Game Theory of Cheating Autonomous Vehicles

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***Abstract*—The future of transportation will be autonomous vehicles, which communicate with each other making smart and intelligent decisions. For example, vehicles need not to stop at intersections when vehicles autonomously coordinate themselves for the order of crossing. Cooperative decision-making has the potential to solve challenging traffic management problems and enhance transportation safety and efficiency. Nevertheless, the ideal communication and coordination protocols for the Connected and Autonomous Vehicles (CAVs) have unexpected security concerns. Self-interested vehicles may not always want to cooperate. We consider an advanced CAV network in which vehicles can directly communicate with each other sharing intentions and other information such as location and speed. Game theory is applied to study the interactions of CAVs in a conflicting environment. Both cooperative and noncooperative scenarios are considered, especially when one party may be untruthful (i.e., lying to gain advantage, e.g., crossing intersection first while asking other vehicles to slow down). The untruthful player benefits at the cost of the cooperative players. Socially optimal game outcomes are only possible when players are cooperative. Through game theoretical study, we identify two preventive measures, i.e., speed limits and safety gaps, which may be dynamically adjusted to induce CAVs to play truthfully thus reaching the socially optimal solution.**

I. Introduction

An autonomous vehicle (AV) is a vehicle capable of sensing its environment and operating without human involvement. Taking inputs from sensors, based on machine learning, AVs classify objects in their surroundings and predict how they are likely to behave, making autonomous decisions about speed and steering without direct driver input.

While current AVs rely entirely on sensors, the holy grail of smart AVs for the future with the help of next generation wireless networks is that AVs communicate directly with each other for better decision making. Connectivity and automation provide the opportunity to enhance safety and mitigate congestion in transportation systems. A significantly enhanced variety of V2I (Vehicle to Infrastructure), V2V (Vehicle to Vehicle) and V2X (Vehicle to Everything) solutions, supported by the 5G/6G wireless systems, is anticipated to fulfill the vision of having a highly diverse and connected transportation environment [1]. Such technologies can enhance the efficiency of transportation systems through reduction of idling, number of stops, unnecessary accelerations/decelerations, and improve traffic flows.

Information is essential to realize these benefits and achieve efficiency. Such information may include vehicles' location, speed, and intentions, e.g., turn at the next intersection, planned routes, emergency level, etc., which cannot be acquired by sensors. While sharing information is mutually beneficial and socially desirable, the best all-around situation cannot be realized when AVs are not cooperative and lack of mutual trust.

This paper studies the decision-making of Connected Autonomous Vehicles (CAVs) in a direct-communicating environment. In particular, we are interested in studying how self-interested CAVs may manipulate information to earn an advantageous position in a competitive game. An CAV may cheat by lying about its intention, location or speed. One of the challenging maneuvers of autonomous driving is vehicles' strategic decisions at unsigned intersections. We use this intersection-crossing scenario to explore the possibility of cheating in an autonomous driving environment.

Through game theoretical modeling of CAVs, we characterize the behaviors of CAVs through payoff calculation under various combinations of strategies, and analyze their best responses. TChe social optimum is to have the largest number of vehicles pass the crossing in a given period of time with a collision avoidance constraint. The optimal solution hinges on CAVs' having an accurate model and correct information of the present and future states of all the conflicting CAVs. The model suggests that the efficient intersection crossing and socially optimal solution can be realized in a cooperative game where every CAV is honest and plays truthfully. Nevertheless, in a non-cooperative game, efficiency and optimum is not guaranteed as self-interested CAVs can be better off and benefit from providing false information at the cost of cooperative players. When there is lack of trust, all CAVs tend to lie. The system essentially downgrades to an outcome that is equivalent to the no-communication scenario.

Our research contributes by suggesting two preventive measures, i.e., speed limits and safety gaps (the minimum time between two CAVs for them to pass intersections safely) and studying their effects. Traditionally, only upper speed limit is considered. We argue that lower speed limit is as important as upper speed limit. Through lowering upper speed limit and increasing lower speed limit, there is less lying space for untruthful players. Increasing safety gaps has similar benefits as well. The key to prevent cheating is to reduce the incentive of cheating. Thoughtful design of traffic rules and CAV protocols can change motivation. Simulation study suggests that adjusting the legal speed limits and safety gaps of CAVs can effectively decrease CAVs' incentives to cheat to fully harvest the benefits of CAV networks. The experiments also indicate the optimal turning point where further adjusting speed limits and safety gaps are no longer feasible and may have negative impacts on CAV systems.

The rest of the paper is organized as follows. Section II discusses related works such as game theory in astomous vehicles. Section III develops a new CAV intersection-crossing game model in cooperative and noncooperative scenarios. Players' payoffs, best responses, incentives to cheat and game outcomes are discussed. Section IV conduct simulation studies to evaluate the proposed preventive measures, i.e., upper and lower speed limits and safe gaps, and how adjusting these settings may affect individual payoffs and social benefits. Finally, section V concludes out work.

II. Related Work

AVs are inevitably entering our lives. Projected to fully penetrate and dominate the traffic ecosystem in the future, AVs represent a potentially disruptive yet beneficial change to the transportation ecosystem [2]. During the transition to AVs, AV policymaking is pivotal to mediate the uncertainties in the existing laws and regulations about AV technologies and protocols [3].

The information from V2I/V2V, together with on-board sensors, can potentially increase AVs' decision-making and facilitate collaboration among the connected AVs. Existing literature looks at the potential collaboration and competition of AVs in various scenarios including autonomous driving and turning maneuvers at intersections, which are important parts of traffic networks [4]. A survey reviews recent studies on the planning and decision-making technology at intersections [5].

Game theory has been adopted in transportation studies from both macro and micro perspective [6], [7]. Some of the studies focus on macro-level management such as computing tolls for multi-class traffic [8] and transport modes competition [9]. There has been a rising literature studying games playing between vehicles at micro level decision-making and micro-behavior simulations. It is found applying game theory to vehicular adhoc networks and fuzzy logic control for simulation can minimize traffic congestion and reduce wait time [10]. Optimal control and game theory can establish safety criteria for heavy duty vehicle platooning applications in intelligent transport systems [11]. Game theory captures the dynamic interactive behaviors, being cooperative or competitive, of conflicting maneuvers including but not limited to turning movements [4], roundabout entries [12], car racing [13] and lane changing [14], [15].

While game theory has been used in various autonomous systems [16], we build a novel game theoretical model for fully connected autonomous vehicles which may be dishonest and lying to gain advantages. We make our unique contributions by proposing and evaluating counter measures such as speed limits and safety gaps to induce truthfulness and social optimum in CAV environments.

III. Game Theory of Intersection Crossing

Vehicles passing an intersection is a challenging maneuver for CAVs negotiating order in which vehicles pass the intersection safely and efficiently. We consider an intersection-crossing game in which two CAVs approaching an intersection from two directions (e.g., one going northbound and the other going westbound). For safety concern, the protocol includes an interval between the crossing time of the two CAVs and the interval should be no less than a safety gap. If the calculated time interval is less than the safety gap (i.e., a conflict occurs), both vehicles communicate and negotiate a solution to avoid the conflict (e.g., one accelerates and the other decelerates). If they are unable to negotiate a solution, both vehicles shall stop and wait at the intersection to meet the safety gap. The social optimum is defined as having the maximum number of vehicles safely cross the intersection in a given time.

The economic well-being of CAVs is two dimensional: comfort driving and no wait. Each CAV has a comfort speed (denoted by S^c) to pass the intersection. The goal is to drive smoothly at a speed closest to the comfort speed possible to pass the intersection with zero wait time. Let D_a and D_b be the distances CAV players A and B are from the intersection respectively, and their comfort speeds are S_a^c and S_b^c. The safety gap is g. The autonomous driving rules are:

- If $|\frac{D_a}{S_a^c} - \frac{D_b}{S_b^c}| \geq g$, the two vehicles are not conflicting. They can both cross the intersection at the comfort speed without stop.
- If $|\frac{D_a}{S_a^c} - \frac{D_b}{S_b^c}| < g$, the two vehicles are conflicting. They stop and wait.

A. Utility function

Two vehicles start communicating with each other once they are both in the communication circle. At the moment of communicating, both drive at their comfort speed, which are between the maximum or upper speed limit ($\overline{S}$) and minimum or lower speed limit ($\underline{S}$). When the gap between their projected arrival time reaching the intersection is less than the safety gap, i.e., two vehicles are conflicting, the CAV players face a tradeoff between deviating from the comfort speed and stopping at the intersection.

We use the following additively separable utility function (denoted by μ) to compute the payoff a vehicle receives from comfort drive speed and no wait time:

$$\mu_i = U(S_i^c)(1-f) - C(t) \tag{1}$$

where $i = a, b$ represents the two CAV players A and B. S_i^c is the player's comfort speed at which the player prefers to cross the intersection. $U(S_i^c)$ is the benefit the player receives from crossing the intersection at the comfort speed. C is the cost of stop and wait if the CAV players are conflicting based on the time interval (t) between two players' arrival time at the intersection.

$$C(t) = \begin{cases} C, & \text{if } t < g \text{ (conflicting)}, \\ 0, & \text{if } t \geq g \text{ (non-conflicting)}. \end{cases} \tag{2}$$

where $t = |\frac{D_a}{S_a^c} - \frac{D_b}{S_b^c}|$.

Function f is the rate of acceleration/deceleration that measures the degree of deviation from the comfort speed. Specifically,

$$f = \begin{cases} \frac{S_i^c - S_i^D}{S_i^c}, & \text{if } \underline{S} \leq S_i^D < S_i^c \text{ (deceleration)}, \\ \frac{S_i^A - S_i^c}{S_i^c}, & \text{if } S_i^c < S_i^A \leq \overline{S} \text{ (acceleration)}. \end{cases} \tag{3}$$

where S_i is the actual speed at which the player crosses the intersection that must be in between the upper and lower speed limits. The maximized utility $\mu_i = U(S_i^c)$ is realized at $f = 0$ (comfort speed) and $t \geq g$ (no wait).

B. *Payoff matrix*

Found in a conflicting situation, both CAV players have three choices: to keep driving at the current comfort speed, to decelerate, or to accelerate. Table I illustrates the expected payoffs of the intersection-crossing game between the conflicting CAV players. It is assumed that when one or two players decide to adjust speed, the change in speed is necessary to meet the safety gap.

Of all the possible game outcomes, $\{$*deceleration*, *deceleration*$\}$ and $\{$*acceleration*, *acceleration*$\}$ cannot be the players' choice in which case they sacrifice comfort speed but gain nothing in avoid waiting. $\{$*deceleration*, *acceleration*$\}$ and $\{$*acceleration*, *deceleration*$\}$ are viable strategies and can be socially optimal solutions when the two players cooperate and each adjusts speed by the same percentage to ensure fairness. Optimal rate of acceleration/deceleration f^*, which can be achieved when both players cooperate, is less than the rate (f) when only one player is adjusting speed.

C. *Best responses*

The game outcome depends on how much CAV players value comfort speed, cost of stop and wait, and the counter party's willingness to cooperate. Based on Table I, since the game is symmetric, if player B chooses "current speed", player A chooses deceleration/acceleration if $U(S_a^c)(1-f) > U(S_a^c) - C$ or "current speed" if $U(S_a^c)(1-f) < U(S_a^c) - C$. If player B chooses "deceleration" or "acceleration", the best response of player A is to keep the current speed. As a non-zero-sum game, there exists no single optimal strategy that is preferable to each player, nor is there a predictable game outcome.

Observation 1: The socially optimal outcome cannot be realized if the game is noncooperative. To achieve social optimum, the game has to be cooperative with a mutual agreement that both parties shall adjust speed by an equal percentage in a conflicting environment.

Observation 2: The party who remains current speed receives the highest payoff, therefore, there is an incentive for a party to cheat to induce the other party to adjust speed unilaterally.

D. *Cooperative and noncooperative games*

Being cooperative means all CAVs play truthfully and communicate true speed and intention. A socially optimal game outcome requires no-wait-time on both sides and a minimum combined change in speed, which corresponds to the game outcome $\{$*deceleration*, *acceleration*$\}$ or $\{$*acceleration*, *deceleration*$\}$. That is, both truthful players coordinate a common rate of acceleration/deceleration satisfying

$$|\frac{D_a}{S_a^c(1-f)} - \frac{D_b}{S_b^c(1+f)}| = g \tag{4}$$

or

$$|\frac{D_a}{S_a^c(1+f)} - \frac{D_b}{S_b^c(1-f)}| = g \tag{5}$$

Nevertheless, CAV players have incentives to provide false information to the opponent. Suppose player i lies about its current speed to induce the truthful player to adjust speed to the level that allows the lying player to pass the intersection at the comfort speed, thus player i receiving the highest payoff. There are two possible ways of cheating.

Option 1. The lying player i induces the truthful player to speed up by communicating a false intention to slow down and a false current speed higher than its comfort speed at which $S_i^F(1-f) = S_i^c$ and $\frac{D_i}{S_i^F(1-f)} - \frac{D}{S^c(1+f)} = g$. The desirable false speed S_i^F equals the following:

$$\frac{S_i^c}{1 - \frac{\frac{D}{\frac{D_i}{S_i^c} - g} - S^c}{S^c}} \tag{6}$$

Therefore, the lying player must communicate a false speed no less than S_i^F as in Eq. 6 to induce the truthful player to speed up enough to enable the lying player to cross the intersection at the comfort speed with no stop.

Option 2. The lying player i induces the truthful player to slow down by communicating a false intention to speed up and a false current speed lower than its comfort speed at which $S_i^F(1+f) = S_i^c$ and $\frac{D}{S^c(1-f)} - \frac{D_i}{S_i^F(1+f)} = g$. The desirable false speed S_i^F equals the following:

$$\frac{S_i^c}{1 + \frac{S^c - \frac{D}{\frac{D_i}{S_i^c} + g}}{S^c}} \tag{7}$$

Therefore, the lying player must communicate a false speed no higher than S_i^F as in Eq. (7) to induce the truthful player to slow down enough to enable the lying player to cross the intersection at the comfort speed with no stop. In both cases, D and S^c are associated with the truthful player.

Realizing the tendency of player i cheating, the other player would not cooperate. When neither player cooperates, the game outcome is $\{$*current speed*, *current speed*$\}$, which is equivalent to no communications at all. The direct-communication network can be self destructive under misaligned incentives.

TABLE I: The payoff matrix of two conflicting CAV players in an intersection-crossing game.

Player B / Player A	current speed	deceleration	acceleration
current speed	$U(S_a^c) - C$, $U(S_b^c) - C$	$U(S_a^c)$, $U(S_b^c)(1-f)$	$U(S_a^c)$, $U(S_b^c)(1-f)$
deceleration	$U(S_a^c)(1-f)$, $U(S_b^c)$	$U(S_a^c)(1-f) - C$, $U(S_b^c)(1-f) - C$	$U(S_a^c)(1-f^*)$, $U(S_b^c)(1-f^*)$
acceleration	$U(S_a^c)(1-f)$, $U(S_b^c)$	$U(S_a^c)(1-f^*)$, $U(S_b^c)(1-f^*)$	$U(S_a^c)(1-f) - C$, $U(S_b^c)(1-f) - C$

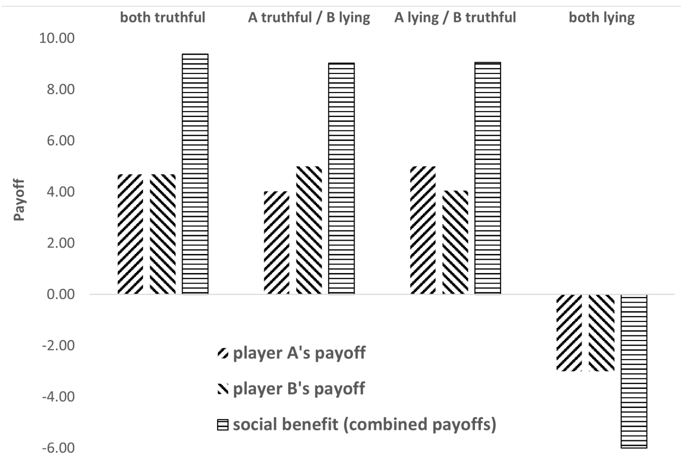


Fig. 1: Cooperative CAV game where players are truthful leads to social optimum. Unilateral lying strategy is better than all players lying (essentially no communication) for the society.

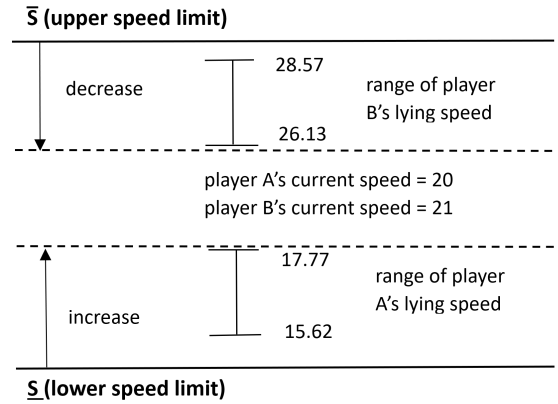


Fig. 2: By adjusting both upper and lower speed limits (unit as meters per second), CAV players' lying space is reduced, thus inducing them to play truthfully.

E. Preventive measures

The CAV intersection-crossing game is a non-zero-sum game that is not strictly competitive because there are both competitive and cooperative elements in the game. The conflicting vehicles have complementary interests in addition to opposed interests. As all players face the tradeoff between comfort speed and wait time, they can cooperate for mutual benefit or betray for individual reward. Cooperation cannot be established without mutual trust among self-interested players. The key is to design mechanisms that prevent players from cheating.

One insight from the game model is that there are exogenous variables that affect the players' payoffs: the upper-bound and the lower-bound of the crossing speed $\overline{S}$ and $\underline{S}$, and the safety gap g. Therefore, we propose adjusting the speed limits and safety gaps to change the feasibility of lying. Traditionally, policy makers consider maximum or upper speed limit. We recommend that minimum or lower speed limit is equally important for optimal CAV systems. We explore the possibility of designing mechanisms to induce CAV players to play truthfully by considering how speed limits and safety gaps work on incentives, as discussed in the next section.

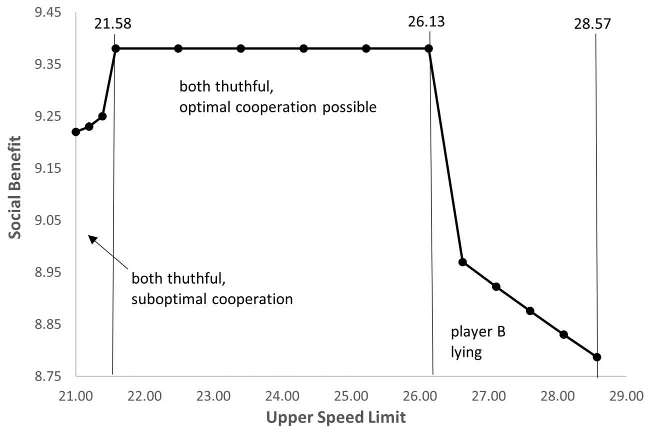
IV. Simulation Results

To study the efficacy of speed limits and safety gaps on preventing cheating, we conduct simulations of the CAV intersection-crossing game. The following parameters are used for simulations: safety gap $g = 5$ seconds between the crossing time of the two vehicles; at the moment two CAVs start direct communications, player A is 450 (D_a) meters from the intersection and player B is 500 (D_b) meters from the intersection. The comfort speeds of the two vehicles are $S_a^c = 20$ and $S_b^c = 21$ in terms of meters per second (approximately 45 mph). The interval between the two vehicles' arrival time at the intersection is $t = 1.31 < g$ thus the two CAVs are conflicting.

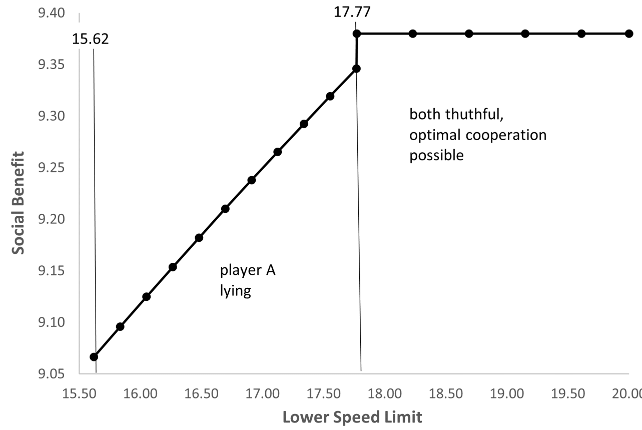
When both vehicles are truthful, player A accelerates by $f^* = 7.9\%$ and player B decelerates by $f^* = 7.9\%$, and they cross the intersection with a time interval $t = g = 5$. $S_a^o = 21.58$ and $S_b^o = 19.34$ where S_a^o and S_b^o are the players' optimal cooperative speeds. Cooperation generates the optimal social welfare (combined payoffs of player A and player B) equaling 9.38 at parameters $U(S^c) = 5$ and $C = 8$. Nevertheless, player B has an incentive to lie about its current speed to induce truthful player A to accelerate by more than 7.9% while player A also has an incentive to lie about its current speed to induce player B to decelerate by more than 7.9%.

A. Social benefits at the presence of lying players

Figure 1 compares individual payoffs and social benefit at the presence of truthful and/or lying players. When both players are truthful, they receive the same payoff and social optimum is realized. If only one player cheats, the lying player gains at the cost of the truthful player. Social benefit decreases compared to cooperation but the decrease is merely in the suboptimal speed adjustment of the truthful player, which is small. In other words, it is not a serious problem if only one party is lying by communicating a false speed since the cooperation of the truthful player avoids the big fall in social benefit. Nevertheless, if both players lie, both players stay



(a) Upper Speed Limits



(b) Lower Speed Limits

Fig. 3: Either decreasing upper speed limits or increasing lower speed limits (or both) increases social benefits by shifting players from lying to truthful thus optimal cooperations are possible.

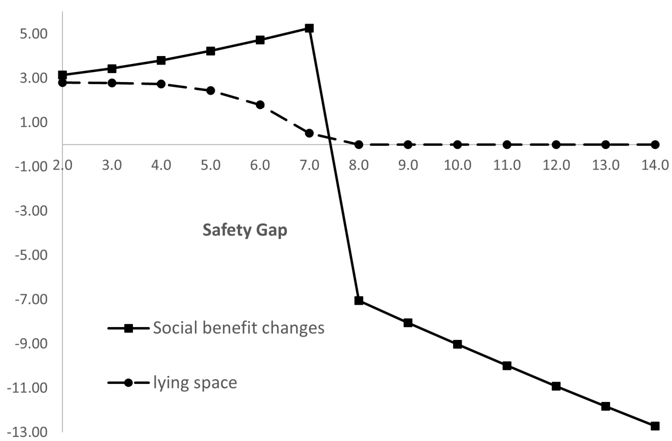


Fig. 4: Safety gap (unit as seconds) may be adjusted as a preventive measure to reduce lying space and induce CAVs to play truthfully. Social benefits change positively until a threshold point where larger gap is no longer a feasible option.

in the original conflicting zone and suffer a negative payoff, the worst scenario for the CAV network, i.e., both lying is equivalent to the no-communication environment.

B. *Effects of speed limits*

Since player B has an incentive to lie about the current speed to induce truthful player A to speed up, the false speed must fall in the range of conflict to be credible, i.e., $|\frac{D_a}{S_a^c} - \frac{D_b}{S_b^F}| < g$ where S_b^F is the false speed player B communicates with player A, and $S_b^F \in (26.13, 28.57)$. On the other hand, since player A has an incentive to lie about the current speed to induce player B to slow down, the false speed must fall in the range of conflict to be credible, i.e., $|\frac{D_a}{S_a^F} - \frac{D_b}{S_b}| < g$ where S_a^F is the false speed player A communicates with player B, and $S_a^F \in (15.62, 17.77)$.

Figure 2 illustrates the feasible lying range for both players to allow each player to cross the intersection at comfort speed. To make lying credible, the advertised speeds must be within the speed limits. Therefore, adjusting the upper and lower speed limits reduces players' possibility to cheat. If transportation authority sets the upper and lower speed limits as $[17.77, 26.13]$, both players behave truthfully.

While adjusting speed limits is effective to prevent cheating, it is a double-edged sword in that narrowing speed will also limit the room for legitimate cooperative CAV players to accelerate or decelerate for normal CAV operations. Figure 3 illustrates such tradeoff between social optimum and cheat prevention.

In particular, Figure 3a shows how adjusting upper speed limit affects social benefit given $\underline{S} \geq 17.70$. Several ranges occur:

- At $\overline{S} \in (26.13, 28.57]$, it is possible for player B to cheat. Social benefit increases as $\overline{S}$ decreases. That is, lowering upper speed limit reduces player B's range of lying.
- At $\overline{S} \in [21.58, 26.13]$, two cooperative parties adjust speed optimally and generate the optimal social benefit of 9.38.
- At $\overline{S} \in [21, 21.58)$, two parties partially cooperate as the upper speed limit does not allow player A to reach $S_a^o = 21.58$. Following the protocol, player A accelerates to $\overline{S}$, and player B decelerates as necessary to meet the safety gap. In this case, suboptimal cooperation appears and social benefit decreases as $\overline{S}$ decreases.

Figure 3b shows how adjusting lower speed limit affects social welfare given $\overline{S} \leq 26.13$. Two ranges occur:

- At $\underline{S} \in [15.62, 17.70)$, it is possible for player A to cheat. Social benefit increases as $\underline{S}$ increases.
- At $\underline{S} \in [17.70, 20]$, two cooperative parties adjust speed optimally and generate the optimal social benefit of 9.38.

C. Effects of safety gaps

Safety gap affects social benefit through the impact on players' feasible range of lying about speed and the rate of acceleration/deceleration to follow the safety protocol. Figure 4 shows how the safety gap affects the lying player's incentive to cheat and the corresponding change in social benefits (drawn as 10 times of the original value for better illustration) compared to the cooperative situation.

The dotted line in Figure 4 shows how the feasible region of player B's lying speed zone changes with the safety gap. The feasible region of the lying zone shrinks as the safety gap increases thus increasing social benefit. It shrinks to zero when the safety gap increases from 7 to 8 hence cheating is no longer possible for player B. Beyond the threshold safety gap, both players play truthfully.

The solid line shows the combined social welfare effects of the two opposing effects of the safety gap. Initially, increasing the safety gap increases social benefit through the reduction of cheating. The positive effect reaches the highest point where player B no longer has an incentive to cheat. The cooperative rate of acceleration/deceleration is increasing in the safety gap between truthful players. Once both players are truthful, social benefit starts falling as a larger safety gap leads to more discomfort when a larger rate of acceleration/deceleration is necessary to cooperate.

In summary, the safety gap has two opposing welfare effects on individual players and social benefit. On one hand, a larger safety gap decreases players' incentives to cheap with reduced feasible zone of lying. On the other hand, increasing the safety gap decreases individual payoffs and social benefit as a large safety gap increases the optimal rate of speed adjustment necessary to meet the safety gap.

V. Conclusion

Communication and autonomous technologies make connected automatous vehicles (CAVs) from science fiction to reality. Direct communication between CAVs enables the timely convey of information and significantly improves efficiency of the CAV networks. However, these disruptive technologies also bring security concerns that self-interested vehicles may act untruthfully to gain advantages, thus breaking the whole system. In this paper we investigate the problem of the lying vehicles using a game theoretical approach to capture the interactions between conflicting vehicles crossing an intersection, facing a tradeoff between comfort driving speed and no wait time. Various situations are studied under both cooperative or noncooperative scenarios. Most importantly, we propose two preventive measures, i.e., upper and lower speed limits and safety gaps, to prevent vehicles from lying, thus reaching socially optimal situation. Results suggest that lowering upper speed limits, increasing lower speed limits, and increasing safety gaps are effective in inducing vehicles to be truthful and cooperative. Critical points where further adjustment is no longer feasible are also identified. It is our hope that this study provides useful insights for policy makers and operators to achieve socially optimal CAVs of the future.

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