicles by using negotiation method compared to the baseline. (b)-(j) Exit times of different vehicles under different cases compared to the baseline. Negotiation is not needed in region 5 but is necessary in regions 3 and 2. The brown and yellow crosses denote the exit times of vehicles using the negotiation protocol in regions 3 and 2, respectively, as shown in panel (a).

6. Conclusion

In this study, we proposed a novel negotiation technology for cooperative maneuvering of CAVs. This protocol can effectively help CAVs to avoid conflict in a multitude of traffic scenarios, such as merges and unsignalized intersections, while ensuring the time efficiency of the traffic. To realize the negotiation protocol, a conflict chart is proposed to determine the necessity of initiating negotiation based on the status and intent information shared by other vehicles. The response messages and maneuver decisions are then constructed accordingly. Simulations of vehicles at an unsignalized intersection demonstrated the effectiveness of the proposed framework. Our future work will mainly focus on the influence of delay on the performance of negotiation protocol, and systems with mixed traffic where CAVs share the road with connected human-driven vehicles (CHVs).

Appendix

According to [1], the time $t_{2,\text{in}}$ can be represented as a function of $a_{2,\text{in}}$ ($t_{2,\text{in}} = f(a_{2,\text{in}}; r_2, v_2, v_2^{\min}, v_2^{\max})$) based on the equation of motion (1) with the bounds of velocity and acceleration. We can prove that the function $f()$ is monotonically decreasing, ensuring the existence of its inverse function ($a_{2,\text{in}} = f^{-1}(t_{2,\text{in}}; r_2, v_2, v_2^{\min}, v_2^{\max})$). Then, the controller for vehicle 2 can be obtained by substituting the $T_{1,\text{out}}^{\min}$ into the inverse function $u_2(t) = f^{-1}(T_{1,\text{out}}^{\min}(\text{t}); r_2, v_2, v_2^{\min}, v_2^{\max})$, which is shown in Fig. 7.

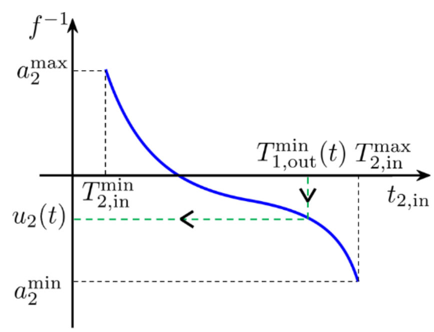

Fig. 7. -The blue curve represents the relationship between vehicle 2's acceleration $f^{-1}()$ and the given time $t_{2,\text{in}}$.

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