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Dynamical Control Strategy on Two-lane Roads with Speed Limitations under Intelligent Transportation System

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Abstract: In this study, we study the traffic states on two-lane roads with different speed limitations with lane-changing in urban traffic system. We draw the flow-density map with lane-changing on the two-lane roads with speed limitations. It is found that the traffic flow will drop in high densities. To maintain high flow in high densities, we put forward the dynamical control strategy. The dynamical control strategy can help to ease the traffic jams in high densities. We derive the flow-density plot applying the dynamical control strategy and it is found that the dynamical control strategy can indeed help to ease the traffic jams in high densities.

Key words: Lane-changing, dynamical control strategy

INTRODUCTION

Urban traffic system has its own characteristics. In the urban traffic system, there are always multilane and sometimes with different speed limitations. For example, in a three-lane road, the vehicle on the left lane drives faster than that on the middle lane and the vehicle on the middle lane drives faster than that on the right lane. In China, traffic keeps to the right and the left is always the overtaking lane. So, it is normal that different lanes have different top speeds. Though many useful results have been proposed but the scholars make the speed limitation out of their consideration.

In this study, we pay our attention on the high mobility with lane-changing under high densities on multilane road with different speed limitations. The study is organized as follow. Traffic model and lane-changing rules are introduced in Section 2. In Section 3, we put forward a dynamical control strategy to get high traffic flow in high densities and the simulation results are also presented in Section 3. Section 4 is devoted to the summary.

MODEL AND LANE-CHANGING RULES

Many scholars have made deep studies on the traffic modeling (Bando *et al.,* 1995; Ben-Naim *et al.*, 1994; Helbing and Tilch, 1998; Kurata and Nagatani, 2003; Lv *et al.*, 2011; Nagel and Schreckenberg, 1992). One of the most classic model is the optimal velocity model (OVM for shortly), which is presented by Bando *et al.* (1995). The following equation shows the mathematical expression of this model:

$$\frac{dv_n(t)}{dt}=k[V(\Delta x_n(t))-v_n] \tag{1}$$

where, $V(\Delta x_n)$ is the optimal velocity function which depends on the headway Δx_n, v_n is the velocity of the n th vehicle and k is the sensitivity coefficient. Helbing and Tilch identified the optimal velocity by using actual measurement data in 1998 (Helbing and Tilch, 1998). The optimal velocity function can be denoted as:

$$V(\Delta x_n(t))=V_1+V_2\tanh[C_1(\Delta x_n(t)-l_c)-C_2] \tag{2}$$

where, l_c is the length of the vehicle, V_1, V_2, C_1 and C_2 are constant. The simulation results show over-high acceleration and unrealistic minus velocity of the OVM. To solve the problem, Zhipeng Li put forward the velocity-difference-separation model based on the optimal velocity model (VSDM for shortly). The new model is shown in the following:

$$\frac{dv_n(t)}{dt}=k[V(\Delta x_n(t))-v_n]+\lambda\Theta(\Delta v)\Delta v(1+\tanh(C_1(\Delta x_n(t)-l_c)-C_3))^3+\lambda\Theta(-\Delta v)\Delta v(1-\tanh(C_1(\Delta x_n(t)-l_c)-C_3))^3 \tag{3}$$

where, Θ is step function and the optimal function is as same as the one above. The simulation results show that the new can overcome the over-high acceleration and unrealistic minus velocity. We adopt it to simulate the forward movement of the vehicle.

As mentioned above, drivers' driving behaviors can be divided into two parts: The forward movement and the sideward movement. The forward movement can be simulated by the VSDM. As a result, the sideward

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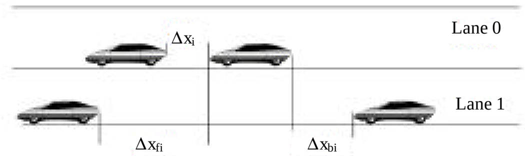

Fig. 1: Schematic illustration of two-lane with speed limitation

movement must be simulated by some rules (Lv *et al*., 2011). A car can change from its original lane to the target lane if:

$$\Delta x_{fi} > \Delta x_i,\ \Delta x_{bi} > \Delta x_{cf},\ \Delta v_j > \Delta v_i \quad (4)$$

where, Δx_{fi} is the headway of car i and car ahead on the target lane and Δx_{bi} is the headway of car i and car behind on the target lane, x_{cf} is the safety distance. Δ_{vi} is the velocity difference of the vehicle and the vehicle ahead of it on the same lane and Δv_j is the velocity difference of the vehicle and the adjacent vehicle on the target lane, which is illustrated by Fig. 1.

SIMULATION AND DYNAMIC CONTROL STRATEGY

We conduct our simulation in two periodic boundary lanes. There are two lanes with different speed limitations: the highest speed of a car on lane 0 is 16.67 m sec^{-1} (60 km h^{-1}) and the highest speed of a car on lane 1 is 8.33 m sec^{-1} (30 km h^{-1}). The length of the lane is L = 1000.We assume that the car will change to the other lane at once the lane-changing rule is satisfied. Initially, all cars distribute randomly along on the two lanes and the initial number of vehicles on the two lanes is equal.

Traffic states on two-lane highways: For better contrast, we firstly study the traffic flow state on two-lane highways without lane-changing. The speed limitation on lane 0 is 16.67 m sec^{-1} (60 km h^{-1}) and the speed limitation on lane 1 is 8.33 m sec^{-1} (30 km h^{-1}). We let the length of the lane L unchangeable while varying the density ρ which is defined as $\rho = 1/\Delta x_{int}$, Δx_{int}, is the headway. Initially, all cars distribute on the lane with the same headwayΔx_{int} = L/N, which N is the total number of cars on the lane. We update the position, velocity information of the vehicles according to Eq. 2 and Eq. 3, where we set k = 0.41, λ = 0.3 in Eq. 2 and C_1 = 0.13 m^{-1}, C_2 = 1.57, l_c = 5.0 in Eq. 3. Here we set every step corresponds to 0.1s.

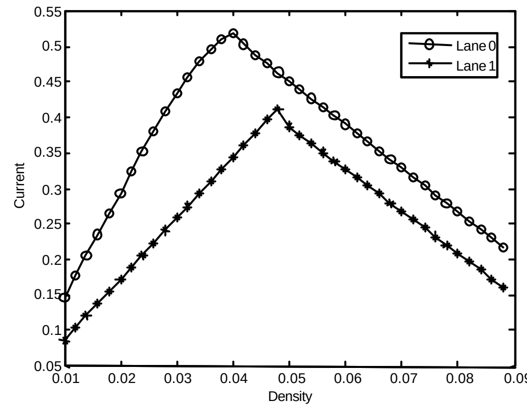

Fig. 2: Diagram of current-density after averaging the current over 990000-1000000 steps

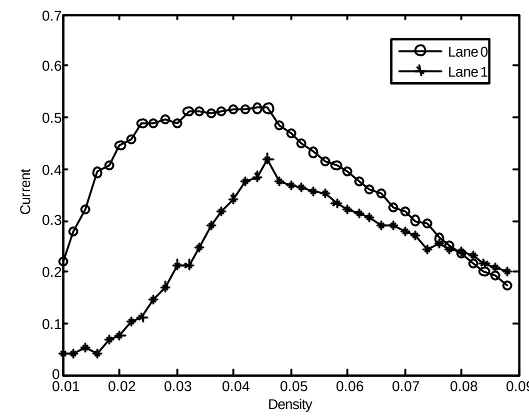

Fig. 3: Plot of current-density of lane-changing after averaging the current over 990000-1000000 steps

Figure 2 shows the diagram of traffic current against density by averaging the current over 990000 and 1000000 steps. The open circles stand for the traffic current on lane 0 and the arterisks mean the traffic current on lane 1. We can easily read from the figure that the current on lane 0 will drop when the density is greater than 0.04. The current on lane 0 climbs to the peak around the density of 0.04. It means that the current on lane 0 will drop in the middle and high densities. And the fluctuation of traffic current on lane 1 is like that on lane 0.

Nextly, we study the traffic flow conditions on two-lane highway with lane-changing. All cars on two-lane highway move forward according to Eq. 2 and 3 and change lane according to Eq. 4. We set x_{cf} = 5.0 in Eq. 4 and the parameters in Eq. 2 and 3 are the same with those mentioned above.

Figure 3 displays the plot of traffic current against density by averaging the current over 990000 and 1000000 steps. The open circles stand for the traffic current on

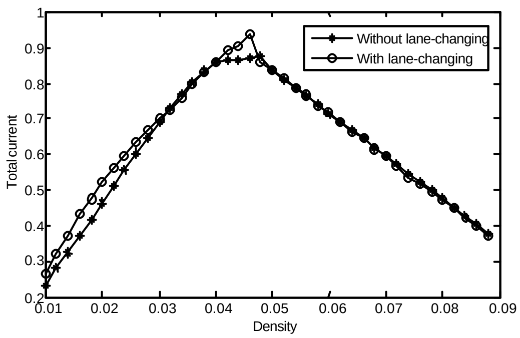

Fig. 4: Plot of the total current against density with lane-changing and without lane-changing after averaging the current over 990000-1000000 steps

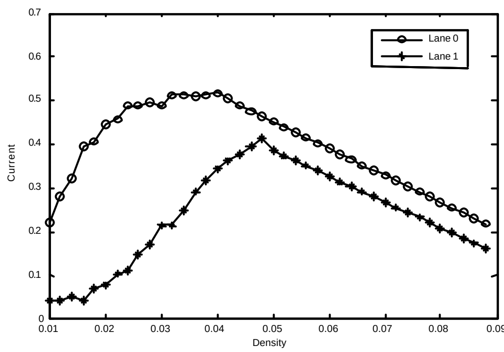

Fig. 5: Plot of current against density after averaging the current over 990000-1000000 steps under single dynamical control strategy

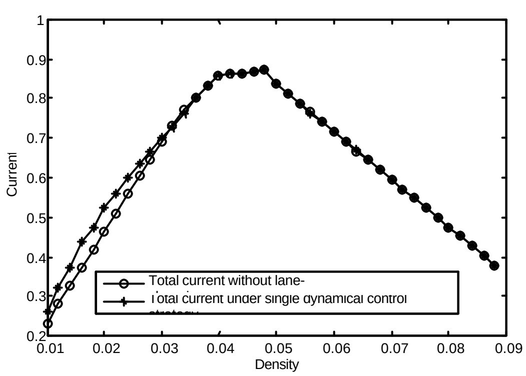

Fig. 6: Plot of total current against density after averaging the current over 990000-1000000 steps under ideal conditions and single dynamical control strategy

lane 0 and the arterisks mean the traffic current on lane 1. The currents on both lane 0 and lane 1 increase with the density enhancing, however, when the density reaches a certain value, the current will drop. In particular, the current on lane 0 can maintain a high value during a period of density.

Figure 4 revesls the total current against density on both lanes with lane-changing and that without lane-changing by averaging the total current over 990000 and 1000000 steps. The open circles stand for the total current with lane-changing and the arterisks mean the total current without lane-changing. We can read that the total current when vehicles can change lane is higher than that without lane-changing in the low and middle densities. However, there is little difference in the middle and high densities in either case. We can infer that drivers can drive fast by changing lane in the low and middle densities while in the high densities, it is better for drivers not to change lane optionally since it will not help to improve the traffic current.

In our real traffic driving, the condition that the current on both lanes drops is not hoped. The traffic jam can happen on one lane but we don't expect the traffic jam happens on both lanes. In the traffic congestion, we still hope the vehicles on one lane can move smoothly though there may be jam on other lane. Therefore, we try to put forward a control stategy to prevent the drop of current.

Simple dynamical control strategy: We study the traffic states when vehicles can't change lane after certain density. As the lane 0 is the fast-moving lane, we try to maintain that the vehicles on lane 0 can move fast. From Fig. 2 we can find that the current on lane 0 will drop down after the density of 0.04. So, we try to enforce the vehicles on lane 1 not to change to lane 0 when the density is greater 0.04. At the same time, the vehicles on lane 0 can change to lane 1 once the lane-changing rules are satisfied.

Figure 5 exhibits the plot of current-density on lane 0 and lane 1 in that case by averaging the current over 990000-1000000 steps. The open circles represent current on lane 0 and the arterisks stand for the current on lane 1. The current on both lanes still drop down with the density increasing.

Figure 6 demonstrates the total current on both lanes under single dynamical control strategy by averaging the total current over 990000-1000000 steps. The open circles represent the total current under the ideal condition, that is no lane-changing. The arterisks mean the total current under single dynamical control strategy.It is clearly that the single dynamical control strategy can't help improve the total current.

Effective dynamical control strategy: We concluded that the single dynamical control strategy doesn't perform on improving the total current and maintaining high capacity on the fast lane as we expect. It is obvious that the reason for the drop of current under high densities is that there are so many vehicles and they can't change lane since the lane-changing rule can't be satisfied. To improve the capacity on the fast lane, we can remove some vehicles one by one according to some rules.

As we have discussed above, we put forward a new dynamical control strategy: Under middle and high densities, we check every vehicle on lane 0 to find the vehicle of the biggest Δx_f, then since lane 0 is the fast lane and lane 1 is the slow lane, the vehicle decelerates until the vehicle approaches the front vehicle on lane 1, then the vehicle change to lane 1 after the front vehicle. We manage vehicles on lane 0 until the number of vehicles on lane 0 reaches the lower limiting value, then we make the vehicle on lane 1 change to lane 0 in order to make the slow car on lane 1 have the chance to move fast on lane 0, or the drivers on lane 1 must be furious. Since, the vehicles on lane 1 drive slower than those on lane 0, we should choose the vehicle of the biggest Δx_b to change to lane 0, where Δx_b is the distance between the vehicle and the back vehicle on lane 0. After finding the vehicle ready for lane-changing, the vehicle can change to lane 0 in front of the back vehicle immediately. We conduct this behavior every once in a while until the number of vehicle on lane 1 reaches the upper limiting value.

To check the validity of this dynamical control strategy, we conduct simulations under periodic boundary two-lane with speed limitations. According to Fig. 3, we set the lower limiting value 0.04 and the upper limiting value 0.05, that is to say the vehicle on lane 0 will change to lane 1 when the vehicle number on lane 0 is greater than 50 and the vehicle on lane 1 will change to lane 0 when the vehicle number on lane 0 is less than 40. The acceleration process of vehicle can be decided by:

$$\frac{dv_n(t)}{dt} = k[v_f(t) - v_n(t)] \tag{5}$$

where, v_n (t) is the velocity of the nth vehicle on lane 0, v_f (t) is the velocity of the vehicle ahead of the nth vehicle on lane 1 and k is the sensitivity coefficient. We set k = 0.5 in our simulation. We conduct the simulation until 1000000 steps and we find the vehicle ready for lane-changing every 10000 steps, namely very 100 sec.

We firstly study the effectiveness of the new dynamical conrol strategy under high density. Figure 7 shows the current against time on lane 0 and lane 1 under the new dynamical conrol strategy when the density is 0.07. The open circles represent the current on lane 0 and the arterisks stand for the current on lane 1. Figure 8 shows the vehicle number against time on lane 0 and lane 1 under the new dynamical conrol strategy when the density d = 0.07. The open circles represent the vehicle number on lane 0 and the arterisks stand for the vehicle

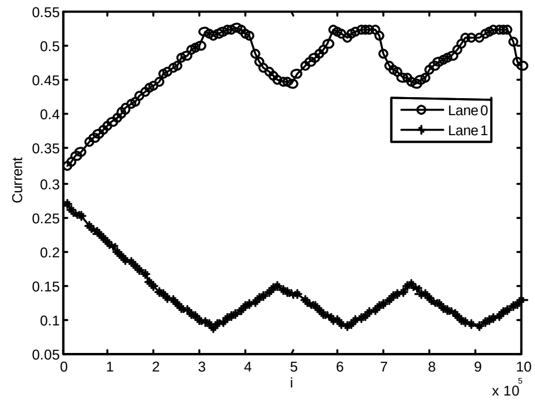

Fig. 7: Plot of current against time on lane 0 and lane 1 under new dynamical control strategy

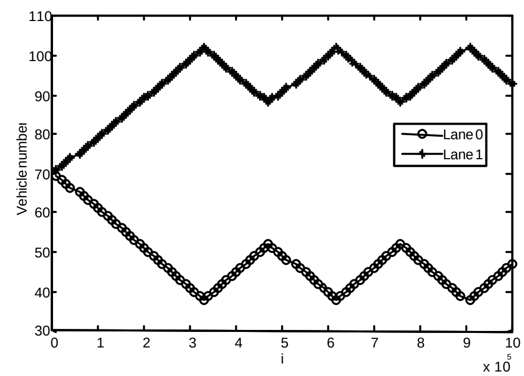

Fig. 8: Plot of vehicle number against time on lane 0 and lane 1 under new dynamical control strategy

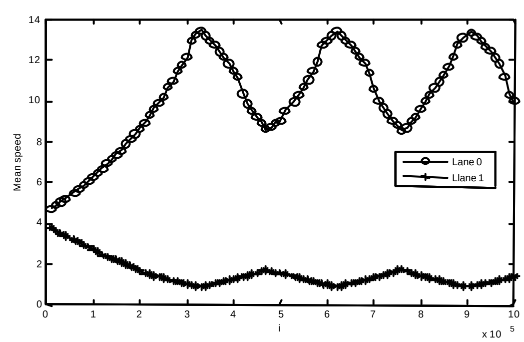

Fig. 9: Plot of mean velocity against time on lane 0 and lane 1 under new dynamical control strategy

number on lane 1. Figure 9 shows the mean speed against time on lane 0 and lane 1 under the new dynamical conrol strategy when the density d = 0.07. The open circles represent the mean velocity on lane 0 and the arterisks stand for the mean velocity on lane 1. We can see that the current can maintain high values on lane 0 although the current on lane 1 is low. The vehicle number on lane 1 is

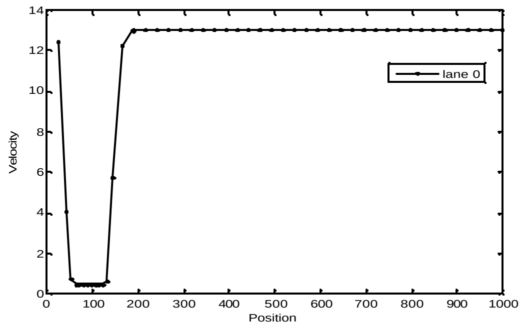

Fig. 10: Plot of position-velocity on lane 0 at i = 1000000 under density = 0.07

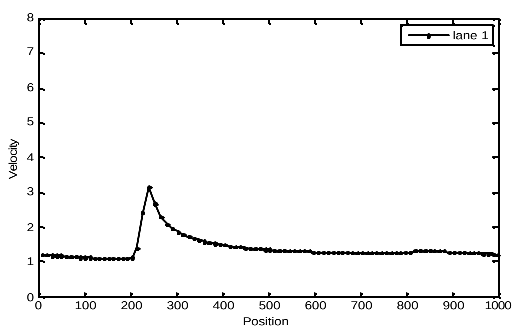

Fig. 11: Plot of position-velocity on lane 1 at i = 1000000 under density = 0.07

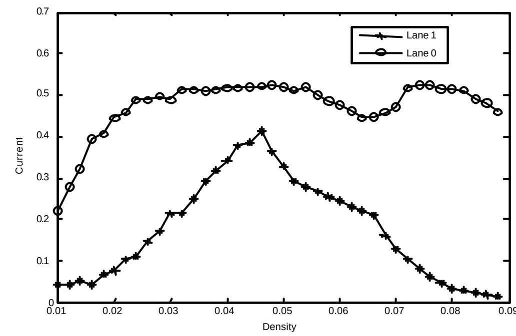

Fig. 12: Plot of current against density on lane 0 and lane 1under ideal condition and new dynamical control strategy

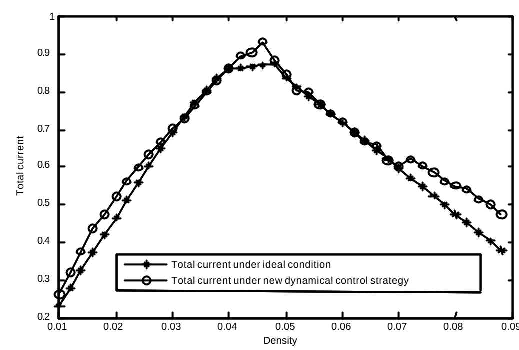

Fig. 13: Plot of total current against density on lane 0 and lane 1under ideal condition and new dynamical control strategy

always bigger than that on lane 0. As a result, the mean speed on lane 1 is lower than that on lane 0. Although, the mean velocity on lane 0 changes a little big, the vehicles on lane 0 can move fast and the current on lane 0 is high conclusionly.

Figure 10 shows the relationship of every vehicle's position-velocity on lane 0 at i = 1000000. Most vehicles can move fast on lane 0 but there are still some vehicles moving slowly and it's inevitable since in high density, the number of vehicle is large and it is impossible that all vehicles change to lane 1 or the vehicles on lane 1 can't move any longer and the drivers driving on lane 1 must be very angry. Figure 11 shows relaionship of every vehicle's position-velocity on lane 1 at i = 1000000. Almost all vehicles on lane 1 move slowly and the traffic come into a jam. It seems that the vehicles on lane 0 can move smoothly at the cost of sacrificing the vehicles on lane 1.However, that one lane comes into a jam is better than that both two lanes come into jams in real traffic system.

It seems that the new dynamical conrol strategy works well under high density of 0.07. Nextly, we study the traffic flow on the two lanes. Figure 12 displays the current against density on lane 0 and lane 1 at i = 1000000. The open circles stand for the current on lane 0 and the arterisks represent the current on lane 1. And Fig. 13 shows the total current against density under ideal condition and new dynamical control strategy. The open circles stand for the total current by using the new dynamical control strategy and the asterisks represent the total current under ideal condition. It is obvious that the current on lane 0 doesn't drop down in the middle and high densities and it can maintain high values even in high densities. It can be concluded that by using the new dynamical control strategy, the total current enhances especially in the peak value and in the high densities.

CONCLUSION

In this study, we study the traffic states on two-lane roads with different speed limitations in urban traffic system. We find that the traffic flow will drop down with density increasing and the traffic will come into jam. To solve this problem, we put forward some dynamical control strategies to improve traffic flow in middle and high densities. Firstly, the simple dynamical control strategy is raised though it is not so effective to alleviate the traffic jams in high densities. Then, a new and effective dynamical control strategy is presented. It is proved that the new dynamical control strategy can help to ease the congestion on lane 0 (the fast lane) in middle and high densities. The new dynamical control strategy is instructive and can be easily implemented under intelligent transportation system. And this work is useful to help improve traffic flow and relieve the traffic jams in middle and high densities.

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