A dynamic variety model to describe the traffic flow of target lane affected by lane change on urban road

Shejun Deng¹, Yuyi Zhong¹, Haizhong Wang², Xiaofei Ye³ and Jun Chen⁴

Abstract
In order to discover the variation of the traffic flow caused by lane change, the article analyzes the minimum safety distance and the lane change time between the lane change vehicle and the vehicles of the target lane based on the theory of vehicle lane change model and Bureau of Public Roads model. The influence time of lane change is determined by choosing two adjacent lanes as the research object according to the minimum safety distance of three kinds of combination. A model to describe the affected speed on lane 2 was established when the vehicle changed lane from 3 to 2 based on the measured data. The research results show that the speed of the target lane affected by the lane change is closely related to the volume of the adjacent two lanes and the acceleration of lane change vehicle. Then, while the more small acceleration of the lane change vehicle was, it would be more big variation traffic speed of the target lane. Finally, when the acceleration of the lane change is between 0.1 and 2.0 m/s², the influence is more serious than others.

Keywords
Traffic engineering, dynamic variety model, lane change, influence time, urban road

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Introduction
Lane change is the common driving behavior of traffic flow, which involves the traffic characteristics of the driver’s feeling, perception, judgment, and operation. When the traffic density is low, it is beneficial for driver to obtain the desired speed and improve the efficiency of traffic. When traffic density is heavy, the opportunity to change lane is small. If the driver is forced to change lane, it will affect the speed of current and target lane, which is easy to result in traffic conflict and form potential traffic safety hazard.¹

Usually, we focus on the models of lane change and aim at different conditions such as lane change behavior decisions, safe distance, and lane change time by the method of simulation and experimental data analysis.²⁻⁴ And the model to describe the impact of the lane change on traffic flow is rare. Similar research mainly focuses on the interference effects. For example, Jing et al.⁵ analyzed the relationship between the number of vehicles and traffic density. LY Wei⁶ analyzed the behavior of vehicles affected by the change lane of bus with the method of cellular automata model. S Oh⁷

¹College of Civil Science and Engineering, Yangzhou University, Yangzhou, China
²College of Engineering, Oregon State University, Corvallis, OR, USA
³College of Maritime and Transportation, Ningbo University, Ningbo, China
⁴School of Transportation, Southeast University, Nanjing, China

Corresponding author:
Shejun Deng, College of Civil Science and Engineering, Yangzhou University, Yangzhou 225009, China.
Email: yzrxs6@163.com

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investigated a variety state of traffic flow and found that it will affect the efficiency of the traffic flow and reduce traffic capacity of the downstream. Based on the measured data, HZ Xu8 established the influence speed model of traffic flow owing to lane change. W Yu9 analyzed the relationship between lane change and traffic congestion by using the traffic wave model. ML Wang10 established a lane change model based on fuzzy control theory and quantitatively analyzed the influence of different lane change times on the traffic flow through the simulation comparison. Some research shows that different accelerations, safe distances, and traffic condition of two adjacent lanes will lead to different effects on the target lane during the different condition of lane change.11,12

Less studies can be found toward the analysis of lane change time, especially lack of the micro-changes characteristics of each lane under the influence of multifactor coupling while the existing studies mainly focus on the macro-change characteristics of traffic flow.

The article established a calculation model of lane change time through the theoretical analysis of the characteristics of safe distance. In addition, combining with the instance, we established a model to describe the dynamic variety traffic speed of a single lane influenced by lane change. It has been verified by simulation and reality that the model has some practical significance to research the characteristics of traffic safety and variation of the delay on motorized road in the future.

The model of the dynamic variety traffic speed affected by lane change

In order to study the variety performance of the vehicles affected by lane change, this article tries to use the theoretical method to find some related orderliness through analyzing the behavior of lane change. Because we mainly focus on the influence of target lane caused by lane change, this article neglects the distance of the vehicle back and forward, which plans to change lane. Some rules were made that the order number of the lane which is more close to the center of the road would be named 1, the next one should be 2, and so on. Figure 1 shows the initial position of the vehicles on lanes 2 and 3. In order to analyze the trajectory of vehicle, we establish a coordinate system and define left edge as X-axis and upward as Y-axis. As shown in Figure 1, O is the lane change vehicle on lane 1, C is the vehicle before it, D is the vehicle behind it, A is the front vehicle of the target lane, and B is the rear one of the target lane. WO is the width of vehicle changing lane, W_\text{A} is the front vehicle’s width on target lane, W_1 is the width between the far left of O and the far right of A, W_2 is the width between the far left of O and the far left of A, W_3 is the width of target lane, L_A is the length of A, L_O is the length of O, and O_1 is the left anterior angle of O.

Analysis of the safety distance characteristics between O and A

Trajectory of the vehicles O and A was shown in Figure 2. In order to elaborate the relationship between A and B, the vehicle has finished the process of lane change. Based on the coordinate system, this article assumes that the horizontal and vertical coordinates of the lane change vehicle are x_o(t) and y_o(t), respectively, at one moment.

The horizontal and vertical coordinates of A are x_a(t) and y_a(t), respectively. Assuming that the moment while O_1 reaches the boundary between lanes 2 and 3 as t_{\text{adj}} + t_c and t_{\text{adj}} is the moment to start speeding up laterally, and t_c is the duration time after acceleration. At the moment of t_{\text{adj}} + t_c, O_1 crosses the horizontal line LA right of the vehicle A and assumes that they meet with the line LA at C. So t_{\text{adj}} + t_c is the time when the lane change vehicle moves to C. Then, some equations can be drawn as follows

\[
\begin{aligned}
    w_1 &= w_2 - w_\text{d} \\
    x_o(t) &= x_a(t) - L_A - w_o \cdot \sin[\theta(t)]
\end{aligned}
\]  (1)
where $\theta(t)$ is the angle between the vehicle O and the horizontal direction at the moment $t_{adj} + t_c$, which can be figure out as follows

$$\theta(t) = \arctg \frac{\partial y_o(t)}{\partial x_o(t)} = \arctg \frac{\partial v_o(t)}{\partial u_o(t)} = \arctg \frac{v_{lat}(t)}{v_o(t)}$$

(2)

and $w_2 = y_A(t_{adj} + t_c)$ and $w_1 = y_0(t_{adj} + t_c)$. Substituting them into formula 1, we can get the equations as follows

$$\begin{cases}
y_o(t_{adj} + t_c) = y_A(t_{adj} + t_c) - w_A \\
x_o(t) = x_A(t) - L_A - w_O \sin[\theta(t)]
\end{cases}$$

(3)

If $t \geq t_{adj} + t_c$, when the lane change vehicle crosses the line LA, it easily leads to side collision with A. When the vehicle finishes the lane change, it easily leads to tailgating with A, so if $T \geq t \geq t_{adj} + t_c$, it is dangerous for lane change vehicles. In order to avoid collision, they need to be satisfied with equations as follows

$$\begin{cases}
y_o(t_{adj} + t_c) < y_A(t_{adj} + t_c) - w_A \\
x_o(t) < x_A(t) - L_A - w_O \sin[\theta(t)]
\end{cases}$$

(4)

Assuming the horizontal distance between the left front point of O_1 and the right rear point of A_3 as $S(t)$, then we can calculate $S(t)$ as follows

$$S(t) = \int_0^t (a_A(\tau) - a_O(\tau))d\tau + \int_0^t (v_A(\tau) - v_O(\tau))d\tau$$

$$+ S_{AO}(0) = S_A(t) - L_A - w_O \sin[\theta(T)] - S_o(t) + S_{AO}(0)$$

(5)

where $S_{AO}(0)$ is the initial longitudinal distance between the headstock of O and the tailstock of A at the moment ready to change lane. Other symbols are synonymous.

Therefore, if the collision of the lane change vehicle should be avoided, it must meet with two requirements, which is $S(t) > 0$ and $S_{AO}(0)$, and should meet the minimum safe distance requirement.\(^\text{13}\) The formula is as follows

$$S_{AO}(0) = \max \left\{ \int_0^t (a_O(\tau) - a_A(\tau))d\tau + (v_O(0) - v_A(0))t \right\}$$

(6)

and $S_A(t) - L_A - w_O \sin[\theta(t)] - S_o(t) + S_{AO}(0) > 0$.

**Analysis of the safety distance characteristics between O and B**

Similarly, in order to avoid friction or collision, the vehicle O must keep the minimum safe distance with B after changing lane; the position of each vehicle is shown in Figure 3.

Assuming the horizontal distance between the left rear point of O_2 and the right front point of B_2 as $S(t)$, then

$$S(t) = \int_0^t (a_O(\tau) - a_B(\tau))d\tau + \int_0^t (v_O(\tau) - v_B(\tau))d\tau + S_{BO}(0)$$

$$= x_o(t) + L_o \cos[\theta(t)] + w_O \sin[\theta(t)] - x_B(t) + S_{BO}(0)$$

(7)

where $S_{BO}(0)$ is the initial longitudinal distance between the headstock of O and the tailstock of B at the moment just ready to change lane. Other symbols are synonymous. Therefore, if the collision of the lane change vehicle should be avoided, it must meet with two requirements, which is $S(t) > 0$ and $S_{BO}(0)$, and should meet the minimum safe distance requirement. The formula is as follows

$$S_{BO}(0) = \max \left\{ \int_0^t (a_B(\tau) - a_o(\tau))d\tau + (v_B(\tau) - v_o(\tau))d\tau \right\}$$

and $x_o(t) + L_o \cos[\theta(t)] + w_O \sin[\theta(t)] - x_B(t) + S_{BO}(0)$

(8)

**Analysis of influence time caused by the lane change vehicle**

Related studies have shown that\(^\text{14}\) each driver has desirable speed during certain traffic density, which is related to vehicle's mechanical performance, driver's...
characteristics, speed limit rule, and so on. The vehicle will intend to change lane while the influence of slow
one ahead leads to lower speed than expected within a
certain range. Usually, the vehicle changes lane from
lower speed lane to higher speed one, so this article
mainly aims to this type and carries on some research.

From the analysis of formula (8), we can know that
if we want to compute the safe distance between the
lane change vehicle and target vehicle, we need to mea-
sure the speed and acceleration of them. But the actual
measurement is difficult. In order to find the general
rule of lane change, the article assumes that lane change
vehicle is driving at a constant acceleration and other
vehicles keep constant motion while changing lane.

The time for changing lane between $O$ and $A$. The changing
time is defined that there is a safe distance between O
and $A$ after changing. Figure 2 shows the trajectory of
the vehicles $O$ and $A$. We define $t_0$ as the beginning
of changing lane, $t_1$ as the end time, $t_a$ as the time for
changing, so $t_a = t_1 - t_0$. After changing O’s speed in
accordance with those in target line, that is, $v_o(t) = v_A(t)$, the time for accelerating is

$$t_a = \frac{v_A - v_0}{2a_o}$$

(9)

where $a_o$ is acceleration of $O$, m/s$^2$; $v_A$ is the speed of O
after changing, m/s; and $v_0$ is the speed of $O$ before
changing, m/s. During this time ($t_a$), $O$’s driving distance is

$$S_O = v_0t_a + \frac{1}{2}a_o t_a^2$$

(10)

and $A$’s driving distance is $S_A = v_A t_a = v_A (t_1 - t_0)$.

So the longitudinal distance between $O$ and $A$ after
changing is

$$S(t) = v_o t_a - \left( v_0 t_a + \frac{1}{2}a_o t_a^2 \right) - w_o \sin \theta(t) + S_{AO}(0)$$

$$= \left( -\frac{1}{2} a_o \right) t_a^2 + (v_A - v_O) t_a + (S_{AO}(0) - w_o \sin \theta(t))$$

(11)

If we avoid $O$ not to collide with $A$, it must satisfy the condition $S(t) > 0$, then

$$\left( -\frac{1}{2} a_o \right) t_a^2 + (v_A - v_O) t_a + (S_{AO}(0) - w_o \sin \theta(t)) > 0$$

(12)

Figure out in equation (12), then

$$t_{1,2} = \frac{(v_A - v_0) \pm \sqrt{(v_A - v_0)^2 + 2a_o (S_{AO}(0) - w_o \sin \theta(t))}}{a_o}$$

$$< t_a < \frac{(v_A - v_0) + \sqrt{(v_A - v_0)^2 + 2a_o (S_{AO}(0) - w_o \sin \theta(t))}}{a_o}$$

(13)

Because the usual value of $\theta$ is about $3^\circ-5^\circ$ and $w_o$
is 1.5 m, $0.1 < w_o \sin \theta(t) < 0.2$.

Generally, $w_o \sin \theta(t) < S_{AO}(0)$. So

$$(v_A - v_0) - \sqrt{(v_A - v_0)^2 + 2a_o (S_{AO}(0) - w_o \sin \theta(t))} < 0$$

and when formula (13) is satisfied

$$0 < t_a < \frac{(v_A - v_0) + \sqrt{(v_A - v_0)^2 + 2a_o (S_{AO}(0) - w_o \sin \theta(t))}}{a_o}$$

(14)

The time for changing lane between $O$ and $B$. The changing
time is defined that there is a safe distance between O
and $B$ after changing. Figure 3 shows the trajectory of
the vehicles $O$ and $B$. We defined $t_0$ as the beginning
of changing lane, $t_1$ as the end time, $t_a$ as the time for
changing, so $t_a = t_1 - t_0$. After changing O’s speed in
accordance with those in target line, that is, $v_o(t) = v_B(t)$, the time for accelerating is

$$t_a = \frac{v_B - v_0}{2a_o}$$

(15)

During this time ($t_a$), $O$’s driving distance is

$$S_O = v_0 t_a + \frac{1}{2} a_o t_a^2$$

(16)

and $B$’s driving distance is $S_B = v_B t_a = v_B (t_1 - t_0)$.

So the longitudinal distance between $O$ and $B$ after
changing is

$$S(t) = -v_B t_a + \left( v_0 t_a + \frac{1}{2} a_o t_a^2 \right) + w_o \sin \theta(t) -$$

$$S_{BO}(0) = \left( \frac{1}{2} a_o \right) t_a^2 - (v_B - v_O) t_a + (S_{BO}(0) - w_o \sin \theta(t))$$

(17)

If we avoid $O$ not to collide with $B$, it must satisfy the condition $S(t) > 0$, that is

$$\left( \frac{1}{2} a_o \right) t_a^2 - (v_B - v_O) t_a + (S_{BO}(0) - w_o \sin \theta(t)) > 0$$

(18)
Figure out in equation (18), then

\[ t_{1,2} = \frac{(v_B - v_O) \pm \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \]

\[ t_o = \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \]

or \( t_o < \frac{(v_B - v_O) - \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \)

Generally, \( w_o \sin \theta(t) < S_{BO}(0) \).

So

\[ \frac{(v_B - v_O) - \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} < 0 \]

and when formula (19) is satisfied

\[ t_o > \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \]

The time influenced by the lane change. From the analysis above, we know that in order to avoid collision between O and A, the time for changing is required to satisfy the formula as follows: \( 0 < t^A_o < \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \), where \( t^A_o \) is the changing time that can ensure minimum safe distance between O and A after changing. That is to say, it should be as short as possible and not go beyond the threshold, so that O can avoid rear-end collision with A. For O and B, it requires \( t^B_o > \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \), where \( t^B_o \) is the changing time that can ensure minimum safe distance between O and B after changing. It should be as long as possible and greater than the limit so that they can avoid collision.

When the vehicle changes from lane 3 to lane 2, if B leaves far enough from O, we can neglect the influence between them and just need to meet the longest changing time of A. If A is far enough from O, we also can neglect the influence between them, and only need to meet the shortest change time of B. If the distance between A and B, and the lane change vehicle O, is moderate, then the influence of them should be considered.

Based on the analysis of the actual data, we find that the vast majority of vehicles consider the front vehicle on the target lane as the object priority. So, this article first studies the situation, which meets the requirement of the vehicle A, where

\[ 0 < t^A_o < \frac{(v_A - v_O) + \sqrt{(v_A - v_O)^2 + 2a_o(S_{AO}(0) - w_o \sin \theta(t))}}{a_o} \]

If we want to meet the requirement of B at the same time, it needs \( t^B_o > \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \).

We assume that the vehicles’ transport condition on the target lane is consistent, that is, \( v_B = v_A \), and consider different minimum safe distances and suggest vehicles are changed with the same acceleration \( a_o \).

1. \( S_{AO}(0) = S_{BO}(0) \)

The limits of \( t^A_o \) and \( t^B_o \) are the same. In order to change the lane successfully, the lane change vehicle needs to satisfy \( t_o \in (t^A_o \cap t^B_o) \). It is the critical point to determine whether O affects A or B.

2. \( S_{AO}(0) \neq S_{BO}(0) \)

The limit of \( t^A_o \) is greater than \( t^B_o \). In order to meet the requirement for changing lane, there may be varieties of types, so we analyze with different time caused by lane change.

\[ \begin{align*}
(a) & \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} < t_o < \frac{(v_B - v_O) + \sqrt{(v_A - v_O)^2 + 2a_o(S_{AO}(0) - w_o \sin \theta(t))}}{a_o} \\
(b) & 0 < t_o < \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \\
\end{align*} \]

That is, O satisfies the shortest changing time \( t_o \in (t^A_o \cap t^B_o) \), where there is no influence on A or B.

At this situation, the vehicle O can meet the safe change requirement with A, but it will impact B. The influential time is

\[ T_{effect \ of \ lane \ change} = t^B_o - t_o = \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} - t_o \]

where \( 0 < t_o < \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \).

(c) \( t_o > \frac{(v_B - v_O) + \sqrt{(v_B - v_O)^2 + 2a_o(S_{BO}(0) - w_o \sin \theta(t))}}{a_o} \)

If the vehicle O meets the safe changing requirement with B, it will fail to meet with A. It means O will collide with A; thus, we do not consider this state.

3. \( S_{AO}(0) < S_{BO}(0) \)
The limit of \( t_a^1 \) is less than \( t_a^\beta \). In order to meet the requirement for changing lane, there are various types. So, we analyze with different time caused by lane change.

\[
(a) \quad \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} < t_a < \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)}
\]

It can meet the requirement of A and B for changing lane at the same time. Vehicle O needs to satisfy the shortest changing time \( t_a \in (t_a^1 \cap t_a^\beta) = \emptyset \), but this situation is impossible because the intersection is an empty set. (b) \( 0 < t_a < \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} \)

If vehicle O wants to change the lane to the point of A successfully while there is clearance between them, the vehicle B must slow down, follow, or stop to wait. Thus, the vehicle changing lane will have an effect on B. The influential time is

\[
T_{\text{effect of lane change}} = t_a^\beta - t_a = \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} - t_a
\]

where \( 0 < t_a < \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} \)

(c) \( t_a^\beta > \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} \)

If the vehicle O wants to change the lane to the point of B successfully while there is clearance between them, the vehicle O should fail to meet the safe changing requirement with B. It means O will collide with B; thus, we do not consider this state.

To sum up, the effect of the lane change vehicle O on the vehicles A and B can be expressed as

\[
T_{\text{effect of lane change}} = t_a^\beta - t_a = \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} - t_a
\]

In the formula,

\[
\begin{cases}
0 < t_a < \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)}, & S_{BO}(0) > S_{BO}(0), \\
0 < t_a < \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)}, & S_{BO}(0) < S_{BO}(0).
\end{cases}
\]

Relevant research\cite{15} indicates that the minimum safe distance between the lane change vehicle and the vehicle A on the target lane is

\[
S_{AO}(0) = -\frac{(v_A - v_O)^2}{2a_o} + L_A + w_o \sin(\theta(t))
\]

Analyzing formula (24), we can know that the value of \( S_{AO}(0) \) is \([L_B + w_o \sin(\theta(t)), + \infty]\). Since this article assumes that the vehicles' transport condition in the target lane is consistent, the vehicle O is the same type as the vehicle on target lane, so it means \( v_B = v_A \) and \( L_B = L_O \). Then, \( S_{AO}(0) < L_{BO}(0) \); obviously, the condition is impossible. Thus, if the vehicle O has clearance with B, it will have an impact on B. So, the influential time is

\[
T_{\text{effect of lane change}} = t_a^\beta - t_a = \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} - t_a
\]

where \( 0 < t_a < \frac{(v_y - v_O)}{a_O} + \sqrt{\left((v_y - v_O)^2 + 2a_O(S_{BO}(0) - w_0 \sin(\theta(t)))\right)} \)

**Application of the model**

**Introduction**

Choose Zhongshan South Road which is an arterial road with two-way six lanes in Nanjing city of China as the research object for data collection and analysis. To facilitate the unified research, this article defines the number rule of the lane. The lane closest to the center line of the main road is 1, then the number is 2 and 3, respectively, as shown in Figure 4. There are four ways to change the lane: lane 1 to lane 2, lane 2 to lane 3, lane 3 to lane 2, and lane 2 to lane 1. From the investigation, we find the type that the vehicle change lane from lane 3 to lane 2 is more frequent, as shown in Figure 5.

Table 1 shows comparison of lane change time and analysis of four types. It can be seen that the mean value of time while vehicle change from lane 1 to lane 2 is minimum and it is maximum while from lane 3 to lane 2. The maximum time is 3.23 s from lane 1 to lane 2, but 11.00 s from lane 3 to lane 2. It suggests when from lane 1 to lane 2 changing lane is freedom so spend relatively short time. However, from lane 3 to lane 2, because of lane change condition does not include all, vehicles will implement forced changing so that it needs a long time. Thus, this article mainly studies the model that the vehicle changing lane impacts lane 2 traffic flow.
The model to describe the variety speed in the city of China

This article takes 1 min as observation time interval and takes each lane as the research object, and set up velocity–volume model through data analysis and arrangement: \( V = \frac{v_0}{1 + 1.399(q_3/c_3)^{0.55}} \) for lane 2 and \( V = \frac{v_0}{1 + 1.909(q_3/c_3)^{1.65}} \) for lane 3.

Related studies have shown that,16 vehicle’s speed after affected is closely related to the social vehicles’ initial velocity, impact time and the distance between the location of the parking vehicles began to slow and entrance. And it can be described as

\[
v = -2.031 + 0.842v_f - 0.047v + 0.101s.
\]

Through the data analysis, we found that the average speed of society vehicles is closely related to traffic and its lane change rule can use BPR (Bureau of Public Roads) function model to describe,17 when the road conditions and traffic conditions are generally identical. If it substitutes other data for \( v_f, T_s, \) and \( s \) in the model, it can also reflect the lane change rule.

Because this article assumes that the vehicle changes from low speed way to high speed way, and that there is no reduction behavior after finishing changing, the \( S \) value is 0. When the vehicle changes from lane 3 to lane 2, the model that lane change vehicle impact vehicles on target lane 2 can be described as

\[
v = \frac{v_0}{1 + 1.399(q_3/c_3)^{0.55}} - 0.047v + 0.101s,
\]

\[
\frac{v_0}{1 + 1.399(q_3/c_3)^{0.55}} - \frac{v_0}{1 + 1.909(q_3/c_3)^{1.65}} \left[ \frac{\sqrt{2\left(\frac{v_0}{1 + 1.399(q_3/c_3)^{0.55}} - \frac{v_0}{1 + 1.909(q_3/c_3)^{1.65}}\right)^2 + 2a_0L_b}}{a_0} - t_a \right]
\]

\[
(27)
\]

Sensitivity analysis of the model

Select Zhongshan South Road in Nanjing city in China as an example. We take further sensitivity analysis on the influence of vehicles’ various speed by using established influence model. Then, we analyze the mechanism of influence further while the vehicle changes lane.

Suppose traffic volume of lane 2 is from 100 to 400 pcu/h and lane 3 is 500 pcu/h, the vehicle tries to

Table 1. Comparison and analysis of time eigenvalues for four types of lane change.

| Type     | Time | Minimum | Maximum | Mean   | Standard deviation | Variance |
|----------|------|---------|---------|--------|--------------------|----------|
| Lane 1-2 | 26   | 0.6500  | 3.2300  | 1.755038| 0.5545072          | 0.307    |
| Lane 2-1 | 50   | 1.2660  | 5.6350  | 2.176200| 0.8217266          | 0.675    |
| Lane 2-3 | 74   | 1.0380  | 7.5290  | 2.424635| 1.3525162          | 1.829    |
| Lane 3-2 | 144  | 0.9450  | 11.0000 | 3.004736| 1.3494604          | 1.821    |
change from lane 3 to lane 2. Figure 6 compared velocity on lane 2 before and after. It can be seen that lane change caused vehicles slow down; meanwhile, if the
volume of lane 2 increases, then amplitude of speed change will be reduced. It is accordance with the actual situation and proves that model is accurate.

Figures 7–12 show the speed of vehicles on lane 2 affected by change from lane 3 to lane 2. The acceleration in the diagram is 0.01 to 4.0 m/s². So, some conclusions can be drawn as follows:

1. When traffic volume of changing lane is 500 and 600 pcu/h and target lane is 0 and 500 pcu/h, or when the former’s traffic volume is 100 and 200 pcu/h and the latter’s is 1000 and 1500 pcu/h, the lane change with different acceleration had a greater influence on the velocity of vehicles on target lane.
2. The smaller the acceleration, the greater the change of speed. On the contrary, the larger the acceleration, the smaller the change of speed.

Conclusion

The speed of the target lane affected by the lane change is closely related to the volume of the adjacent two lanes, and the acceleration of lane change vehicle and the influential time can be calculated as follows:

\[
T_{\text{effect of lane change}} = t_b^\theta - t_a = \frac{(v_b - v_0) + \sqrt{2(v_b - v_0)^2 + 2a_vL_b}}{a_v} - t_a.
\]

When the volume of the lane was from 500 to 600 pcu/h while the target lane was from 0 to 500 pcu/h or when the volume of the lane was from 100 to 300 pcu/h while the target lane was from 1000 to 1500 pcu/h, the speed of the target was deeply affected by the lane change. While the more small acceleration of the lane change vehicle was, it would be more big variation traffic speed of the target lane. Finally, when the acceleration of the lane change is between 0.1 and 2.0 m/s², the influence is more serious than others.

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ORCID iDs

Shejun Deng https://orcid.org/0000-0003-1893-8673
Xiaofei Ye https://orcid.org/0000-0001-8795-4955

References

1. Sun D and Kondyli A. Modeling vehicle interactions during lane change behavior on arterial streets. Comp Aided Civil Infrastruct Eng 2010; 25: 557–571.
2. Nagel K and Schreckenber M. A cellular automaton model for freeway traffic. J Physique I 1992; 12: 2221–2229.
3. Hua XD, Wang W and Wang H. A two-lane cellular automaton traffic flow model with the influence of driving psychology. J Phys 2011; 8: 404–411.
4. Wang H, Liu ZQ and Zhang ZX. Double-head car-following and lane change combined model. J Southeast Univ 2015; 45: 985–989.
5. Jing M, Deng W and Wang H. Two-lane cellular automaton traffic flow model based on car-following behavior. J Phys 2012; 61: 244502.
6. Wei LY, Wu RH and Wang ZL. Lane change behavior based on mixed traffic flow. J Jilin Univ 2014; 44: 1321–1326.
7. Oh S and Yeo H. Impact of stop-and-go waves and lane changes on discharge rate in recovery flow. Transport Res Part B 2015; 77: 88–102.
8. Xu HZ, Cheng GZ and Pei YL. Study on effect of lane change behavioral characteristic to velocity. Sci Paper Online 2010; 5: 754–762.
9. Yu W. Research on relationship between lane change and reason of traffic congestion. Chengdu, China: Southwest Jiaotong University, 2013.
10. Wang ML. Analysis of the influence of vehicle lane change behavior on traffic flow. Changchun, China: Jilin University, 2016.
11. Vadim AB and Petros I. Personalized driver/vehicle lane change models for ADAS. IEEE Trans Vehic Tech 2015; 64: 4422–4431.
12. Talebpoura A, Mahmassania HS and Hamdarb SH. Modeling lane-changing behavior in a connected environment: a game theory approach. Transport Res Part C 2015; 7: 216–232.
13. Guo WL. Study on lane changing safety spacing model of the urban road. Master’s Thesis, Changsha University of Science and Technology, Changsha, China, 2009.
14. Xu JQ, Chen ZS and Ding Y. A model study and simulation of lane changing based on driving behaviors. *J China Jiaotong Univ* 2011; 28: 68–72.
15. Xu LH, Ni YM, Luo Q, et al. Lane change model based on minimum safety distance. *J Guangxi Normal Univ* 2011; 29: 1–5.
16. Deng SJ, Ye XF and Chen J. A model to describe the influence of the traffic flow on the main road due to off-street parking at the section of access. *J Harbin Inst Tech* 2016; 48: 101–107.
17. Deng SJ. *The research of the impact of the entering vehicles on the entrance of parking lots*. Nanjing, China: Southeast University, 2014.