RESEARCH ON THE NETWORK CONFIGURATION IN THE INITIAL STAGE OF URBAN RAILWAY PLANNING

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Abstract: The configuration of urban railway network is one of the most important contents in the initial stage of urban railway planning. When the scale of urban railway system is determined, the network configuration will directly influence traffic attraction ability and operation efficiency of the system. In this paper, we first define two elementary units of the network and based on their relations, most of the existing urban railway systems are analyzed and subdivisions, which may be useful in the following study, are summarized. We then discuss possibility to use two methods to evaluate the static characteristics of the network, namely the link-matrix method and the structural parameter analysis method. Then interactions between the city conformation and the network configuration are qualitatively analyzed. Finally we bring forward a series of strategic principals when determining the network configuration in the initial stage of urban railway planning.

Keywords: Network Configuration, Static Characteristics of the Network, City Conformation

1.BASIC ANALYSIS OF THE CONFIGURATION OF URBAN RAILWAY NETWORK

The configuration of urban railway network is one of the most important contents in the initial stage of urban railway planning. When the scale of urban railway system is determined, the network configuration will directly influence traffic attraction ability and operation efficiency of the system once put into use. Therefore it's necessary to study the basic topological characteristics of elementary forms of the railway network under the ideal conditions when the geological attributions, the conformation and the developing pattern of the city are not taken into account.

1.1 Elements of Urban Railway Network

Relations of links are the main contents in the initial stage of network planning, while the dispositions of stops are not considered. So urban railway network can be turned into directionless finite graphics G as in mathematics. Graphics G is made up of two subsets, namely subset V and subset E. Elements in subset V are called nodes, including intersections and ends of links, or interchanges and terminus. Elements in subset E are called links, namely lines between two nodes.

Based on the connectivity of nodes, graphics G can be classified into three kinds, namely connected graphics, nonconnected graphics and null graphics. If a sequence of alternately connected nodes and links is defined as a chain, in null graphics subset E is null and nodes are isolated with each other while in connected graphics any two nodes are connected with at least one chain. Connectivity of nonconnected graphics is between that of null and connected graphics and this kind of graphics can be divided into several connected sub-graphics.

When taking the purpose of transportation into account, null graphics is apparently not suitable as railway network. Nonconnected graphics do exist in practice, but conveniency of the network is decreased by the necessity of transferring by other modes. Since the objective of planning is to make trip more convenient, connected graphics is sure to substitute for nonconnected graphics. Therefore only connected graphics is discussed in this paper.

Connected network has a variety of forms, but from the viewpoint of Theory of Graphics, all network can be divided into two kinds of elementary units, namely loop unit and limb unit. Any two nodes in loop unit are connected with at least two chains while in limb unit with only one chain. Based on constitutive units, railway network can be classified as two kinds:1)tree-like network, which is completely constituted with limb units;2)circular units, which is constituted with limb units and loop units or only the later.

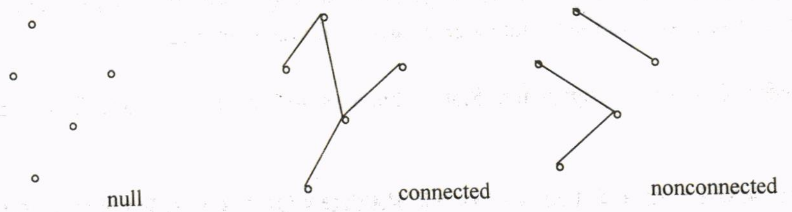

Figure 1 Null, Connected and Nonconnected Graphics

Analyzing the existent railway network of the world, we can find 7 basic configurations.

a. Mongline or parallel lines:
Mongline network has limited attraction range, which is distributed along the railway. Only when traffic flow is mainly in one direction is this kind of network suitable. Mongline is always diameter or radius running through center of the city, and parallel lines are often extension of mongline for the request of operation.

b. Single circular network
Usually circular railway line runs around the CBD or the central area of the city. Supposing in the distance of 1km along the line can trippers walk in 10 minutes to use the railway, 40km long single circular network can attract trippers in 80 square meter range. So for a city of only middle scale, single circular network can provide enough service.

c. Fishbone-like network
Fishbone-like network is a typical tree-like network. In this kind of network exist several main lines, while other assistant lines have one end on main lines. For lacking of gridding structure, connectivity of fishbone-like network is somewhat low and transfer between lines is inconvenient. Moreover, the section between two interchanges on main lines bears substantive transfer trips, so flow distribution between main lines and assistant lines is apparently disproportionate, which bring great difficulty for operation organization.

d. Radialized network
There is only one interchange of all lines in radialized network, through which direct transfer between any two lines can be carried out. Since trip flow is substantive in interchange stop, there is great disturbance among different transfer flows, which can cause congestion and disorder. On the other hand, interchange always locates in city center, so trip between city suburbs is somewhat inconvenient.

e. Gridding network
In gridding network there are at least 4 lines that form a group of parallelograms. Lines of gridding network distribute evenly in central area of the city while extending into the suburb. The existence of gridding structure greatly increases connectivity of the railway system, while parallel lines mainly along two directions can provide prodigious transportation capacity and make trip flow and transfer between lines distribute more evenly. But lacking of diagonal lines will make trip between city center and suburb much inconvenient.

f. Cross-radialized network
Cross-radialized network is made up of at least 3 diagonal lines that run through city center and intercross each other to form a series of triangle gridding structure. The gridding structure and evenly distributed interchanges greatly increase connectivity of the network. Although lines running in more than two directions facilitate trip between city center and suburb, the concentration of interchanges in city center will make trip between suburbs inconvenient.

g. Radialized-circular or cross-radialized-circular network
Radialized-circular or cross-radialized-circular network is the integration of radialized or cross-radialized network and circular network. These two types are suitable for large-scale railway system. The circular line (lines) intersects all diagonal lines and therefore greatly improves transfer conveniency between diagonal lines. For radialized-circular network, the circular line decreases the difficulty of traffic organization in the central interchange; for cross-radialized-circular network, connectivity is even better than cross-radialized network. Besides, more widely separated interchanges will reduce transfer flow on circular line and

avoid too apparent difference of usage between circular and diagonal lines.

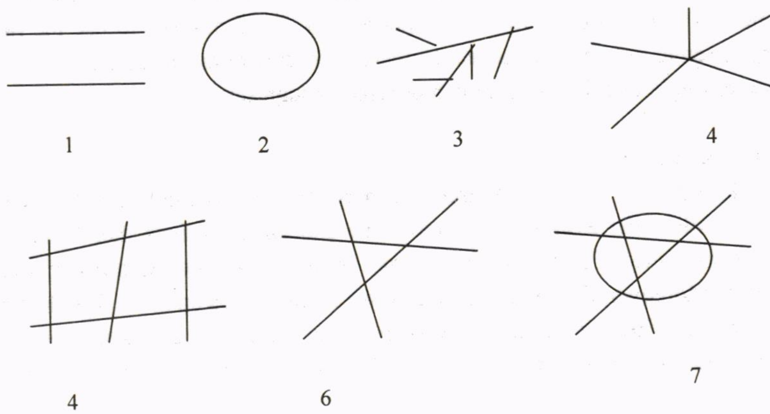

Figure2 Basic Configurations of Railway Network

1.2 Topological Analysis of the Railway Network

Topological analysis is always used to evaluate static characteristics of urban railway network. There are mainly two approaches as follow.

1.2.1 Link-matrix

Topological structure of graphics can be efficiently descripted by link-matrix, which is corresponding one by one to graphics G. If graphics G has n nodes the corresponding link-matrix A is defined as n*n. If node i and node j are connected with at least one link, then the element in row i and column j $a_{ij}=1$;otherwise $a_{ij}=0$. If not taking direction into account, link-matrix A is symmetrical.

Link-matrix is mathematical abstraction of network attributes and can facilitate later analysis. But this matrix can't reflect more than one route directly between two nodes, and must combine with other methods.

1.2.2 structural parameters of the network

Supposing E is the number of links, V is the number of nodes and T is the number of sub-loops, the parameter of static characteristics of railway network including following items:

a. $Order = E - V + T$ (1)

b. Ratio of links to nodes $\beta = E / V$ (2)

c. Degree of connectivity γ, which is the ratio of factual number of links to maximal number of links when any two nodes are connected with one and only one link.

$$\gamma = \frac{E}{V \times (V-1)/2} \times 100\% \tag{3}$$

d. Attractive intensity of the network

$$A = \frac{\sum_{i=1}^{N} A_i}{N} \tag{4}$$

Here A_i is the attractive intensity of the ith line including essential and transfer flow, and N is the number of the lines.

e. Geometrical number of transfer

$$C = \max_{i=1}^{N}[\min_{j=1}^{N} C_{ij}] \tag{5}$$

Here C_{ij} is the number of transfers from line i to line j.

f. Number of interchanges M. Equilibrium should be achieved between M and traffic flow distribution. If there are too many interchanges, investment in construction of the project will increase, otherwise transfer flow between lines will increase burden of links in partial area to a great extension.

1.3 Transportation Efficiency of Railway Network

When geographical characteristics, conformation and develop pattern of the city are ideal, and when distributions of population and employment are the same, different railway network will have different transportation efficiency.

Overall time divided by overall mileage of trips in the whole city can indicate one aspect E_1 of transportation efficiency of railway network. E_1 reflects the celerity of the system and will increase following the reduction of overall time T_T while the overall mileage T_L is constant.

$$T_T = \sum_{i=1}^{n}\sum_{j=1}^{n} N_{ij} T_{ij} \tag{6}$$

$$T_L = \sum_{i=1}^{n}\sum_{j=1}^{n} N_{ij} L_{ij} \tag{7}$$

$$E_1 = T_T / T_L \tag{8}$$

Here n is the number of transportation zones, N_{ij} is the number of trips from area i to area j using the railway system, T_{ij} is the time of trips from area i to area j using the railway system, and L_{ij} is the average distance from area i to area j.

Another indicator of transportation efficiency of railway network is E_2, which means the number of transfers per trip. E_2 reflects the conveniency of the system and the reduction of E_2

implies that the network configuration is more consistent with the distribution of transportation demand.

$$T_N = \sum_{i=1}^{n}\sum_{j=1}^{n} N_{ij} \tag{9}$$

$$T_{TR} = \sum_{i=1}^{n}\sum_{j=1}^{n} N_{ij} Tr_{ij} \tag{10}$$

$$E_2 = T_{TR} / T_N \tag{11}$$

Here n is the number of transportation zones, N_{ij} is the number of trips from area i to area j using the railway system, and Tr_{ij} is the average number of transfers from area i to area j using the railway system.

To compare transportation efficiency of different network configurations, we should first suppose that capacity of the railway system and characteristics of the city, such as the conformation, area, population, distribution of population, distribution of employment and average number of trips per person, are the same. Besides, the geological and topological attributes are supposed to be uniform, and basic network configurations to be standardized (for example, in radialized network the angle formed by any two nearest diagonal lines and the distance from the central interchange to the terminus on any diagonal lines are the same). Then using software such as TransCAD, the above two parameters E_1, E_2 of different network configurations can be calculated and the efficiency of the network can be compared.

Topological analysis of railway network is highly abstract. Since conditions of different cities and configuration of different railway systems are much differentiated, to use this method is apparently not enough. The discrepancy between the result of topological analysis and practical conditions will be more obvious following the increase of numbers of the lines. Moreover, complex railway systems reflect more influence of traffic flow distribution, geological and topographical characteristics and developing pattern of the city than that of the network configuration itself.

2.RECIPROCITY OF URBAN RAILWAY NETWORK CONFIGURATION AND CITY CONFORMATION

Transportation and city are closely connected. On one hand, geographical conditions, developing pattern and distribution of the traffic flow based mainly on the first two factors will greatly influence the railway planning. On the other hand, as one of the largest infrastructures of the city, the railway system will be inevitably counteractive to city conformation.

2.1 Influence of City Conformation on Railway Network Configuration

2.1.1 influence of the geographical and topographical conditions

This kind of influence is embodied mainly as limitation of natural conditions on the positions and extending directions of the lines, and it's basically out of economical consideration. Another influence of geographical condition on railway network configuration is that geographical condition can to some extend determine the developing pattern of the city, and consequently, in the way described in 2.1.2, influence the network configuration.

For example, if a city develops along a river on one side and along mountain ranges on the other side, the railway lines extend always along the main developing axis. For city by the sea, since the city center is often near the seaside, railway lines can extend along the coastline or into the inner land and the network configuration is often tree-like. However, a city on the plain will not be limited by topographical conditions and may extend simultaneously in various directions, so the railway network will also extend evenly in various directions.

2.1.2 Influence of developing pattern

Except for limitations of land planning on extension of railway lines, developing pattern influences railway network configuration mainly by influencing the distribution of traffic production and attraction. The high investment of construction and operation demands high benefit once put into use, and only when railway lines extend in the same direction as the main traffic flow, can railway system attract maximal customers. If city activities concentrate highly in the central area of the city and several large-scale residential areas disperse in the suburb, there will be certainly concentrated flow between center and suburb of the city. Under this condition, gridding network is apparently not suitable.

For geographical conditions and developing pattern of the city are interrelated, to evaluate railway system efficiency of the seven basic configurations under different geographical conditions becomes a formidable task. However, if necessary data are available, we can achieve the goal using the same idealized method in 1.3.

2.2 Counteraction of Railway Network Configuration on City Conformation

Evolvement of city conformation is traceable to transformation of space structure of the city, which itself is the outer appearance of urbanization, and is the direct reflection and result of changes in functional structure of the city. Price and the corresponding utilization mode of land are main factors in changes of functional structure, and at the same time are greatly influenced by transportation conveniency of the land and degree of competition among varieties of activities. As transportation system of the city continuously develops, traffic conveniency of the land also constantly changes and at a certain period is decided by the structure and capacity of the transportation system. And transformation of city conformation will often intensify or weaken the scope and degree of transportation technique utilization. The above mechanism is shown in Fig 3

Development of transportation system and change in transportation convenience of the land can apparently transform city conformation, and each innovation of transportation technique is corresponding to a specific mode of space structure of the city. In period of walk/carriage (1800～1890),cities often developed around the CBD as a series of concentric circles. In period of car (1925～1959),cities are characterized as dispersion of population, and separation of residential area and employment. But transportation corridors have not formed and cities developed still as concentric circles. In period of mass-transit and freeway (1950～nowadays), city conformation gradually turns to be radialized.

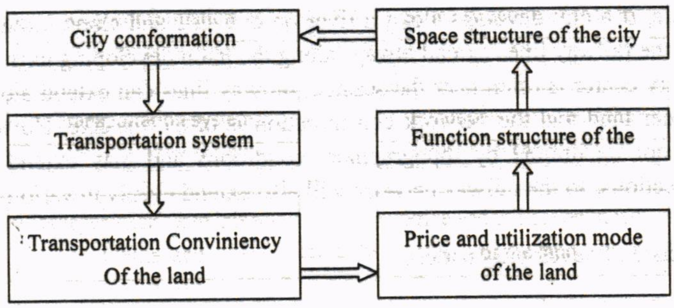

Figure3 Feed Back Mechanism of Transportation System and City Conformation

Urban railway system can greatly improve transportation conveniency of city suburb. So urban population that demand high quality of living conditions will increasingly tend to reside in suburb areas, which will attract commercial and service organizations to congregate around railway stops in suburb and help to form sub-center of the city. At the same time, the improvement of transportation conveniency of primary city center will stimulate intensive utilization of the area and maintain the energy of city center. Therefore urban railway system will accelerate the formation of multicentral structure of cities.

Different elementary units of railway network have different influence on distribution of traffic flow and city conformation. In limb unit, lines running through the city center will lead traffic flow to central area and intensify the vigor of the city center. Assistant lines extending from main lines will enlarge influential area of interchanges, lead to highly concentrated commercial and service activities and expedite the formation of sub-centers of the city. Circular unit out of the CBD or the city center can avoid unnecessary transfer trip to central area and can facilitate interrelations between outer areas of the city.

Moreover, since different elementary configurations of urban railway network have different transportation characteristics, they will also have different influence on distribution of population and city conformation.

a. Mongline or parallel lines:
If the configuration of urban railway network is mongline or parallel lines, transportation conveniency of areas along the railway lines is notably larger than that of areas away from railway lines. So price of land along railway lines will increase apparently and therefore lead to highly intensive exploitation of this region and highly concentration of residential areas and infrastructures. Thus the city will develop like a belt.

b. Single circular network

Single circular network runs always around the city center and can't provide convenient connection between city center and suburbs, so this kind of urban railway system may lower the intensity of land utilization in central area and is disadvantageous to maintain the vigor of city center. And the little difference in transportation convenience of suburbs may lead to similar development in different directions.

c. Fishbone-like network

City with fishbone-like railway network may develop several city centers along main lines, where traffic flow is much larger than assistant lines because of substantive transfer flow. Main lines between two interchanges are arteries of the city and will be intensively exploited. To maintain the advantage of convenient transportation, congregation of facilities and population is as near to railway lines as possible and forms several centers of intensive activities along main lines.

d. Radialized network

City with radialized urban railway network is always unicentral. The transportation conveniency of the city center, where all railway lines begin, is much higher than that of any other areas. Thus it becomes the first choice of varieties of facilities and activities, and the degree of concentration will be intensified as the increasing development of the central area. The final result will be one highly exploited city center.

e. Gridding network

Railway lines in gridding network distribute evenly, and there is little difference of transportation conveniecy in the central areas. Therefore the difference of exploitation intensity in the city center can be efficiently reduced, so it's often hard to form highly exploited city center. However, in suburbs, transportation conveniency of areas along railway lines is higher than that of areas away from railway lines. This difference will lead to concentrated facilities and population along railway lines

f. Cross-radialized network

The highly intensive railway lines and interchanges in cross-radialized network make transportation conveniency of the central area much higher than that of the outer region. Thus like city with radialized network, there is always a highly developed city center. The concentration of facilities and employment in this center, along with movement of residential areas to suburbs for better living conditions, produces large amount of centripetal traffic flow, while high transportation conveniency along diagonal lines leads to the formation of corresponding radialized populous belts.

g. Radialized-circular or cross-radialized-circular network

The diagonal lines extending far into the outer areas in radialized-circular or cross-radialized-circular network will facilitate exploitation of suburbs. But the existence of circular line will differentiate the influence of these two kinds of network on city conformation and that of simple radialized or cross-radialized urban railway network. There are two conditions according to position of the circular line.

Circular line running around the CBD can efficiently reduce transfer flow inward and therefore mitigate congestion there. But since the circular line itself lies in the central area, the density of lines and interchanges will be increased and more highly intensive exploitation of the city center will be an inevitable result.

Circular lines running around the city center will provide convenient connection between suburbs. The high transportation conveniency at the intersection of circular line and diagonal lines will facilitate the formation of multicentral cities.

3.PRINCIPLES TO DETERMINE URBAN RAILWAY NETWORK CONFIGURATION

The configuration of urban railway network is mainly decided by the characteristics of the network itself, geographical condition and developing pattern of the city and the corresponding distribution of traffic flow. On the other hand, the railway network configuration will also influence the city conformation. Therefore to find appropriate network configuration, we must consider this three factors.

3.1 Characteristics of the Network

Although the influence of city conformation will be increasingly more important than the characteristics of the network itself as the urban railway network becomes more complex, static parameters such as connectivity of the network are still one kind of assistant approach for planning and evaluation. Principles out of this consideration are as follow:

a. Efficiency: To be able to influence larger area with the same scale
b. Uniformity: Lines of the network should distribute evenly to guarantee an appropriate density. At the same time, there must be enough interchanges to minimize numbers and time of transfer, and the interchanges should be adequately dispersed.
c. Connectivity: Any two lines in railway network should be connected directly or by other railway lines so that to form an independent system.
d. Benefit: To achieve maximal benefit per unit of investment, the railway lines should be nearly straight and avoid parallel lines in near distance so as to minimize overall travel time.

3.2 Geographical Condition, Developing Pattern and Distribution of Traffic Flow

Because of the great influence of urban railway system on city activities, planning of urban railway should facilitate travel of citizens and should consider the adaptability of the network configuration to geographical condition and developing pattern of the city. Principles out of this consideration are as follow:

a. Network configuration should be adaptive to the specific geographical and topographical conditions of the city and avoid important pipelines underground so as to facilitate its implement and reduce the cost.
b. When choosing positions of the lines, we should consider the protection of buildings along the lines especially cultural relics.
c. If taking rules of trip production and attraction into consideration, railway network should cover as many as intensively populous or highly active areas such as residential area, industrial area and commercial area. Railway lines should also connect the CBD, sub-centers and other important locations of the city to improve the efficiency of operation.
d. To attract traffic flow on the road and facilitate transfer with buses, railway lines should extend along directions of the main roads and the interchanges of railway system should be consistent with existent interchanges of bus system and intercity transportation.
e. Network configuration should be propitious to uniformly distribution of traffic flow so as to utilize efficiently the capacity of vehicles and make organization of operation much easier.
f. Network planning should be consistent with developing patterns of the city and consider sufficiently the transformation of land function and concomitant changes in the distribution of traffic flow.

3.3 Reaction of Urban Railway Network Configuration on City Conformation

At present there are mainly two trends in development of cities. First, the developing mode as concentric circles turns into extension along axises or corridors. Second, cities with one single center are being superseded by multicentral cities.

The central idea of these two trends is the improvement of living environment and intensive utilization of lands. In traffic corridors, sub-centers and the central area of the city lands are densely exploited and are connected with convenient transportation, while being separated with green lands. Because city activities are not too concentrated and there are few differences in the degree of exploitation in the city, transportation demand will evenly distribute and environment capacity will be enlarged.

Large cities in China are mostly unicentral, with commercial areas, residential areas and employment all concentrating in the city center. When city develops, it just extends from the central area as concentric circles. However, unicentral cities, especially when they are highly populous, have apparent deficiencies such as congestion and declination of living conditions. Thus it's necessary to change this kind of city conformation. And because of characteristics such as large capacity, celerity, conveniency, safety and operation according to stationary schedule, urban railway system can attract large amount of traffic flow, greatly improve transportation conveniency of areas along the lines and therefore incentive the transformation of city conformation. So when planning urban railway network, we should consider adequately this reaction and follow the below principles.

a. Planning of urban railway network should be consistent with that of the city and run along developing corridors.
b. For large cities, railway network configuration should urge the formation of sub-centers. For example, large interchanges should be built at transportation centers such as railway stations.
c. At most one circular line can be built out of the central area of the city, otherwise area between two circular lines will be highly exploited and hinder the formation of multicentral cities.

4.CONCLUSION

The configuration of urban railway network is one of the most important contents in the initial stage of urban railway planning. When the scale of urban railway system is determined, the network configuration will directly influence traffic attraction ability and operation efficiency of the system.

In this paper, seven elementary configurations of the network are first defined and analyzed. We then discuss the possibility to use two methods to evaluate the static characteristics of the network, namely the link-matrix method and the structural parameter analysis method. Then interactions between the city conformation and the network configuration are qualitatively analyzed. And finally we bring forward a series of strategic principals when determining the network configuration in the initial stage of urban railway planning. In the next stage, we will evaluate transportation efficiency of the seven elementary configurations under different ideal conditions by using appropriate software.

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