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A node-centric network congestion estimation method considering average spatio-temporal scale

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Abstract. Congestion estimation is a significant issue to analyse and mitigate network congestion. Many researchers have used various estimation methods based on the load data of roads in a single moment. However, congestion is always node-centric and formed around intersections gradually. An estimation method to describe the average congestion around intersections or nodes is also valuable and needed to discover the most congested parts but is absent according to our literature researches. In this paper, we propose a node-centric network congestion method, which can evaluate the average spatio-temporal congestion scale around nodes. Based on the widely used simulation platform NetLogo, the simulation results have proved the reasonability of the proposed estimation method by the stable values of the fixed traffic network intersections, which becomes increasingly stable as time goes on, and it is found that the node-centric values calculated by our estimation method is more stable than the values by the edge-centric because of its superiority. This node-centric network congestion estimation method considering average spatio-temporal scale will be widely used because of its simplicity and universality.

1. Introduction

Nowadays, along with the rapid acceleration of network applications, congestion has increased in various networks obviously, such as traffic networks, internet, mobile communication networks. Congestion has become one of the top failures and most stubborn diseases of networks [22] and is attracting more and more research attention due to its larger and worse cascading consequences [2, 3, 7, 10, 17, 18]. It is reported that the economic loss of the traffic congestion is about 2% of the GDP and the road congestion is also the primary air pollution source [32, 34]. Due to the traffic network congestion, more than an hour a day is spent on commuting to and from work in US metropolitan [20], and the situations are worse in many developing countries [21]. A proper network congestion estimation method to estimate network congestion is basic to understand and solve the serious network congestion problem. So, it is of great importance to build a proper network congestion estimation method.

The widely used estimation methods to estimate network congestion are built mainly by calculating the load of roads in a single moment. The classical and typical estimation methods, are as follows: one



is the congestion coefficient [6], which is expressed as $J(t) = (\sum L_a(t) \times t_a) / (\sum L_a(t) \times t_{a0})$, and in this estimation method, the road travel time t_a is usually calculated by BPR(Bureau of Public Road) function $t_a = t_{a0} \left(1 + \alpha (L_a(t) / C_a)^\beta\right)$ [14, 16, 24, 31], so the J which is dependent on the varying load L_a , was a unstable number as time varies so it is edge-centric and varying with time. Besides, the efficiency coefficient [29], which is expressed as $e_{ij}(t) = e_{ij}(0) (C_i / L_i(t))$, is another typical congestion estimation method to express the network congestion, which is also dependent on the load of road $L_i(t)$, which is edge-centric and varying with time. Except for these classical and typical estimation methods, there are some other newly proposed congestion estimation methods. Yang et al. [33] proposed a traffic congestion estimation method using multiple spatio-temporal properties based on GPS data, which is also edge-centric and varying with time. Mallah et al. [19] used the dynamical characters of vehicle travel time on road to classify the time delay reasons, such as incidents, work zones, weather or special events. Krbálek [13] introduced a lattice thermodynamic estimation method to describe the congestion situation on every road section in a single moment. By counting the number of social networking site (SNS) messages on road in a single moment, Kusmawan et al. [15] introduced a traffic congestion degree to divide the traffic congestion into several classes, such as “bad traffic” or “crazy traffic”. Zeroual et al. [35] proposed a set of equations to describe the traffic flow on the road, but did not give a direct traffic congestion estimation method. Singh et al. [26] proposed an efficient load balancing method for ad hoc networks to improve its efficiency and to avoid congestion and the load is also given on different paths. The researches mentioned above proposed various estimation methods to describe network congestion, but these estimation methods are edge-centric and varying with time, because they are not designed to reflect the average, stable and accumulative congestion, which is also of great importance for congestion.

Recently, some researchers have realized the node-centric phenomenon and given some node-centric estimation methods, while the node-centric network congestion estimation method considering average spatio-temporal scale is still absent. In traffic network, Hao et al. [9] believed that traffic congestion always happened at intersections and proposed a hybrid multiple criteria decision-making method including multiple criterion to evaluate traffic congestion. Zhao et al. [36] also realized the importance of traffic flow at intersections and built a cellular automata estimation method to consider the speed of front vehicle, brake lights, and traffic flows. However, they focused on the road hybrid estimation method in a single moment, which is not designed to reflect the average, stable and accumulative congestion scale. In other networks, Cai et al. [1] realized the importance of airspace congestion and used multi-objective air traffic network flow optimization estimation method to address the problem of airspace congestion. In communication networks, many researches [8, 27] study the congestion by considering the relationship between nodes loads and the node processing ability to avoid congestion, which is node-centric and pays attention to the load congestion accumulative scale because the extra part out of the memory size will be lost. Though congestion always happens around nodes in actual situation and also captures some attention of researchers, there is still a lack of a mathematical estimation method to describe the stable congestion scale around intersections or nodes.

2. Network Congestion Characteristics

2.1 Node-Centric congestion

As mentioned above, though congestion is dynamic varying with time, it always happening around nodes in real situations, such as road traffic congestion [36], air traffic congestion [1], communication networks congestion [8, 27]. So it is better to calculate the node-centric load scale than the edge-centric, especially under air traffic network or communication networks, because the most time delay occurs on nodes. Here we give the Figure 1 to illustrate this situation.

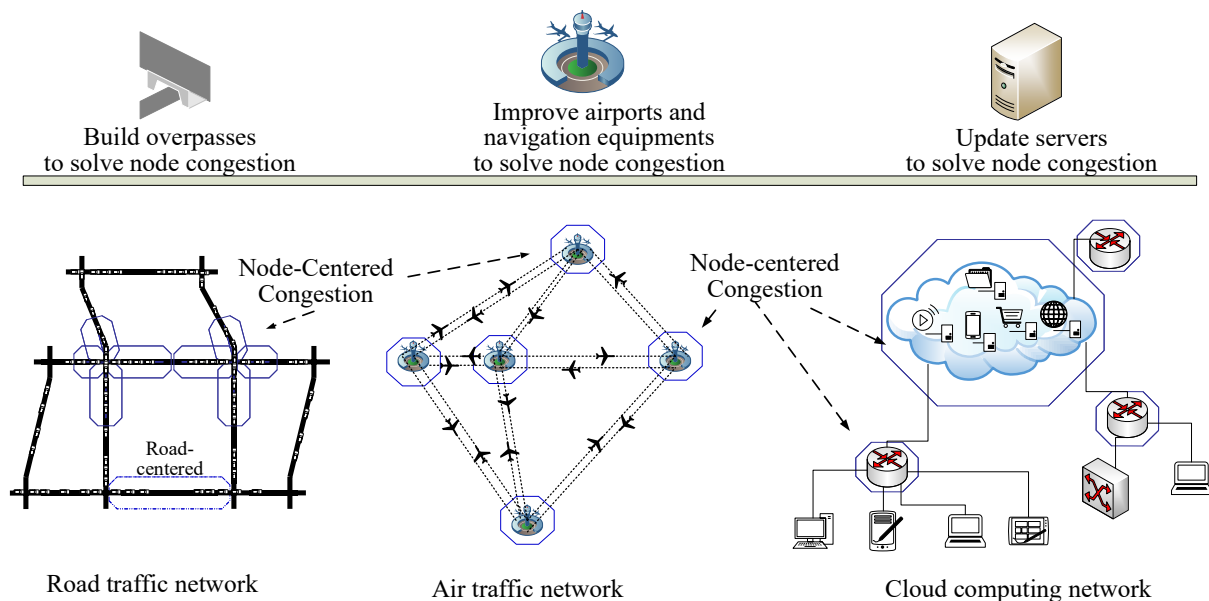


Figure 1. Node-centric congestion

Actually, because of the often and stable node-centric congestion, the processing ability and memory size of cloud computing network are always enlarged according to the congestion situation. The airports and road intersections are also rebuilt or enlarged, and plenty of overpasses appear because of network congestion.

2.2 Dynamical variation and statistical stability

Traffic network congestion is dynamically varying at most time due to multiple factors, such as rush hour, big event. But actually the average traffic congestion for a certain unit in a long period turns out statistical stable. Chow [5] presented an empirical assessment of urban traffic congestion in central London, and proposed that congestion could be classified as recurrent and non-recurrent, the non-recurrent congestion is about 15% of the observed congestion, which is due to non-recurrent factors such as accidents, special events, and strikes. This research implies that congestion is always stable, especially when the non-recurrent factors can be avoided. So it is possible to find the stable value of average accumulative scale in a long period, and this stable value is of significant importance to evaluate the congestion.

2.3 Complex and multiple factors

The reasons of traffic network congestion are dynamical, accidental, complex and including multiple factors, such as, traffic accidents, traffic rules, drivers' habits, road conditions. And these multiple factors are always coupling and interactional. So the former value calculated to describe the congestion is always varying with time. And our estimation method can effectively avoid consideration about the multiple influence factors because the congestion scale is the result of multiple influences and a main aspect of congestion.

3. Congestion estimation method reflecting average spatio-temporal scale

In this section, we introduce an original and numerical congestion estimation method which can reflect the average stable congestion spatio-temporal scale as follows.

3.1 Problems in typical estimation method

In this section, we introduce an original and numerical congestion estimation method which can reflect the average stable congestion spatio-temporal scale as follows.

In the typical congestion estimation method [25], the parameter to estimate congestion is as follow:

$$J(t) = (\sum L_a(t) \times t_a) / (\sum L_a(t) \times t_{a0}) \quad (1)$$

Usually, the road travel time t_a is usually calculated by BPR function [6]:

$$t_a = t_{a0} \left(1 + \alpha (L_a(t) / C_a)^\beta \right) \quad (2)$$

where the recommend value of α and β are 0.15 and 4 respectively [28], and C_a is the capacity of the road a , which is a fix number.

If we bring formula (2) into formula (1), then:

$$J(t) = \left(\sum L_a(t) \times \left(1 + \alpha (L_a(t) / C_a)^\beta \right) \right) / (\sum L_a(t)) \quad (3)$$

In formula (3), J is the function of $L_a(t)$, and there are two problems to solve. One is that $L_a(t)$ is always varying with time because of many factors, and generally it is more valuable to know a stable congestion situation than to know it in a single moment. The other is that usually the $L_a(t)$ on a road is not more unstable than around an intersection, so the J calculated by the load on roads, would also be worse to describe the traffic congestion than calculated by the load around nodes.

3.2 Network Congestion Spatio-Temporal Scale Estimation Method

In order to describe the average network congestion scale accumulated in a period, we give the following equations:

For a node or intersection,

$$J = \begin{cases} \lim_{T \rightarrow +\infty} \frac{1}{T} \int_0^T (L(t) - L) dt, L(t) \geq L \\ 0, L(t) < L \end{cases} \quad (4)$$

For a network which contains N nodes,

$$J = \lim_{T \rightarrow +\infty} \frac{1}{T} \sum_{t=0}^T \sum_{n=1}^N (L(n,t) - L_n), L(n,t) \geq L_n \quad (5)$$

Where the formula (4) and formula (5) are suitable for continuous and discrete load respectively, $L(n,t)$ is the load of the n -th intersection at time t . L_n is the limit of load on the n th intersection, when the load exceeds this limit, this intersection is congestion one. N , is the number of intersections. T , is the length of time period.

Criterion for judgement: for a traffic network, which has been reasonably defined in multi-agent simulation platform, the limit J should exist. If a value calculated from a former estimation method to describe the network congestion can not be stable as time increase, this estimation method is not a successful one. Hence, the J can describe average congestion scale accumulated in a period, which is similar to the average volume of an iceberg beyond the surface of the water.

4. Simulation and discussion

4.1 Traffic case based on NetLogo

Traffic network congestion, is a recoverable dynamic cascading process, which is caused by multi-agent interaction. NetLogo is a famous and popular simulation platform for complex systems with multi-agent interaction, which is developed by Northwest University in American [12, 30]. Nowadays, NetLogo has been widely used and accepted in many valuable researches in various fields [4, 11, 23]. So we chose the NetLogo as our simulation platform.

The graphic interface of this case based on NetLogo can be seen as follows in figure 2.

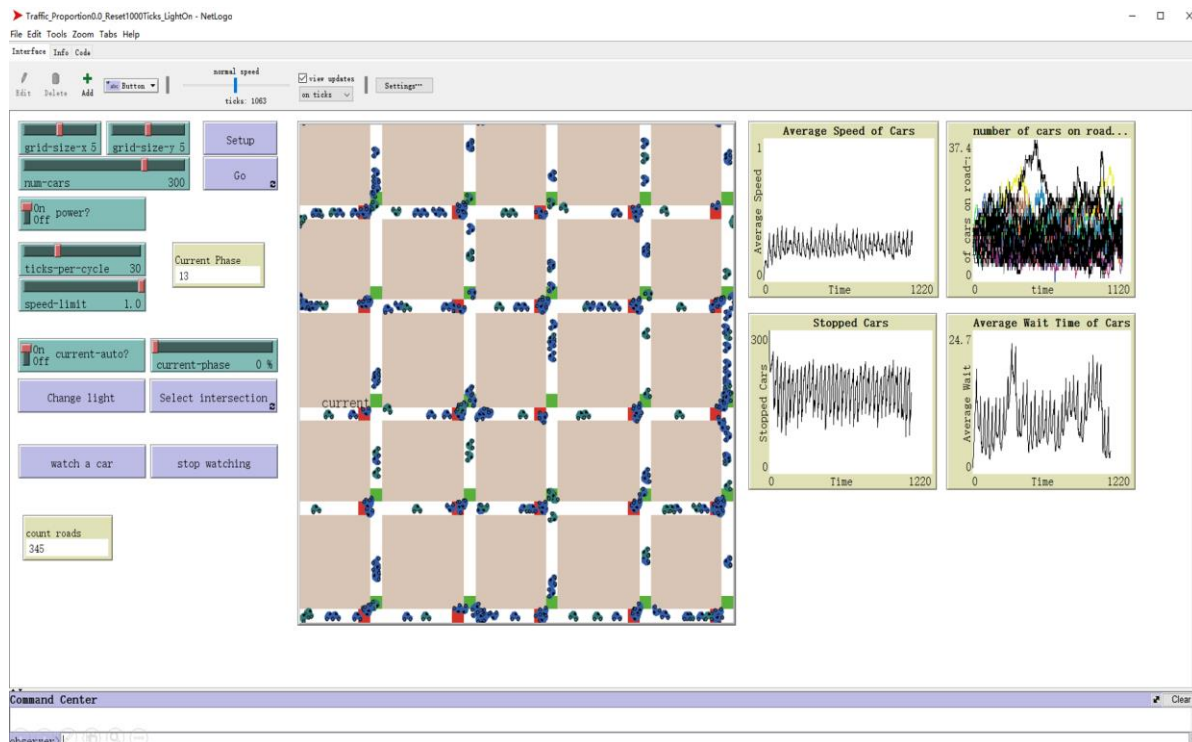


Figure 2. Graphic interface of this traffic case in the NetLogo simulation
And the parameters, rules and attributes for the traffic network case can be shown in table 1.

Table 1. Configuration of the traffic case in the NetLogo simulation

Attributes	Value
topology	Lattice network
Node Scale	25
Edge Scale	50
Number of cars	300
Map Size	37*37
Traffic light	On or off
Traffic light cycle	30
OD pairs	Random, Each car has a house and a work, which are OD pairs. The cars will alternately drive from their home to work and then from their work to home.
Rule for cars	Speed: acceleration 0.099, speed limit 1.0 Path: The car will choose the shortest path and avoid the congestion. Others: if there are cars in front of the car, slow down, otherwise, speed up. Set the speed variable of the car to an appropriate value (not exceeding the speed limit) based on whether there are cars on the patch in front of the car.

From the traffic network congestion case above, we can collect plenty of data as the simulation goes on.

4.2 Data collection

Here, we could collect the number of cars on every intersection in a single step, and we saved as much as 265000 steps. The data format can be shown in table 2.

Table 2. The number of cars on every intersection

Step	1 st intersection	2 ^{ed} intersection		N th intersection
t_0	10	12		11
t_1	9	13		12
t_2	8	15		14
$\vdots$	$\vdots$	$\vdots$	$\dots$	$\vdots$
t_{n-1}	9	26		15
T	4	25		18

4.3 Results and Comparisons

Here we drew a changing distribution of node-centric car number varying with time in figure 3. The congestion scale is the number of cars at different intersections. When the scale exceeds the given congestion limit at an intersection, this intersection is a congestion one and the exceeding part can respect the congestion scale which is yellow in figure 3.

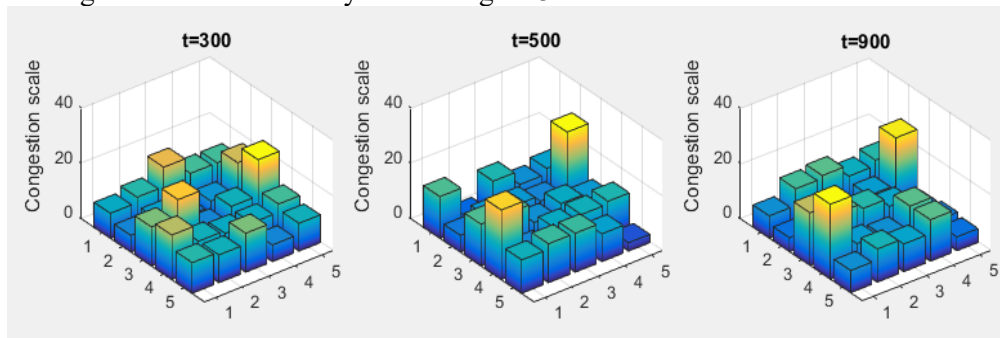


Figure 3. The changing distribution of congestion varying with time

Since it is more valuable to know a stable congestion situation than to know it at a single intersection in a single moment. And we gave a stable congestion value J based on our proposed estimation method in figure 4.

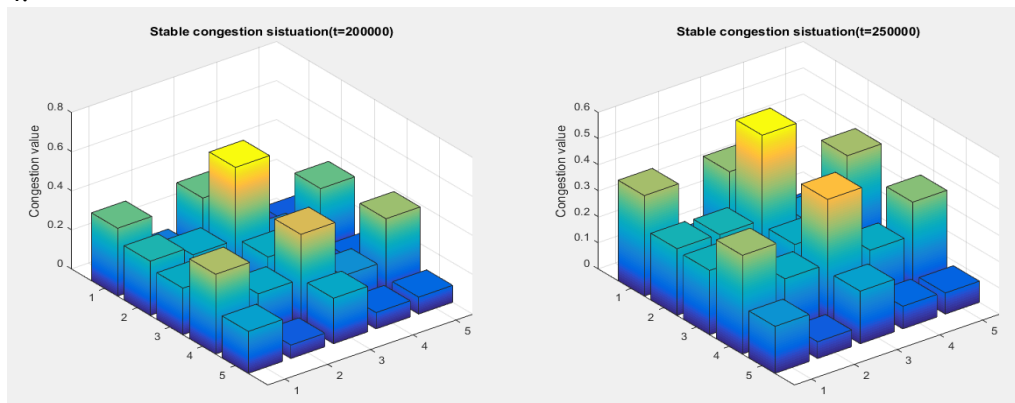


Figure 4. The stable distribution of congestion

As shown in figure 4, the stable distribution of congestion can be obtained based on our estimation method, and the most congested intersection would come into being and be most badly needed to enlarge the processing ability.

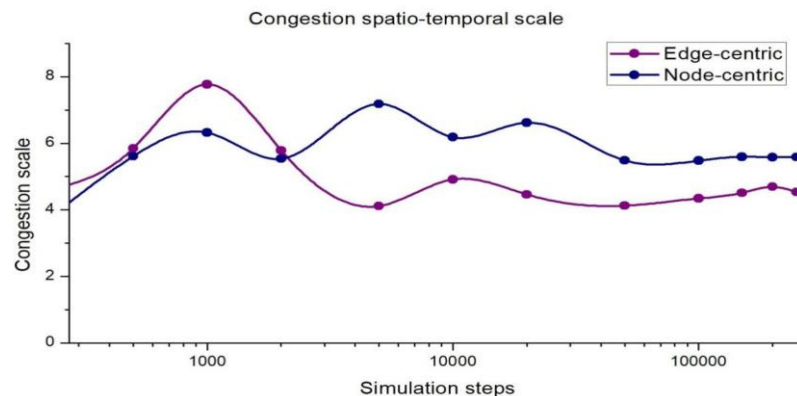


Figure 5. Comparison of congestion scale with different estimation method

The congestion value J based on spatio-temporal scale can be shown in figure 5. And it is obvious that the node-centric congestion value is more stable than edge-centric value.

5. Conclusions

The proposed estimation method can give a proper and stable value to describe intersections or networks congestion, which is basic to understand the intersection or whole network congestion situation and find the most serious one. And this estimation method can be further used to estimate the information influence on network congestion as the information proportion varies. This estimation method is also suitable in many other networks, such as communication network, power network.

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References:

- [1] Cai K Q, Zhang J, Xiao M M, Tang K and Du W B 2017 Simultaneous optimization of airspace congestion and flight delay in air traffic network flow management *IEEE T INTELL TRANSP* PP 1-11
- [2] Cai Y, Cao Y, Li Y, Huang T and Zhou B 2016 Cascading failure analysis considering interaction between power grids and communication networks *IEEE T SMART GRID* **7** 530-8
- [3] Cai Y, Li Y, Cao Y, Li W and Zeng X 2017 Modeling and impact analysis of interdependent characteristics on cascading failures in smart grids *INT J ELEC POWER* **89** 106-14
- [4] Carbo J, Sanchez-Pi N and Molina J M 2018 Agent-based simulation with NetLogo to evaluate ambient intelligence scenarios *J SIMUL* 1-10
- [5] Chow A H F, Santacreu A, Tsapakis I, Tanasaranond G and Cheng T 2014 Empirical assessment of urban traffic congestion *J ADV TRANSPORT* **48** 1000-16
- [6] Daskin M S 1985 *Urban transportation networks: equilibrium analysis with mathematical programming methods* (Massachusetts:Massachusetts Institute of Technology) 463-6
- [7] Fan W, Liu Z, Hu P and Mei S 2016 Cascading failure model in power grids using the complex network theory *IET GENER TRANSM DIS* **10** 3940-9
- [8] Gholipour M, Haghighat A T and Meybodi M R 2017 Congestion avoidance in cognitive wireless sensor networks using TOPSIS and response surface methodology *TELECOMMUN SYST* 1-19

- [9] Hao N, Feng Y, Zhang K, Tian G, Zhang L and Jia H 2017 Evaluation of traffic congestion degree: An integrated approach *INT J DISTRIB SENS N* **13** 1-14
- [10] Hou Y, Xing X, Li M, Zeng A and Wang Y 2017 Overload cascading failure on complex networks with heterogeneous load redistribution *Physica A Statistical Mechanics & Its Applications* **481** 160-6
- [11] Jimenez-Romero C and Johnson J 2017 SpikingLab: modelling agents controlled by spiking neural networks in NetLogo *NEURAL COMPUT APPL* **28** 755-64
- [12] Kahn K 2015 An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo *PHYS TODAY* **68** 55-65
- [13] Krbálek M and Kittanová K 2011 Lattice thermodynamic model for vehicular congestions *Procedia-Social and Behavioral Sciences* **20** 398-405
- [14] Kucharski R and Drabicki A 2017 Estimating macroscopic volume delay functions with the traffic density derived from measured speeds and flows *J ADV TRANSPORT* **2017** 1-10
- [15] Kusmawan P Y, Hong B, Jeon S, Lee J and Kwon J 2015 Computing traffic congestion degree using SNS-based graph structure. In: *IEEE/ACS International Conference on Computer Systems and Applications*, pp 397-404
- [16] Li F B 2013 Research on path selected method in multitask-point road networks based BPR function *Applied Mechanics & Materials* **336** 1616-20
- [17] Li Z, Liu P, Xu C, Duan H and Wang W 2017 Reinforcement Learning-Based Variable Speed Limit Control Strategy to Reduce Traffic Congestion at Freeway Recurrent Bottlenecks *IEEE T INTELL TRANSP* PP 1-14
- [18] Liu H R, Hu Y L, Yin R R and Deng Y J 2017 Cascading failure model of scale-free topology for avoiding node failure *NEUROCOMPUTING* **260** 443-8
- [19] Mallah R A, Quintero A and Farooq B 2017 Distributed classification of urban congestion using VANET *IEEE T INTELL TRANSP* **18** 2435-42
- [20] Mckenzie B and Rapino M 2011 Commuting in the United States: 2009 *Time* 1-20
- [21] Pereira R H M and Schwanen T 2013 Commute time in Brazil (1992-2009): differences between metropolitan areas, by income levels and gender *Institute for Applied Economic Research* 1-26
- [22] Qi L, Zhou M C and Luan W J 2018 A two-level traffic light control strategy for preventing incident-based urban traffic congestion *IEEE T INTELL TRANSP* PP 1-12
- [23] Railsback S, Ayllón D, Berger U, Grimm V, Lytinen S, Sheppard C and Thiele J 2017 Improving execution speed of models implemented in NetLogo *Journal of Artificial Societies & Social Simulation* **20** 3-11
- [24] Sharon G, Levin M W, Hanna J P, Rambha T, Boyles S D and Stone P 2017 Network-wide adaptive tolling for connected and automated vehicles *Transportation Research Part C Emerging Technologies* **84** 142-57
- [25] Sheffi Y 1984 *Urban transportation networks: equilibrium analysis with mathematical programming methods* (Prentice-Hall)
- [26] Singh J and Rai C S 2018 An efficient load balancing method for ad hoc networks *INT J COMMUN SYST* **5** 1-8
- [27] Wang J, Jiang C, Zhang H and Ren Y 2017 Aggressive congestion control mechanism for space systems *IEEE Aerospace & Electronic Systems Magazine* **31** 28-33
- [28] Wang S S, Wei H and Zhen-Bo L U 2006 Deduction of Link Performance Function and Its Regression Analysis *Journal of Highway & Transportation Research & Development* **33** 1-9
- [29] Wang X, Li X and Chen G 2006 *Complex network theory and application* (Beijing:Tsinghua University Press)
- [30] Wang Z, Li H and Li W 2017 *A realizing tool for social science computation-NetLogo Programing* (Beijing: ET Press)

- [31] Wei J, Wei L and Cui Y 2017 Reversible lane scheme selection model based on the BPR function and environmental benefits. In: *International Conference on Materials Science, Machinery and Energy Engineering*
- [32] Wei L 2012 *Research on a real time navigation algorithm avoid traffic jam based on simplified road network model*. (Chongqing: Chongqing University)
- [33] Yang Y, Xu Y, Han J, Wang E, Chen W and Yue L 2017 Efficient traffic congestion estimation using multiple spatio-temporal properties *Neurocomputing* **267** 344-53
- [34] Yu L and Song G 2016 *City traffic flow* (Beijing: Beijing Jiaotong University Press)
- [35] Zeroual A, Harrou F, Sun Y and Messai N 2017 Monitoring road traffic congestion using a macroscopic traffic model and a statistical monitoring scheme *Sustainable Cities & Society* **35** 494-510
- [36] Zhao H T, Liu X R, Chen X X and Lu J C 2018 Cellular automata model for traffic flow at intersections in internet of vehicles *Physica A: Statistical Mechanics & Its Applications* **494** 40-51