A Right-of-Way Assignment Strategy to Ensure Traffic Safety and Efficiency in Lane Change

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Abstract—How to guarantee absolute safety and meanwhile maintain traffic efficiency remains difficult for intelligent vehicle studies. This paper discusses how to deal with these two problems in lane change scenarios. Its key idea is to develop a right-of-way assignment strategy for clear collision avoidance conditions. Both theoretical analysis and numerical testing results are provided to show the effectiveness of the proposed strategy. Experiments demonstrate that this new strategy is not only collision-free as the so-called Responsibility-Sensitive Safety (RSS) strategy but also increases traffic efficiency.

Index Terms—Right-of-way, lane change, safety, traffic efficiency

I. INTRODUCTION

SAFETY is the first criterion of autonomous driving. Whether an intelligent vehicle can guarantee safety lies in many factors, including perception accuracy/latency and decision correctness. In this paper, we focus on the decision for traffic safety. Plainly speaking, we are interested when to make special actions (e.g., ac/deceleration, lane change) with respect to the given driving scenario, aiming to strictly guarantee collision-free to all the neighboring vehicles/pedestrians.

every vehicle is connected and autonomous. We can use cooperative driving techniques [1]-[7] to arrange their movements to avoid collisions. However, in the foreseeable future, human-driven and autonomous driving vehicles will coexist for a long time. So, in this paper, we highlight the second way in which every intelligent vehicle should make appropriate and relatively independent decisions/actions to interact with other intelligent vehicles to avoid collision.

For example, based on the concept of "absolute safety", researchers of Mobileye proposed the Responsibility-Sensitive Safety (RSS) strategy to derive collision avoidance conditions for automated vehicles [8]. Generally speaking, the essential idea of the RSS strategy is to keep safe distances from other vehicles and always prepare to give the right-of-way rather than take it. In order to confirm the efficiency of the RSS strategy, Mobileye listed 37 accident scenarios, covering 99.4% of NHTSA’s accident scenario data [9]. The test results show that it could effectively avoid collisions and has reached a sound available state.

However, further analysis shows that the initial RSS strategy is quite conservative in the interaction between vehicles and often leads to low traffic efficiency. For example, it was shown in [10] that we could slightly modify the initial RSS strategy to better balance the requirement of traffic safety and traffic efficiency within the car-following scenario. Whether the initial RSS strategy could be improved in some more complex driving scenario attracts increasing interests now.

In this paper, we study the lane change scenario which had drawn continuous attention in various transportation studies [11], [12]. Human drivers often arise accidents during the lane-changing process. According to the data of The National Highway Safety Administration (NHTSA), traffic accidents caused by lane change account for up to 27% of all [13]. The current intelligent vehicles cannot guarantee absolute safety for lane change, either.

Many studies on lane change emphasize the classification and modeling of human driver behavior in lane change for traffic simulation [14]-[16]. Gipps [14] presented a framework for lane change decisions in form of a decision tree and considered whether to merge is determined by the combined effect of six potential conflicts. On the basis of the Gipps lane change model, MITSIM model [15] was proposed in 2002, which thought the lane-changing process should be divided into three stages: i) determine whether there is a need to change; ii) judge the acceptant gaps, and iii) make the action of lane-change. Differently, Southern Integrated Transportation System (SITRAS) [16] took both the competition and cooperation between vehicles into account. Then, evolutionary gaming, data-driven ensemble learning, and some other models were also proposed to give a more reasonable description of lane-changing behavior [17]-[19]. Although these studies
provided a basis for lane change studies of intelligent vehicles, their results did not give a clear hint on how to completely avoid collision [20].

The initial RSS strategy did not propose a special strategy for the lane change scenario. Instead, a set of general rules was proposed to ensure collision free for arbitrary scenarios that include lane change scenario. This may not always be a good choice since the RSS designed minimum allowable distance for lane-change is too large, which makes lane change a luxury in most cases. So, we are interested in the study whether we could noticeably improve the vehicle’s performance in some special scenarios via dedicated strategies.

Moreover, the initial RSS strategy did not explicitly define "what is the right-of-way" or "when to transfer the right-of-way" [21]. The check of collision free conditions is mostly built upon instantaneous distance judgment in the RSS strategy. This leads to complicated calculation, if we want to analyze some complex scenarios (e.g., lane-change) that may last for a short or long time period [22]-[25].

The major assumptions involved in this paper are listed below:

- We assume all vehicles know and follow the same rules.
- We assume the lane-changing vehicle has decided to merge and determine the target lane at the beginning.
- We assume that other drivers or intelligent vehicle could communicate with the studied vehicles in some certain way (e.g. the front/rear-lights of vehicles), even if we do not consider Vehicle-to-X (V2X) communications or cooperative driving here. Such communications are very useful to help each other understand who gets the right-of-way and when to get/transfer the right-of-ways. This assumption leads to a stage-to-stage model for "right-of-way" assignment and thus greatly reduces the calculation of collision conditions.

Based on the above considerations, we propose a new strategy that addresses the assignment and communications of the right-of-way to ensure traffic safety and efficiency in lane change scenarios. Based on our previous study [10], we could see that, via correct communications, the whole decision problem could be easily decomposed into several much simpler sub-problems based on the transferring time points of the right-of-ways. We call this method as a situation-aware strategy for specified tasks within special driving scenarios [26]-[29].

The simulation results indicate that our strategy significantly shortens the minimum lane-changing distance required by the RSS strategy and improves the success rate of lane-change in a fixed time, under the premise of ensuring safety.

To better present our findings, the rest of this paper is arranged as follows. Section II introduces DLC lane change scenario and defines the right-of-ways; Section III explains the detailed transfer processes of the right-of-ways between vehicles in lane change and formulates the associated collision free conditions; Section IV provides numerical study results to verify the superiority and rationality of our new strategy. Finally, Section V concludes the paper.

II. PROBLEM PRESENTATION AND RIGHT-OF-WAY

A. Problem Presentation

As pointed out in [11], [12], lane changes can be categorized into two types: Mandatory Lane Changes (MLC) occurs when drivers need to follow their paths, and Discretionary Lane Changes (DLC) occurs when drivers would like to improve running speeds. In this paper, we focus on DLC studies, since DLC lane change can be solved via a similar approach.

In order to better illustrate our strategy, we first introduce the scenario involved in the paper. The nomenclatures used in this paper are given in Table I and illustrated in Fig. 1 partly.

In DLC scenarios, we usually only consider five vehicles that interact with each other; see Fig. 1. The lane-changing Vehicle L aims to switch from the lane I to the lane II. The relative position and symbols of five vehicles are labeled respectively. We assume that the average speed of the lane II is higher and take the right-to-left scenario as examples, which is more common in DLC [30], [31]. The left-to-right scenario can be

![Fig. 1. An illustration of DLC scenarios.](image-url)
approximately regarded as a similar mirroring process [32] in which our strategy applies as well.

| Symbol          | Definition                                                                 |
|-----------------|-----------------------------------------------------------------------------|
| $l_{\text{vehicle}}$ | the length of a vehicle                                                     |
| $f_{ij}$        | the length of The Forbidden Area between vehicle i and j                   |
| $N_{ij}$        | the length of The Negotiation Area between vehicle i and j                 |
| $d_{\text{front}}$ | the safety distance in front                                              |
| $d_{\text{rear}}$ | the safety distance in rear                                               |
| $d_{ij}$        | the distance between vehicle i and j                                       |
| $\Delta t$     | the response time lag                                                      |
| $v_{i,\text{max}}$ | the maximum speed of vehicle i                                             |
| $v_i$           | the initial speed of vehicle i                                            |
| $a_{i,\text{max,brake}}$ | the maximum deceleration rate of vehicle i                               |
| $a_{i,\text{min,brake}}$ | the minimum deceleration rate of vehicle i                               |
| $a_{i,\text{max,accel}}$ | the maximum deceleration rate of vehicle i                               |
| $\lambda$      | the value of traffic flow value                                            |
| $h$             | the value of headway                                                      |

### B. The Definition and Rules of the Right-of-Way

Before our lane-changing strategy, it is essential to give a precise definition of "right-of-way". We define it as "The right to occupy/use a special temporal-spatial area" [21].

There are four basic rules to determine who should get the right-of-way:

1. The right-of-way should be considered, only when there are two or more traffic participants may collide with each other.

2. The temporal-spatial areas corresponding to certain right-of-way can be divided into two kinds: "absolute right-of-way" and "relative right-of-way". The former is inviolable, and the latter can be transferred between different owners after negotiation. Correspondingly, we can define The Forbidden Area as the superposition of absolute right-of-way's temporal-spatial areas, The Negotiation Area as relative right-of-way's temporal-spatial areas, and The Free Area as the non-right-of-way's (to all surrounding) temporal-spatial areas.

3. When there is a conflict between the owner and non-owners in a certain area, the non-owners need to avoid conflict initiatively and shall be responsible for the potential accidents.

4. We do not need to calculate who gets the right of way at every moment. Instead, a vehicle may hold the right-of-way for a certain temporal-spatial area for a while, before another vehicle gets the right-of-way for the same area. This property often help us decompose the negotiation and decision process into stages to reduce the complexity of calculation.

### C. Three Stages of DLC

Similar to [14]-[20], we consider the DLC as a three-stage process which is divided by the transfer time point of the right-of-way. To explain why this method could noticeably reduce the analysis, we first analyze the human lane-change strategy and the initial RSS strategy as comparisons, as shown in Fig. 2.

In human driving, the DLC process is divided into three stages naturally, namely the Longitudinal Spacing Adjustment Stage, the Right-of-Way Negotiation Stage and the Action Stage [33]. These three stages are indispensable and answer the question of "where to change lane", "Is it allowed to change lanes" and "how to change lanes", respectively. Specifically in the negotiation stage, most human drivers choose courtesy changing, which represents they will communicate with the surrounding vehicles to notify them and request permission.

The advantage of three-stage model lies in its capability to highlight the information interaction about the right-of-way. However, human drivers' calculations of the acceptable gap are rough and subjective, which many result in misunderstandings between each other. Moreover, some radical human drivers may engage in dangerous behaviors, such as "forced changing", which means sudden lane-changing behavior without negotiation. This behavior is widely believed to be responsible for the high accident rate.

![Fig. 2. The flow charts of two existing DLC strategies.](image_url)

(a) The human strategy [33] (b) The RSS strategy [8]
behavior. D has no way to predict lane change in advance, until the action stage has begun. In the long run, this is not a safe and reasonable strategy. This may lead to a waste of the limited road spaces.

The key difference between the human model and the RSS model is addressed in Fig. 2(a) and (b), respectively. We aim to combine the superiorities of the three-stage model and the clear collision avoidance rules. The new strategy should be sequential, specificity and negotiated. At any certain time point, all traffic participants are clearly aware of the ownership of the right-of-way and the corresponding driving behaviors. In order to standardize the process of information exchange, we divide the lane change process into the following three stages: The Longitudinal Spacing Adjustment Stage, The Right-of-Way Negotiation Stage and The Action Stage, which are shown in Fig. 3.

![Diagram](image)

**Fig. 3.** The flow chart and stages of the new DLC strategy.

1) **The Longitudinal Position Adjustment Stage**

In the first stage, Vehicle L should judge whether it is suitable for changing lane. Obviously, it is not when D accelerates or B, C decelerates.

Setting \( d_{front} = \min(d_{CL}, d_{BL}) \) and \( d_{rear} = d_{DL} \), we obtain that

\[
\begin{align*}
    d_{front} & \geq \max(F_{BL}, F_{CL}) \\
    d_{rear} & \geq F_{DL} + N_{DL} \\
    a_D & \leq 0, a_B \geq 0, a_C \geq 0
\end{align*}
\]

(1)

where the variable \( F_{ij} \) represents the length of The Forbidden Area between i (the owner) and j. Similarly, the variable \( N_{ij} \) represents the length of The Negotiation Area. The detailed calculation formulas will be introduced in the next section.

Then, Vehicle L can request the right-of-way from D only when it is in The Free Area of B and C, meanwhile in The Negotiation Area of D. We obtain that

\[
\begin{align*}
    d_{front} & \geq \max(F_{BL}, F_{CL}) \\
    F_{DL} & \leq d_{rear} \leq F_{DL} + N_{DL} \\
    a_D & \leq 0, a_B \geq 0, a_C \geq 0
\end{align*}
\]

(2)

2) **The Right-of-Way Negotiation Stage**

Obviously, the negotiation process only happens between Vehicle L and D. if L is located in The Negotiation Area of D, it should turn on the turn signal, which represents the request for the right-of-way. Through the lane-changing warning of V2V, D will receive this request and respond in \( \Delta t \) seconds. There are two options for D:

- Reject the request: The reject intention can be expressed by acceleration, whistle, V2V and so on. In this case, L should immediately give up and wait for the next appropriate headway;
- Accept the request. The intention can be expressed by decelerating or maintaining the original speed. So after \( \Delta t \)
seconds, the right-of-way of The Negotiation Area changes instantaneously.

3) The Action Stage
During this stage, Vehicle L should complete the process of lane changing smoothly to reduce the impact on traffic flow. At the same time, D should adjust the speed to keep away from L when necessary.

III. Detailed Calculations for DLC Scenarios

In this part, we introduce the distance calculation methods during DLC, according to the aforementioned assignments of right-of-way.

According to the priority and complexity, we successively discuss right-of-way assignment in the order of Vehicle A, B, C and D. Because the right-of-way between L, A, B, and C is clear and never change during DCL. The only thing we should care is the change of the right-of-way between L and D.

1) Interaction Between Vehicle L and A
The interaction between Vehicle L and A can be viewed as a car-following scenario. So if necessary, A must unconditionally avoid L to ensure safety. In other words, there is no need to consider the allocation of the right-of-way between L and A in the course of lane changing, see Fig. 4.

Fig. 4. The right-of-way between Vehicle L and A.

2) Interaction Between Vehicle L and B
This can be viewed as another car-following scenario, see Fig. 5. Vehicle B owns the right-of-way in the forbidden area, the safety gap $F_{BL}$ [10] is defined as:

$$ F_{BL}(t) = \left[ v_L(t) + \frac{v_L^2(t)}{2a_{L,\text{brake}}(t)} - \frac{v_B^2}{2a_{B,\text{max,brake}}} \right]^+ $$

$$ a_{L,\text{brake}}(t) = a_{L,\text{min,brake}} + \frac{v_L(t)}{v_{L,\text{max}}}(a_{L,\text{max,brake}} - a_{L,\text{min,brake}}) $$

(3)

(4)

Fig. 5. The right-of-way between Vehicle L and B.

3) Interaction Between Vehicle L and C
Since Vehicle C is in front of L all the time, it owns the absolute right-of-way within a certain area, as shown in Fig. 6. L is forbidden to enter The Forbidden Area at any time. Since the length of $F_{CL}$ is determined by the longitudinal speeds of two vehicles, which also conforms to the definition of (4).

Fig. 6. The right-of-way between Vehicle L and C.

4) Interaction Between Vehicle L and D
The right-of-way assignment in this scenario is more complicated because Vehicle L needs to require right-of-way from D. The front area of D can be divided into three areas, shown as Fig. 7.

Fig. 7. The right-of-way between Vehicle L and D.

The right-of-way of The Forbidden Area belongs to Vehicle D, which means L is forbidden to enter; In The Negotiation Area, L can change lane after getting the permission from D. On this occasion, L will get the absolute right-of-way to form a forbidden area, and it turns to D slow down intuitively to keep away; The Free Area is far enough for L to change lane without the consent of D. This corresponds with common sense that the traffic efficiency should be improved under the premise of safety.

The length of this area $F_{DL}$ is defined as:
\[ F_{DL}(t) = \left[ \frac{v_D - v_D^2(t)}{2a_{D,\text{max,brake}}} + \frac{v_D^2}{2a_{D,\text{min,brake}}} \right]^+ \]  
\( a_{D,\text{brake}} = a_{D,\text{min,brake}} + \frac{v_D(t)}{a_{D,\text{max,brake}}} (a_{D,\text{max,brake}} - a_{D,\text{min,brake}}) \) (6)

We assume Vehicle D moves at a constant speed above. While it decelerates, the definition of \( F_{DL} \) will become:

\[ F_{DL}(t) = \left[ \frac{v_D - v_D^2(t)}{2a_{D,\text{max,brake}}} + \frac{v_D(t) - a_{D,\text{min,brake}}^2}{2a_{D,\text{max,brake}}} \right]^+ \]  
\[ \frac{v_D(t) - v_D^2(t)}{2a_{D,\text{max,brake}}} \] (7)

The distance between the boundary of The Free Area and the front point of Vehicle D is

\[ F_{DL}(t) + N_{DL}(t) = \left[ \frac{v_D - v_D^2(t)}{2a_{D,\text{max,brake}}} + \frac{(v_D(t) - a_{D,\text{min,brake}}^2)}{2a_{D,\text{max,brake}}} \right]^+ \] (8)

We adopt the minimum safety distance defined by RSS, which means "Even using minimum accelerated speed to brake, the rear vehicle also can avoid any impact caused by the front vehicle".

### IV. NUMERICAL TESTING RESULTS

Both the RSS strategy and the new strategy guarantee collision free. To compare their performance on traffic efficiency, we design two experiments to observe "the average times for lane change under different traffic flows" and "the success rates for lane change in fixed times", respectively.

#### A. Simulation Settings

In order to simulate the simulation and presentation, we simplified the scenario partly, assuming that all vehicles have the same size and dynamic performance. Our further testing results show that different parameter settings do not vary the conclusions.

According to the standard of SAE [34] and FMVSS135 [35], we assumed: \( a_{\text{max,accel}} = 2 \text{m/s}^2 \), \( a_{\text{min,brake}} = 2 \text{m/s}^2 \), \( \rho = 1 \text{ s} \), \( v_{\text{max}} = 25 \text{ m/s} \), \( a_{\text{max,brake}} = 6 \text{ m/s}^2 \).

We set that Vehicle L wants to join a 20m/s traffic flow with the state of 15m/s and 1m/s². In order to determine the headway model of traffic flow, we referred [36]. The researchers had tried all the proposed distribution models to fit the empirical headway data and found the Log-normal model yield best fitting results. Thus, to simulate the distribution of headway, we used the Log-normal model, which is written as:

\[ f(h) = \frac{1}{\sqrt{2\pi}\sigma h} \exp \left( -\frac{\ln h - \mu}{2\sigma^2} \right) \] (9)

where variable \( h \) represents the possible value of headway. \( \mu \) is the location parameter and \( \sigma \) is the scale parameter. The mathematical expectation is:

\[ \frac{3600}{\lambda} = E(h) = \exp(\mu + \sigma^2 / 2) \] (10)

where the variable \( \lambda \) represents the value of traffic flow. According to [36], we assumed \( \sigma = 0.8 \) in this part and used the equation (10) to calculate parameter \( \mu \) under different \( \lambda \).

However, the traffic flow discussed in this paper is not completely natural. With the aid of space sensors and V2V communication, it is reasonable to assume that all vehicles can maintain a safe distance longer than minimum safety gap. So we finally set the headway \( h \) as:

\[ h = \max(h, F_{ij} / \text{average}) \] (11)

#### B. The Results of the Average Time for Lane Change

In this experiment, we recorded the average time costed for lane change under different traffic flows, from 200 veh/h to 1600 veh/h.

To reduce the error caused by chance, we carried out 10000 tests and take average. The simulation results were recorded in Fig. 8. We can see that, with the increase of \( \lambda \), the average time of the RSS strategy has become unbearable. In the larger traffic flow, DLC almost became a luxury for drivers. Differently, the new strategy ensures that more than 25% vehicles of the target lane are willing to decelerate to yield and lane change can be completed in 1 minute.

![Fig. 8. The average times under different traffic flows.](image)

C. The Results of the Success Rates for Lane Change

In this experiment, we examine the success rates for lane change in fixed time, from 20s to 180s. Similar to the first experiment, we carried out 10000 tests to take average. The success rate results were recorded in Fig. 9.

We highlight the different time periods with three colors. Here we chose 600 veh/h and 1200 veh/h for low-flow and high-flow respectively. Overall, the success rate of our strategy has been greatly improved compared with RSS, which benefits from negotiation mechanism and leads to shorter minimum lane change distances.
In this paper, we demonstrated a right-of-way assignment strategy by setting clear collision avoidance conditions to improve the lane-changing model of RSS. The introduction of negotiation not only makes the communication between vehicles more efficient, but also improves the utilization of limited road resources, thus ensuring that the process of right-of-way assignment is more efficient, reasonable and safe. However, to ensure the feasibility of the strategy, we must assume that all vehicles know and follow the same rules at the beginning. If this assumption does not hold (e.g. for the "crazy drivers" who are unavoidable in current transportation systems), we either need to make very conservative collision avoidance conditions (which usually lead to very complicated calculations and intolerable traffic efficiency) or have to suffer from collision risk.

For example shown in Fig. 10, we assumed the human driver of Vehicle D was less rational. He acquiesced to the lane change request during the negotiation stage but suddenly accelerated at a certain time of the action stage. In this case, L and D disagreed on the ownership of right-of-way, which was likely to cause danger. So in such cases, what we need to do is identifying the responsible entity and minimizing the severity of the accident, rather than pulling away enough distance to pursue "absolute safety".

Fig. 9. The success rate of lane-change in fixed time.

Fig. 10. The suddenly acceleration of Vehicle D during the action stage leads to a collision.

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