A Multi-lane Cellular Automata Model Based on Elastic Safe Lane Change Rule

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Abstract. Based on the analysis of STCA model and X-STCA model, combined with the actual situation of vehicle lane-changing, the lane-changing choice probability $P$ and safety parameter $\lambda$ reflecting driving psychology is introduced, and the concept of lane change risk is redefined. This paper proposes an elastic safety lane-changing rule that is more in line with traffic conditions, and further establishes a multi-lane cellular automaton traffic flow model based on this rule. And the model can reduce the accident rate in terms of safety.

Introduction

In the traffic flow model of the cellular automata theory, the 184 rule proposed by Tungsten was first introduced into the traffic flow management system\cite{1}. Then in 1992 Negel and Schreckenber proposed a basic single-lane traffic flow cellular automaton model called the Nasch (NS) model, but the model has limitations that cannot be overtaken. Therefore, many scholars have proposed various improvements\cite{2}. One of the most important improvements is the STCA (Symmetric Two-Channel Cellular Automata) two-lane model proposed by Chowdhury in 1997. This model extends the NS model, and introduces rules of the a lane-changing that make the model more in line the actual of traffic flow\cite{3}. However, in the STCA model, the safe lane change distance satisfied by all lane changing vehicles is a fixed value, but the reality is not the case\cite{4}. On the basis of the STCA model, Wang Yongming, Zhou Leishan and other scholars put forward the concept of elastic safe lane change, considering the impact of the expected lane rear car on the safety of the lane changing vehicle\cite{5}.

However, in actual traffic flow, when the driver decided to change the lane, he should not only consider the influence from the rear vehicle in the adjacent lane, but also consider the influence from the front vehicle in the adjacent lane. Reference \cite{6} proposed a cellular automaton traffic flow model M-STCA based on the improved safe lane change distance rule, but the setting of the lane change risk value is only for this model. It is happened in the specific special circumstances, not universal. In the literature \cite{7}, Xu Hongxue et al. comprehensively considered the possible conflicts between the lane-changing vehicles in the same-directional two-lane system and the vehicles in the same direction and adjacent lanes, and proposed a more perfect safe lane change distance rule. The same direction two-lane cellular automaton traffic flow model X-STCA.

Since the actual urban roads are not only two-lane roads, but also many multi-lane ones. Therefore, based on the research results of STCA model and X-STCA model, this paper proposes a multi-lane cellular automaton model, which is more suitable for urban road conditions.

STCA model and X-STCA Model

STCA Model

The STCA model is an extension of the NS model. The introduced lane change rules are more in line with the state of the traffic flow. The rules are as follows\cite{6}:
where, $C_i(t)$ is whether the i-th car has changed lanes at time t; 1 indicates lane change, and 0 indicates deceleration driving or parking waiting in the original lane; $v_i(t)$ is the speed of the i-th car at time t; $d_i(t)$ is the distance between the i-th car and the vehicle in front of the same lane at time t; $d_{i,\text{from}}(t)$ is the distance between the i-th car and the vehicle in front of the adjacent lane at time t; $d_{i,\text{back}}(t)$ is the distance between the i-th car and the vehicle behind the adjacent lane at time t; $d_{\text{safe}}$ is the safe lane change distance specified in the model is usually set to a fixed value $v_{\text{max}}$.

In formula (1), $d_i(t) < \min\{v_i(t+1), v_{\text{max}}\}$ indicates that the vehicle is blocked in the original lane; $d_{i,\text{from}}(t) > d_i(t)$ indicates that the vehicle can get faster speeds in adjacent lanes. $d_{i,\text{back}}(t) > d_{\text{safe}}$ indicates the condition of the safe lane change required to be met when the vehicle changes lanes, that is, the vehicle needs to maintain a safe driving distance with the vehicle behind the adjacent lane during the running. Normally, $d_{\text{safe}}$ is set to a fixed value of $v_{\text{max}}$, which is also a disadvantage of the STCA model.

**X-STCA Model**

The literature [7] analyzes the shortage of the lane change distance rule of the STCA mode and perfecting the description of the change risk. The vehicle has a certain risk when the lane is changed, and the risk comes mainly from the conflict which caused by front vehicle and rear vehicle in the adjacent lane. When the lane of vehicle is changing and the vehicle is driving a time step, the conflict degree depends on two factors: The distance between the lane changing vehicle and the vehicle behind the adjacent lane, and the distance between the lane changing vehicle and the vehicle in front of the adjacent lane. And this literature proposed a new model of symmetric same direction two-lane cellular automaton based on the safe lane-changing distance constraint rule.

To ensure traffic safety, it make the $d_{\delta,\text{other}}(t+1) \geq 1, d_{\delta,\text{back}}(t+1) \geq 1$ as the buffer distance constraint to deduce the safe lane-changing distance constraint rule and traffic flow model. Where, $d_{\delta,\text{back}}(t+1)$ is the distance between the lane changing vehicle and the vehicle behind the adjacent lane; $d_{\delta,\text{other}}(t+1)$ is the distance between the lane changing vehicle and the vehicle in front of the adjacent lane. Based on this, the lane change distance rule is derived. Figure 1 and Figure 2 are the micro-scene scenes of the lane change under two constraints.

![Figure 1](image_url)
Figure 2. Lane changing circumstance (restrained by $d_{s,\text{other}}(t+1) \geq 1$).

As shown in Fig. 1 and Fig. 2, the vehicle b is changing lane at the moment $t$ and driven a time unit. Based on Figure, we can build the relation formula (2) and (3).

$$d_{b,\text{back}} + \min\{v_{a}(t+1), v_{\text{max}}\} = \min\{v_{b}(t+1), v_{\text{max}}\} + d_{s,\text{back}}(t+1)$$

(2)

$$d_{b,\text{other}} + \min\{v_{a}(t+1), v_{\text{max}}\} = \min\{v_{b}(t+1), v_{\text{max}}\} + d_{s,\text{other}}(t+1)$$

(3)

The safe lane change rules that can be derived model of X-STCA by constraint $d_{s,\text{other}}(t+1) \geq 1$

$$d_{s,\text{back}}(t+1)$$ are as follows:

$$C_{i}(t+1) = \begin{cases} 
1, & \left\{ \begin{array}{l} 
d_{i}(t) < \min\{v_{i}(t+1), v_{\text{max}}\} \\
d_{i,\text{other}}(t) > 1 + \min\{v_{i}(t+1), v_{\text{max}}\} - \min\{v_{i,\text{other}}(t+1), v_{\text{max}}\} \\
d_{i,\text{back}}(t) > 1 + \min\{v_{i,\text{back}}(t+1), v_{\text{max}}\} - \min\{v_{i}(t+1), v_{\text{max}}\} \\
0, & \text{其它}
\end{array} \right. 
\end{cases}$$

(4)

This lane change rule takes full account of the safety aspect and tends to be more cautious about the driver’s possible behavior.

Two-lane Model Considering Driver’s Psychological Factors

In order to further improve the safety of safe lane-changing, in the literature [7], we give the following assumptions: the rear vehicle of the adjacent lane is moving in the maximum speed of $v_{\text{max}}$, and the front vehicle of the adjacent lane is moving in the minimum speed of $v_{\text{min}}$. In this paper, the choice of the lane change probability $P$ of choice and the safety parameter $\lambda$ reflecting the driving psychology are introduced in this paper. Generally, $\lambda \in [0,1]$ [8], the rules of the lane change are as follows:

$$d_{i}(t) < \min\{v_{i}(t+1), v_{\text{max}}\}$$

(5)

$$d_{i,\text{other}}(t) > 1 + \min\{v_{i}(t+1), v_{\text{max}}\} - \min\{\lambda \cdot v_{i,\text{other}}(t+1), v_{\text{max}}\}$$

(6)

$$d_{i,\text{back}}(t) > 1 + \min\{\lambda \cdot v_{i,\text{back}}(t+1), v_{\text{max}}\} - \min\{v_{i}(t+1), v_{\text{max}}\}$$

(7)

$$\text{rand}() < P_{i}$$

(8)

That is, if the current vehicle satisfies the lane change condition, the lane change is performed with the probability $P_{i}$.

where, $\lambda \cdot v_{i,\text{other}}(t+1)$ is the estimation of vehicle speed in front of adjacent lanes by lane change
vehicles, under the influence of the driver's psychological safety parameter $\lambda; \lambda \cdot v_{i,\text{back}}(t+1)$ is the estimation of vehicle speed in behind of adjacent lanes by lane change vehicles; $\text{rand}() < P_i$ indicates that the vehicle performs the lane change with the probability $P_i$.

**Multi-lane Safe Lane Change Model**

The objects studied by Wang Yongming and Xu Hongxue are mainly two-lane lane changing rules, while the urban roads are mostly multi-lane. Therefore, it is necessary to study the multi-lane changing rules. Pedersen et al. proposed a lane change mechanism between three lanes, the same as the two lane lane change rule. In this paper, under the two-lane rule, we explore the rule of multi-lane elastic safety change distance, and propose a multi-lane cellular automaton model based on elastic safety change. The model is more in line with the actual situation of urban roads.

The following are the rules for the multi-lane safe change of lanes, which take into account the psychological factors of the driver:

1. Change of lane to the left

$$C_i^{left}(t+1) = \begin{cases} 
1, & \text{if } d_i(t) < \min\{v_i(t+1), v_{\max}\} \\
1, & \text{if } d_{i,\text{other}}^{left}(t) > 1 + \min\{v_i(t+1), v_{\max}\} - \min\{\lambda \cdot v_{i,\text{other}}^{left}(t+1), v_{\max}\} \\
1, & \text{if } d_{i,\text{back}}^{left}(t) > 1 + \min\{\lambda \cdot v_{i,\text{back}}^{left}(t+1), v_{\max}\} - \min\{v_i(t+1), v_{\max}\} \\
0, & \text{if } \text{rand}() < P_i^{left} 
\end{cases}$$

where, $d_{i,\text{other}}^{left}(t)$ is the distance between the lane change vehicle and the nearest front vehicle in the adjacent left lane; $d_{i,\text{back}}^{left}(t)$ is the distance between the lane change vehicle and the nearest rear vehicle in the adjacent left lane; $v_{i,\text{other}}^{left}(t)$, $v_{i,\text{back}}^{left}(t)$ are the speed of the front and rear vehicles closest to the lane change vehicle and the adjacent left lane. $1 + \min\{v_i(t+1), v_{\max}\} - \min\{\lambda \cdot v_{i,\text{other}}^{left}(t+1), v_{\max}\}$ is the safety distance between the lane change vehicle and the nearest front vehicle in the adjacent left lane; $1 + \min\{\lambda \cdot v_{i,\text{back}}^{left}(t+1), v_{\max}\} - \min\{v_i(t+1), v_{\max}\}$ is the safety distance between the lane change vehicle and the nearest rear vehicle in the adjacent left lane.

2. Change of lane to the right

$$C_i^{right}(t+1) = \begin{cases} 
1, & \text{if } d_i(t) < \min\{v_i(t+1), v_{\max}\} \\
1, & \text{if } d_{i,\text{other}}^{right}(t) > 1 + \min\{v_i(t+1), v_{\max}\} - \min\{\lambda \cdot v_{i,\text{other}}^{right}(t+1), v_{\max}\} \\
1, & \text{if } d_{i,\text{back}}^{right}(t) > 1 + \min\{\lambda \cdot v_{i,\text{back}}^{right}(t+1), v_{\max}\} - \min\{v_i(t+1), v_{\max}\} \\
0, & \text{if } \text{rand}() < P_i^{right} 
\end{cases}$$

where, $d_{i,\text{other}}^{right}(t)$ is the distance between the lane change vehicle and the nearest front vehicle in the adjacent right lane; $d_{i,\text{back}}^{right}(t)$ is the distance between the lane change vehicle and the nearest rear vehicle in the adjacent right lane; $v_{i,\text{other}}^{right}(t)$, $v_{i,\text{back}}^{right}(t)$ are the speed of the front and rear vehicles closest to the lane change vehicle and the adjacent right lane. $1 + \min\{v_i(t+1), v_{\max}\} - \min\{\lambda \cdot v_{i,\text{other}}^{right}(t+1), v_{\max}\}$
is the safety distance between the lane change vehicle and the nearest front vehicle in the adjacent right lane; \(1 + \min\{\lambda \cdot v_{i,back}(t+1), v\_{max}\} - \min\{v_i(t+1), v\_{max}\}\) is the safety distance between the lane change vehicle and the nearest rear vehicle in the adjacent right lane.

(3) If the conditions of (1) and (2) are satisfied at the same time and \(rand() < P\), the lane is changed. That is, when the vehicle is blocked by the preceding vehicle in the original lane and there is a sufficiently safe space for lane-changing in the adjacent left and right lanes, the vehicle performs the lane change with the probability \(P\). \(P_i = P_{left}\) is the probability of changing lanes to the left; \(P_i = P_{right}\) is the probability of changing lanes to the right.

**Summary**

In this paper, through the analysis of STCA model and X-STCA model, combined with the actual situation of vehicle changing, this paper introduces the choice change probability which reflects the driving psychology. A traffic flow model of multi-lane cellular automata based on elastic safety change rules is established. The model is more in line with the actual driving situation of urban roads. The process is feasible and adaptable, and is simple and easy to implement.

**References**


