A More Realistic Highway Traffic Simulation Model Considering the Following Car Horning

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Abstract. In the present paper, a new CA-based model considering the following car horning is established and is analyzed in great detail. Firstly, how the following car horning can influence the traffic system is discussed. Secondly, by applying the cross-covariance method, proper parameters are indicated to explore the phase transition features of the model. The results show that the model proposed in this paper can simulate complex and realistic traffic phenomena.

Keywords: Traffic Simulation; Cellular Automaton;Following Car Horning

1. Introduction

Recently, various transportation simulation softwares have been widely used to investigate the traffic system, among which the TRANSIMS (Transportation Analysis Simulation System) is the most famous. When it comes to the multimedia traffic simulation, the first and the most important step is to build a pragmatic traffic model, the next step is to transfer the traffic model onto the simulation platform.

The city traffic is a complex non-linear system, empirical as well as theoretical studies of traffic flow have been widely used during the past decades. It is self-evident that the empirical analysis strongly depends on the external conditions, such as the weather influences etc. These dependencies mean that some of the subtleties of the observed data set can lead to different results. That is, to established a realistic empirical model is not an easy task. In some sense, a well-established simulation model is cost-effective, although both theoretical simulations and empirical investigations are still under debate.

Based on the observed data set, Kerner[1][2][3] introduced the three-phase traffic flow theory, three qualitatively different phases are suggested, which are (i) the Free-Flow, (ii) the Synchronized Flow and (iii) the Wide Moving Jam. By using statistical analysis, Neubert et al. established a framework for the classification of these different states[4]. These works will be acted as the first criteria to evaluate the model proposed in this paper which should be able to reproduce the phase transition between these three phases by optimizing the parameters involved. The second criteria concerns whether the simulation model is easy to be computerized or not.

Up to now, the CA-based model has been proven to be effective in simulating traffic flow. In 1992, Nasch and Schreckenberg developed the pragmatic NS model[5] based on the rule 184[6], the state of the traffic system at time t+1 can be obtained from the state at time t by applying the following 4 steps, (i)Acceleration, (ii)Deceleration, (iii)Randomization and (iv)Movement.

Although the NaSch model can simulate the spontaneous formation of the jam on the single-lane road, it still has its shortcomings. To solve the defects, various improved versions of the NaSch model have been developed so far, Such as the slow-to-start model[7][8][9], the Velocity Dependent Randomization model[10], the Velocity Effect Model[11], the CD and MCD model[12][13], the SDNasch model[14], the FI

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model[15][16], the KKW model[17][18][19], the CA-based Optimal Velocity model[20], as well as the car deceleration model considering its own velocity[21] etc.

These enormous scientific efforts focus basically on the interaction between the current car (the vehicle at site n) and the leading car (the vehicle at site n+1) . The distance to the leading car and the behavior anticipation of the vehicles in front of the current vehicle are most frequently used to construct the CA-based simulation model. Up to this point, seldom of the works deals with the interactive effect between the current car and the following car (the vehicle at site n-1). In real traffic the driver of the current vehicle is to be influenced when hearing the horning of the following vehicle. It should be noted that the horning effect of the following vehicle is less important in the free-flow due to the relatively long headway distance, but this effect can't be neglected in the congested traffic.

In order to describe the traffic more realistically, a further improved NaSch Model is firstly established in this paper, which is named the FCH-NaSch model. Next, computer simulations as well as the numerical analysis are made. By analyzing the numerical results, we can see that the FCH-NaSch model developed in this paper is in accordance with the real traffic.

The rest of the paper will be organized as follows: the FCH-NaSch model is proposed in section 2. The computational simulation and numerical analyzing is presented in section 3. The conclusion will be given in section 4.

2. Updating Rules

(1).Determination of the Acceleration Probability Function P_a :

$$P_a = \begin{cases} P_m, & if \ d_n \leq 1 \ or \ B_n = 1, \ slow \ to \ start \\ P_n, & if \ H_{n-1}(t) = 0 \ and \ d_n > 1, \ acclarate1 \\ P_l, & if \ H_{n-1}(t) = 1 \ and \ d_n > 1, \ acclarate2 \end{cases}$$

(2). Determination of the Randomization Probability Function P_r :

$$P_r = \begin{cases} P_b, & if \ B_{n+1}(t) = 1 \ and \ T_h < T_s = 1 \ and \ H_{n-1}(t) = 0 \\ P_o, & if \ B_{n+1}(t) = 0 \ and \ H_{n-1}(t) = 0 \\ P_h, & if \ H_{n-1}(t) = 1 \end{cases}$$

(3). Acceleration:

$$if \ B_n = 0 \ then$$
$$\{$$
$$if \ d_n \leq 1, \ then \ V_n(t+\frac{1}{3}) = \min(V_n(t)+1, V_{max}); \qquad (P_m)$$

$$if \ H_{n-1}(t) = 0 \ and \ d_n > 1, \ then \ V_n(t+\frac{1}{3}) = \min(V_n(t)+1, V_{max}); \ (P_n)$$

$$if \ H_{n-1}(t) = 1 \ and \ d_n > 1, \ then \ V_n(t+\frac{1}{3}) = \min(d_n, V_{max}); \qquad (P_l)$$

$$\}$$
$$else$$
$$\{$$
$$V_n(t+\frac{1}{3}) = \min(V_n(t)+1, V_{max});$$
$$\}$$

(4). Randomization:

if $B_{n+1}(t) = 1$ and $T_h \leq T_s$ and $H_{n-1}(t) = 0$, then

$$V_n(t + \frac{2}{3}) = \max(\ V_n(t + \frac{1}{3}) - 1, 0); \qquad (P_b)$$

if $B_{n+1}(t) = 0$ and $H_{n-1}(t) = 0$, then

$$V_n(t + \frac{2}{3}) = \max(\ V_n(t + \frac{1}{3}) - 1, 0); \qquad (P_o)$$

if $H_{n-1}(t) = 1$, then

$$V_n(t + \frac{2}{3}) = \max(\ V_n(t + \frac{1}{3}) - 1, 0); \qquad (P_h)$$

(5).Deceleration:

$$V_n(t + 1) = \min(d_n, V_n(t + \frac{2}{3}));$$

(6). Movement:

$$X_n(t + 1) = X_n(t) + V_n(t + 1);$$

(7).Car Braking Status Updating:

if $V_n(t + 1) < V_n(t)$,

then

$B_n(t + 1) = 1;$

else

$B_n(t + 1) = 0;$

(8).Car Horning Status Updating:

if $d_n(t + 1) = gap_{security}$ and $rand < P_{horn}$, then

$H_n(t + 1) = 1;$

else

$H_n(t + 1) = 0;$

In the mathematical model mentioned above, rand is an uniformly distributed random number between 0 and 1. V_n and X_n are used to indicate the velocity and the place of the current vehicle respectively. n+1 represents the leading vehicle and n represents the following vehicle. Cars are numbered in the driving direction. $B_n(t) = 1$ means that the vehicle at site n and time t brakes and the brake light is switched on, otherwise $B_n(t) = 0$. $H_n(t) = 1$ means that at site n and time t the current vehicle is horning, otherwise $H_n(t) = 0$. d_n is the distance of the current vehicle to its predecessor, const $gap_{security}$ is the security distance to avoid accident which will be set to 1 cell in this model. Parameter $T_h = d_n / V_n(t)$ stands for the time headway between the current vehicle and the vehicle ahead. Parameter $T_s = \min(V_n(t), h)$ stands for the time scope within which a driver can react. By setting $T_h < T_s$ to make sure that the driver will not overreact when deccelerating, the value h will be set to 6s in this model. P_{horn} is the horning probability for each car. To illustrate the details further, we will explain the model as follows:

(i).For each car, the braking effect of the last step is considered, if the current vehicle switched on the brake light on the last step, the slow-to-start (see ref. [9]) acceleration will be applied. P_m, P_n, P_n will be indicated firstly. The following car horning effect will be considered when accelerating. When $P_a = P_n$, the

velocity of the car is enhanced by one unit. When $P_a = P_l$, the next velocity of the current car will be set according to the headway distance to its predecessor (see ref. [15]).

(ii). To get a higher flow rate, like the SDNaSch model (see ref [14]), the randomization step will be placed before the deceleration step. In the randomization step, instead of only one randomization probability P_l is used, three different randomization probability P_b, P_o, P_h will be set due to the braking effect and the following car horning effect.

(iii).After the movement step, the status of the vehicle will be updated.

3. Computer Simulation and Numeriacl Analysis

In this paper the simulation is performed on the one-dimensional cellular automaton. A ring of 1000 cells is to be used, the length of the cell is given by 7.5m, the length of the road

$$L = 1000 \; sites \; \approx 7.5 \; km \tag{1}$$

One time step corresponds to 1s, the velocity of each vehicle is in the range from 0 cell/s to 5 cell/s. The maximal velocity

$$V_{max} = 5 \; cells/s \approx 135 \; km/h. \tag{2}$$

We started with average initial condition, N cars were uniformly distributed on the road. Thus, three most common variables are global flow rate J, mean speed V and the vehicle density ρ, which are defined as the follows:

$$\rho = \frac{N}{L}, \quad V_{avg} = \frac{1}{T} \sum_{t=t0}^{t0+t-1} V(t) \quad J = \rho \times V_{avg} \tag{3}$$

The open boundary will be applied in the simulation, the boundary checking step will be carried out after each evolution. If the car has exceeded the first site, it will leave the traffic system. In the meantime a new car with random velocity will be introduced into the traffic system if the last site is empty.

3.1. The Analyzing of the FCH Effect

As mentioned above, when the density is relatively low, the following car horning effect on the traffic system will be relatively week. We set the average vehicle density to $\rho = 0.2$ which corresponds to 28 veh/km. This given vehicle density is related to the Synchronized Flow, the distinguishing of which will be illustrated in the next section. The spatial-temporal pattern depicted in Fig 1 shows that the traffic congests are alleviated when the probability P_l is increasing. Fig 1.(d) is an bit of exaggeration which can only exist theoretically. In the real traffic, not all drivers accelerate when hearing the horning. The pattern showed in Fig 1.(d) is only used to stress the following car horning effect on the congested traffic.

The following car horning effect on the traffic can be more clearly viewed by using the fundamental diagram. In the density range from 0 to 1.0, we depict the flow-density plane for different probability P_l.
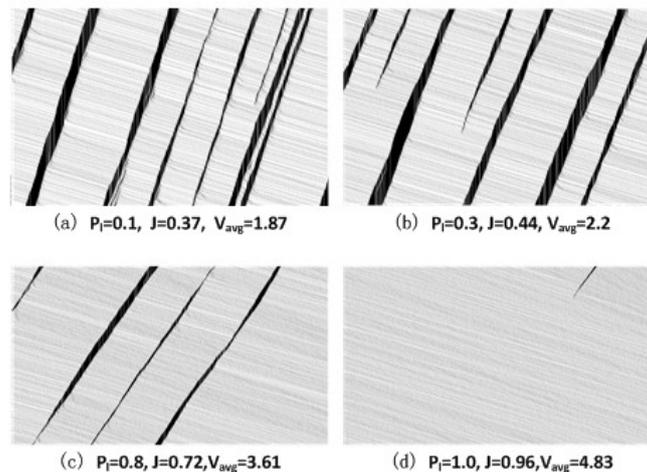

(a) P$_l$=0.1, J=0.37, V$_{avg}$=1.87   (b) P$_l$=0.3, J=0.44, V$_{avg}$=2.2

(c) P$_l$=0.8, J=0.72,V$_{avg}$=3.61   (d) P$_l$=1.0, J=0.96,V$_{avg}$=4.83

Fig 1: The spatial-temporal diagram pattern under different probability P1.The average vehicle density is set to p=0.2

From Fig.2 It can be suggested that, in the free flow the following car horning effect on the traffic is limited. But, when the vehicle density exceeds some critical density ($\rho_c \approx 0.2$ in this model), it is showed that the higher the horning acceleration probability P_l is, the higher are the average flow rate and the average velocity.
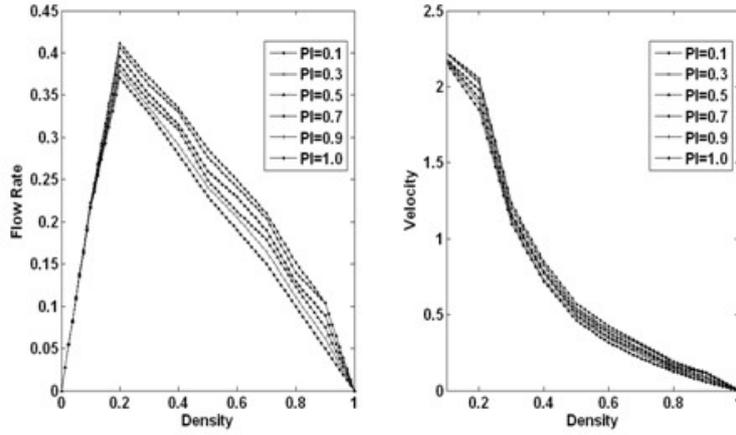

Fig 2: The Fundamental Diagram of the Model under Different Horning acceleration probability pl.

3.2. The Phase transition features of the Model

In kerner's work (see ref. [1]) , it is supposed that the hypothetical steady states of synchronized flow cover a two-dimensional region in the flow-density plane. By setting $P_m = 0.01$, $P_l = 0.35$, $P_b = 0.8$, $P_o = 0.5$, $P_h = 0.1$, we make the fundamental data analysis of 1 min period . The results in Fig 3 suggest that the FCH-Model proposed in this paper can simulate synchronized flow where average speed is greater than 40km/h. Due to the adjustment effect caused by the horning, the amplitude of the flow rate in the congested traffic is relatively limited. The following car horning effect helps to evacuate the congested traffic.

$$CC_{J,\rho}(\tau) = \frac{\langle J(t)\rho(t+\tau)\rangle - \langle J(t)\rangle\langle \rho(t+\tau)\rangle}{\sqrt{\langle J^2(t)\rangle - \langle J(t)\rangle^2}\sqrt{\langle \rho^2(t)\rangle - \langle \rho(t)\rangle^2}}$$

(4)

To investigate the phase transition features of the FCH-NaSch model more precisely, the cross-covariance (see ref. [4]) is introduced, by using which the synchronized flow will be distinguished from the stop-and-go pattern. It has been proven that, in stop-and-go traffic, large values of the cross-correlation can be obtained. But the synchronized flow is characterized by decoupling of density and flow rate. According to (4), in the synchronized flow $CC_{J,\rho}(0) \approx 0$ can be observed, in the stop-and-go pattern $CC_{J,\rho}(0) \approx 1$ is suggested.

As just mentioned, in the simulation for congested traffic, vehicle density between 20~30 veh/km which corresponds to $\rho \approx 0.16 \; to \; 0.22$ is used to simulate the synchronized flow. Vehicle density between 30~50 veh/km which corresponds to $\rho \approx 0.23 \; to \; 0.36$ is applied to simulate the stop-and-go pattern. Vehicle density lower than 20 veh/km is appropriate to describe the free flow in this paper.
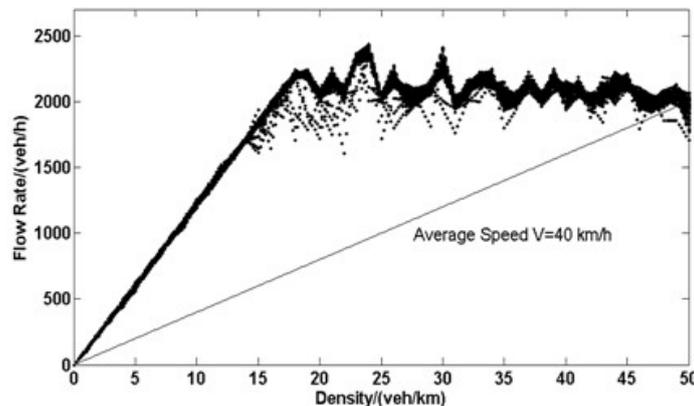

Fig 3: The "1 minute" flow-density diagram

When parameters $P_m = 0.01$, $P_l = 0.35$, $P_b = 0.8$, $P_o = 0.5$, $P_h = 0.1$ are indicated, Fig 4 shows the spatial-temporal pattern of these three traffic phase, and the time series analysis of the mean speed of the model can be seen from Fig 5 to Fig 7.
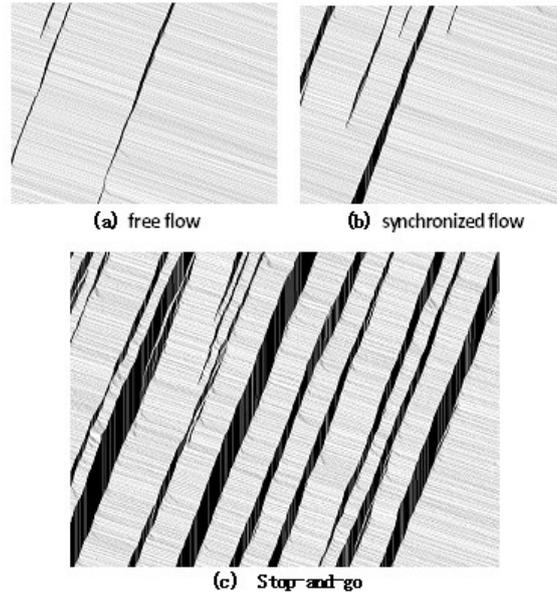

(a) free flow   (b) synchronized flow

(c) Stop-and-go

Fig 4: Different spatial-temporal patterns similated by the model.

The simulation is performed on a homogeneous single-lane highway road (a road without bottlenecks). Fig 4 (a) is obtained by setting the density to 15~20 veh/km($\rho \approx 0.14$), Fig 4 (b) to 20~25 veh/km ($\rho \approx 0.17$) , Fig 4 (c) to 35~40 veh/km($\rho \approx 0.25$). In the free flow pattern, most of the vehicles move in their anticipated speed, but tiny vehicle concentration phenomenon can still be observed. It is noted that in Fig 4 (b), the synchronized flow sometimes is accompanied by narrow moving jams of low vehicle speed. In the stop-and-go pattern depicted in Fig4 (c) overlapping states of wide moving jam and synchronized flow are observed. Complex traffic phenomena can be simulated by the FCH-NaSch model proposed in this paper by setting appropriate parameters.

The congested traffic is always accompanied by the "speed drop" phenomenon. The time series analysis of average velocity in 100 min period is applied to reproduce this phenomenon. By installing a virtual detector on the road the 1-minute aggregates of vehicle speeds can be obtained. In free flow (Fig 5), relatively large mean speeds can beobserved, which are ranged from 115 km/h to 125 km/h. Due to the sufficiently long headway distance between vehicles, the speeds of vehicles mainly depend on the individual driving habit of the drivers, which is reflected by the sharp fluctuations of the speed curve. In the previous discussion about Fig 4, it is suggested that overlapping states of wide moving jam and synchronized flow are observed in congested traffic.
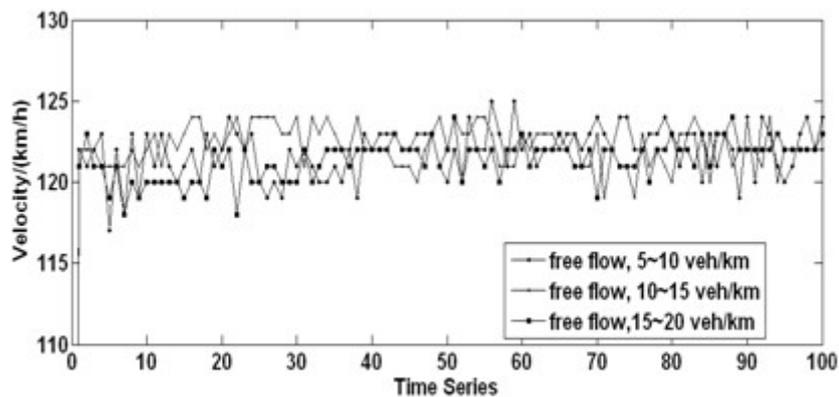

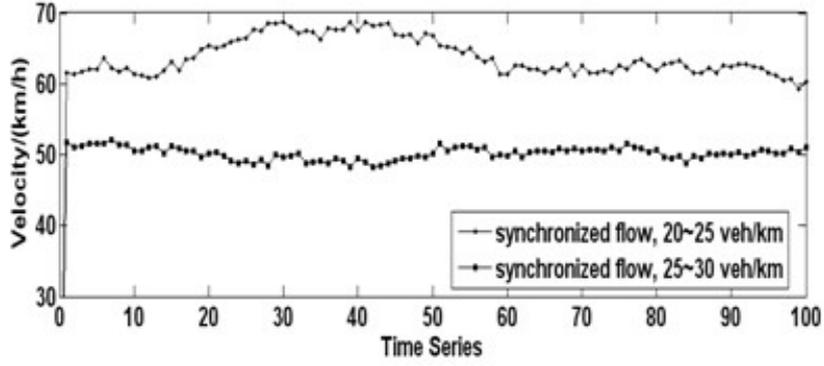Fig 5: The time series features of the vehicle velocity during 100 minutes in the Free-Flow state

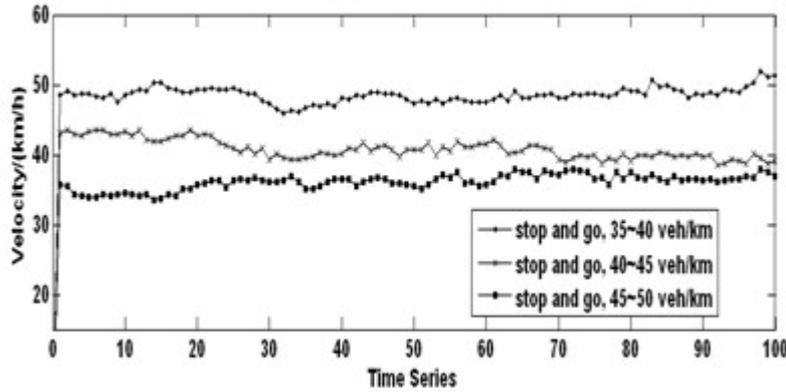Fig 6: The time series features of the vehicle velocity during 100 minutes in the Synchronized-Flow state

Fig 7: The time series features of the vehicle velocity during 100 minutes in the stop-and-go state

Apart from that, the time series of 1-minute aggregates of speeds shown in Fig 5 and Fig 6, which are characterized by minute fluctuation, allow us to suggest that the following car effect helps to enlarge the headway distance between vehicles. Despite that the steady state of traffic is only a kind of postulation (ref. [1]), the trend towards a time-independent speed curve still can be seen especially in congested traffic. The enlarging of headway distances between vehicles in congested traffic and the trend to steady state caused by the following car horning allow us to suggest that the FCH-NaSch model is characterized by the evacuation effect.

3.3. Transfering onto the simulation platform

In the previous section, a model for vehicle flow has been constructed and analyzed in detail. In this part, some of the critical indicators about how we can transfer the traffic model onto the simulation platform are briefly introduced.

Before transferring the traffic model onto a simulation platform, one must indicate the following parameters properly:

(i): The length of the simulation road:

$$L_{sim\_road} = L_{sim\_cell} \times K$$

Where L_{sim_cell} is the simulation length represented by each cell. K is the total number of the cells used in the model.

(ii) The average flow rate of the model as in equation (2).

(iii) The average velocity of the model as in equation (3). But the unit of the velocity must be converted to the metric unit (km/h) by considering the simulation length of each cell.

(iv) The shape of the road to be simulated. In the traffic model, a straight road is hypothesized. But the real shape of the simulation road must be considered when we transfer the traffic model onto a multi-media platform.

4. Conclusions

Based on the NaSch model, a new model considering the following car horning is proposed in this paper. In the new model, the current vehicle movement is not only influenced by the anticipation to its predecessor, by also by the car following it. Two probability functions are introduced in this paper, namely the acceleration probability function and the randomization probability function. These two functions are used to refine the movement of vehicles.

The following car horning effect on the traffic system is investigated firstly on the spatial-temporal pattern and then on the fundamental diagram. The simulation results show that the higher the probability P_l is, the higher are the average flow rate and the average vehicle speed. Especially, the following car effect on the traffic is more obvious in the congested traffic.

By applying the cross-covariance method, the parameters are reasonably indicated to simulate the free flow, the synchronized flow and the stop-and-go pattern. The spatial-temporal patterns and the time series diagrams are plotted. In the spatial-temporal pattern, complex traffic phenomena like the overlapping states are observed. By analyzing the time series of speeds, one can suggest that the evacuation effect of the model is related to the following car horning. In our future work the calibration and verification of the model using real traffic data set will be performed.

5. Acknowledgement

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