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On Coupling of Multi-Traffic System and Accessibility of the Transit Networks

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Abstract: In this paper, urban traffic accessibility is regarded as the external manifestation of the dynamic process of the coupling of several traffic systems. Firstly, the relationship between a subway system, a bus rapid transit system, and a common bus system are analyzed, as well as the relationship between the traffic networks and the ground road network, and the coupling networks are constructed to objectively and comprehensively reflect the coordination structure of a city's traffic system. Then based on the static structure of the coupling traffic networks, dynamic process of vehicles and personnel flow is analyzed, and the networks' dynamic characteristics is studied to get a congestion propagation model, so as to provide the basis for quantitative evaluation for the accessibility of the multi-traffic system. Finally, an algorithm to solve the accessibility of the system is designed and the practical reachability of the traffic networks of a sample city is calculated.

Introduction

Transport mobility is an important factor in defining the population's accessibility to services and facilities, also an indispensable prerequisite for a tourism system. Many studies on travel behavior indicate that urban form and transit accessibility are important factors to determine people's travel behavior such as neighborhood choice and travel distance. Transport infrastructure plays an important role in shaping the configuration of spatial socio-economic structures and influences regional accessibility. The main component of accessibility in urban areas is the relation between the transportation network and land use. Improvements in technology have an effective role on the location of urban functions on behalf of urban transportation networks in addition to the economic and social life in the cities. So, many studies are focused on this area.

In the study of regional accessibility on public transportation [1], accessibility index accessible time, accessible distance and public transport service status are used as data base, and the accessibility mobility and accessibility indicators of the region are analyzed. The secondary accessibility model of public transportation is established based on the existing spatial barrier model, and the accessibility distribution is studied by spatial analysis. The paper [2] tends to optimize distribution of air cargo transportation network by adjusting cargo aircraft flights. The purpose is to effectively allocate air cargo transportation resource and provides decision support for macro-control policy. Aiming to simulate the multi-objective decision process of network design problem, a multi-objective bi-level programming model combined with cargo transportation route selection is proposed to maximize network accessibility and utilization. The model is solved by NSGA-II algorithm and the trade- offs between the objectives are reflected by Pareto optimal solutions.

In article of [3], on the basis of factors affecting network accessibility, two types of algorithms were studied and the framework of the network accessibility system was designed and implemented. The paper [4] examines the impacts of bicycle-train integration policies on train ridership and job accessibility for public transport users. The analysis shows that improving the quality of bicycle routes and parking can substantially increase train ridership and potential job accessibility for train users. Large and medium stations are more sensitive to improvements in bicycle-train integration policies, while small stations are more sensitive to improvements in the train level of service. The distribution of residential parcels is analyzed in paper [5] from a rarely explored angle—that is, its location in relation to services and facilities. The aims of the study are first to develop an index of the accessibility of various urban resources to each residential parcel in a metropolitan area of Adelaide using spatial data analysis in Geographical Information Systems and then to develop a relationship with socio-economic and land use attributes of statistical areas using ordinary least squares (OLS) and geographically weighted regression analysis. As expected the ‘Distance to CBD’ variable has a positive relationship with metropolitan Accessibility/Remoteness Index of Adelaide (metro-ARIA) meaning that the farther away statistical areas have lower accessibility to services. In the case of population density variable, the relationship is mostly negative except few areas in the far south, west and northern areas, which showed a positive relationship. The study of [6], focused on the Road Emergency Rehabilitation Problem, divided into the Road Network Accessibility Problem (RNAP) and the Work-troops Scheduling Problem (WSP). The first one consists in finding traversable paths for relief teams to reach the population, and the later generates a repairing schedule to improve access to refugee areas. A utility-based travel impedance measure is developed in paper [7] for public transit modes that is capable of capturing the passengers’ behaviour and their subjective perceptions of impedance when travelling in the transit networks. The proposed measure is time-dependent and it estimates the realisation of the travel impedance by the community of passengers for travelling between an origin–destination (OD) pair. The paper [8] explored the homogeneous vs. heterogeneous characteristics of the German commuting network, by focusing on the role of accessibility and considered home-to-work commuters travelling between 439 German districts, for the year 2002. The final results seemed to highlight the tendency, in Germany, towards a multi-nodality network, where accessibility could play a fundamental role.

In paper [9], a city’s traffic system was constructed from a bus traffic networks and a subway network, and the robustness and fragility of the system were studied. In paper [10], the characteristics of bus network are discussed based on new rail transit line. On the basis of comparing the characteristics of rail transit and bus, classification and characteristics of bus lines are analyzed considering the competition and cooperation relation, topological structure relation and function integration relation with rail transit line respectively.

For a long time, traffic systems’ researches are mostly limited to the internal characteristics of a single system, study on the relationship between multiple systems for various levels of traffic network is still in infancy. In those few studies, the relationships between different traffic networks were mainly analyzed based of statistics data. For the lack of study of the logical relationships between these traffic systems, overall structure and effective model were not formed, and there was only limited effect in solving traffic problems. Transportation system is an open complex system consisting of multiple interacting subsystems. There are dynamic mutual feedback between multiple components and its social, economic and natural environment, such as material exchange, energy flow and information transmission. In this project, several traffic networks and their coupling structures were studied from the perspective of complex network theory. Based on analysis of the dynamic relationship model of multi-traffic systems, the synchronization and congestion state between different traffic systems were used to described the stability and patency of a city's traffic networks, so as to find some ways to optimize and improve their overall performance, and promote the development of the city transportation.

Research Methodology

In this study, urban traffic accessibility is regarded as an external manifestation of dynamic process of the coupling of multi-traffic systems. The coupling structures between different urban traffic networks are to be analyzed, and their parameter characteristics and coupling dynamic characteristics calculated. After that, congestion propagation model of the coupling networks is established and reachability algorithms are designed so as to provide a theoretical basis for reasonable planning and coordinated development of urban traffic systems. With mainly concern to public travel systems, this paper conducts the study mainly from the following two aspects:

(1) Construct the coupling model of urban multiple traffic networks and study its dynamic characteristics.

(2) Study the accessibility of urban traffic system based on the coupling model.

In the study, coupling structure between a subway network, a BRT (bus rapid transit) network, and a common bus network were analyzed first, as well as the coupling structure between these traffic networks and a ground road network. Then, a coupling transport network was described to reflect objectively and comprehensively a city's traffic coordination structure. After that, based on the static structure of the coupling traffic network, the dynamic process of the interaction of the vehicle flow and the personnel flow was analyzed, and their dynamic characteristics was studied and a congestion propagation model was established, which providing a basis to quantify the accessibility of a multi-transportation system. Finally, according to the characteristics of large scale and complex structure of the coupling network of the multi traffic systems, a feasible reachability algorithm was designed, and the simulation of a city's traffic system reachability was carried out.

Keys to the Study

The general technical route is: constructing coupled traffic network > analyzing the network's dynamics and establishing its propagation model > research of the accessibility. The research methods, technical routes, experimental plans are summarized as follows:

Main data sources

(1) National bus database of China (http://db.myds.cn/bus_database.aspx): The database contains more than more than 16600 bus line data of 203 major cities in 33 provinces, municipalities and special administrative regions except Taiwan, and the database is updated once in a while. It includes the data of bus line information, bus station, starting time, ticket system, ticket price, distance and so on, and provides further development tools of the database.

(2) Google Earth is the virtual globe software developed by Google, which sets satellite photos, aerial photography and GIS on a three-dimensional model of the earth. We can browse the high-resolution satellite images from all over the world through a client software downloaded to our computer.

(3) National Basic Geographic Information Center of China: provide the Chinese Astronomical geodetic network, GPS network, gravity network, geoid and other multi-precision spatial datum results and multi-resolution aerial and satellite remote sensing image data.

(4) DigitalGlobe (http://www.digitalglobe.com/): DigitalGlobe is a global leading commercial high resolution earth image product and service provider, with its own satellite group and a comprehensive image library (including more than 4 billion square kilometers of earth images and related products). It provides a series of online and offline products and services to allow customers to easily access their photos and like or integrate it into their own business operations and applications.

Construction of coupling traffic network

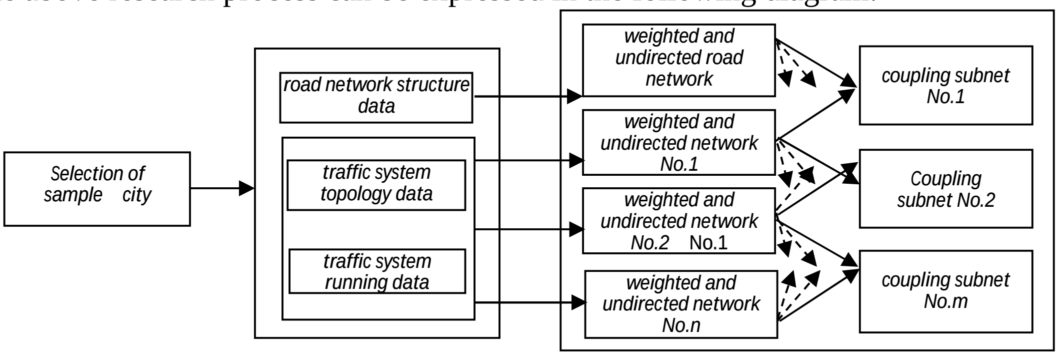
A join node of two networks is called a coupling node. All coupling nodes of the networks and their connections form their coupled subnet. Multiple traffic networks and their coupling subnets eventually form a coupled traffic network, and they are interacted by the coupled structure. Therefore, this part of our research includes data acquisition, data processing, coupling subnet construction, and so on.

(1) Data collection: selection of sample city; extraction and collection road network structure data, main traffic system network topology data and their running data.

(2) Data processing: the corresponding weights are given to each road section of the sample city, according to its traffic capacity, and an undirected network of the city's roads is constructed; then a weighted and undirected network of the traffic system is constructed according to the network topology of the city's roads and their running data.

(3) Coupling subnet construction: the ground road, the subway, the BRT, the common bus and other traffic systems are connected by the coupling nodes, and the coupling subnet between them is constructed from these coupling nodes.

The above research process can be expressed in the following diagram:



Analysis of network dynamics and establishment of congestion propagation model

The classical model of SIR infectious disease is used as the basic frame of the coupled traffic network congestion propagation mathematical model. It describes the flow process of the vehicle, analyzes the change law of the traffic flow of the coupling node, and predicts the probability of the congestion. In this model, the coupling nodes can be divided into 3 different types: *S*, *I* and *R*. *S* type nodes have no congestion, but if they are connected to congestion nodes, their congestion probability is increased by a large scope; *I* type nodes have already appeared congestion and may transmit the congestion to *S* nodes; *R* type nodes are in adjusted state after congestion, and their congestion will not be transmitted to other nodes. After adjustment, they can resume normal operation and become *S* type nodes. Using $s(t)$, $i(t)$ and $r(t)$ to represent the density of *S*, *I* and *R* nodes, the congestion propagation is represented as follows:

$$\frac{\mathrm{d}s(t)}{\mathrm{d}t} = -\rho_u i(t)s(t), \tag{1}$$

$$\frac{\mathrm{d}i(t)}{\mathrm{d}t} = -\rho_u i(t)s(t) - \gamma_t i(t), \tag{2}$$

$$\frac{\mathrm{d}r(t)}{\mathrm{d}t} = -\gamma_u i(t). \tag{3}$$

Among them, ρ_u is the probability of congestion propagating from *I* to *u* when a *S* type node *u* adjacent to an *I* type node. It is the key of congestion propagation model, and the calculation method is a difficult point of this part of research.

Study of the accessibility

According to the partition theory, the urban traffic network is divided into *n* traffic zones. The centroid of a partition is a node in the network topology, and the accessibility of the whole traffic network is solved by examining the accessibility of each node of its.

Suppose there are *m* paths between nodes *u* and *v*. d_{uv}^{i} is the length of one of them call *i* path , and d_{uv}^{Mini} is the shortest distance among all of them. Then, the maximum reachability k_{uv} of the two is the shortest distance dividing the sum of distances of all paths between them.

$$k_{uv} = \frac{d_{uv}^{\mathrm{Mini}}}{\sum_{i=1}^{m} d_{uv}^{i}} \tag{4}$$

Johson algorithm is an efficient algorithm for finding the shortest path of all node pairs in a network. It is the synthesis of Bellman-Ford algorithm, Reweighting and Dijkstra algorithm. The main process is as follows:

(1) Add node *u* to the network *G*, so that the weight of edges from *u* to every node of *G* is 0.
(2) By means of the Bellman-Ford algorithm, take *u* as a source node, find the shortest path from *v* ($v \in G$) to *u*. If there is a negative loop, the algorithm will terminate.
(3)Update the weight of each edge <*u*,*v*> of *G* according to the length of the shortest path and get a new network *G'*: $w(u,v)=w(u,v)+ d_{vu}^{\mathrm{Mini}} - d_{uv}^{\mathrm{Mini}}$
(4) Remove *u* and calculate the shortest distance from *v'* ($v' \in G'$) to the other using Dijkstra algorithm.

The reachability (K_u) of *u* is the sum of the maximum reachability of *u to* all other nodes in the network:

$$k_u = \sum_{v=1}^{n} k_{uv}, u \neq v. \tag{5}$$

The reachability (a_N) of the whole network is solved by the reachability of each node.

$$a_N = \sum_{u=1}^{n} k_u. \tag{6}$$

This part of the research can be expressed in the following diagram:

Max reachability (k_{uv}) *of u to V* → *Reachability* (K_u) of *u* → *Reachability* (a_N) for the *entire network*

By way of above calculation model, the accessibility of a number of urban coupled traffic networks is studied. The simulation results are compared with the statistical data published by the related traffic databases to optimize the accessibility model.

Conclusion

This project is based on coupling network to study the accessibility of multi-traffic systems. It will provide new methods for the study and solution of urban traffic problems, and the social benefits will be very obvious. It involves the theory and methods of information technology such as traffic network, coupling network and algorithm design. The key to the study is to break through two technical difficulties: one is the structure of the coupling traffic network and its dynamics research, and another is the accessibility algorithm of the multi-traffic systems. we have put forward feasible research methods and technical routes.

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