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Cooperative Driving and Lane Changing Modeling for Connected Vehicles in the Vicinity of Traffic Signals: A Cyber-Physical Perspective

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ABSTRACT The vicinity of traffic signals is one of the most critical areas in road systems. New information technology paradigms like vehicle-to-vehicle and vehicle-to-infrastructure communication are applied to improve traffic operations at intersections; for example, a typical cyber-physical system enables efficient traffic state estimation and traffic modeling. A new model of vehicle cooperative driving under a typical scenario vicinity of traffic signals and Vehicle to X environment was proposed in this paper. Based on the intelligent driver model, the model planned trajectories for vehicles in the vicinity of traffic signals in advance to reduce stopping frequency and travel time and improve the throughput of the road according to traffic conditions, such as signal cycle state, the distance to traffic signals, and the situation regarding adjacent vehicles. In accordance with the relationship between the host vehicle and the surrounding vehicles, the model also planed the cooperative lane changing strategy in this scenario to improve safety and comfort in the process of lane changing. A simulation experiment compared the proposed model with the traditional intelligent driver model, and analyzed its performance in different traffic conditions. The feasibility and superiority of the model were confirmed.

INDEX TERMS Cyber-physical systems, cooperative driving, lane changing, Vehicle to X (V2X) technology.

I. INTRODUCTION

Signal control is widely used in intersections, t-junctions, expressway ramps, and other areas with vehicle flow conflicts. The vicinity of traffic signals, as the connection between the general road and traffic signals, is an important part of traffic systems and significantly affects the efficiency and safety of urban roads [1]. Cooperative driving and lane changing are the two most basic driving behaviors. Vehicle following in the vicinity of traffic signals is not only affected by road traffic density but is also limited by traffic signals. Drivers should focus on the state of the signal conversion and consider the driving conditions of adjacent vehicles at the same time, so that they do not concentrate totally on driving, causing frequent start-stops and acceleration and deceleration as well as creating a drag on traffic efficiency [2]. Moreover, frequent start-stops, acceleration and deceleration can cause additional fuel consumption, which results in environmental pollution [3]. Most lane changing behavior in the vicinity of traffic signals is Mandatory Lane Changing [4]. The decision-making process is more complicated for lane changing than following because drivers need to consider more vehicles [5]. According to a related survey, traffic accidents caused by lane changing account for only 5% of traffic accidents and 10% of traffic delays. At the same time, 75% of lane changing accidents occur because a lack of perception of the surrounding environment [6]. Therefore, it is important to understand the surrounding environment when changing lanes.

Transportation Cyber-Physical Systems (TCPSs), which embrace the latest advances in communications, computing, electronics, sensing and control, are a promising approach to issues such as transportation safety, efficiency, and sustainability [7]–[8]. CPS modeling technology completes the modeling of discrete information states on the system with a finite state machine as well as modeling of continuous physical dynamics of a system with differential equations. It can more clearly describe systems with discrete dynamics and continuous dynamics. [8]. With the development of communication technology, the application of Vehicle to X (V2X) technology in vehicles has become inevitable, and it is regarded as having great potential in improving driving safety and reducing traffic accidents. Moreover, it provides technical support to improve the traffic and driving environment [9]. With the development of V2X technology, transportation systems have become a typical component of physical information systems.

In this paper, cooperative driving and lane changing behavior were modeled under a fixed length of traffic signals. Coordinated driving and lane changing are two basic driving behaviors. A number of scholars have carried out research on the cooperative driving of vehicles in the vicinity of traffic signals [10]–[16]. Reference [16] puts forward a cooperative optimization algorithm for vehicles in the vicinity of intersections. The algorithm divides vehicles at adjacent intersection areas into several platoons and specifies different driving strategies for the first vehicle and other vehicles of the same platoon to improve the efficiency of a traffic system. The algorithm is solved through the Particle Swarm Optimization (PSO) algorithm. Because of the time complexity of the PSO algorithm, it requires a longer time to solve problems when there are more vehicles in the system, and it has higher requirements for the operation of the system. References [15] and [17] propose two coordinated driving optimization strategies for vehicles in the vicinity of intersections. The former puts forward an algorithm that can coordinate the conflicts of traffic flow from different directions for the intersection areas without traffic signals, but the algorithm assumes that vehicle acceleration is kept constant from the point of entry into the vicinity of traffic signals until the vehicles leave the conflict zones. In addition, the latter also assumes that the acceleration of the vehicle can maintain a constant and uniform change. In fact, the traffic flow density in the vicinity of the intersection area may be changed on a large scale due to complicated urban road conditions. Therefore, the applicability of the two models is limited. Additionally, vehicles may turn around at the intersection and make a mandatory lane change in the vicinity of traffic signals. However, these studies do not take into account the lane change of vehicles. In terms of cooperative lane changing, many scholars have conducted related research [18], [19]. Most of these studies focus on optional lane changing, and there are few that address mandatory lane changing in the vicinity of traffic signals. Thus, this paper mainly aims to build a cooperative driving and lane changing model in the vicinity of traffic signals by making full use of V2X communication to improve the security and efficiency of the regional transportation system in addition to reducing its impact on the environment.

The rest of this paper is organized as follows. In Section 2, based on the Intelligent Driver model, the cooperative driving model in the vicinity of traffic signals under a V2X environment is proposed. On the basis of Section 2, Section 3 presents the lane changing model. Section 4 performs a simulation of the model, and Section 5 summarizes.

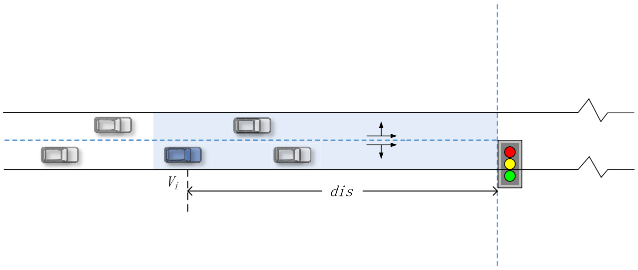


FIGURE 1. Illustration of the vicinity of traffic signals.

II. THE COOPERATIVE DRIVING MODEL

As shown in Figure 1, in the vicinity of traffic signals, when one vehicle is following another vehicle, the driver must pay attention to the status of the car in front and the state of the traffic signals to adjust his driving behavior. Assuming a green signal, if a vehicle is able to pass through the intersection within the time of duration of the green light, drivers often choose to follow the front vehicle through the conflict area, and the speed of the vehicle is restricted by the speed of the vehicle in front. If there is no vehicle in front, drivers can pass through the conflict zone at the ideal speed. If a red light is signaled or is imminent, drivers will slow the vehicle down or stop.

In the above process, the lack of information may cause many problems. For example, due to inaccurate judgment, a light may turn red when vehicles are moving in the conflict area and are unable to stop; this is the so-called dilemma zone [3]. In addition, drivers need to pay attention to traffic signals, so they tend to decelerate frequently, resulting in longer travel times and increases in fuel consumption as well as congestion [20].

In the V2X environment, drivers can obtain the status of front vehicles and traffic signals anywhere and at any time, which creates the conditions for coordinated driving. Thus, drivers are able to access the status information of the signal and adjust the vehicle as early as possible, pass the signal control area at an appropriate speed, and avoid long stops. Therefore, this section planned the coordinated driving process of a vehicle in the vicinity of traffic signals for the purpose of determining the driving trajectory in advance and reducing delays from stopping.

Assuming the period of the traffic signal is T_C and the green light and red light last for T_G and T_R, then,

$$T_C = T_G + T_R \tag{1}$$

At time t, the state of the traffic signal can be defined as follows:

$$t_{light} = t \bmod T_C \in \begin{cases} [0, \quad T_G), & greenx\ light \\ [T_G, \quad T_R), & red\ light \end{cases} \tag{2}$$

where t_{light} represents the traffic signal period of the current moment.

Assuming the position, velocity and acceleration of V_i at time t are $x_i(t)$, $v_i(t)$ and $a_i(t)$, respectively, and the motion of the vehicle conforms to the following kinematics equation:

$$x_i(t+k) = x_i(t) + kv_i(t) + \frac{1}{2}k^2 a_i(t) \tag{3}$$

$$v_i(t+k) = v_i(t) + ka_i(t) \tag{4}$$

where k denotes the time step.

References [21]–[23] propose a kind of intelligent driving model that can describe the flow driving of a host vehicle on a general road. In addition, the model has good generality and can describe different traffic flows from free flow to congestion flow. In this model, the acceleration of the following vehicle is described as follows:

$$a_1 = \alpha(1 - (\frac{v_i(t)}{v_{\max}})^{\delta} - (\frac{s_i^*(v_i(t), \Delta v_{i,i-1}(t))}{\Delta x_{i,i-1}(t)})^2) \tag{5}$$

$$s_i^*(v_i(t), \Delta v_{i,i-1}(t)) = d_{\min} + v_i(t)T + \frac{v_i(t)\Delta v_{i,i-1}(t)}{2\sqrt{\alpha\beta}} \tag{6}$$

where α denotes the maximum acceleration; ρ denotes the comfortable deceleration; $v_{\max}$ is the maximum speed; $\Delta v_{i,i-1}(t)$ represents the speed difference between the first i vehicle and the front vehicle; $\Delta x_{i,i-1}(t)$ represents the distance between the first i vehicle and the front vehicle; s_i^* denotes drivers' expected distance for the current state, and it is determined by Formula (6). $d_{\min}$ is the static safe distance; T is a safe time interval; $\delta > 0$ is an acceleration index. The original IDM model does not consider the cooperative driving problem of vehicles under conditions with traffic signals.

Next, based on the IDM model, we conducted analysis according to the specific condition of vehicle V_i in the vicinity of traffic signals, calculated vehicle acceleration under all kinds of conditions, and put forward a cooperative driving model for vehicles in the vicinity of traffic signals.

When vehicle V_i approaches the vicinity of a traffic signal, we first considered whether it was the first vehicle of a whole platoon. If yes, it tends to drive at a free flow rate (maximum speed or road speed limit) before acquiring the traffic signal information. Correspondingly, acceleration at this time is 0 (it has reached the free flow speed) or comfort acceleration α (it has not reached the free flow speed). If not, it will follow the front vehicle, and the acceleration can be determined by Formula 5 and 6.

In order to avoid stopping, drivers need to plan routes in advance after acquiring the traffic signal information. Figure 2 describes V_i approaching the vicinity of traffic signals at t_0. In Figure 2, the horizontal axis represents time, and the vertical axis represents the distance between the vehicle and the traffic signals. When V_i approaches the vicinity of traffic signals and enters the V2X communication range, assuming that traffic signals have a fixed period – because it can pass through the conflict area only during the green light cycle – the time interval is identified; namely, the trajectory is limited to area 1 and area 3. Based on Figure 2, if the average speed of V_i satisfies the following conditions:

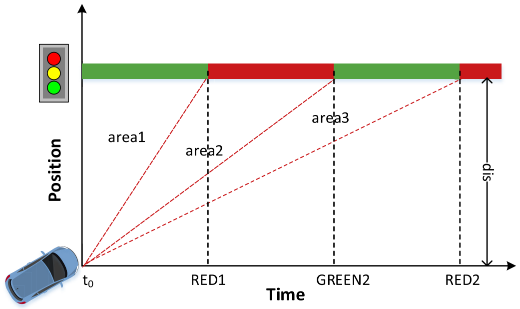


FIGURE 2. **Situation of the vehicle in the vicinity of traffic signals.**

$$\bar{v}_i \in [\frac{dis}{T_G - t_{light}}, v_{free}] \cup [\frac{dis}{T_C - t_{light}}, \frac{dis}{T_C - t_{light} + T_G}] \tag{7}$$

When it reaches the signal control area, it will be the green cycle. Further, it is not difficult to prove that its trajectory must fall within area 1 and area 3 if the speed of V_i in the conflict zone is satisfied by Formula 7 from time t_0 to the time it reaches the conflict zone. But the problem has not been fully solved: There may be many collections that are disjoint from each other (corresponding to following a series of green light cycles), so it is necessary to determine the light interval that is the most appropriate time period for the vehicle to pass through the area. The first vehicle in the platoon tends to move at free flow v_{free}, so we only need to determine which green range v_{free} belongs to or is closest to. The ideal velocity $v_i^*(t)$ was defined as the speed of V_i at time t that made it possible to pass through the conflict zone without stopping, and the first vehicle in the platoon,

$$v_i^*(t) = \min(v_{free}, v_i^{upper}(t)) \tag{8}$$

where $v_i^{upper}(t)$ is the upper limit of the corresponding or near green light interval. The vehicle acceleration can be determined by Formula 9:

$$a_2 = \alpha(1 - (\frac{v_i(t)}{v_i^*})^{\delta} - (\frac{d_{\min} + v_i(t)T + \frac{v_i^2(t)}{2\sqrt{\alpha\beta}}}{MAXDIS})^2 \tag{9}$$

In Formula 9, *MAXDIS* represents an infinite distance, and it indicates that V_i, as the first vehicle in the platoon, is always expected to travel at the speed that is as close to the speed limit as possible.

Others vehicles following the first vehicle in the platoon eventually choose the speed that is often close to the average of vehicles in front because the vehicle speed is limited by the speed and position of the vehicles in front. Therefore, the ideal speed is related to the speed of the front vehicle, which can be given by Formula 10:

$$v_i^*(t) = \min(v_{i-1}(t), v_i^{upper}(t)) \tag{10}$$

where $v_i^{upper}(t)$ is the upper limit of the green light interval corresponding to or near $v_{i-1}(t)$. The vehicle acceleration can

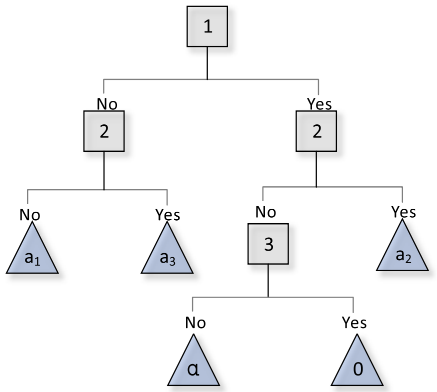


FIGURE 3. **Decision tree of the new model.**

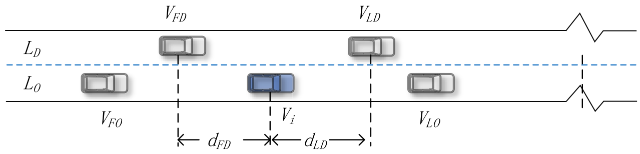


FIGURE 4. **Situation scenario of lane changing.**

be determined by Formula 11:

$$a_3 = \alpha(1 - (\frac{v_i(t)}{v_i^*})^\delta - (\frac{d_{\min} + v_i(t)T + \frac{v_i^2(t)}{2\sqrt{\alpha\beta}}}{\Delta x_{i,i-1}(t)})^2 \quad (11)$$

Based on the above analysis, the vehicle acceleration decision tree model is shown in Figure 3.

In Figure 3, the triangle represents the decision acceleration, and the square represents the conditions. a_1, a_2 and a_3 are determined by Formulas 6, 9 and 11, respectively. The conditions in Figure 3 are as follows:

(1) Leading vehicle?
(2) Entered the V2X communication area?
(3) Already at maximum velocity?

III. THE LANE CHANGING MODEL

As stated in the Introduction, lane changing behavior in the vicinity of traffic signals is mostly mandatory lane changing behavior. The traditional lane changing model assumes that drivers will not change lanes unless the host vehicle is far enough away from the adjacent vehicles on the target road. If lane changing is not feasible, drivers cannot change lanes. This is clearly not in conformity with actual situations, particularly in the case of mandatory lane changing.

Figure 4 shows a typical lane changing scene. In Figure 4, lane changing behavior involves two lanes (origin lane L_O and destination lane L_D) and 5 vehicles: lane changing vehicle V_i, leading vehicle in origin lane V_{LO}, destination lane front vehicle V_{LD}, and the following vehicle in destination lane V_{FD}. Assuming that the vehicles in the figure were equipped with V2X communication, when drivers want to change lanes, they first determine whether the surroundings meet safety conditions. If not, V_i first sends the lane changing request information that contains its own location and speed flow to V_{FO} and V_{FD}, which need to timely adjust motions to match the lane changing. Before lane changing initiates, safety conditions are addressed as shown in Formula 12.

$$d_{LD}(t) \geq d_{\min} + h_1 v_i(t) \quad (12)$$

Studies have shown that the duration of the lane changing process is slightly related to lane changing speed [24]. Under the condition of fixed lane changing time, the lateral acceleration and motion trajectory of the lane changing vehicle can be described by Formula 13-14 [25]:

$$a_{lat}(t) = \frac{2\pi H}{t_{lat}^2} \cdot \sin(\frac{2\pi t}{t_{lat}}) \quad (13)$$

$$y_{lat}(t) = -\frac{H}{2\pi} \cdot \sin(\frac{2\pi t}{t_{lat}}) + \frac{Ht}{t_{lat}} \quad (14)$$

where a_{lat} denotes the lateral acceleration; H denotes the lane width; t_{lat} denotes the duration of lane changing and y_{lat} denotes the lateral space.

When V_i moves to lane L_D from L_O, the following target gradually transits to V_{LD} from V_{LO}. According to the lateral displacement of V_i, its longitudinal acceleration is given by Formula 15:

$$a_i^{long}(t) = \frac{y_{lat}(t)}{H} \cdot a_i^{LD}(t) + \frac{1 - y_{lat}(t)}{H} \cdot a_i^{LO}(t) \quad (15)$$

where a_i^{long} denotes the longitudinal acceleration of V_i, a_i^{LD} denotes the IDM acceleration of V_i following V_{LD}, a_i^{LO} denotes the IDM acceleration of V_i following V_{LO}.

In the process of V_i changing lanes, V_{FO} and V_{FD} accelerate longitudinally, as given by Formula 16-17, respectively.

$$a_{FO}^{long}(t) = \frac{y_i^{lat}(t)}{H} \cdot a_{i,LD}(t) + \frac{1 - y_i^{lat}(t)}{H} \cdot a_{i,LO}(t) \quad (16)$$

$$a_{FD}^{long}(t) = \frac{y_i^{lat}(t)}{H} \cdot a_i^{LD}(t) + \frac{1 - y_i^{lat}(t)}{H} \cdot a_i^{LO}(t) \quad (17)$$

IV. SIMULATION

In this section, the research objects are 8 vehicles on a nearly flat road in the vicinity of traffic signals; they are equipped with the IDM model and the model proposed by this section. The road is 600m in length, has no slope and is one lane. The traffic signals are located at 500m. The simulation experiments lasted for 80s, and the acceleration, velocity and position of the vehicles were updated with a time step of 0.1s. The initial speed of the vehicles was 8 m/s, and the initial position of the vehicles was determined by Formula 18:

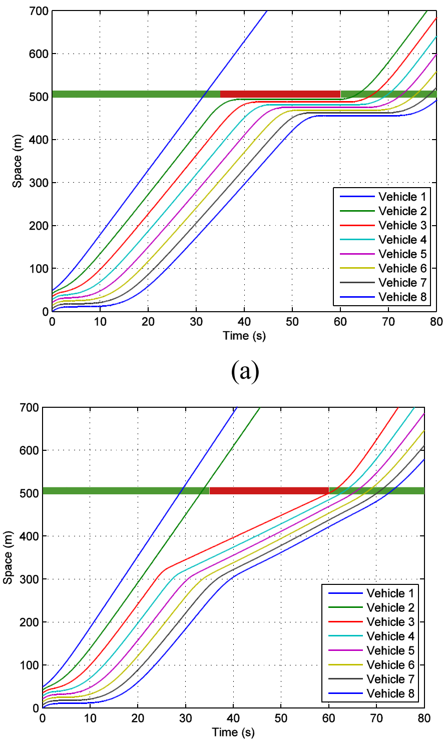
$$x_i(0) = \frac{n - i}{\rho} \quad (18)$$

where ρ is the density of the vehicles and n is the total number of vehicles. The other parameter values in the experiment are shown in Table 1:

Scenario 1: the traffic light cycle $T_G = 35s$ and $T_R = 25s$ were set up. Comparison and validation were conducted with the traditional IDM model and the model proposed in this

TABLE 1. Simulation parameters.

Parameter	Definition	Value
α	Comfortable acceleration	$2m/s^2$
β	Maximum deceleration	$4m/s^2$
$v_{\max}$	Maximum Velocity	$16.67m/s$
$v_{\min}$	Minimum Velocity	$0m/s$
δ	Acceleration Index	4
$d_{\min}$	Static Safety Distance	$7m$
T	Safety Time Interval	$1.5s$
k	Time Step	$0.1s$
h_1	Reaction Time of Lane Changing Vehicle	$0.3s$
h_2	Reaction time of Following Vehicle in Destination Lane	$0.6s$
H	Lane Width	$3.5m$
t_{lat}	Duration of Lane Changing	$6s$



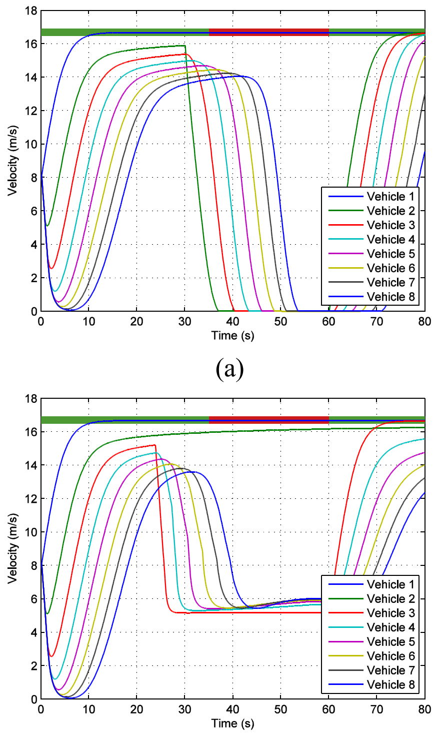
(a)

(b)

FIGURE 5. Each vehicle's trajectory. (a) IDM. (b) Proposed model.

section. Figure 5 and figure 6 show the change in displacement and speed of the vehicles in the two models over time.

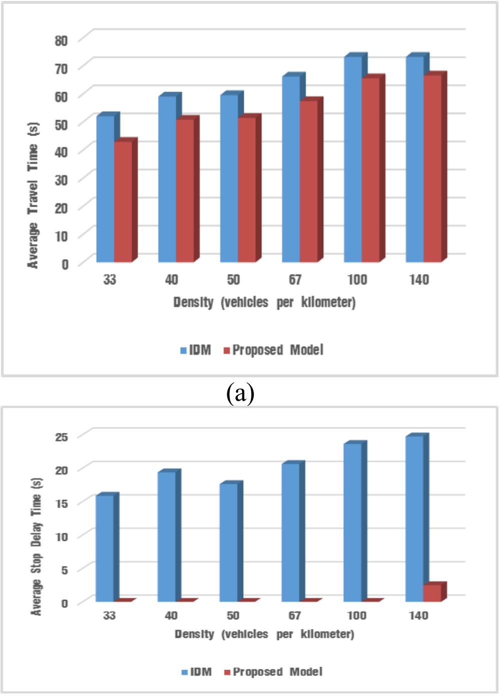
In Figure 5, only 1 vehicle passed within the first green light cycle in the IDM model, while 2 vehicles successfully passed through in the proposed model, showing that it reduced the travel time of vehicle 2 and improved traffic efficiency. In addition, Vehicle 3-8 avoided waiting at the signal light because they judged that they could not pass within the green light cycle and slowed down in advance.



(a)

(b)

FIGURE 6. Each vehicle's velocity. (a) IDM. (b) Proposed model.

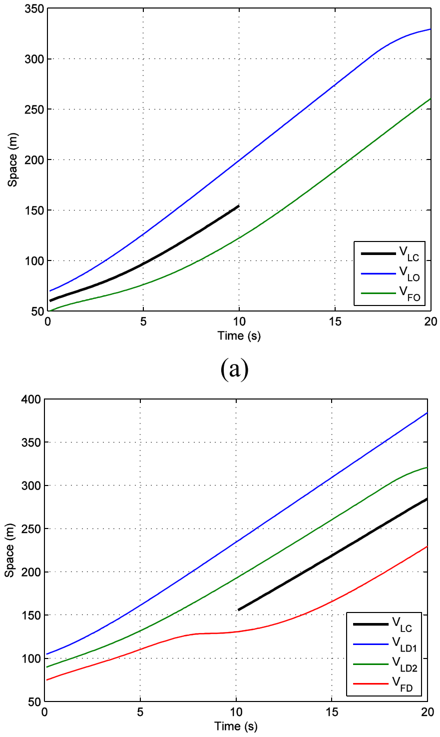


(a)

(b)

FIGURE 7. Average travel time and average stop delay time. (a) Average travel time. (b) Average stop delay time.

Scenario 2: The traffic light cycle $T_G = T_R = 30s$ was set up. 6 traffic densities were set up, namely, $\rho_1 = 33veh/km$, $\rho_2 = 40veh/km$, $\rho_3 = 50veh/km$, $\rho_4 = 67veh/km$,



(a)

(b)

FIGURE 8. **Lane changing trajectories. (a) Origin lane. (b) Destination lane.**

$\rho_5 = 100veh/km$, and $\rho_6 = 140veh/km$. Figure 7-8 show the statistical results of the average travel time t and the average stop delay time, respectively (with less than $1m/s$ as the standard), of vehicles with the increase in traffic density.

Figures 7 shows that the proposed model can save an average of 12.98% of the total travel time and 98.32% of the stop delay time relatively to the IDM model.

Scenario 3: Suppose that there are two lanes L1 and L2, eight vehicles run on each lane, lane changing is allowed, lane L1 and lane L2 have traffic densities of $\rho_{L1} = 67veh/km$ and $\rho_{L2} = 100veh/km$, respectively, and the other settings are the same as in Scenario 1. It is observed that vehicle V_{LC} changed its lane from lane L1 to lane L2 between the 5th and the 15th seconds. Fig. 8 displays the trajectory curves during the lane change. In Fig. 8(b), before the lane change, the following vehicle V_{FD} on the destination lane decelerates to assist V_{LC} with the lane change, while V_{LC} adjusts its own speed and completes the lane change and then follows the leading vehicle V_{LD} on the destination lane. In Fig. 8(a), after completion of the lane change, the following vehicle V_{FO} on the original lane begins to accelerate and follows the leading vehicle V_{LO} on the original lane.

V. CONCLUSION

In this paper, the traditional Intelligent Driver Model was extended from the perspective of Cyber-physical Systems to make it work in a particular scenario involving the vicinity of traffic signals and V2X environment. Simulation experiment results show that the proposed model can shorten the average travel time and reduce the stop time relative to the IDM model. For example, vehicles that cannot pass through the conflict area in the traditional IDM model within the green light cycle can pass through in the new model, so efficiency is improved. At the same time, modeling of cooperative lane-changing behavior was completed, so vehicles can easily change lanes in conjunction by cooperating with other vehicles. However, much work remains. For example, we have not yet considered the influence of different vehicles and different drivers' driving habits and characteristics on collaborative driving behavior. Such work will be conducted in the future.

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