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Cooperative Driving at Lane Closures

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Abstract—**Cooperative driving via vehicle communication attracts increasing interests recently, since the motions of vehicles can be conducted in the safe and smooth manner. In this paper, cooperative driving at lane closures is studied. First, the solution space of all allowable driving schedules is described by a spanning tree in terms of vehicle safe passing order. The corresponding trajectory planning method is then proposed to generate the acceptable lane changing profiles. The proposed algorithm is fast and reliable, but sometimes yields conservative solutions than previous algorithms.**

I. INTRODUCTION

INSPIRED by the increasing demands on driving safety and efficiency, a variety of techniques had been introduced to improve the performance of the existing roadway systems in the last three decades [1]-[2]. Among them, cooperative driving with aid of inter-vehicle communication is now accepted as a potential way to alleviate traffic jam and reduce accidents.

The concept of cooperative driving was proposed to enable some driverless vehicles coexist on roads in cooperation with each other, since it is able to guide vehicles performing safe and efficient lane changing/merging, i.e. in PATH Project in USA, Chauffeur Project in EU, and Demo 2000 Cooperative Driving System in Japan. Though these projects had gained significant progress since their inception, there are still lots of problems to be solved before cooperative vehicles being sold to the public. Generally, most studies [3]-[8] focus on three questions: how to collect cooperatively, how to exchange the information among the vehicles efficiently and how to guide the vehicles using the received information.

The answers to the former two questions are inter-vehicle/ vehicle-infrastructure communication [9]-[11] and all kinds of mobile sensor fusion over the yielded communication networks [12]-[15]. This enables the vehicles to share information about their driving status and goals, which greatly extend the horizon of drivers or intelligent driving systems.

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The latter question is partly answered by using cooperative scheduling and trajectory planning [3]-[8], [16]-[17] recently. Cooperative scheduling is quite useful when determining the passing order of the vehicles to certain areas. For instance, the cooperative scheduling at road intersections (especially blind intersections without traffic lights) were discussed in [8], [16]- [17], where some algorithms aiming to avoid deadlock during planning were proposed. When the allowable passing orders (scheduling solutions) of vehicles are determined, cooperative trajectory planning will be applied to design the time varying velocity profiles of the vehicles. By using this, the motion of individual vehicles can be performed in a safe, smooth and deterministic manner. This is particularly helpful to heavy duty vehicles, since their acceleration/deceleration capacity is quite low. Finally, the optimal driving plan will be chosen from the potentials according to the pre-selected performance index, i.e. driving efficiencies (average time consumed in this area).

In this paper, the idea of cooperative driving is extended to study collision free driving at lane closures. Lane closures are frequently used to provide a work space for road maintenance or accident handling. Varied devices were proposed to increase speed limit compliance in lane closures. For instance, Portable Changeable Message Signs (PCMS) with speed display is now widely used to reduce the speed of vehicles traveling through lane closures and increase safety [17]-[18].

Another method is dynamic lane changing and merging [19]- [21]. However, most previous approaches will be outperformed by cooperative driving naturally, since they assumed that all the encountered vehicles/drivers cannot know each others' driving decision. Thus, the possible merit of cooperative driving at lane closures is studied here.

The rest of this paper is arranged as follows. Section 2 first describes the basic driving scenarios at lane closures and then represent vehicle cooperative scheduling algorithm. Section 3 analyzes the related cooperative trajectory planning problems. The virtual vehicle mapping technique and the fast trajectory generation algorithm is presented. Section 4 then extends the corresponding results by considering traffic congestions caused by lane closures and the placement of warning signs. Finally, Section 5 concludes the paper.

II. COOPERATIVE SCHEDULING

A. *Driving Scenarios at Lane Closures*

Usually, vehicles arrive continuously at a lane closure area. At a particular time, only a few vehicles which are moving in the vicinity of the beginning point of lane closures need to be considered. If concentrated on rural highways which are not so crowed, the continuous traffic flow can be truncated into some small segments with 10 to 20 vehicles. This assumption notably simplifies the planning problem without losing generality.

The simple truncating algorithm applied here is to label the vehicles by the times they enter the virtual rectangle around the beginning point of the lane closures. As shown in Fig.1, the five shadow vehicles inside the rectangle will be considered as a group to take part in cooperative driving; while other vehicles will not be considered temporarily. The shape and size of this virtual rectangle will be determined appropriately by velocities of the vehicle and inter-vehicle communication protocol that has been employed.

Fig.1. Vehicle flow truncating algorithm.

Moreover, it is also assumed that all vehicles have relatively low speeds when approaching the closing point. Slowing down allows the vehicles to have enough time to negotiate with each others and prepare for suddenly emerged pedestrians (workers at the work zone). Since this paper mainly discuss cooperative driving schedule and trajectory planning in this paper, it is assumed that all the vehicles can appropriately know any needed information including each other vehicle's driving decision via vehicle communication.

B. Solution Tree Generation

Generally, a valid driving schedule can be represented as the order of the vehicles passing the closing point. To illustrate this idea, consider a typical driving scenario shown in Fig.2.

One safe driving schedule for the scenario Fig.2(a) is to let vehicle ***B*** pass the closing point first; then let vehicle ***A*** change lane 1 to lane 2. Apparently, this schedule can be written as the following sequence

$$\boldsymbol{B}_2^2 \ \boldsymbol{A}_1^2 \tag{1}$$

where $\boldsymbol{A}_1^2$ is right to $\boldsymbol{B}_2^2$ represents that vehicle ***A*** will pass the closing point after vehicle ***B***. The subscript denotes the possible start lane of vehicle and the superscript denotes the possible destination lane of vehicle.

Driving scenarios with more than one lane open, i.e. shown in Fig.2(b) is more complex, since vehicles can pass the closing point simultaneously. For instance, a possible driving schedule for Fig.2(b) can be written as

$$\boldsymbol{A}_1^2 \ \boldsymbol{B}_2^3 \ \boldsymbol{C}_3^3 \tag{2}$$

where ***A*** and ***B*** are in one subset indicating they approximately pass the closing point at the same time. It is apparent that each subset in a valid driving schedule should constitute of a safe driving pattern (vehicle pairs).

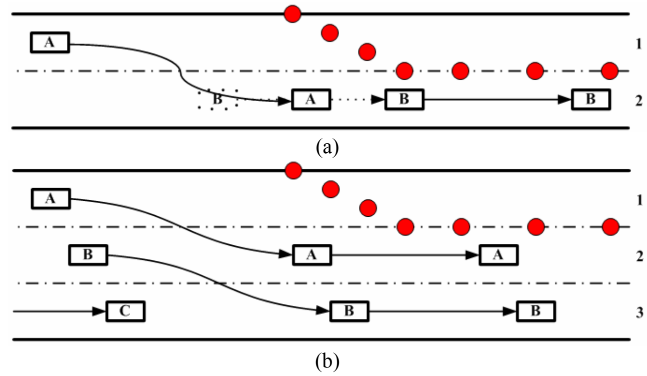


Fig.2. Lane merging at a lane closure area with each lane top-down nominated: (a) two-lane road with one lane closed; (b) three-lane road with one lane closed.

Obviously, there is another safe driving schedule for the scenario Fig.2(a), which can be written as

$$\boldsymbol{A}_1^2 \ \boldsymbol{B}_2^2 \tag{3}$$

If vehicle ***A*** lags vehicle ***B*** a relatively long distance, driving plan (1) would takes less time than driving plan (3). If vehicle ***B*** lags vehicle ***A*** a relatively long distance, plan (3) would be a better choice. Since different driving schedules lead to different passing times, an optimal cooperative driving plan needs to find the schedule that completes the total driving process with the least time.

In general, to enumerate the allowable driving schedule will yield a solution tree in which each node represents a particular driving plan (sequence) except for the root node. Normally, the schedule tree generation algorithm can be written as:

Solution Tree Generation Algorithm.

Suppose there are N vehicles under consideration.

1. *Generate the root node of the tree;*
2. *Generate the children nodes for the root node which represent all the possible permutation orders of the vehicle sequence without separator symbols, and prune all the obtained nodes that represent invalid order of driving.*
3. *For each node in the second level of the tree, generate N-1 children by labeling the possible lane change plans into the driving sequence that is represented by it.*

A great number of nodes in this tree will be discarded in Step 2 directly, since they represent invalid driving schedules, for which no trajectory planning is needed. One apparent fact is that leading vehicles will always pass the closing point earlier than lagging vehicles in the original lane. Many unsafe driving schedules can be pruned from the solution tree, except those driving schedules are implicitly forbidden by vehicle velocity/ acceleration constraints. For example, in the driving scenario shown in Fig.3, vehicle ***B*** should always pass the closing point earlier than vehicle ***A***. Thus, the branch ***D A C F B*** is invalid. The driving plan tree stemmed only has a few valid nodes after pruning and labeling, see Fig.4.

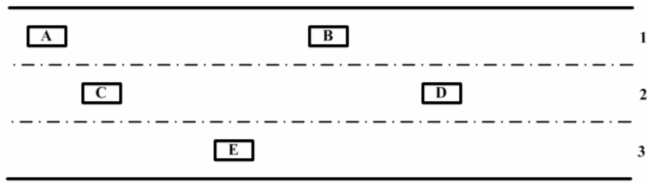


Fig.3. A driving scenario, where lane 1 and 2 will be closed ahead.

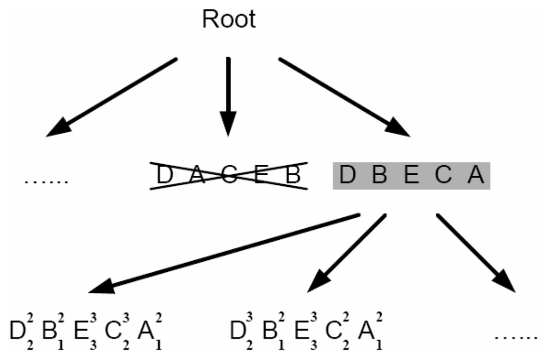


Fig.4. A schedule tree stemmed from the driving scenario shown in Fig.3. The crossed out node represents the explicit inappropriate driving schedules.

III. COOPERATIVE TRAJECTORY PLANNING

A. Divisions and Segmentation of Trajectories

The trajectory profile of each vehicle in the driving schedule will be generated one by one with respect to the corresponding driving order passing the junction. For simplicity, let's assume every vehicle should 'know' the trajectories of other vehicles.

Generally, the car-following and lane changing/ merging scenarios around lane closures is categorized into four cases:

Case A) the leading vehicle moves in the lane. Same as the following vehicle, see Fig.5;

Case B) lane changing to avoid collision with the cones, such as vehicle ***A*** in Fig.2(a).

Case C) the leading vehicle moves in the same lane, but the following vehicles changes lane, see Fig.6;

Case D) the leading vehicle changes lane, but the following vehicle moves in the same lane, see Fig.7;

Case E) both the leading vehicle and the following vehicles change lane, see Fig.8.

Fig.5. Driving scenario of Case A).

Moreover, the whole trajectory of a vehicle which changes lane will be segmented into several parts: the straight moving parts and the lane changing parts; i.e. Fig.9. The sub trajectories of these parts are calculated individually. To further simplify the problem, it assumes that the vehicles will only ac/decelerate when straight moving and the speed will be roughly maintained during steering.

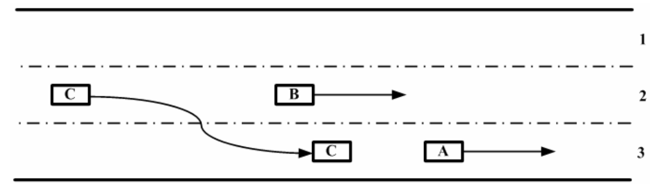


Fig.6. Driving scenario of Case C).

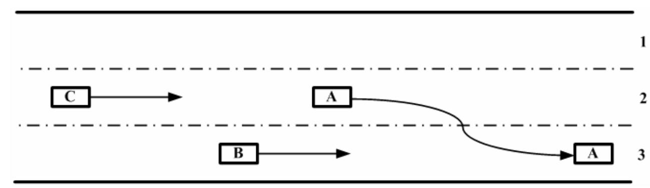
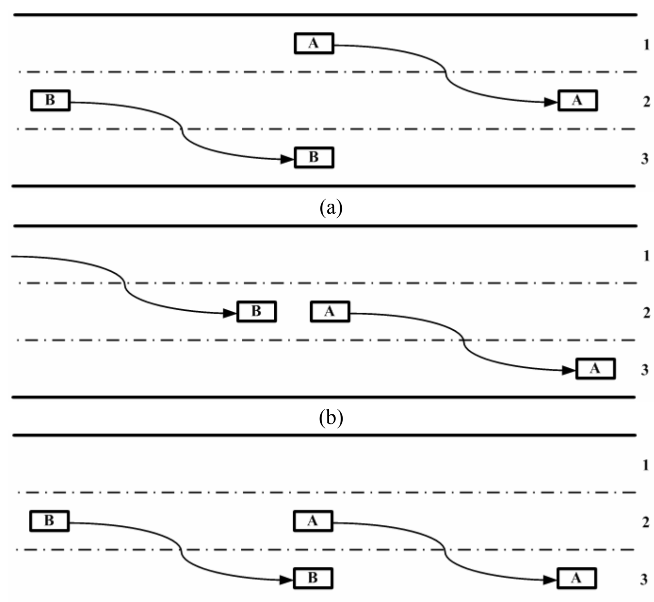


Fig.7. Driving scenario of Case D).



(c)

Fig.8. Driving scenarios of Case E).

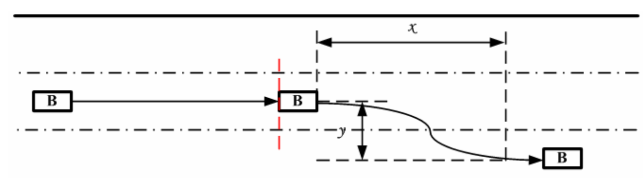


Fig.9. Segmentation of the trajectory of a vehicle.

Because it aims to improve traffic efficiency, the cooperative driving plan should keep the headway between the potential leading/virtual vehicle and itself to the minimum safe distance. The main task of trajectory planning is the find the collision free trajectory efficiently.

B. Fast Collision Free Trajectory Planning Algorithm

The desired trajectory is designed to be simple so that it can be easily transferred via inter-vehicle communication. In this paper, if a vehicle will not change lane around the lane closing point, it is required to follow the general slowdown guidance shown in Fig.10, which is written as

If $0 \le t < t_1$, Then $\dot{x}(t) = v_1$;

If $t_1 \le t < t_2$, Then $\dot{x}(t) = v_1 - (v_2 - v_1)\dfrac{t - t_1}{t_2 - t_1}$;

If $t_2 \le t$, Then $\dot{x}(t) = v_2$.

where x is the horizontal displacement, and y is the vertical displacement from the current position to the road guideline of the start lane, see Fig.9.

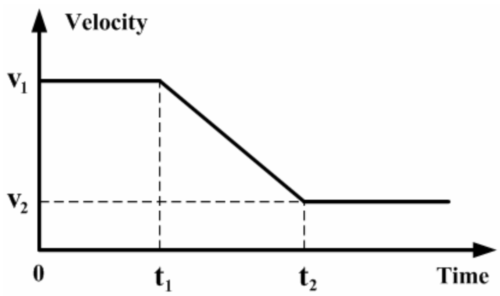


Fig.10. General decelerate profile of vehicle ***A*** and ***B*** in Fig.5.

1) Trajectory Planning for Case A)

Suppose the previous velocities of vehicle ***A*** and ***B*** before vehicle ***A*** decelerates are v_{A1} and v_{B1}, the desired steady state velocity is v_{End}. The gap between the two vehicles is l_{Start} when vehicle ***A*** begins to decelerate, and the desired steady state gap is l_{End}. Without losing much generality, let's further assume $l_{Start} \ge l_{End}$, $v_{B1} \ge v_{A1} > v_{End}$.

A simple yet road-capacity-optimal collision-free tracking trajectory of vehicle ***A*** can be chosen as follows:

Both vehicle ***A*** and ***B*** just decelerates once. And vehicle ***B*** decelerates to v_{End} after vehicle ***A*** begins to decelerate. The final gap should be bigger than l_{End}. Then vehicle ***B*** tracks vehicle ***A*** strictly within the lane closures.

Suppose the velocity changing time points of vehicle ***A*** are known as $t_{A1} = 0$ and t_{A2} shown as Fig.10; and the velocity changing time points of vehicle ***B*** are t_{B1} and t_{B2}.

Thus, there are two driving scenarios to be studied

i) vehicle ***B*** does not decelerate until vehicle ***A*** decelerates to v_{End}, and then vehicle ***B*** decelerates to v_{End}. Thus, $t_{A1} < t_{B1}$.

Obviously, the collision-free check consists of three parts: vehicle ***B*** does not bump into vehicle ***A*** when only vehicle ***A*** decelerates; no vehicle decelerate; and vehicle ***B*** does not bump into vehicle ***A*** when only vehicle ***B*** is decelerating.

The first condition leads to

$$v_{B1}t_{A1} - \frac{v_{A1} + v_{End}}{2}t_{A1} < l_{Start} - l_{End} \tag{4}$$

The second condition leads to

$$v_{B1}t_{B1} - \frac{v_{A1} + v_{End}}{2}t_{A1} - v_{End}\left(t_{B1} - t_{A1}\right) < l_{Start} - l_{End} \tag{5}$$

The third condition leads to

$$\begin{aligned} v_{B1}t_{B1} + \frac{v_{B1} + v_{End}}{2}\left(t_{B2} - t_{B1}\right) - \frac{v_{A1} + v_{End}}{2}t_{A1} \\ - v_{End}\left(t_{B2} - t_{A1}\right) < l_{Start} - l_{End} \end{aligned} \tag{6}$$

ii) vehicle ***B*** decelerates before vehicle ***A*** decelerates to v_{End}, and then both vehicles decelerate to v_{End}. Considering traffic efficiency, normally vehicle ***B*** should end up deceleration later. Thus, $t_{B1} < t_{A1}$, $t_{A2} < t_{B2}$.

Obviously, the collision-free check consists of three parts: vehicle ***B*** does not bump into vehicle ***A*** when only vehicle ***A*** decelerates; vehicle ***B*** does not bump into vehicle ***A*** when both vehicles are decelerating, and finally vehicle ***B*** does not bump into vehicle ***A*** when only vehicle ***B*** is decelerating.

The first condition leads to

$$v_{B1}t_{B1} - \frac{v_{A1} + v_{End} + \left(v_{A1} - v_{End}\right)\dfrac{t_{B1}}{t_{A1}}}{2}t_{B1} < l_{Start} - l_{End} \tag{7}$$

The second condition leads to

$$\begin{aligned} v_{B1}t_{B1} + \frac{v_{B1} + v_{End} + \left(v_{B1} - v_{End}\right)\dfrac{t_{A2} - t_{B1}}{t_{B2} - t_{B1}}}{2}\left(t_{A2} - t_{B1}\right) \\ - \frac{v_{A1} + v_{End}}{2}t_{A1} < l_{Start} - l_{End} \end{aligned} \tag{8}$$

The third condition still leads to Ineq.(6).

The program should choose a better plan from the above two cooperative driving schedules according to the vehicle initial conditions. If conditions allowed, the first plan might be better since it may yield shorter final gap.

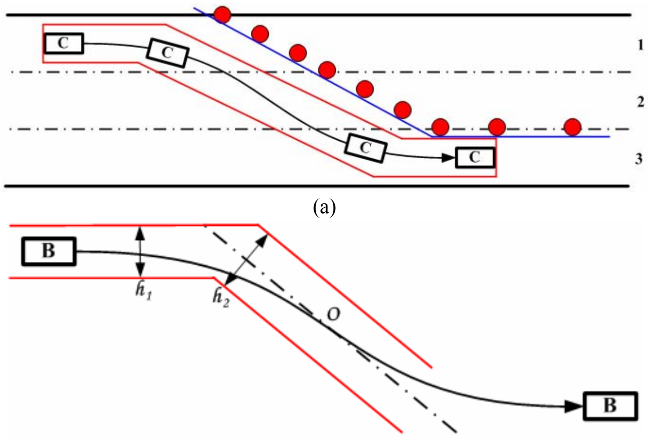
The acceleration process when vehicles are leaving the work zone could be easily derived similar to the strategy above. The leading vehicle accelerates first, and then, so does the follower.

2) Trajectory Planning for Case B)

Fast lane changing trajectory validation regarding intrinsic vehicle mechanics constraints attracts continuous interests in the last decade [22]-[29].

As pointed out in [24], mature human drivers reckon the present vehicle and road information and subconsciously select the trajectory and make the associated control actions. To save trajectory planning time cost, it is suggested in this paper that all the vehicles should pre-calculate and store its possible lane changing trajectories as well as the associated steering control signals under different velocities. When needed, the vehicle can then pick up the appropriate trajectory from these potential solutions.

The "S"-type lane changing trajectory is first approximated as a three-part area as the red irregular shape show in Fig.11(a). More precisely, it is a combination of two trapezoids at the two sides and one parallelogram in the middle. To check whether a vehicle will collide with the cones can be transferred to check whether this approximate envelop of the trajectory has any common part of the cones area whose boundaries are described by two lines; see the blue lines shown in Fig.11(b). It is clear that such a collision test is only related to line segment collision test in 2D space and therefore simpler than the polynomial-based collision tests studied in [25]-[27].



(b)

Fig.11. Approximation of the lane changing trajectory and the collision test.

The determination process of this three-part area is shown in Fig.11.(b). If the lane changing trajectory of a vehicle is described by a 5th-order polynomial to relative position (x, y)

$$\begin{cases} x(t) = a_5 t^5 + a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0 \\ y(t) = b_5 t^5 + b_4 t^4 + b_3 t^3 + b_2 t^2 + b_1 t + b_0 \end{cases} \tag{9}$$

where $t \in [0, T]$. And the corresponding coefficients a_i, b_i, $i = 1, \ldots, 5$ can be determined by applying the interpolation algorithm given in [22].

The slope of the border of the parallelogram is set to be the same as the tangent of the curve at the center O; see Fig.11(b)

$$\left.\frac{dy}{dx}\right|_{t=\frac{T}{2}} = \left.\frac{5a_5 t^4 + 4a_4 t^3 + 3a_3 t^2 + 2a_2 t + a_1}{5b_5 t^4 + 4b_4 t^3 + 3b_3 t^2 + 2b_2 t + b_1}\right|_{t=\frac{T}{2}} \tag{10}$$

The heights of the trapezoids at the two sides are set to be h_1 and the height of the parallelogram is set to be h_2. Based on simulations, for most ordinary passenger cars, h_1 and h_2 can be roughly chosen as

$$h_1 = \min(2w_{lane}, 3w_{vehicle}, l_{vehicle}) \tag{11}$$

$$h_2 = \max(2w_{vehicle}, 1.5l_{vehicle}) \tag{12}$$

where w_{lane} is the width of the lane, $w_{vehicle}$ is the width of the vehicle, $l_{vehicle}$ is the length of the vehicle.

However, when considering long vehicles like transportation trucks or lane changing in slow and crowded vehicle flow, h_1 and h_2 need to be carefully calculated for each kind of lane changing trajectory respectively.

3) Trajectory Planning for Case C)-E)

The collision test for driving scenarios E) can be carried out by dividing the three-part lane changing trajectory envelop into smaller pieces according to the same time coordinate and then evaluate sequentially. For instance, the trajectories of vehicle ***A*** and ***B*** in Fig.12 are divided into 9 segments and checked to see whether the k th parts of these two trajectories cover each other partly, $k = 1, \ldots, 9$. Since the border of such small segments is easy to determine, the collision test is thus straightforward and simpler than the previous plans.

If truncate the straight moving trajectory into small pieces according to the same time coordinate. Such methods can also be applied to driving scenarios C)-D).

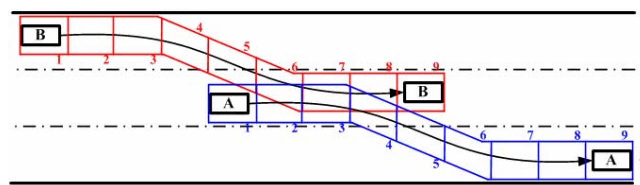


Fig.12. Grid of the trajectory and collision check.

Finally, the total time cost of trajectory is countered from the time when the cooperative driving process begins to the time when the last vehicle leaves the interested lane closing area. All the un-discarded driving plans in the solution tree will be compared, and the one with least time cost will be chosen as the final cooperative driving plan.

IV. Further Discussions

Simulations show that cooperative driving can help to reduce the delay at the lane closures. Indeed, the environment (vehicle, road, etc.) information transferred over inter-vehicle network acts as a mobile and adaptive warning message signs for the drivers/vehicles [20]-[21]. Normally, the distance between the message sign and the lane closing point should be longer if the density of the traffic flow becomes higher. This is because more vehicles need to change lane, which results in longer lane changing areas. Thus, the method proposed appears to be more flexible over time, since the message signs cannot be moved arbitrarily.

Moreover, cooperative driving is safer and more efficient than the independent driving using game theory [30]-[31]. It would be interesting if not all the vehicles are equipped with inter-vehicle communication devices to have full information about the trajectory of the other drivers. Simulations show that the driving performance will quickly degrade as the percentage of the uncooperative vehicles increases [32]. More efforts will be made into this direction in the near future.

Besides, the scheduling of the vehicles can also be generated based on some heuristic rules, i.e. neural networks and fuzzy rules. For instance, the fuzzy inference rules may be written as

"*If a vehicle **B** lags a relative long distance from a vehicle **A**, and the relative speed between these two are small, then let vehicle **B** pass the closing point later than vehicle **A**.*"

Whether these human-like scheduling generation methods introduce more conservative to the system remains as an open and important question and needs further discussions.

V. Conclusion

This paper extends the idea of cooperative driving platoon to collision free driving at lane closures. Specially, the trajectory planning method for lane changing and merging is studied. The proposed algorithm is fast and reliable, but sometimes yields conservative solutions than previous algorithms. How to keep a balance between calculation costs and conservatives would be an interesting topic for further discussions.

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