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Traffic Planning
Preliminary Communication
Accepted: Jan. 9, 2013
Approved: Sep. 24, 2013

MODELLING THE ACCESSIBILITY CLASSIFICATION OF RAILWAY LINES: A CASE STUDY OF NORTHEAST CHINA RAILWAY NETWORK

ABSTRACT

A major problem addressed in railway network planning relates to distinguishing the role of the railway line in the network, and making a reasonable classification of the lines based on their role. Accessibility has been widely used to measure the role of transportation infrastructure in various studies, but few quantitative models for the classification of the role have been presented yet. In this paper, the line accessibility classification model is proposed, which aims to distinguish the role of railway lines in the network and to classify the lines into different grades. The practicability of the model is demonstrated through the case study of Northeast China railway network where the railway lines in Northeast China can be classified into three grades. The line accessibility classification model is supposed to be a strategic decision support tool for planners and policy makers to determine the classification of railway lines.

KEY WORDS

railway network, accessibility, classification, network planning

1. INTRODUCTION

In China, the economic development and railway network construction evidently go hand in hand, and the urban growth and regional integration depend heavily on the quality of the railway network. To support the objectives and policies for a balanced and sustainable development of the country, the "Medium and Long-term Railway Network Planning (adjusted in 2008)" (MLRNP2008) [1] was promulgated by the State Council of the People's Republic of China. According to MLRNP2008, the total length of China's railway network in operation is foreseen to reach 120,000 km by the end of 2020, including the high-speed rail lines of 16,000 km (operating speed over 200 km/h), new normal speed lines of 41,000 km (operating speed less than 200 km/h) and upgraded lines of 44,000 km (operating speed less than 200 km/h). At that time, the entire railway network will cover all the cities with a population of over 200,000, and the high-speed rail network will cover all the cities with a population of over 500,000.

A major problem arising in the railway network planning is to distinguish the role of railway lines. The role of the railway line is a critical factor to determine the technical standards and equipment types; thus it has significant impacts on determining the investments and benefits of the future railway construction projects. However, it is difficult to classify the role of railway lines in a complex railway network, especially in large scale regions. The 'role' of a railway line is a comprehensive concept, which is usually distinguished by qualitatively described factors, such as 'the skeleton role' or 'the liaison and supplement role'. To measure the concept of role, accessibility is widely used in transport planning, urban planning and geography studies [2]. Gutiérrez et al. [3] chose the weighted average distance as the accessibility indicator and studied the impacts of the future European high-speed train network on the changes of accessibility in Europe. Gutiérrez [4] selected three indicators (weighted average travel times, economic potential and daily accessibility) to analyze the accessibility impact of the future Madrid-Barcelona-French border high-speed line.

Taylor et al. [5] considered generalized travel cost, the Hansen integral accessibility index, and the ARIA index as accessibility indicators to evaluate the vulnerability in Australia's road networks. Wang et al. [6] analyzed the expansion of China's railway network with an accessibility approach, and evaluated the railway network impacts on the economic growth and urban systems. In these previous studies, different accessibility indicators have been used to evaluate the impacts of transportation infrastructures on the social and economic development. None of them, however, made a classification of infrastructures in the transport network based on the accessibility effects.

To the authors' knowledge, there are few quantitative models to determine the classification of the role of railway lines in a complex network. In this paper, based on the accessibility indicator measured by the average distance, the line accessibility classification model is proposed, with the aim of distinguishing the role of railway line in a network and classifying the lines into different grades. The remainder of the paper is organized as follows: Section 2 provides a brief overview of accessibility definitions and measures; Section 3 presents the line accessibility classification model; in Section 4 the model is applied to a case study in Northeast China railway network; Section 5 summarizes the main findings and the applicability of this model.

2. ACCESSIBILITY DEFINITIONS AND MEASURES

In numerous research studies, accessibility is defined and measured in a variety of ways, including 'the potential of opportunities for interaction' [7, 8], 'the ease with which activities may be reached from a given location using a particular transportation system' [9, 10], 'an aspect of the freedom of action of individuals' [11, 12], etc. Accessibility is closely related to mobility, economic development, social welfare and environmental impacts, so it can be considered as a proxy of a set of related, e.g., economic, social and environmental effects of transport infrastructure [13]. In this study, the definition of 'the potential of opportunities for interaction' is suitable, which means increasing accessibility can promote the opportunities for interaction between cities. Based on this definition, the accessibility measure we chose should reflect the degree of the interaction between cities.

Ingram [14] introduced the integral accessibility defined as the degree of interconnection between a point and all other points within the region, which was measured on the basis of average distance to focus on the effect of accessibility. Since the aim of this study is to identify the role of the railway line in the network, which, in our opinion, should be an inherent characteristic of the line, the focus of the study is purely on the railway lines. Therefore, the average distance-based measure of integral accessibility defined by Ingram [14] is appropriate.

The principal characteristic of this measure is that it is measured on physical infrastructure, assuming that the opportunities are the same everywhere, but it still has a behavioural interpretation, and its scale of application has always been finer than the measure based on opportunity [15]. However, compared with travel time or cost, the distance-based indicator has the limitation for analysing the economic benefit and utility impact of the railway network on the region, but it has been proven that the distance-based indicator is much more realistic than other indicators for accessibility [16]. Furthermore, the proposed measure is simple and easy to interpret for planners and policy makers, and it is easy to access the necessary data.

3. LINE ACCESSIBILITY CLASSIFICATION MODEL

3.1 Definition of accessibility indicators

To build the line accessibility classification model, three accessibility indicators are defined as follows:

1) City accessibility indicator CA_i is defined as the degree of interaction between a certain city and all other cities within the region. The operational form is the average value of the shortest travel distances between city *i* and all other cities in the network *G*:

$$CA_i = \frac{1}{N}\sum_{j=1}^{N} D_{ij} \tag{1}$$

where N is the total number of cities in the network G; D_{ij} is the shortest travel distance between city *i* and city *j*, calculated by actual railway length, which is a constant value after the completion of the railway line, so it is much more reliable to represent the role of the line by using the length as the parameter.

This indicator presents the average travel distance between city *i* and a random city within the network. The lower the value of CA_i, the higher the accessibility level of city *i*.

2) Region accessibility indicator RA_G is defined as the degree of interaction between the cities within the region. In the same manner, the operational form of RA_G is the average of CA_i in the network G:

$$RA_G = \frac{1}{N}\sum_{i=1}^{N} CA_i \tag{2}$$

This indicator gives an estimate of the average travel distance between two cities that are randomly selected among N cities. The lower the value of RA_G, the higher the accessibility level of the region.

3) It is evident that a line plays a great role in the network if the loss of the line significantly diminishes the accessibility of the network. Based on that notion, the line accessibility indicator LA_k can be derived by measuring the percentage change of RA_G when cutting off the given line k:

$$LA_k = \frac{RA_{G-k} - RA_G}{RA_G} \times 100\% \quad (3)$$

where RA_{G-k} is the region accessibility indicator for network G without line k; RA_G is the region accessibility indicator for the initial network G.

This indicator is defined as the degree of the impact of a given line on the interaction within the region. The higher the value of LA_k, the higher grade should be assigned to the line. So the line accessibility classification model we proposed next is mainly based on the line accessibility indicator LA_k.

3.2 Line accessibility classification model

In this study the regional railway network is regarded as a closed system and presented as an undirected weighted network based on graph theory, which is a branch of mathematics that has been applied to the analysis of network structure since 1930s [17].

In order to formulate the model, let us consider the following notation.

- i, j – indices of points;
- e_k – index of undirected lines between point i and point j, $e_k = (i,j)$, where $k = \{1,2,\ldots,m\}$, m is the number of lines in the network;
- W_{e_k} – index of weights of line e_k, which equals its length in this model;
- G – index of the railway network, $G = (V,E,W)$;
- V – set of points (cities), $V = \{1,2,\ldots,n\}$, where n is the number of points in network G;
- E – set of undirected lines (railway lines), $E = \{e_k\}$;
- W – set of weights of the lines, $W = \{W_{e_k}\}$;
- $P(i,j)$ – index of the shortest path from point i to point j;
- P – set of the shortest paths, $P = \{P(i,j)\}$;
- $N(e_k)$ – index of the frequency of e_k in set P;
- E_0 – set of lines with $N(e_k) = 0$ (redundant lines which are not in set P);
- E_x – set of hanging lines (which are the only links to some points) in network G;
- E_c – set of lines excluding E_0 and E_x in network G, $E_c = E - E_0 - E_x$.

With the notation above, the model can be set up in the following steps.

Step 1: For a given network $G = (V,E,W)$, the city accessibility indicator CA_i can be calculated according to Eq. (1). Based on all the city accessibility indicators CA_i $(i = 1,\ldots,N)$, the region accessibility indicator RA_G can be determined according to Eq. (2). During the above procedure, the shortest path $P(i,j)$ from any point i to j and the frequency $N(e_k)$ of e_k in the set of the shortest paths P can be selected. When $N(e_k) \neq 0$, e_k has contributions to the region accessibility indicator RA_G. When $N(e_k) = 0$, the region accessibility indicator RA_G does not change with or without e_k, which means that these lines are redundant in the network due to their high impedance. So let E_0 denote the set of lines with $N(e_k) = 0$, and the lines in E_0 should be assigned to the lowest grade in the network.

Step 2: The set of hanging lines, which are the only links to some points, are represented as E_x. To make sure all the points are connected in the network, the hanging lines can't be cut off, otherwise some points would be isolated in the network, resulting in the city accessibility indicator CA_i and region accessibility indicator RA_G infinite. Therefore, the hanging lines should be assigned to the highest grade due to their extremely significant role in the network.

Step 3: Let us determine set E_c by $E_c = E - E_0 - E_x$. Cut off line e_k $(e_k \in E_c)$ from network G and recalculate the accessibility indicators CA_i and RA_{G-k}. According to Eq. (3), the line accessibility indicator LA_k can be calculated. After the calculations of all lines in set E_c, a set of $LA_k(l)\,(l = 1,2,\ldots,m)$ is determined, where l is the serial number of the line in the descending sequence of LA_k, m is the number of lines in set E_c. Then the $LA_k(l)$ curve along l can be drawn and the piecewise linear regression method is used for the analysis. Finally, a piecewise linear distribution curve can be obtained, and the curve is divided into N+1 intervals by N inflection points, which indicates N+1 categories of line grade in the network. And the line accessibility grade can be assigned to each line based on the category it belongs to.

This methodology that we developed for the classification of lines in a network is based on the basic network topological structure; thus it can be applicable not only to railway network planning, but also to other similar networks, such as road network and airline network. The classification method presented in this paper is a gross simplification, but it is capable of providing a foundational framework for further study and application. In the following section, the application of the model is demonstrated through the case study of Northeast China railway network.

4. CASE STUDY: NORTHEAST CHINA RAILWAY NETWORK

Northeast China has a population of 120 million and an area of approximately 1,450,000 km^2, including Liaoning Province, Jilin Province, Heilongjiang Province, and the eastern part of Inner Mongolia Autonomous Region, which is the old industrial base in China. The Plan of Revitalizing Northeast China (PRNC) was formulated in 2007 by the National Development and Reform Commission to accelerate the pace of the regional development and promote coordinated regional economic development [18]. According to PRNC, the railway network of the region should be improved to speed up the economic development.

An outline of Northeast China railway network, which connects all the cities in this region, is shown in *Figure 1*. According to PRNC and MLRNP2008, the whole railway network improvement project in Northeast China can be divided into three phases. First, build and upgrade the normal speed railways by 2010. Second, build the major central high-speed railway by 2015. Third, complete the high-speed railway network by 2020. Thus four time scenarios are considered in the application of the line accessibility classification model: year 2005 as the base period for evaluation of the old network; year 2010 for the classification of new normal speed railways; year 2015 for evaluating the impacts of the central high-speed railway; and year 2020 for the classification of the high-speed railways.

Figure 1 - Outline of Northeast China railway network

4.1 Analysis of the base network 2005

The network consists of 30 cities with a population of over 500,000 and 54 lines, as shown in *Figure 2*. The names of the cities are listed in *Table 1*, according to the descending sequence of population. The results of the city and region accessibility indicators are listed in *Table 1* and *Table 2*.

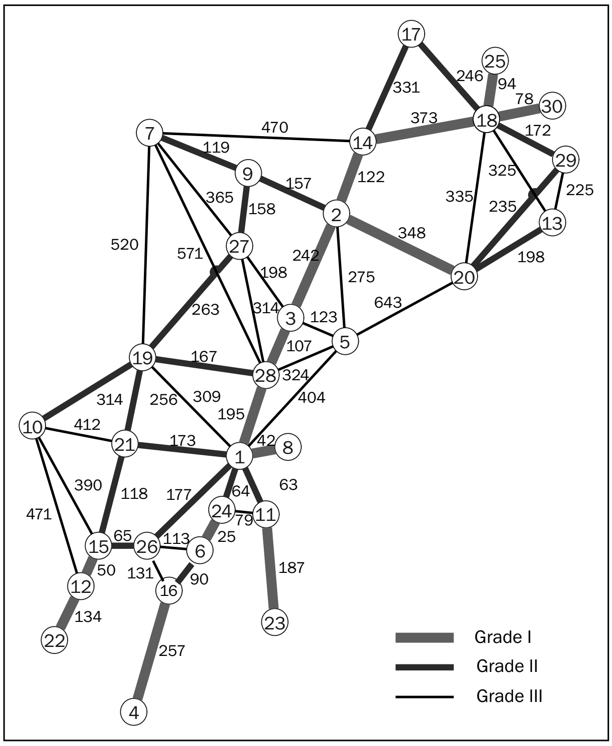

Figure 2 - Line accessibility grades of Northeast China railway network 2005

The descending sequence of $N(e_k)$ is shown in *Figure 3*. It shows that the first four points are much higher than the others, and

$$\sum_{k=1}^{4} N(e_k) \Big/ \sum_{k=1}^{54} N(e_k) \times 100\% = 35\%.$$

The lines corresponding to the four points are (3,28), (1,28), (2,3) and (2,14). These four lines are just the central route in the network from Shenyang (1) to Tuo-

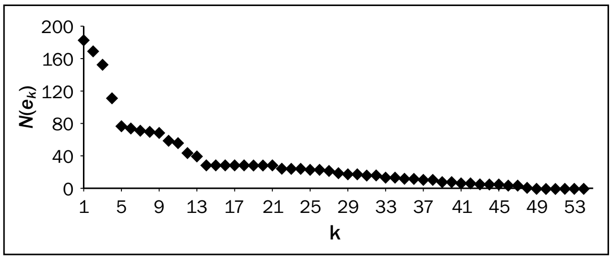

Figure 3 - Descending sequence of $N(e_k)$ of Northeast China railway network 2005

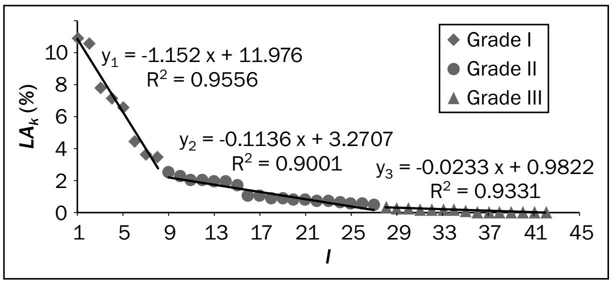

Figure 4 - Line accessibility classification in Northeast China railway network 2005

Table 1 - City accessibility indicator values

No.	City Name	A (2005)	B (2010)		C (2015)		D (2020)		
		CA_i (km)	CA_i (km)	Percent change (%) B vs. A	CA_i (km)	Percent change (%) C vs. B	CA_i (km)	Percent change (%) D vs. C	Percent change (%) D vs. A
1	Shenyang	490.60	475.77	3.02	357.57	24.84	277.37	22.43	43.46
2	Harbin	537.83	537.23	0.11	382.07	28.88	304.60	20.28	43.37
3	Changchun	477.60	470.30	1.53	350.17	25.54	275.27	21.39	42.36
4	Dalian	824.03	805.73	2.22	526.27	34.68	457.27	13.11	44.51
5	Jilin	553.17	527.67	4.61	445.57	15.56	331.27	25.65	40.11
6	Anshan	539.73	514.00	4.77	375.63	26.92	301.87	19.64	44.07
7	Qiqihar	712.90	598.80	16.01	566.43	5.41	410.83	27.47	42.37
8	Fushun	529.80	514.97	2.80	396.77	22.95	316.57	20.21	40.25
9	Daqing	609.50	593.50	2.63	501.63	15.48	366.70	26.90	39.84
10	Chifeng	769.87	712.00	7.52	654.70	8.05	499.70	23.67	35.09
11	Benxi	538.80	520.13	3.46	407.97	21.56	303.37	25.64	43.70
12	Huludao	656.37	616.27	6.11	515.47	16.36	440.83	14.48	32.84
13	Jixi	908.23	854.03	5.97	746.10	12.64	597.50	19.92	34.21
14	Tuohua	613.83	613.23	0.10	458.07	25.30	411.23	10.22	33.01
15	Jinzhou	613.03	572.93	6.54	472.13	17.59	397.50	15.81	35.16
16	Yingkou	584.17	577.13	1.20	410.13	28.94	337.27	17.77	42.27
17	Yichun	840.10	839.50	0.07	684.33	18.48	633.20	7.47	24.63
18	Jiamusi	831.30	829.53	0.21	675.43	18.58	410.83	39.17	50.58
19	Tongliao	543.87	511.80	5.90	438.63	14.30	367.97	16.11	32.34
20	Mudanjiang	758.10	703.90	7.15	595.97	15.33	426.70	28.40	43.71
21	Fuxin	582.03	532.40	8.53	453.77	14.77	321.70	29.10	44.73
22	Qinhuangdao	781.43	741.33	5.13	640.53	13.60	565.90	11.65	27.58
23	Dandonng	713.33	683.40	4.20	577.30	15.53	386.03	33.13	45.88
24	Liaoyang	525.73	502.33	4.45	368.63	26.62	293.87	20.28	44.10
25	Hegang	919.03	917.27	0.19	763.17	16.80	498.57	34.67	45.75
26	Panjin	584.83	547.47	6.39	438.80	19.85	376.17	14.27	35.68
27	Songyuan	568.93	553.40	2.73	495.20	10.52	411.30	16.94	27.71
28	Siping	470.10	459.33	2.29	346.83	24.49	271.93	21.60	42.15
29	Qitaihe	912.10	857.90	5.94	749.97	12.58	558.40	25.54	38.78
30	Shuangyashan	904.10	902.33	0.20	748.23	17.08	483.63	35.36	46.51

Table 2 - Region accessibility indicator values

A (2005)	B (2010)		C (2015)		D (2020)		
RA_G (km)	RA_G (km)	Percent change (%) B vs. A	RA_G (km)	Percent change (%) C vs. B	RA_G (km)	Percent change (%) D vs. C	Percent change (%) D vs. A
663.15	636.19	4.07	518.12	18.56	401.18	22.57	39.50

hua (14), connecting all the three province capitals Shenyang (1), Changchun (3) and Harbin (2). It indicates that the central route of the network exactly fits the first-grade axis of the cities in this region, which should be formed according to PRNC and the central high-speed line would be built first.

The $LA_k(l)\,(l = 1, 2, \ldots, 42)$ curve along l is shown in *Figure 4*; the lines are classified into three accessibility grades (Grade I, Grade II and Grade III). Besides, there are six hanging lines regarded as Grade I in the network, i.e., (1,8), (4,16), (11,23), (12,22), (18,25), (18,30). And the six redundant lines (5,20), (5,28), (7,14), (7,27), (10,12), (27,28) are regarded as Grade III. The accessibility grades of the total 54 lines are clearly shown in *Figure 2*.

Figure 2 indicates that the lines of Grade I and II are sufficient to connect all the 30 cities (except point 5) and form the skeleton network, including two main arteries of Route Ha-Da (2-3-28-1-24-6-16-4) and Route Shen-Shan (1-26-15-12-22), and other four main routes of Ha-Jia (2-14-18), Sui-Bin (2-20-13), Bin-Zhou (2-9-7), Shen-Dan (1-11-23). Those are the main links in Northeast China railway network with high volumes of passengers and freight and are constructed with high standards, which proves that the line accessibility grade corresponds well to the actual situation.

Table 3 - Comparison of line accessibility grade (LAG) and railway design class (RDC) (Unit: numbers of line)

LAG/RDC	I	II	III
I	12	9	0
II	2	9	17
III	0	1	4

The line accessibility grades and railway design classes of the 54 lines are compared and the results are listed in *Table 3*. According to the Code for Design of Railway Line [19], the railway design class is a significant technical standard in railway design, which is determined by the role a line plays in the network and the transport volumes it carries. From *Table 3*, the line accessibility grade (LAG) of a line is usually equal to or lower than the railway design class (RDC). For example, there are 21 lines with RDC I, among which 12 lines with LAG I and 9 lines with LAG II. Observed from *Table 3*, however, there are exceptions of only three lines with higher LAG than RDC, i.e., Shenyang-Fushun (1-8) and Benxi-Dandong (11-23) with LAG I higher than RDC II, and Chifeng-Tongliao (10-19) with LAG II higher than RDC III. This deviation can be attributed to the transport volumes. In this model, the line accessibility grade is developed to reflect the role of the line, and the transport volumes are not considered. If the transport volumes were involved in the model, the results would be much more consistent. However, as a quantitative method, the results of this model are still capable as the quantitative basis for planners and policy makers to classify the role of railway lines.

4.2 Evaluation of the new network plan

According to PRNC, Harbin (2) and Dalian (4), the economic belt should form a first-grade axis and the eastern and western corridors should form the second-grade axis. Accordingly, by 2010, the consolidation of the eastern corridor form Mudanjiang (20) to Dalian (4) and the improvement of western corridor from Qiqihar (7) to Jinzhou (15) are considered. The construction projects include Route Mudanjiang-Dalian and Route Qiqihar-Jinzhou. These railway lines are modelled as normal speed lines. By 2015, Harbin-Dalian high-speed route will be completed. Up to 2020, the high-speed railway network consisting of other 7 high-speed routes will be accomplished, including the routes of Harbin-Qiqihar, Harbin-Mudanjiang, Harbin-Jiamusi, Mudanjiang-Jiamusi, Changchun-Jilin, Shenyang-Chifeng and Shenyang-Dandong.

In these three scenarios (year 2010, year 2015 and year 2020), the new networks have been evaluated by the line accessibility classification model. In year 2015 and 2020, there are two kinds of railway lines: normal speed lines and high-speed lines. As the average travel speed of the normal lines is about 100 km/h and the high-speed lines is over 200 km/h, the length of high-speed lines are cut down to half to take into account the benefits of the higher speed.

The results of city accessibility indicator CA_i and region accessibility indicator RA_G are listed in *Table 1* and *Table 2*, respectively. According to *Table 1* and *Table 2*, the improvement of the railway network will constantly increase the region accessibility level by 4.07% (2010 vs. 2005), 18.56% (2015 vs. 2010), 22.57% (2020 vs. 2015) and totally 39.5% (2020 vs. 2005), respectively, and all the cities will experience great accessibil-

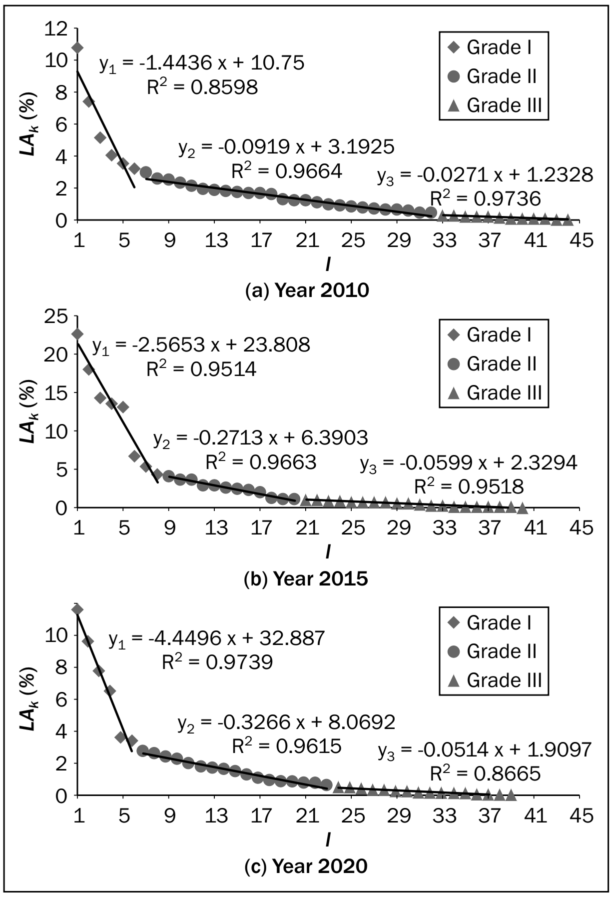

Figure 5 - Line accessibility classification in Northeast China railway network 2010-2020

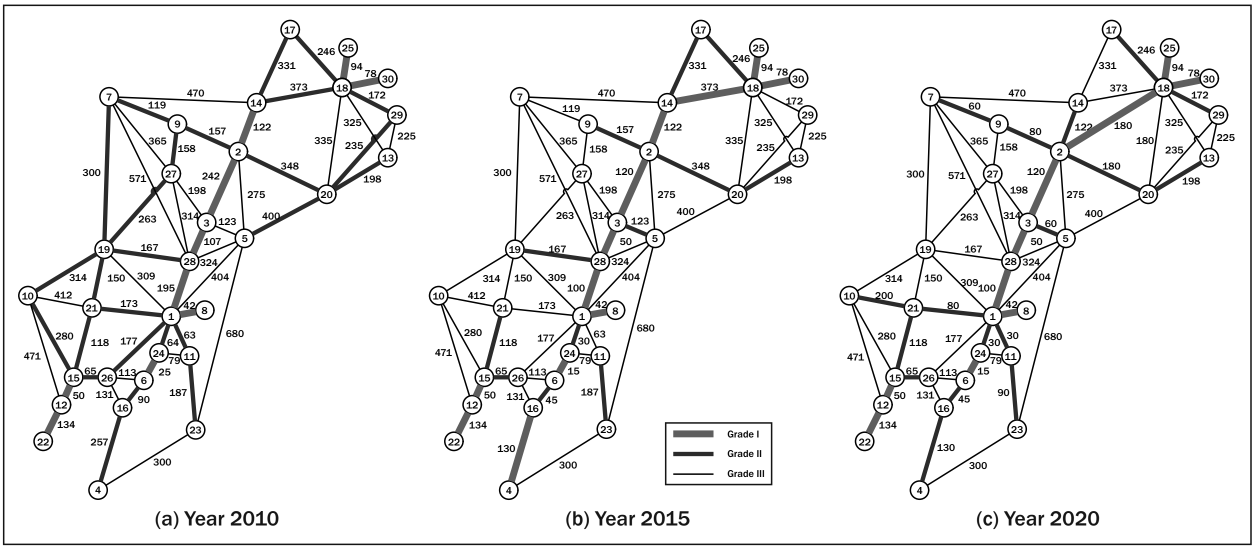

Figure 6 - Line accessibility grades of Northeast China railway network 2010-2020

ity increase, either core or periphery, especially by the construction of high-speed railways.

The line accessibility indicator $LA_k(l)$ curves and the corresponding line accessibility grades of the three phases are shown in Figures 5 and 6. Based on the relationship between LAG and RDC, as discussed in previous section, the railway design classes of these new railway lines are recommended as follows.

In 2010, comparing *Figure* 6(a) and *Figure 2*, it is indicated that Route Mudanjiang-Dalian and Route Qiqihar-Jinzhou take the role of supplementing in the network and only increase the region accessibility by 4.07%, so these two routes should be designed as Class II.

In 2015, the line accessibility of the seven central lines were improved evidently by reducing the distances, and the number of lines of Grade II was dramatically decreased from 26 to 12 (2010 vs. 2015), as shown in Figures 5(a) and (b). On the one hand, it is observed that the summation of LA_k values of the seven lines reaches 52.6% of all lines, indicating the dominant role of high-speed railway lines in the network. On the other hand, the normal speed lines are weakened on both sides (See *Figure* 6(a) and (b)). For this reason, the line accessibility grade of high-speed lines should be analyzed within the high-speed railway network rather than comparing with the normal speed lines, as done in scenario 2020.

In 2020, there are eight high-speed routes including 17 lines, forming the high-speed railway network in Northeast China. There are three design ranks of high-speed railways in China: 300~350 km/h, 250~300 km/h and 200~250 km/h. According to the line accessibility grade of these lines (See *Figure* 6(c)), the design speed ranks of each route are recommended as follows:

- 300~350 km/h: Route Harbin-Dalian; Route Harbin-Jiamusi;
- 250~300 km/h: Route Harbin-Qiqihar; Route Harbin-Mudanjiang; Route Changchun-Jilin; Route Shenyang-Chifeng; Route Shenyang-Dandong;
- 200~250 km/h: Route Mudanjiang-Jiamusi.

5. CONCLUSION

In this paper, the line accessibility classification model is proposed for the classification of railway lines in a complex railway network. Based on the concept of accessibility, the line accessibility indicator is developed to measure the degree of the impact of a given line on the interaction within the region and the line accessibility grade is introduced to distinguish the role of different railway lines.

The application and verification of this model is demonstrated by the case study of the Northeast China railway network in four scenarios 2005, 2010, 2015 and 2020. The results of scenario 2005 indicate that the line accessibility classification corresponds well to the actual situation, and generally the line accessibility grade of a line is usually equal to or lower than the railway design class. According to the line accessibility grade results in 2010, 2015 and 2020, the railway design classes of normal speed lines and design ranks of high-speed lines are recommended, and it is found that these two kinds of railway lines should be analyzed separately.

The line accessibility classification model presented in this paper is powerful to classify railway lines and it can be used as a strategic decision support tool for transport network planning. The accessibility study is extended in this paper, not only to measure the role of transportation infrastructure, but also to classify the infrastructure based on the accessibility measure. Besides, this methodology we developed is based on the basic network topological structure and the comprehensive concept of accessibility; thus it is capable of providing a foundational framework for further analysis of other similar network planning problems.

The model we proposed does not take the city hierarchy into account, which is also a major factor in railway network planning, so it is worth to improve the model by integrating the city hierarchy and line accessibility classification. Also the technological factors and the line service quality factors can be considered to make corrections of the line weight so as to take further analysis of the levels of quality and efficiency in the network. In the future, we intend to investigate these issues.

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摘要

铁路线路可达性分级模型: 中国东北铁路网实例研究

在制定铁路网络规划时，一个首要的问题是确定线路在铁路网中的作用，并根据线路的作用划分线路等级。目前众多研究建立了各种可达性指标来度量交通设施的作用，但对于交通设施作用分级的研究却很少。本文提出了铁路线路可达性分级模型，用于确定线路在铁路网中的作用并划分线路等级。采用本文所建模型对中国东北铁路网进行了实例研究，研究表明中国东北地区铁路网可划分为三个等级。本文所提出的铁路线路可达性分级模型可为规划和政策制定者提供决策支持。

关键词

铁路网；可达性；分级；路网规划

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