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Multimode Dynamics of the Beijing Road Traffic System

Zundong Zhang, Limin Jia and Xiaoliang Sun

Abstract—The Beijing road traffic system, as a typical huge urban traffic system, provides a platform for analyzing the complex characteristics and the evolving mechanisms of urban traffic systems. Based on dynamic network theory, we construct the dynamic model of the Beijing road traffic system in which the dynamical properties are described completely. Furthermore, we come into the conclusion that urban traffic systems can be viewed as static networks, stochastic networks and complex networks at different system phases by analyzing the structural randomness. As well as, we demonstrate the evolving process of the Beijing road traffic network based on real traffic data, validate the stochastic characteristics and the scale-free property of the network at different phases.

Keywords—Dynamic Network Models, Structural Randomness, Scale-free Property, Multi-mode character

I. Introduction

WITH the fast growing of cities and urban areas in countries (especially in China), urban traffic systems have encountered more and more problems, such as, traffic balance and predict, congestion elimination, traffic guidance and management, etc. To solve these problems may need us to deeply understand and precisely describe the inherent dynamics and the evolving mechanisms of urban traffic systems.

In this paper, based on the Beijing road traffic system, we discuss how to use dynamic network theory and methods to model and analyze dynamical characteristics and evolving patterns of urban traffic systems. The modeling and analyzing of complex behaviors of urban traffic systems is a hot issue in urban traffic research and complexity science. By identifying system modes, this paper analyzes the scale-free property of urban traffic systems at different phases.

Consequently, we introduce the dynamic network model of the Beijing road traffic system in which the Level-Of-Service (LOS) is adopted to determine traffic state of traffic flow on roads. Firstly, the model has the ability of reflecting the dynamical characteristics on road traffic flow by integrating LOS into the weight equation. Secondly, from the perspective of whole network, the model concludes that the Beijing road traffic network has three system modes: static network mode, stochastic network mode and complex network mode; where the static network mode represents the network structure is fixed, the stochastic network mode is that the network structure would be changing with time, and the complex network mode means that the network is scale-free.

The scale-free property is one of the distinguished property of various real complex networks [1–6]. And it is concerned by researchers from urban traffic area, but a benchmark still lacks..Lämmer et al. proved that the distribution of vehicular flows over the roads in the network composed of 20 largest German cities obeyed a power-law [7]. Kalapala et al. showed that the dual degree distribution of the national road networks of the United States, England and Denmark follows a power law with exponent $2.2 \leqslant \alpha \leqslant 2.4$ [8]. Other researchers studied the subway network, the public transit network, with focusing on topological and geographic structure only.

The multi-mode character of urban traffic systems provides a promising way for researching on evolving mechanism of these systems. The structural randomness of the dynamic network model of the Beijing road traffic system represents the dynamics of traffic flow at network level. In different modes, the network characteristics are demonstrated in a simple way through analytical experiments based on real traffic data. By analyzing and validating the structural randomness and the scale-free property, this paper concludes that, in a $24h$ time cycle, the Beijing road traffic network shows the characteristics of static networks, stochastic networks and complex networks at different phases respectively.

Z.Zhang, L.Jia and X.Sun are with the State Key Lab of Railway Control and Safty, and Traffic and Transportation School of Beijing Jiaotong University

II. Backgroud and Motivation

The Beijing road traffic system, as a typical huge urban traffic system, has 140000 various roads and several million vehicles, and faces more and more traffic jams and unbalance which causes that the traffic management encounters plenty of problems and traditional analytical approaches can not explain complex phenomena effectively.

Fig. 1 is the full view of the roads in which the thicker lines are freeways and arterial.

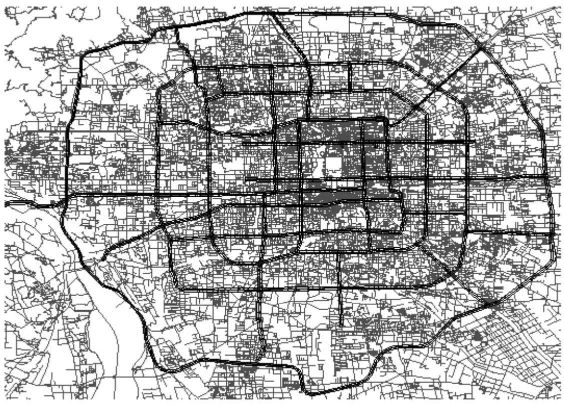

Fig. 1. The full view of Beijing Road Traffic System

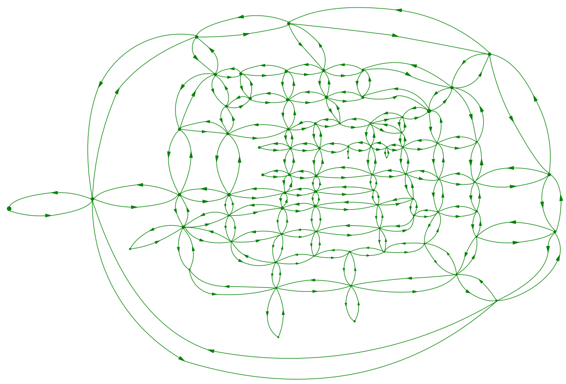

Fig. 2. The network of Beijing Road Traffic System

All the freeways and arterials have been equipped with detecting sensors, which means the real-time detection data of traffic flow on them can be provided for supporting the dynamic network modeling. Otherwise, the sensor-equipped road is dominant to the adjacent roads whose design class is lower. So, we deliver the major-road network in Fig. 2 based on the sensor-equipped roads.

III. Dynamic Modeling

The point in dynamic modeling of urban traffic networks is to describe the dynamical characteristics on road level and network level. The LOS, firstly introduced in Highway Capacity Manual, is often used to evaluate the traffic state of traffic flow on roads [9]. On the other hand, the degree distribution represents the dynamics on network level. The analyzing method of scale-free is detailedly introduced in Reference [10].

LOS is a measure-of-effectiveness by which traffic engineers determine the quality of service on elements of transportation infrastructure, including six levels: $\{\mathbb{A},\cdots,\mathbb{F}\}$ with $\mathbb{A}$ being best and $\mathbb{F}$ being worst [9]. Based on that, we introduce the LOS value and the LOS level as following. The LOS value represents the degree of the volume at any time to the capacity of a road (known as V/C ratio), reflects the traffic connectivity on the road. As well, the LOS levels are six in the Beijing road traffic LOS evaluating system, where $\{\mathbb{E},\mathbb{F}\}$ is the congestion class in the system.

In this paper, the traffic network composed of freeways and arterials, as the modeling object, is shown in Fig. (2), where, the complete set of nodes, marked as N, $N = \{n_1,\cdots,n_{76}\}$; the complete set of edges, marked as E^{m}, $E^{\mathrm{m}} = \{e_1,e_2,\cdots,e_{252}\}$. An edge e is the directed connection between two nodes:

$$e = e(n_{\mathrm{o}},n_{\mathrm{d}}), n_{\mathrm{o}},n_{\mathrm{d}} \in N, n_{\mathrm{o}} \neq n_{\mathrm{d}},$$

where, n_{o} and n_{d} are the start node and the end node respectively.

The dynamics of urban traffic systems is represented by the network model at two sides: one is the time-vary weight updated with LOS; another is the dynamical network structure appeared obviously when traffic state on some roads reaches the given limit. The weight at any time implies the degree of affordable volume at the time; the higher of its value, the better of the traffic situation.

Based on the method proclaimed in the technical report of the Beijing road traffic LOS evaluating system, this paper integrates 'V/C' ratio into the equation of the LOS value (marked as ϕ^{v}):

$$\phi^{\mathrm{v}}_{\mathrm{r}}(t) = \frac{V(t)}{C},$$

where, r is the given road; $V(t)$ is the volume at time t; C is the capacity of r, provided by Beijing Traffic Management Bureau. So, we define the weight (w) as:

$$w(t) = 1 - \phi^{\mathrm{v}}(t).$$

From the perspective of traffic connectivity, when traffic state on a road reaches a certain degree (that means the traffic state is congested), the time that vehicles cost on the road is over expected, which means the road at that time is unavailable. Consequently, the t-time edge set of the dynamic network model includes only the roads whose LOS levels at the time are not in the congestion class. Therefore, we define the LOS level (marked as $\phi^{\mathrm{c}}(t)$) at any time with value range $\{\mathbb{A},\cdots,\mathbb{F}\}$ as following. The LOS level at any time is determined by the equation $\phi^{\mathrm{c}}(t) = f(\phi^{\mathrm{v}}(t))$ with the mapping function$f : [0,1) \rightarrow \{\mathbb{A},\cdots,\mathbb{F}\}$.

In the dynamic network model, the dynamical characteristics on roads are represented by the time-varying weights. When the LOS level $\phi^{\mathrm{c}}_{\mathrm{r}}(t)$ satisfies $\phi^{\mathrm{c}}_{\mathrm{r}}(t) \in \{\mathbb{E},\mathbb{F}\}$, the corresponding edge would not be included into the dynamical edge set $E(t)$. So, the edge set at any time, marked as $E(t)$, is defined as following.

$$E(t) = \{\forall e \in E | \phi^{\mathrm{c}}_{\mathrm{e}}(t) \notin \{\mathbb{E},,\mathbb{F}\}\},\ E(t) \subseteq E^{m}. \quad (1)$$

As stated above, the dynamic network model has the structural randomness which means the edge set is changing with time. The structural randomness of the dynamic network plays an important role in defining the dynamic model and proving the scale-free property.

Definition 3.1: The Dynamic Network Model (DNM) for the Beijing urban road traffic system can be described by a triple:

$$DNM(t) = DNM(N,E(t),W(t)),$$

where, N is the complete set of the vertexes; $E(t)$ is the t-time edge set(see in Eq. (1)); $W(t) = \{w_e(t)|e \in E(t)\}$ is the set of the t time weight of the edges in $E(t)$.

The equations of the In-Degree and the Out-Degree in Mdl. DNM are following.

Definition 3.2: The In-Degree, κ^{in}, of any vertex n at any time period t is the sum of the t time weights of the edges whose the end vertex is n:

$$\kappa^{\mathrm{in}}_{\mathrm{n}}(t) = \sum w_{\mathrm{e}}(t),\ e(n_{\mathrm{d}}) = n,\ e \in E(t).$$

Definition 3.3: The Out-Degree, κ^{out}, of any vertex n at any time period t is the sum of the t time weights of the edges whose the start vertex is n:

$$\kappa^{\mathrm{out}}_{\mathrm{n}}(t) = \sum w_{\mathrm{e}}t,\ e(n_{\mathrm{o}}) = n,\ e \in E(t).$$

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In the dynamic model, the dynamics of the Beijing road traffic system is represented at the following two aspects. The time-varying weights represent the dynamical traffic state on roads. The structural randomness, on the other hand, reflects the dynamical traffic networks state. The dynamic model provides a basis for the following work on the multi-mode demonstration and the scale-free analysis.

IV. Experimental Analysis

In this paper, all experiments for validating and analyzing is designed based on the real traffic data from the Beijing road traffic sensor network. From the experiments, we validate and analyze the multi-mode and the scale-free property of the dynamic network.

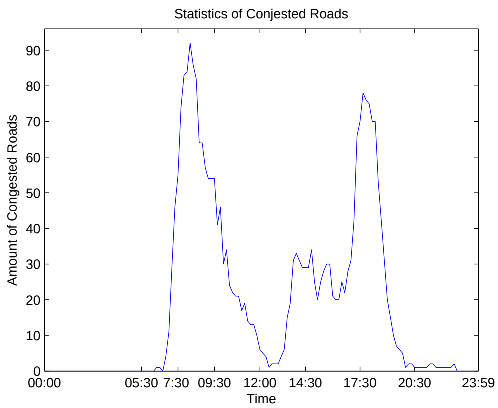

Fig. 3. Statistics of Congested Roads (24h)

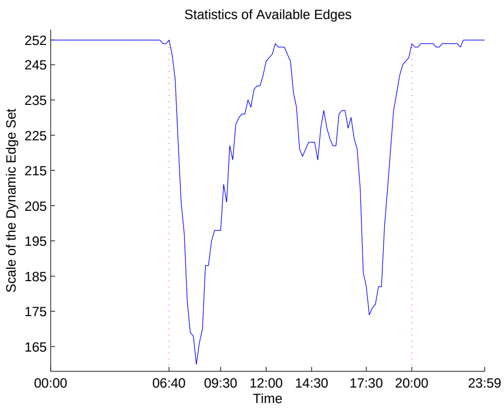

Fig. 4. Scaling the edge set E (24h)

Fig. (3) exhibits the amount of congested roads in one day. Fig. (4) demonstrates the scales of E in Mdl. DNM changing with time, which implies the randomness of the network structure. As shown in the figures, before "6:40" and after "20:00", there is no edges excluded in the network, which means no jams happen. During that time, the traffic network is characterized by static network properties. Except for those time periods, congestion appears stochastically, which means the traffic network shows stochastic network properties. By comparing in-degree and/or out-degree distribution of the snapshot networks of the dynamic network at different selected time, this paper puts forward the scale-free property of the dynamic network.

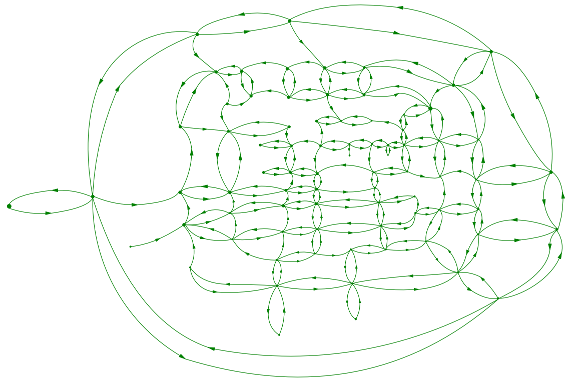

Fig. 5. DNM's network structure at 7:20.

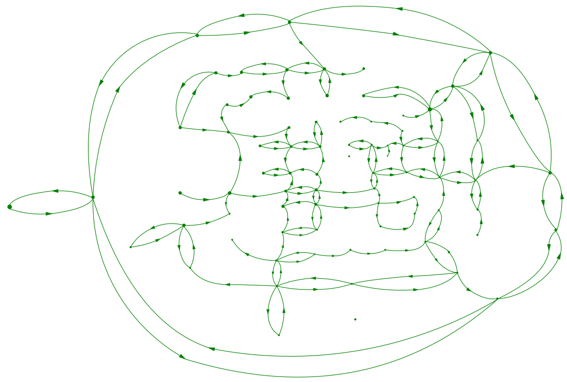

Fig. 6. DNM's network structure at 7:50.(The out-degree distribution $p(x)$ with $x_{min} = 5279.658$ satisfies: $p(\kappa > 5279.658) \propto \kappa^{-2.9749}$.)

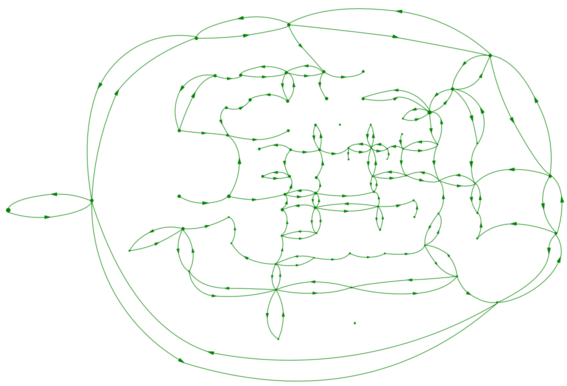

Fig. 7. DNM's network structure at 8:00.(The out-degree distribution $p(x)$ with $x_{min} = 3023.258$ satisfies: $p(\kappa > 3023.258) \propto \kappa^{-2.2450}$.)

As shown, the out-degree distributions (of the snapshot networks in Fig. (6) and Fig. (7)) and the in-degree distribution

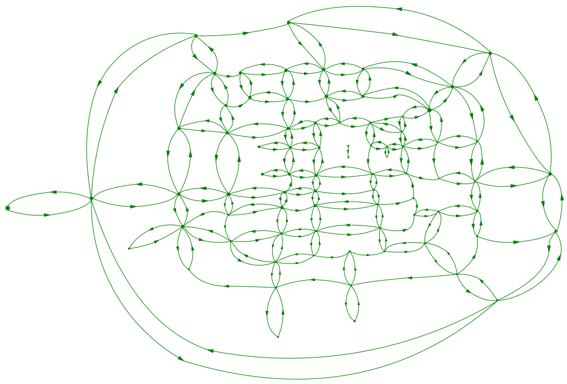

Fig. 8. DNM's network structure at 10:00

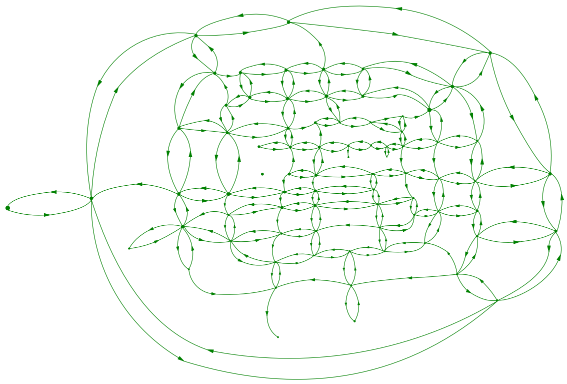

Fig. 9. DNM's network structure at 17:00

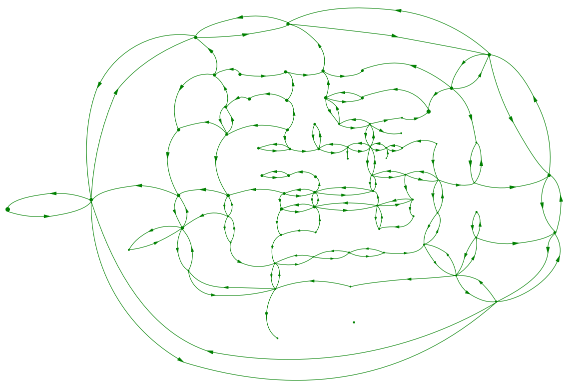

Fig. 10. DNM's network structure at 18:10.(The in-degree distribution $p(x)$ with $x_{min} = 4556.402$ satisfies: $p(\kappa > 4556.402) \propto \kappa^{-2.7957}$.)

(of the snapshot network in Fig. (10) follow a power-law, which means the traffic network at these times are scale-free. The scale-free snapshot networks appear at the time periods that people generally think as the rush hours. During these time periods, the traffic network is denoted by the complex network property. Except for the time periods characterized by static network and complex network, the traffic network shows stochastic properties.

Based on the complete data analysis, we divide the traffic states of the Beijing road traffic network in a

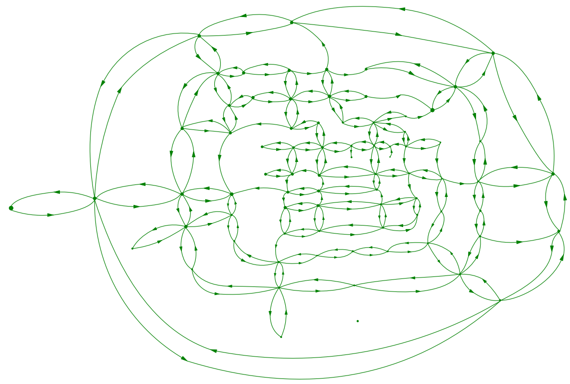

Fig. 11. DNM's network structure at 19:00

time cycle (24h) into the following modes: the static network mode ("00:00-6:40", "20:00-24:00"), the stochastic network mode("6:40-7:20", "8:20-12:00", "12:00-18:00", "18:40-20:00") and the complex network mode ("7:20-8:20", "18:00-18:40"). Through the snapshot network structure, the evolving process of the traffic states of the Beijing road traffic system is demonstrating basically.

V. Conclusion

Based on the Beijing road traffic system, this paper discusses the dynamical characteristics of traffic flow on roads and the structural dynamics caused by the former by constructing the dynamic network model. In the dynamic network model, the edge wights determined by LOS value represent the dynamical characteristics of traffic flow on roads. On the other hand, the structural randomness of the dynamic network is denoted by judging congested roads with LOS levels. From the experiments, we know that the dynamic network model reflects the dynamics of the Beijing road traffic systems at road and network levels, divides the traffic states into three modes: the static network mode, the stochastic network mode and the complex network mode, in which the snapshot networks under the complex network mode are scale-free. As well, the evolving process of the traffic states of the Beijing road traffic network has been demonstrated basically by a series of snapshots.

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