Traffic flow simulation of modified cellular automata model based on producer-consumer algorithm

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Abstract

With the rise of new technologies such as the Internet of Vehicles and the Internet of Things, research on the intelligent connected vehicle has become a hot topic in contemporary times. The modeling and simulation of traffic flow are mainly used to analyze the characteristics of traffic flow and study the formation and dissipation mechanism of traffic congestion to better guide the real traffic. Cellular automata are suitable for the simulation of complex giant systems. Because of the randomness and discreteness of vehicle driving, cellular automata are often used to model and analyze traffic flow. This paper mainly studies the traffic flow formed by intelligent connected vehicles. Based on the traditional NaSch model, the producer-consumer algorithm is introduced to form a multi-buffer vehicle information access mode, and an improved cellular automata model with random updates is constructed. The simulation results show that the improved cellular automata model improves the traffic congestion significantly compared with the original NaSch model in the intelligent network environment, which is consistent with the actual traffic situation. Therefore, the algorithm proposed in this paper can effectively simulate the traffic flow characteristics of intelligent connected vehicles, and provide a theoretical basis for solving traffic problems.

Introduction

36   In recent years, with the rapid development of social economy, the number of urban car
37   ownership is on the rise. However, the expansion of urban roads and the construction of
38   transportation infrastructure are far from being able to meet the substantial increase in the
39   number of cars, thus causing traffic problems such as traffic congestion *(Yao et al., 2021)*. In
40   order to alleviate urban traffic congestion and improve road traffic efficiency, intelligent
41   networked vehicles emerge as the times require *(Chu et al., 2021)*.

42   At present, the proportion of intelligent connected vehicles in urban traffic is increasing day
43   by day *(Wei et al., 2020)*. Scholars at home and abroad have researched the traffic flow
44   simulation of new intelligent connected vehicles. *Zhang et al. (2021)* constructed a mixed traffic
45   flow model with intelligent connected vehicles and analyzed the factors influencing the stability
46   of traffic flow. *Liu et al. (2021)* studied the traffic flow characteristics of intelligent connected
47   vehicles under different proportions in mixed traffic flow and showed that with the increase of
48   intelligent connected vehicles, the speed and density of traffic flow increased to a certain extent.
49   *Pan et al. (2021)* constructed a microscopic traffic flow model to analyze the behavioral
50   decisions of intelligent connected vehicles at no-signal intersections. There are still many
51   deficiencies in the research of urban road traffic flow model under an intelligent network
52   environment, which can not fully show the traffic flow characteristics of new intelligent
53   connected vehicles. Therefore, the traffic flow modeling analysis of intelligent connected
54   vehicles still needs further research.

55   The discreteness of cellular automata model in time, space and state can simplify complex
56   traffic flow problems *(You et al., 2021)*, so it is widely used in the study of traffic flow and
57   becomes a powerful tool for studying road traffic flow problems *(Tian et al., 2020)*. *Matcha et al.*
58   *(2020)* summarized the car following model and simulation framework under mixed traffic flow,
59   constructed 2D driver behavioral models, discussed the interaction between vehicles under
60   mixed traffic flow, and provided a scheme to alleviate traffic congestion. *Jiang et al. (2002)* used
61   cellular automata to simulate synchronous traffic flow and analyze the congestion, dissipation,
62   and other characteristics of traffic flow. Through the difference in acceleration and deceleration
63   behavior under different driving conditions, the Jiang and Wu model was improved by *Tian et al.*
64   *(2009)*, and the deceleration difference was used to reproduce the synchronous flow. *Tian et al.*
65   *(2021)* discussed the cellular automata model for studying synchronous flow in traffic flow. And
66   the importance of randomness in cellular automata model is proposed. *Hua et al. (2020)* studied
67   driving behaviors on roads with three-dimensional facilities such as toll stations and construction
68   areas and proposed a traffic flow model with changes in cellular space width. *Wahle et al. (2001)*
69   proposed a theoretical model of online simulated road traffic flow that can reproduce traffic
70   quality and carried out dynamic management of the road traffic network. *Tong et al. (2020)*
71   evaluated the cellular automata models in the past 20 years, summarized the specific evaluation
72   indicators, and analyzed the simulation quality and reproduction reliability of the models.

73   For intelligent networked vehicles that need to share information in a large range, the
74   traditional traffic flow research based on cellular automata cannot show the randomness of
75   information transmission in information sharing due to its parallelism. This paper proposes an
76   improved cellular automata model based on the producer-consumer algorithm to study the traffic

77 flow characteristics of intelligent connected vehicles.

78 The main contributions of this paper are: (1) The idea of the producer-consumer algorithm is
79 introduced into the cellular automata model, which makes the simulation of road traffic flow
80 more in line with the information sharing mechanism of vehicles under the condition of
81 intelligent network connection. (2) Effectively analyze the application of intelligent network to
82 traffic flow problems, and verify the analysis results that intelligent networked vehicles can
83 improve road traffic congestion. (3) Through the analysis of the simulation results, theoretical
84 guidance is provided for increasing the free flow area in road traffic, increasing the speed of
85 vehicles, and accelerating the dissipation phenomenon of congestion.

86

Related work

88 Traffic flow theory appeared in the 1930s and was mainly studied using the methods of
89 probability theory. *Kinzer et al. (1933)* introduced probability theory to highways in 1933, and
90 discussed the application of Poisson distribution in traffic problems. In 1935, *Greenshields et al.*
91 *(1935)* conducted research on traffic capacity, which constructed a mathematical model through
92 the methods of probability theory and mathematical statistics, and the relationship between flow
93 and speed was proposed. In 1936, *Adams et al. (1936)* treated road traffic as a random sequence
94 and published numerical examples. In 1947, *Greenshields et al. (1947)* used Poisson's law to
95 analyze the traffic performance of urban intersections. In the 1950s, as the industry developed,
96 probabilistic methods could not represent the interactions between vehicles. Car following theory,
97 traffic wave theory and vehicle queuing theory appeared one after another. In December 1959,
98 the convening of the International Symposium on Traffic Flow Theory marked that the traffic
99 flow theory entered a period of rapid development. Scholars mainly conduct research on traffic
100 flow characteristics, traffic flow models, and traffic flow simulation. Due to the complexity and
101 dynamics of the traffic system *(Esser et al., 1997)*, the use of simulation technology to study
102 traffic behavior can more intuitively reveal the basic laws and formation mechanisms of traffic
103 flow phenomena *(Monteil et al., 2014)*. According to the different simulation objects, traffic
104 simulation can be divided into microscopic, mesoscopic and macroscopic traffic flow simulation
105 *(Burghout et al., 2005)*. The microscopic traffic flow simulation studies the individual behavior
106 of vehicles, mainly represented by the car following model and the cellular automaton model
107 *(Ming et al., 2012)*. The real traffic system has a large scale and a wide variety. The cellular
108 automata model has developed rapidly in the field of traffic flow simulation with the progress of
109 computer application technology due to its simple structure and fast calculation *(Brilon et al.,*
110 *1999)*. Therefore, cellular automata has a wide application prospect in the field of transportation.
111 In the early 1950s, Von Neumann proposed the theory of cellular automata to solve the
112 problem of self-replication of machines *(Neumann, 1951)*. In the 1970s, John Horton Conway
113 created a "game of life" that simulates the characteristics of natural life by formulating three
114 simple rules of survival *(Martin et al., 1970)*. In 1986, Cremer and Ludwig first applied cellular

115 automata theory to the simulation modeling of traffic flow, and achieved rapid development in

116 the field of traffic *(Cremer et al., 1986)*. In the 1980s, Wolfram conducted a comprehensive

117 study of the models produced by the 256 rules of one-dimensional cellular automata. Among

118 them, the cellular automata model of Rule 184 was applied in the field of traffic flow and

119 became the basic model to simulate complex traffic flow phenomenon *(Wolfram et al., 1984)*. In

120 1992, Nagel and Schreckenberg introduced cellular automata into highway modeling and

121 proposed the classic NaSch model *(Nagel et al., 1992)*. NaSch model formulates four evolution

122 rules of acceleration, deceleration, random slowing down and position update to realize the

123 simple simulation of single-lane traffic flow. As a classic case of cellular automata applied to

124 two-lane traffic flow, STNS(symmetric two-lane Nagel-Schreckenberg) model was introduced

125 by *Chowdhury et al. (1997)*. The STNS model adds two lane-changing rules based on the NaSch

126 model, which are the driver's lane-changing motivation and the safety distance between vehicles,

127 which can be used to simulate lane-changing behavior in multi-lane traffic flow. After that,

128 *Knospe et al. (2002)* proposed an asymmetric lane-changing rule by extending the expected

129 driving single-lane model, and an asymmetric two-lane cellular automaton model was

130 constructed. These are all studies of discrete cellular automata. In 2012, a continuous cellular

131 automaton based on fuzzy reasoning was proposed by *Yeldan et al. (2012)*. The cellular automata

132 theory has been keeping up with the changes of the times to improve the traffic flow model.

133  Based on 184 model, the applications of cellular automata models in traffic flow can be

134 divided into two categories. The research on urban road traffic flow represented by NaSch model

135 and the research on urban traffic network represented by BML model are respectively. Their

136 extended models are shown in Table 1.

137  Table 1

Theoretical basis

Cellular automata theory

140  A cellular automaton is a dynamic system that evolves in the discrete-time dimension in the

141 cellular space composed of discrete and finite-state cells according to certain local rules*(Chai et*

142 *al., 2015)*. Cellular automata are mainly composed of cellular, cellular space, neighbor, and

143 cellular state evolution rules, which can simulate many complex giant systems in real life

144 according to simple evolution rules *(Valente et al., 2018)*. Cellular can also be called cell, unit,

145 which is the most basic component of cellular automata. Cell space is the collection of all grid

146 points in the cell space. Among them, the cellular space of two-dimensional cellular automata

147 can be divided into a triangular grid, quadrilateral grid, and hexagonal grid according to the

148 geometric space division. The local cell space searched by the central cell to update its status is

149 called the neighbor cell of that cell. One-dimensional cellular automata can determine neighbor

150 cells according to a radius. The common neighbor types of two-dimensional cellular automata

151 include Von Neumann type, Moore type, and extended Moore type. The evolution rule of

152   cellular state is the dynamic function that the central cellular determines the state at the next
153   moment according to its neighbor cellular and its state. The rationality of the setting of evolution
154   rules determines whether the cellular automata model can objectively show the essential
155   characteristics of the system, which is the core of the whole cellular automata model construction.
156
157

Basic cellular automata model -- NaSch model

159   In NaSch model, 1*n squares are used to represent driving roads and form cellular space. The
160   current cell takes the left and right cells as the neighbor cell. The current cell can be empty, or it
161   can be occupied by a vehicle. When occupied by a vehicle, the vehicle speed is between 0 and
162   V_{max}. NaSch model added stochastic factors based on model 184, which is used to simulate
163   various influencing factors in the driving process, and random slowing down probability P is
164   introduced. There are four evolution rules at the moment of cellular $t \sim t + 1$, which are:
165   A*ccelerate*:

166 $$V_n(t + 1) \rightarrow \min\{V_n(t) + 1, \ V_{max}\}$$

167   Indicates that the driver always wishes to travel at maximum speed.
168   *Decelerate*:

169 $$V_n(t + 1) \rightarrow \min\{V_n(t), \ D_n\}$$

170   The driver slowed down to avoid a rear-end collision.
171   *Random slowing down (With probability P)::*

172 $$V_n(t + 1) \rightarrow \min\{V_n(t) - 1, \ 0\}$$

173   Driver deceleration measures caused by various uncertainties.
174   *Location Update*:

175 $$X_n(t + 1) \rightarrow X_n(t) + V_n(t + 1)$$

176   The car continued to drive at the updated speed.
177   Where X_n represents the position of vehicle n, V_n represents the speed of vehicle n. D_n
178   represents the distance between vehicle n and vehicle n + 1, $Dn = X_{n+1} - X_n - L$, where L
179   represents the length of the vehicle.

Producer-consumer model

181   Producer-consumer problem *(Zhang et al., 2017)* was first proposed by Dijkstra in 1956.
182   Producers and consumers share a buffer concurrently for the same period, and producers send the
183   data they produce into the buffer for consumption by consumers. The consumer fetches data
184   from the buffer and frees the buffer. When a producer produces data, if the buffer is full, it needs
185   to wait for the consumer to release an empty buffer before it can continue to put data into the
186   buffer. If the buffer is empty, the consumer must wait for the producer to put data into the buffer
187   before continuing to consume.
188   The traditional producer-consumer model is mainly used to solve the problem of multi-thread
189   concurrent execution in the operating system. In recent years, the technology of the Internet of
190   Vehicles and the Internet of Things have developed rapidly. The producer consumer model is

191 introduced into the modeling of multi-vehicle intelligent networking model optimization
192 *(Vazquez et al., 2021)* to solve the problems of information sharing and vehicle positioning
193 between intelligent connected vehicles, which is of great significance to the research of
194 intelligent connected vehicle traffic flow in real life.
195

Improved cellular automata model

197 Intelligent connected vehicles are equipped with multiple types of sensors, which are used for
198 large-scale information communication between vehicles *(Limbasiya et al., 2019)*. The driving
199 information update of intelligent connected vehicles on the road is not carried out at the same
200 time due to the influence of the distance difference between the vehicle in front, network quality,
201 the driver's psychological state, driving habits and other factors. The NaSch model can simulate
202 the basic acceleration and deceleration operations of vehicles, simulate the phenomenon of
203 random slowing down caused by external factors, and study the formation and dissipation
204 mechanism of traffic flow congestion. However, due to the concurrent execution mechanism of
205 the cellular automata model, the random sharing of information between intelligent connected
206 vehicles cannot be simulated.
207   The idea of sharing information with multiple buffers in the producer-consumer model can
208 extend the single buffer mode used for information processing in traditional cellular automata
209 models (such as NaSch model), and provide a solution to the problem of random information
210 sharing among intelligent connected vehicles. Based on NaSch model, the location information
211 and speed information of intelligent connected vehicles are stored in a multi-buffer group.
212 Information sharing between vehicle sensors in the same period is stored randomly according to
213 the sequence of data generation. After the data is passed into the buffer space, the following
214 vehicle accelerates, decelerates, randomly slows down, and updates its position according to the
215 shared information of the preceding vehicle. After data update, information is passed into the
216 buffer space, forming a closed-loop of information sharing. The order of information access is
217 related to the information processing of intelligent connected vehicles and has randomness. The
218 sequential access mode of the previous cellular automata model is changed, and an improved
219 cellular automata model with multi-buffer random access without putting back based on the
220 producer-consumer algorithm is constructed. The model is used to simulate and analyze the
221 traffic flow of intelligent connected vehicles with sensors, which can effectively show the
222 situation of information processing error updates of intelligent connected vehicles in the same
223 period in real life. The problem of updating traditional cellular automata data at the same time is
224 solved, which is consistent with the randomness of actual road traffic flow.
225   The algorithm in the case of the improved cellular automata model can be summarized as
226 shown in Table 2:
227   Table 2

Results and discussions

229   Table 3

230   The initialization of simulation parameters is shown in Table 3. The experimental road is a single
231   lane with a total length of 1000 cells, and 200 vehicles are randomly distributed on the road in
232   the initial state. Assuming the length of the vehicle is 1 cell, the maximum speed is 5 cells/s. At
233   the start of the simulation, the vehicle is traveling at a speed of 1 cell/s. In the traffic flow graph,
234   the white square represents a vehicle at the position, and the black square represents an empty
235   cell, that is, there is no vehicle at the position. In this experiment, the simulation step size is set
236   to 1000 steps, and the opening boundary condition is used.
237   Figure 1
238   Figure 1 A~D represent the space-time diagrams of the NaSch model, the improved cellular
239   automata model, the model considering the driver factor, and the improved model considering
240   the driver factor, respectively. The abscissa represents the spatial position of the cell, and the
241   ordinate represents the simulation time. Select the most representative 500~1000 spatial
242   positions and 0~200s time cells to form the space-time map of the vehicle for discussion. The
243   white square in the figure indicates that there is no car at the location, and the black square
244   indicates that there is a car at the location. The driving direction of the vehicle is from left to
245   right, and the time goes from bottom to top. As shown in Figure A, the NaSch model shows that
246   the traffic congestion gradually propagates upstream of the road over time, and there is a large
247   number of wide congestion bands. The improved cellular automata model after adding the
248   producer-consumer concept changes the rules of sequential update of vehicles on the road. And
249   the position and speed of the vehicle are updated in a random form, which is more in line with
250   the reality that the vehicle moves forward randomly. As shown in Figure B, as time goes by, the
251   number of blocking strips decreases and the width narrows, the traffic congestion on the
252   upstream side of the road gradually dissipates, and the free flow area in the lane becomes larger,
253   and there is no large-scale congestion area. Compared with the NaSch model, the improved
254   cellular automata model significantly reduces the number of congestion zones, and the traffic
255   congestion situation is greatly improved. It can be seen that the improved cellular automata
256   model can effectively alleviate the traffic congestion on the road.
257   When the current vehicle speed is low, the driver tends to increase the acceleration with a high
258   probability, thereby rapidly increasing the driving speed of the vehicle. At the same time, some
259   drivers tend to maintain the existing acceleration and gradually increase the speed. Based on this
260   phenomenon, a new model is constructed by adding conditions to the classical NaSch model,
261   which is called the model considering the driver factor, which considers the acceleration changes
262   of the vehicle and integrates human behavior with a fuzzy variable. As shown in Figure C, the
263   congestion spreads upstream of the road over time. A wide blocking strip is gradually formed in
264   front of the road and tends to expand. The space-time diagram of the improved model
265   considering the driver factor after adding the producer-consumer concept is shown in Figure D.
266   Compared with Figure C, the traffic congestion dissipates significantly over time, the number of
267   blocking strips on the road decreases, and the width of the blocking strips narrows. The
268   comparison shows that the improved model considering the driver factor can accelerate the
269   dissipation of the congested area and expand the free flow area on the road.
270   Figure 2

271   Figure 2 A~D represent the flow-density diagrams of the NaSch model, the improved cellular
272 automata model, the model considering the driver factor, and the improved model considering
273 the driver factor, respectively. The NaSch model is shown in Figure A, when the vehicle density
274 increases, the traffic flow also increases. When the density increases to about 0.165, the flow
275 reaches the maximum value of 0.49, that is, the optimal density is 0.165. Before reaching the
276 optimal density, the traffic flow on the road is generally in a free-flow state. After reaching the
277 optimal density, the traffic flow changes from a free-flow state to a blocked state, and the traffic
278 is congested and the traffic flow decreases. The flow-density diagram of the improved cellular
279 automata model is shown in Figure B. Compared with Figure A, the optimal density value of the
280 improved cellular automata model is the same as that of the NaSch model. The improved cellular
281 automata model is stronger in overall compactness of the image, and the traffic flow value before
282 reaching the optimal density value is higher than that in the NaSch model. Therefore, compared
283 with the NaSch model, the improved cellular automata model has higher vehicle velocity, less
284 traffic congestion, less metastable traffic flow, and better road traffic conditions.
285   The flow-density diagram of the model considering the driver factor is shown in Figure C.
286 Before reaching the maximum traffic flow, with the increase of vehicle density, the traffic flow
287 showed an upward trend. After that, with the increase of vehicles, the traffic congestion situation
288 intensified, and the traffic flow showed a downward trend. When the vehicle density is about
289 0.17, the traffic flow reaches a maximum value of about 0.58, that is, the optimal density is 0.17.
290 The flow-density diagram of the improved model considering the driver factor is shown in
291 Figure D. When the vehicle density is about 0.155, the traffic flow reaches a maximum value of
292 about 0.57, that is, the optimal density is 0.155. The improved model after the introduction of the
293 producer-consumer concept reduces the optimal density value and increases the overall traffic
294 flow compared to Figure C. The improved model accelerates the dissipation of traffic congestion
295 and the expansion of free-flow areas on the road.
296   Figure 3
297   Build a thermodynamic diagram based on the speed of vehicles on the road. In this experiment,
298 the vehicle speed is divided into six levels from 0 to 5, in which the yellow is the maximum
299 speed of 5cells/s, and the blue is the stationary state, that is, 0cells/s. The abscissa of the
300 thermodynamic diagram represents the spatial position of the cell, and the ordinate represents the
301 simulation time. The driving direction of the vehicle is from left to right, and time moves in a
302 top-to-bottom direction. Select the space-time region composed of 700-1000 spatial positions
303 and 0-300s time cells for thermodynamic diagram analysis.
304   Figure 3 A~D represent the thermodynamic diagrams of the NaSch model, the improved
305 cellular automata model, the model considering the driver factor, and the improved model
306 considering the driver factor, respectively. The NaSch model is shown in Figure A, with the
307 passage of time, the vehicles on the road show a state of low speed, the vehicles stop and go, and
308 the congestion increases. The thermodynamic diagram of the improved cellular automaton model
309 is shown in Figure B, with the passage of time, the blocking bars are reduced, the number of
310 vehicles stop and go is reduced, and the number of vehicles traveling at the maximum desired
311 speed of 5cells/s is increased. Compared with Figure A, the improved cellular automata model

312 improves road congestion, the area of the vehicle free flow state is increased, and most vehicles
313 are in a high-speed driving state. Therefore, the improved cellular automata model can
314 effectively dissipate traffic jams, improve the overall flow speed of the road, and meet the needs
315 of drivers who always expect to travel at the maximum speed.
316   The thermodynamic diagram of the model considering the driver factor is shown in Figure C.
317 With the passage of time, the free flow area on the road decreases, traffic congestion increases,
318 and low-speed vehicles gradually increase. The thermodynamic diagram of the improved model
319 considering the driver factor is shown in Figure D. With the passage of time, the free flow area
320 of the improved model increases, traffic congestion is greatly improved, and most vehicles on the
321 road travel at high speeds. Compared with Figure C, the improved model has fewer stationary
322 vehicles, more high-speed vehicles, and the overall flow velocity of the road is improved. This
323 satisfies the driver's need to always expect to travel at the maximum speed, and improves the
324 driver's driving experience on the road.

Conclusions

326 Based on the NaSch model, this paper introduces the producer-consumer model to improve it.
327 According to the experimental results, the improved cellular automata model is more consistent
328 with the driving conditions of vehicles on the road in real life. According to the analysis of
329 experimental data, it shows that the improved cellular automata model can effectively ease road
330 congestion and accelerate the dissipation of traffic jam. Compared with NaSch model, traffic
331 flow and driving speed are improved to a certain extent, which can meet drivers' requirements on
332 driving roads to a large extent and provide a theoretical basis for alleviating traffic congestion.

Limitations and future work

334 First, the modified model based on the NaSch model proposed in this paper lacks validation and
335 calibration under real-time traffic conditions. At present, only the theoretical model has been
336 improved and simulated, and the model needs real-time traffic flow verification and data
337 collection to be more perfect.
338   Second, the study of road traffic flow is an extremely complex issue. This paper only studies
339 and discusses the road model under single-lane conditions. Traffic flow problems such as driving
340 rules under multi-lane changing conditions, drivers' psychological influences, weather conditions,
341 and manual-automatic mixed traffic flow under vehicle interconnection conditions need further
342 research and discussion.
343 Third, further validation is needed as to whether the model is applicable to both homogeneous
344 and mixed traffic conditions.

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442

Figure 1

Space-time diagram

(A)NaSch model ; (B)Improved cellular automata model ; (C)Model considering driver factors ; (D)Improved model considering driver factors.

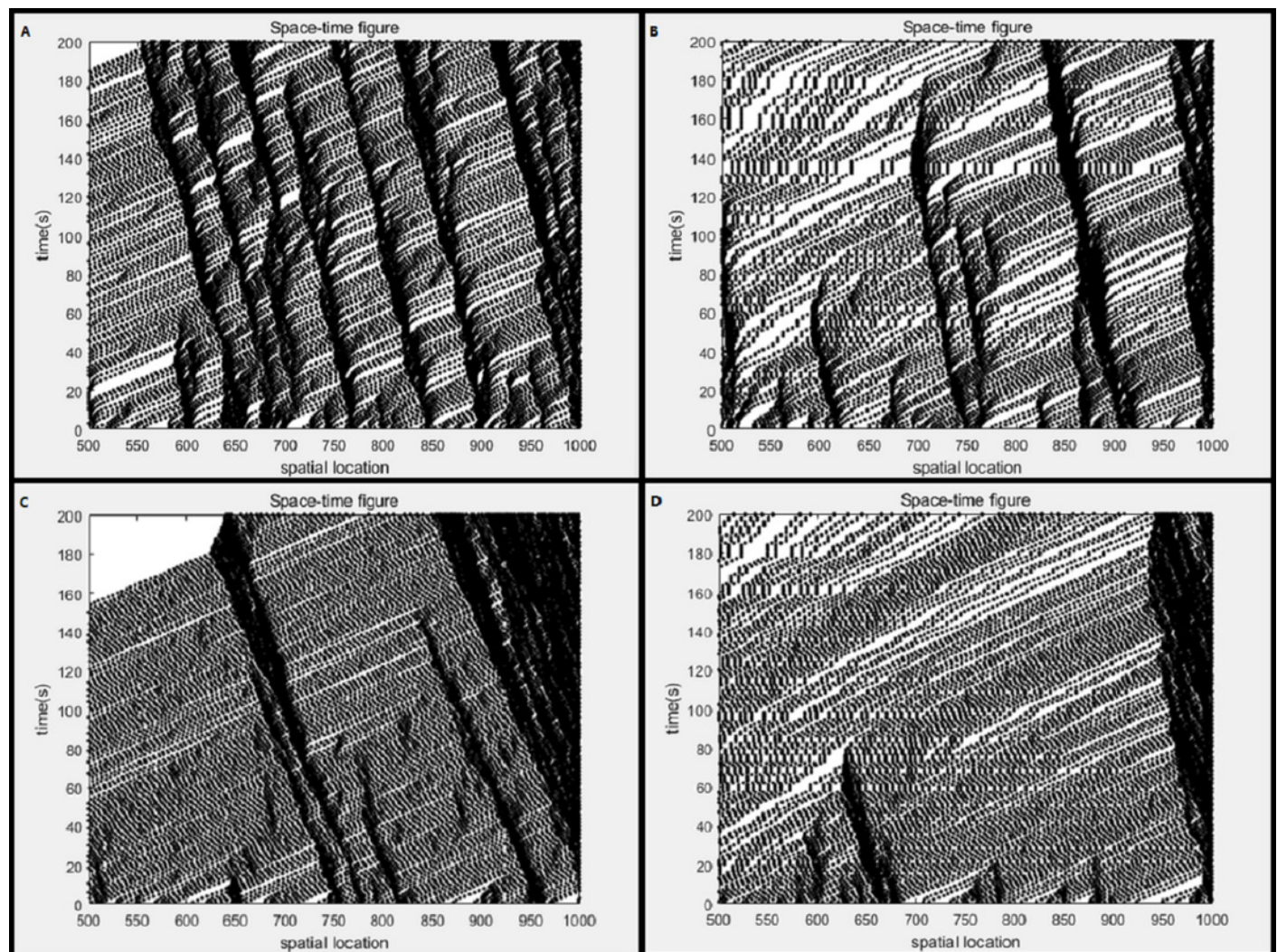



Figure 2

Flow-density diagram

(A)NaSch model ; (B)Improved cellular automata model ; (C)Model considering driver factors ;
(D)Improved model considering driver factors.

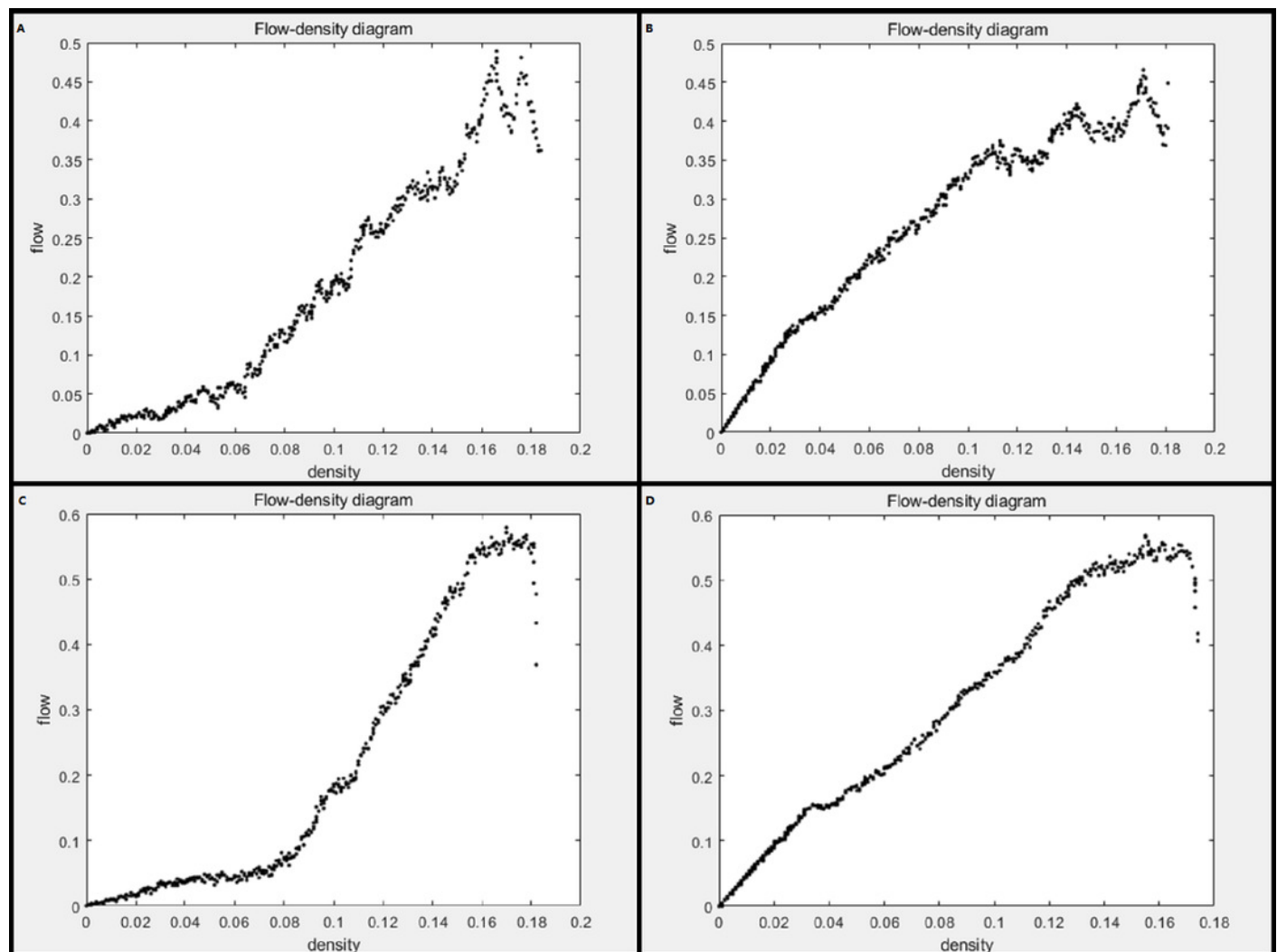
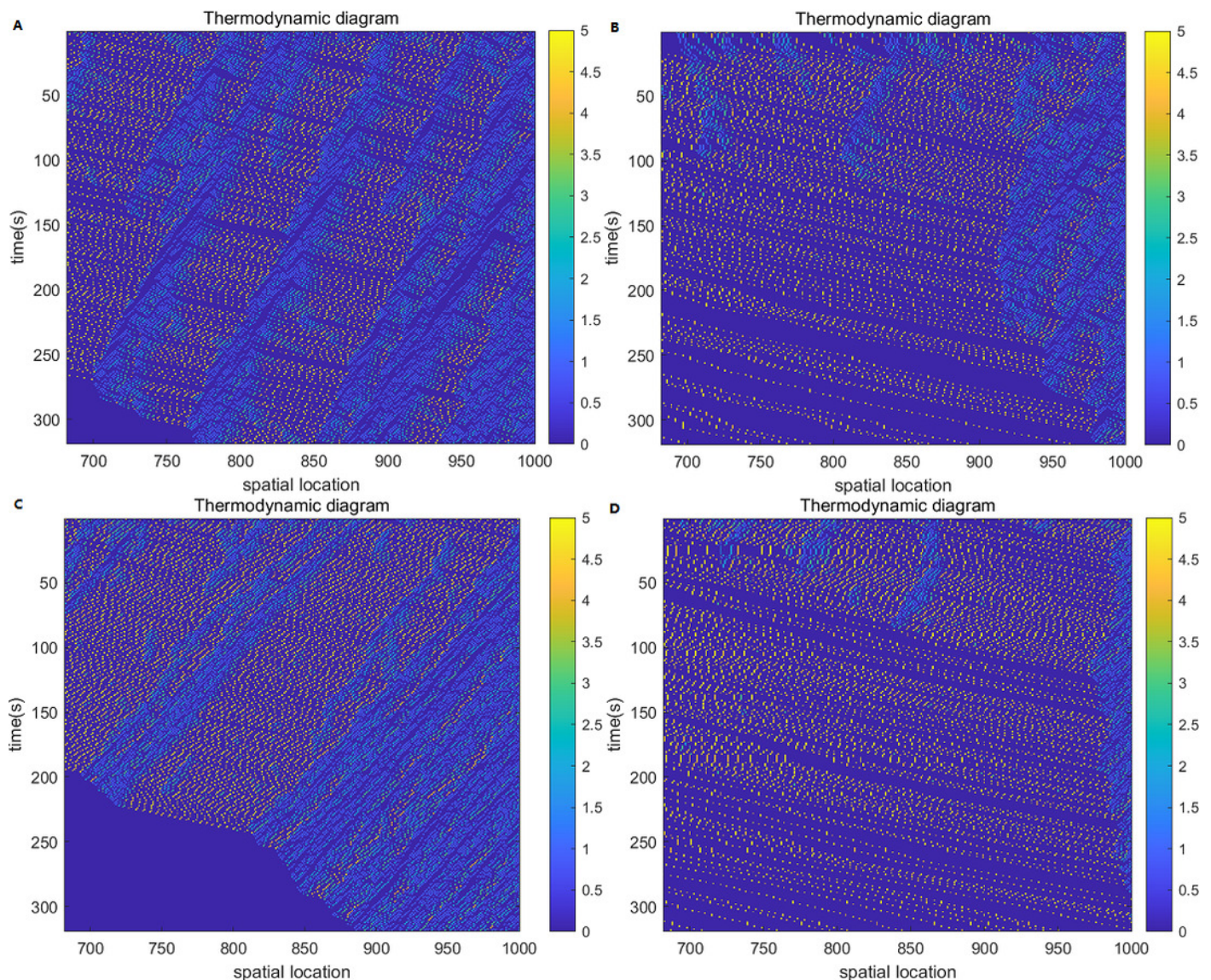



Figure 3

Thermodynamic diagram

(A)NaSch model ; (B)Improved cellular automata model ; (C)Model considering driver factors ; (D)Improved model considering driver factors.

Summary of cellular automata models

1   **Table 1:**
2   **Summary of cellular automata models**

Application	Model	Methods for improvement	Advantage	Disadvantage
Study on the model of expressway traffic	NaSch model	Random slowing down probability is introduced and maximum speed is no longer 1	The rules are simple and can describe the actual traffic phenomenon	The simulation of complex traffic flow phenomenon cannot be completely realized
	TT model	Add slow start rule	Metastable and hysteresis phenomena can be obtained	Traffic flow is lower than NaSch model
	FI model	Improve acceleration rule	Easy to analyze and study	There is a big gap between rules and reality
	KKW model	Consider the speed effect of the front vehicle	There is a new phase called synchronous flow	The influence of the car behind on the car in front is not considered
Study on the model of urban road network traffic	BML model	The first two-dimensional traffic flow cellular automata model	The rules are simple and reveal some basic characteristics of urban traffic flow	Unable to accurately describe some problems in real urban road network traffic
	Gu proposed extended BML model	Change 2D uniform mesh to non-uniform mesh	The traffic lights at each intersection can freely choose the cycle and phase	The model needs to be further refined
	ChSch model	Applying NaSch model rules to the vehicle update process in BML model	Describes the movement of traffic flow on a road between adjacent intersections	A cell represents an intersection
	Freund proposed extended BML model	Change one-way traffic to two-way traffic	Extend the vehicle movement direction to four	The model can be further expanded

Improved cellular automata algorithm

1   **Table 2:**

2   **Improved cellular automata algorithm**

Improved cellular automata algorithm
1: Initialize road parameters
2: index=randperm(i);   %i represents the position of the first car.
%The randperm function is used to randomly extract integers between 1 and i without putting back.
3: for j=1:index   %Loop iteration
4:        v(i-j+1)=min(v(i-j+1)+1,vmax);   %Acceleration process
5:        v(i-j+1)=min(v(i-j+1),d);   %Deceleration process
6:        v(i-j+1)=randslow(v(i-j+1));   %Random slowing of vehicles
7:        z(i-j+1+new_v)=1;   %Location update
8:        v(i-j+1+new_v)=new_v;   %Velocity update
9: end

Simulation parameters of experimental model

1   **Table 3:**

2   **Simulation parameters of experimental model**

Parameters	NaSch model	Improved model	Model considering driver factors	Improved model considering driver factors
Cell space(cells)	1*1000	1*1000	1*1000	1*1000
Initial number of vehicles(cells)	200	200	200	200
Initial vehicle speed(cells/s)	1	1	1	1
Maximum speed(cells/s)	5	5	5	5
Acceleration(cells/s^2)	1	1	1/2	1/2
Iterations(time)	1000	1000	1000	1000
Random moderation probability(%)	0.3	0.3	0.3	0.3
Whether the vehicle update is random	No	Yes	No	Yes