The Influence Analysis of Traffic Flow on Economy Situation Based on Mathematical Model

Hanjun Cui[1, a], Lishan Li[2, b], Dongyue Xu[3, c]

[1]University of North Chapel Hill, Nc, United States

[2]Cheshire Academy, Connecticut, United States

[3]Nanjing Foreign Language School, Nanjing, China

[a]cui1014@ad.unc.edu; [b]lishan.li@cheshireacdemy.org; [c]dongyuexu@yahoo.com

Abstract: On the global scale over the past decades, a rapid growth of urbanization rate has been observed. While benefiting residents, urbanization also causes problems that evoke economic and environmental concerns, traffic congestion being one of the most serious. To provide a vision of deducing air pollution caused by congestion, improving commuting efficiency and raising people's quality of life, this investigation takes Beijing as an example to explore the potential economic benefit of traffic optimization based on telematics. To provide a quantified and intuitive result, the investigation uses a Cellular Automata (CA) model to emulate Beijing's traffic during peak hours, gives Travel Time Buffer Index (TBI), Travel Congestion Ratio (TCR) and Traffic Performance Index (TPI) as essential indicators to quantify traffic performance. Then, on the premise of neglecting the secondary influencing factors, firstly, the hierarchy matrix is used to assign weight to determine the main index of influence, and then the fuzzy analysis method is used to analyze the determined indicators, so as to establish an economic benefit analysis model to analyze the impact of traffic on the economic situation. The simulation results show that the lower the average congestion loss is, the smaller the average vehicle running time is, and the lowest system loss cost is; on the contrary, the higher the average congestion loss is, the greater the average vehicle running time is, and the highest overall system loss cost is.

1. Introduction

Keywords: Cellular automata, Modeling, Traffic optimization, Hierarchy matrix, Fuzzy analysis method, Urbanization

2. Introduction

In 1868, London, the invention of the first gas signal lamp-marked the starting point of urban transportation signal. In 1926, Chicago city adopted the traffic light control scheme, setting a sole traffic light on every crossroad. After that, transportation control technology and related algorithms got rapid developments that decreased environmental pollution, raised safety and efficiency of transportation control. Traffic control plays an essential role on organizing, conducting, and controlling direction, rate, and speed of traffic flows and maintaining traffic order: it separates traffic flow with time conflicts, letting them pass on different time, which secures driving safety, increases crossing efficiency and capacity, and reduce noises and the harm of automobile exhaust emission on the environment.

as the development of people's living standard, more people are looking for better experience on road, which causes shrinking of public transportation that further worsens the traffic jam problem and increases environmental pollution. Last, because many cities put most attention on improving road traffics by expanding motorway to release the pressure of traffic jam, side pavement and cycle path are narrowed. How-ever, our country has a large non-motor vehicle group and pedestrians so the lack of cycle path and pavement deduces driving safety and worsens the traffic jam.

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Ministry of Transport of the People's Republic of China published “Digital Transportation Development Plan Outline” in July 28th 2019, which advances the co-operation of computer science and transportation and improve the data driven modern transportation system. In the outline, it states that transportation will become the major civil application of Beidou GPS, and 5G network and new generation satellites communication system will start to be used in 2025. The level of big data use in transportation will be greatly increased; the service of travel information will be fully covered for the entire trip; the service of delivery will standardize and unify. Transportation will deeply connect with automobile, app, communication, internet, and other relative domains, which can promotes the share of information and develop new industries and technologies. In order to achieve the goal, the outline mentions that it is necessary to build digital data collection system, networking transmission system, and intellectualized application system and move forward on car networking, 5G, satellite communicational information network, national communicational information of highway to form the communicational network of transportation that consist of various networks. In “5G network technology and its wireless coverage on urban rail transportation”, it states that as the continuous development of rail transportation in China, the rapid growth of device connection and data flow provides higher requirements for wireless network communication in situations of urban rail transportation and also make the application of 5G in urban transportation system become a trend in the future. Jing Liang has also develops his agreement on the contribution of 5G on urban transportation system in the future, he states, “With the continuous develop-ment and progress of Cloud computing, big data, Internet of Things (IoT),Artificial Intelligence(AI),5G and other emerging technologies, it is urgent to comprehensively improve the intelligent level of urban rail transit, build a safe, efficient, convenient, green and smart urban transit, and realize the transformation and upgrading of the whole transit industry.”

3. Model and Results Analysis

3.1 A Brief Introduction of the Model Used

3.1.1 Cellular Automata (Ca)

Cellular Automata (CA) is a system of discrete cells that evolve in finite states based on a specific set of rules in a discrete time series. The set of cells is referred to as the cellular space and the set of rules is referred to as the rule space. The essential attributes of a CA are:

1).Spatial Discreteness: the cellular space is divided into minimal units, cells.

2).Temporal Discreteness: There is a unit time difference between each state of the CA.

3).Finite States: each cell could only have finite possible states.

4).Locality: the state of any cell at any moment is only determined by the state of its own and its neighbors, specified in the rule space, at the previous time.

If a Cellular Automata only contains two elementary states, 0 or 1, and the rules only refer to the nearest neighbors of the cell, the Cellular Automata is elementary.

Cellular Automata is widely used in subjects involving emulation and calculational analysis, such as Biology, molecular Chemistry, Mechanics, and Operational Analysis. In this essay, it is used to emulate the traffic flow in Beijing city under certain boundaries to provide an estimation of the potential effect that non-local traffic optimization could generate.

3.1.2 Wolfram Rule 184

Rule 184 is an elementary Cellular Automata and is the most elementary emulation of traffic flow. Under rule 184, the cellular space consists of two colors and 3-space neighborhoods; that is, the rule space is 2-color and 1-range, implying that:

Each unit space is either occupied by the vehicle or unoccupied;

In each unit time, a vehicle could either remain stationary or move one unit space; that is, v is either 0 or 1.

The rule space of Rule 184 is:

If the unit space is unoccupied at t, then
a. If its left neighbor is occupied, then it becomes occupied at t+1; (movement of vehicles)
b. otherwise it remains unoccupied.

4. If the Unit Space is Occupied and

a. its right neighbor is unoccupied at t, then it becomes unoccupied at t+1;
b. otherwise it remains occupied. (safe interval between vehicles)

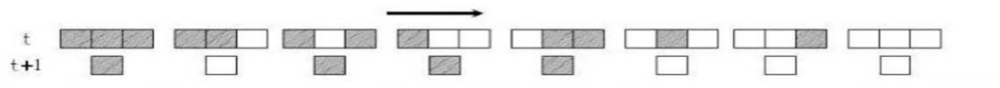

Fig.1 An Illustration of the Rule Space of Rule 184 from t to t+1.

The rule space expressed in Boolean form is
$(p,q,r) \mapsto p\ XOR\ (q\ AND\ (p\ XOR\ r))$. (1)

The situation presented by Rule 184 is relatively simple and inconsiderate compared to real traffic flow; however, it provides a fundamental view of transportation of vehicles with a demonstration of two essential phenomena in traffic: delayed start and safe interval in transportation.

4.1 Analysis of Traffic in Beijing

This essay applies a simplified Cellular Automata (CA) model to analyze the overall performance of traffic flow in Beijing city and quantify the difference before and after traffic optimization. It also introduces the degree of traffic jam, a key indicator, and regresses it to represent variables in real situation, such as average vehicle speed, to enable the correlational analysis between traffic and economic impacts.

4.1.1 Preparations

1). Preliminary Steps and Conditions

As accessible computational capacity is limited, Beijing in this research is not defined in an administrative or municipal sense, but is selected as the area within the 3rd Ring Rd(San Huan). To construct the cellular space, only the arterial roads are kept for analysis in order to simplify calculation.

Fig.2 The Selection of Road Network of Beijing. from Baidu Custom Map

2). Rasterization of the Road Network

Rasterization is a primary method to process information in Geographic Information studies. (AGILE conference, 2009) In the studies related to Geography and Landscape, Triangulated Irregular Network (TIN) generated by Delaunay Triangulation represents the structure of a surface involving height as a variable.

The procedure of triangulation consists of followings:

For P consisting of n points, all triangulations contain $2n-2-k$ triangles, $3n-3-k$ edges; Create angle vector of the sorted angles of triangulation T, $(\alpha 1, \alpha 2, \alpha 3, \dots \alpha 3m) = A(T)$ with α1 being the smallest angle; $A(T)$ is larger than $A(T')$ if there exists an i such that

$\alpha j = \alpha' j$ for all $j < i$ and $\alpha i > \alpha' i$; Best triangulation is triangulation that is angle optimal, i.e. has the largest angle vector.

While Delaunay Triangulation is widely applied, it does not agree with the best interest of this research as the subject of study is a 2-D plane without height, and the alignment of triangular cells adds on the difficulty of designing Cellular Automata rule space. This research thus utilizes $n * n$ network to rasterize selected city area of Beijing on the basis of block and street and selects the part representing road network at the unit of $3 * 3$ pixels:

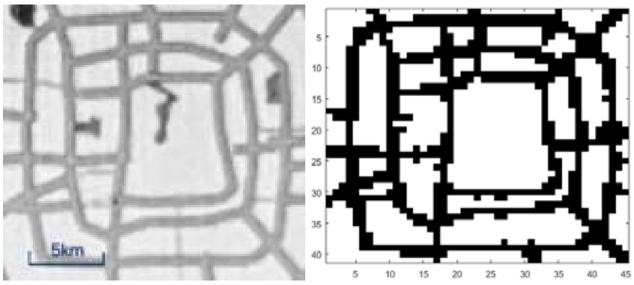

Fig.3 The Selected Road Network of Study Before and after Rasterization.

4.1.2 The Construction of Cellular Automata

The cellular space in this research is divided into square planar. The definition of neighbors of a cell is contingent to Moore type when $n = 1$, and the rule space is specified such that the direction of traffic flow is from upper left to lower right.

(1). Cellular Neighbors

In any CA model, the state of a cell at time $t + 1$ only depends on the staes of it and its neighbors at t. Here we define the neighbor of a cell as a “nine-neighbor square”, or Moore type when $n = 1$, which contains the eight squares surrounding the original cell.

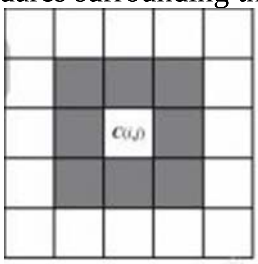

Fig.4 A Cell and Its Neighbors in Moore Type, n=1.

(2). The Rule Space

1) The cellular space is divided into units of 3*3 cells.

2) The direction of movement of vehicles is upper left to lower right; that is, the state of a cell c(i, j)would only be influenced by c(i-1, j), c(i, j+1), and c(i-1, j+1).

3) If a vehicle enters the cell, it could leave randomly at one of five non-neighboring cells in the nine-cell neighbor. E.g. a vehicle entering from c(i-1, j+1) could leave at c(i-1, j-1), c(I, j-1), c(i+1, j-1), c(i+1, j), and c(i+1, j+1).

4) When the vehicle leaves from a unit and enters another, it randomly picks a direction in all possibilities that enable it to keep movement.

5) If the neighboring cell is occupied, then the vehicle would not move at time t.

4.1.3 Simulation and Conclusions

In the program, we assume that at each moment, a vehicle enters at any of its six entry, marked in Fig. 8.

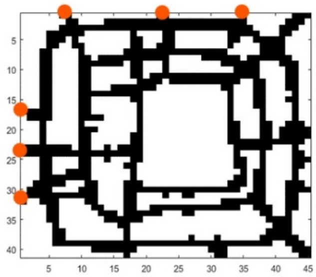

Fig.5 A Vehicle Enters At Any of Its Six Entry

The simulation is first run for three times with $t = 15, 50, 1000$ retrospectively to explore the pattern of traffic flow and jam:

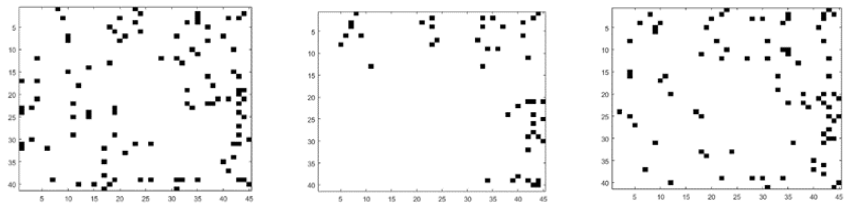

Fig.6 The Terminal State At $t = 15, 50, 1000$. Cells in Black Represent Vehicles.

It seems quite probable that the traffic jam mainly occurs nearing the entries and exits of the road network. Keeping variable of total traffic flow constant, the effect of traffic optimization could is equivalent of decreasing the maximum load in the road network at the peak; thus, a contrast experiment of two groups is set with the first group representing unoptimized group in which each entry generates a vehicle at every moment and $t = 1000$, and the second group representing optimized group in which each entry generates a vehicle at every another moment and $t = 2000$. Each group has run ten(10) trials in Matlab and the result is shown as followed:

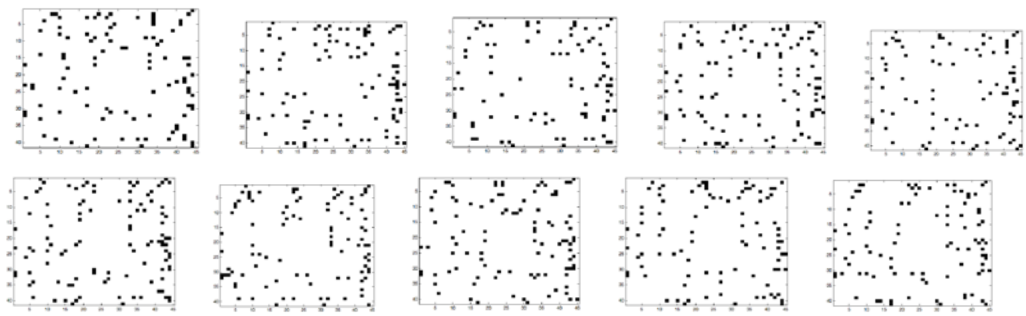

Fig.7 Ten Trials of Unoptimized Group, Vload=1, t=1000.

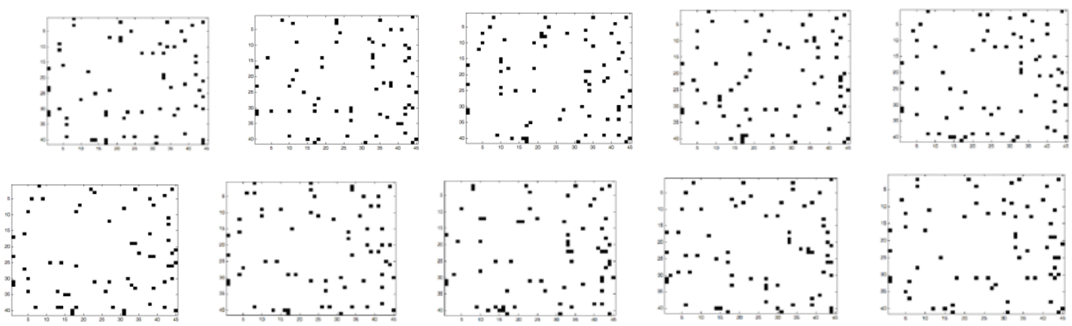

Fig.8 Ten Trials of Optimized Group, Vload=0.5, t=2000.

It seems probable that traffic optimization which controls the maximal load of vehicles at the peak significantly reduces the degree of congestion.

Further exploration of the pattern of congestion involves the combinational analysis of results from each trial. For ten trials in unoptimized and optimized group, the opacity of each result is adjusted to 10% and images are overlapped, so that the deeply shaded area implies a more congesting road segment:

4.2 Economic Modeling and Analysis

Traffic could be regarded as a dynamical system, involving many factors. This research applies Principle Component Analysis (PCA) to take secondary influencing factors out of consideration and to reduce the amount of variables. Analytic hierarchy process is firstly applied to weigh the factors and identify the primary indicators of the correlation. Fuzzy Analysis is then used to analyze selected indicators, which establishes the model for economic benefit to estimate the influence of traffic on economic performance.

4.2.1 Assumptions and Boundaries

1). Assume that secondary factors' influence on the correlation is negligible. In the process of PCA, minor components would not influence the result of the analysis only if the aforesaid assumption holds.

2). Assume that human/pedestrian activity's influence on the traffic flow is negligible. Trespassing pedestrians would occupy the road network, reduce the capacity of the road, and obstacle the movement of vehicles.

3). Assume that no accidents would occur on crossroads. The occurrence of such accidents would significantly reduce the reflux of vehicles.

4). Assume that minor influencing factors of traffic flow, such as random deceleration, are negligible. These minor factors, while helping to increase the biofidelity of the simulation, would not change the result of simulation and analysis on a remarkable scale.

4.2.2 Establishing and Solving the Model of Economic Benefit

Based on Traffic Road Performance Index published by Administration of Quality and Technology of Beijing, Travel Time Buffer Index (TBI), Travel Congestion Ratio (TCR), and Traffic Performance Index (TPI) are main factors to comprehensively represent the operational status of road networks in a quantitative manner. In this research, we define commuting peak hours as following and define day average TPI as the weighed average of TPI in commuting peak hours.

Table 1 Definition of Commuting Peak Hours.

	Morning Peak	Noon Peak	Evening Peak
Workdays	7:00~8:00		17:00~19:00
Weekends/Holidays			16:00~18:00

The procedure of calculation is:

Categorize different classes of road based on GB50220-1995, take the statistical interval T<15min, and calculate the average speed of vehicles;

Categorize the operational status of different classes of road and calculate the road congestive ratio L_i based on table 2:

Table 2 Different Classes Of Road

Road Classes/Operating Levels	Unobstructed	Almost Unobstructed	Slightly Congested	Temperately Congested	Severely Conjested
Highway	V>65	50<V⩽65	35<V<50	20<V<35	V⩽20
Arterial Road	V>40	20<V⩽45	20<V<30	15<V<20	V⩽15
Branchway	V>35	25<V⩽35	15<V<25	10<V<15	V⩽10

Calculate the weighed summation of road congestive ratio Lz using VKT ratio PVKTi as the weighing factor.

$$VKT_i = \sum_{i=1}^{N_i} (V_{Si} \times L_{Si}) \quad (7)$$

$$PVKT_i = \frac{VKT_i}{\sum_{j=1}^{n} VKT_j} \times 100\% \quad (2)$$

$$L_z = \sum_{j=1}^{n} \left(L_y \times PVKT_i\right) \quad (3)$$

Take the calculated road congestive ratio to derive the corresponding TPI from [0, 10] and road operating level. The correspondence is attached in Table 3.

Table 3 the Road Congestive Ratio, Tpi, and Road Operating Level.

Road Congestive Ratio(%)	[0,4]	[5,8]	[8,11]	[11, 14]	[15,23]	[24, +∞)
Traffic Performance Index(TPI)	[0,2]	(2,4]	(4,6]	(6,8]	(8,10]	10
Road Operating Level	Unobstructed	Almost Unobstructed	Slightly Congested	Moderately Congested	Severely Congested	Severely Congested

4.2.3 Analysis of Economic Benefits

1). The analysis of relative stable results under different situations of congestion

Assuming that the time nodes from the beginning to the steady state at different levels are used as the judgment condition of the current system stability, the running state in the system can be judged. The total number of highway pixel blocks is recorded as 693, and the traffic congestion rate is the average stable block divided by the highway pixel block. The average stable block is the number of stable blocks at time 1000. Average vehicle running time, the overall time of steady-state vehicle running in each independent repeated test. Carry out 10 independent repeated tests on the system, and record the time and level of reaching the highest steady state at 1000 time points.

Based on fuzzy analytic hierarchy process, analyzes certain index, which gives the situation of congestion under different transportation circumstances. Then, build the hypothetical map scale α on the analysis above; now every black spot represent the pixel of 4x4 on the original scale. The horizontal axis times vertical axis on the original scale is 41x45 matrix of pixels. Every pixel represent the area of β, which every pixel equally converts to the number of cars n. Record the number of entire pixels of road as 693, the rate of transportation congestion is average stable spot divided by the pixel of road. Do 10 repeated individual tests in the system, record the time and level that achieves the most stable circumstance in the 1000 time frames.

Table.3. the Relationship between Time and Level of Stable Situation

Model	Index of Congestion	Average Time	Average Stable Spot	The Percentage of Congestion	Average Moving Time per Vehicle
1	1.00	379.4	98.2	14.17%	29.00
2	0.80	386.2	79.8	11.52%	27.30
3	0.50	447.4	76.2	11.00%	32.60
4	0.30	461.7	64.6	9.32%	38.10
5	0.60	443.6	59.9	8.64%	31.10

In this table, Model 1 represents that a new car will be added on the entrance at every time frame. Model 2 represents that a new car will be added on the entrance every other time frame. Model 3 represents a car will be added on the entrance per three time frames. Model 4 represents a car will be added on the entrance per four time frames. Model 5 represents a car will be added on the entrance per five time frames.

2). The Analysis of Economic Benefit under Different Situations of Congestion

Builds model of economics benefit, hypothesizes that the number of vehicles on every pixel is n, the running cost for vehicles in the area with a stable congestion circumstance is W, the cost of vehicles in the area without congestion is w, the number of average stable spots under different circumstances is m, average loss from congestion is c, average running time per vehicle is t, then the economic model is built as listed below:

$$W = \left(c \cdot t - w\right) \cdot m \cdot n \quad (4)$$

When the index of congestion is 1, we hypothesize that the average loss from congestion is 10; when the index of congestion is 0.8, the average loss from congestion c is 9; when the index of con gestation is 0.6, the average loss is 8; when the index is 0.5, the average loss c is 7; when the index is 0.3, the average loss c is 5. The cost of running under circumstance without congestion w is 120. Then, the relationship of size of index corresponded with the Model is 170mn, 125.7mn, 108.2mn, 70.5mn, 128.8mn. It is clear that under the circumstance of Model1, the economics cost of the entire system is highest. In Model4, the cost for entire system is lowest. (It is recommended to use Model1 method for traffic flow control in the target area, which can achieve better cost loss control.)

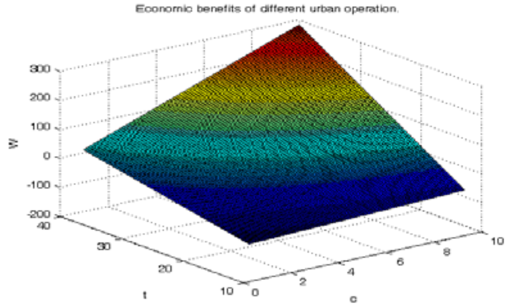

Fig.9 Analytical Graph for Economical Model

Fig.9 is an analytical graph of economic benefit: it is obvious that the lower the average loss from congestion, the shorter the average moving time per car, and the smallest cost for the entire system; oppositely, the higher the average loss from congestion, the longer the average moving time per car, and the highest cost for the entire system.

5. Conclusion

5.1 Advantages and Disadvantages of the Model

Principal component analysis can not only eliminate the relative influence between the evaluation indicators, but also reduce the workload of indicator selection, and its calculation is relatively standardized, which is convenient for computer implementation. It can also use special software components. The interpretation of principal component analysis is generally somewhat vague, not as clear and precise as the meaning of the original variable.

The cellular automata model has high model rigor, strong practicability, and universal applicability. Among them, the simulation model can more vividly describe the corresponding simulation scheme, and can more intuitively reflect the new things expressed, but the simulation process may ignore the small influencing factors, but these factors do not affect the simulation results.

5.2 Model Promotion

Principal component analysis is a basic mathematical analysis method. It is not only used for mathematical modeling, but also has a wide range of applications in demographics, quantitative geography, molecular dynamics simulation, mathematical analysis and other disciplines. It is a commonly used method. Multivariate analysis method.

Although the fuzzy evaluation method adopts fuzzy mathematics, its method is simple and easy to implement. It shows its application prospects on some problems that cannot be quantitatively analyzed from the traditional view, and it solves the ambiguity and uncertainty of judgment. And because the fuzzy method is closer to the thinking habits of the Orientals, it can also be applied to the evaluation of social and economic system problems.

The cellular automata model is proud of the development of logical mathematics, discrete mathematics, and computer automata theory. At the same time, its development has also enabled people to make deeper breakthroughs in the field of mathematics, and even led to the birth of human life sciences. The wide application of Cellular automata is a major breakthrough in human science. Now the cellular automata model has been widely used in the field of transportation and aerospace. The space of cellular automata is discrete, and it is similar to the differential equation at the same time.

References

[1] Rule 184, Wolfram Alpha, accessed July 16, 2020,

[2] Phase Transitions in ECA Rule 184, WolframAlpha, accessed Aug. 29, 2020,

[3] Association of Geographic Information Laboratories for Europe Conference. (2009). Advances in GIScience: proceedings of the 12th AGILE Conference. Berlin: Springer. Retrieved from

[4] Glenn Eguchi, MIT open lectures, 2009,

[5] N. Packard ,S. Wolfram. Two-Dimensional Cellular Automata, Journal of Statistical Physics, Vol. 38. Nos. 5/6. 1985.

[6] https://wenku.baidu.com/view/d71893262f60ddccda38a04a.html

[7] “The coming up of annual report of transportation in 2018: Beijing becomes “most congested”, annual congestion time of commute is 174 hours” BlockWeb, 2018,

[8] “The research of commuter in 2018: the average commute radio in Beijing is 16.79km.” Edited by Fenghuang ,The research about commuter in 2018:the average radio of commute in Beijing is 16.79km-Thousand Dragon web•China Capital Web, 2018,

[9] “Report of Traveling in Chinese cities 2019”Baidu Map ,Annual report of travel-ing in Chinese cities 2019, Baidu Map, 2019, huiyan.

[10] “The statistical report of national economy and social development in Beijing 2018”Bureau of Statistics in Beijing, National Bureau of Statistics Beijing In-vestigation corp, 2019,

[11] “The statistical report of national economy and social development in Beijing 2019” Edited by Mao Congying and Gao Xing, People’s Daily Online, 2019,

[12] “Analytical Run Report of Beijing Transportation 2015.”Originality Doc, 2015,

[13] United States, Congress, Department of Transportation.The Program of Develop-ment of Digital Transportation, Ministry of Transport of the People's Republic of China, 2019, pp. 1–1.

[14] Li Jianing, Cai Xiaolei,and Zhen Jun.”5G and Its Wireless Coverage on Urban Rail Transportation” Modern Urban Rail Transporta-tion.08(2020):125-128. .

[15] Jing Liang, Fang Hui and Zhang Sen.”Urban Rail Transportation Digitalized Cloud Platforms and the Development of Big Data Platforms.” Modern urban rail transportation.08 (2020):129-134.

[16] Sun Fei. “Modern Urban Rail Transportation Wireless Coverage Technology and Its Applications” World of Communication 27.07(2020):201-202.

[17] “The report of traveling in China 2017.” Annual report of city research in 2017, Baidu, 2017,

[18] Zhao Yanbo.”Brief Analysis about 5G Applications in Urban Rail Transportation” The World of Digitalized Data.01(2020):84-85.

[19] “The Cost of Congestion in 2015”, 2015, news.10jqka.com.cn/20160121/ c587468568.shtml.