Use of isochrone maps to assess the impact of high-speed rail network development on journey times: a case study of Nanjing city, Jiangsu province, China

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ABSTRACT
It is well known that the increasing development of transport infrastructure will result in temporal and spatial convergence. As an important component of China’s high-speed rail (HSR) network, an ambitious HSR building program in Jiangsu province will extend the network to cover all cities and 95% of counties by 2030. This study aims to present and analyze the impacts of the evolving HSR network in Jiangsu province over the period of 2010–2030 by developing multi-phased isochrone maps of Nanjing city (the provincial capital of Jiangsu province). During the process, layered cost distance, a new method based on a door-to-door approach in actual travel time calculations, is proposed in order to draw the maps at a more detailed geographical level. Our results are expected to facilitate proactive public policy decisions related to improving the transport network.

1. Introduction
Isochrone maps display areas of similar travel time to a selected starting location on the map (Spiikermann & Wegener, 1994; Ullah & Kraak, 2015). By drawing lines of equal travel times (isochrones) from the selected point, it efficiently determines geo-referenced objects that are accessible within given time constraints in a given network or transport mode (Gamper, Bühlen, & Innererebner, 2012). Isochrone maps are a basic method of visualizing daily accessibility, and have been widely used for analyzing the number of destinations accessible within a given travel threshold (Achuthan, Titheridge, & Mackett, 2010; Martín, Gutiérrez, & Román, 2004) made available by the construction of high-speed rail (HSR) networks in different countries (Gutiérrez, 2001; Jiao et al., 2014). However, most of the existing studies only focus on the train travel time and rarely take into account the inner city travel time, as well as the service waiting time at the railway station(s). Since on a mesoscale the sum of intra-city travel and service waiting times is clearly not less than the time spent onboard, it is likely to lead to large deviations if they are ignored in drawing isochrones maps. Therefore, an improved accurate method for evaluating actual travel time is needed, especially for accurately delineating isochrones maps on a regional scale.

HSR networks can provide an improved service, reduced travel time, increased safety, as well as lower labor costs (Gutiérrez, 2001; Martín et al., 2004), and thus they have been proposed and constructed in many countries throughout the world (Levinson, 2012). By 2013, China had constructed the world’s largest HSR network (Jiao et al., 2014). As an important component of China’s HSR network, Jiangsu province announced the ‘Twelfth Five-year Plan and Mid-to-long Term Rail Transport Plan of Jiangsu Province’ in 2012, in which ‘4+4’ corridor lines will be constructed by 2030 (General Office of Jiangsu Provincial Government, 2012). This rapid development of HSR infrastructure will inevitably bring about the phenomenon of temporal and spatial convergence, and consequently drive changes in isochrone maps resulting from reduced spatiotemporal distances.

The purpose of the present study is to demonstrate the improvement in accessibility within Jiangsu province over the interval of 2010–2030 by drawing a series of isochrone maps for the core area of Nanjing city. During the course of the study, we developed a new method, based on the application of a door-to-door approach to actual travel time calculations, for drawing the maps at a more detailed geographical level. We anticipate that the maps will be very useful for local government in correctly evaluating transport plans and for informing future transport decisions.
2. Methodology

In order to simulate different development phases of the HSR construction, four scenarios (Table 1) were considered in reflecting the impacts of the present and future HSR networks. Since the first HSR line (Shanghai–Nanjing Intercity Railway) in Jiangsu province was opened to traffic in July 2010, the year of 2010 was selected as the base date. Scenario 1 is the 2015 land transport network excluding the HSR lines to simulate the transport network in 2010 (no HSR service); Scenario 2 is the actual 2015 land transport network; and Scenarios 3 and 4 are the planned 2020 and 2030 land transport networks, which contain the current transport network in 2015 as well as the planned HSR network. In addition, it was assumed that the road and conventional rail networks are the same in all Scenarios and only the HSR network differs. Thus, the effect of the reduction in travel time due to the HSR network is singled out.

2.1. Preparing spatial data under a GIS environment

According to the ‘Twelfth Five-year Plan and Mid-to-long Term Rail Transport Plan of Jiangsu Province’ (General Office of Jiangsu Provincial Government, 2012), ‘4+4’ corridor lines consist of four running north–south (Beijing–Nanjing–Hangzhou, Coastal Express Railway, Yancheng–Yixing, and Middle Express Railway) and four running east–west (Shanghai–Nanjing, Lanzhou–Lianyungang, Xuzhou–Yancheng, and Yangtze Riverside Intercity Railway). Nanjing city is the major railway passenger transport hub in Jiangsu province. As the provincial capital of Jiangsu province, it will connect two north–south (Beijing–Nanjing–Hangzhou and Middle Express Railway) and two east–west (Shanghai–Nanjing and Yangtze Riverside Intercity Railway) corridor lines by 2030. Railways with a design speed greater than 250 km/h and intercity railways with a design speed greater than 200 km/h were examined (Figure 1), and a total of 20 HSR lines (Map A) were selected in the study.

Basic geographical data for Jiangsu province were collected from multiple sources: data on administrative divisions, the main rivers and lakes, and conventional railways, were taken from the Jiangsu province administrative map (Provincial Geomatics Centre of Jiangsu, 2011); data on the road network (Map B) were taken in digital form from the atlas of the highway mileage of Jiangsu province and its surrounding areas (Beijing Tianyu Beidou Books Company Limited, 2015); and a digital elevation model Global Digital Elevation Model (GDEM) based on Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) satellite images was also adopted (Map C).

Table 1. Description of four scenarios and their comparison.

| Scenarios       | Description                                                                 |
|-----------------|-----------------------------------------------------------------------------|
| Scenario 1      | The 2015 land transport network excluding the HSR lines to simulate the transport network in 2010 (no HSR service) |
| Scenario 2      | The 2015 actual land transport network                                        |
| Scenario 3      | Scenario 2 plus the planned HSR lines to be opened to traffic by 2020        |
| Scenario 4      | Scenario 2 plus the planned HSR lines to be opened to traffic by 2030        |
| Scenario 2/1    | The changes from Scenario 1 to Scenario 2                                    |
| Scenario 4/2    | The changes from Scenario 2 to Scenario 4                                    |
| Scenario 4/1    | The changes from Scenario 1 to Scenario 4                                    |

2.2. The approach used for travel time measurement

A key aspect of our methodology was to employ a door-to-door approach (Salonen & Toivonen, 2013) in order to take into account every stage of a journey and thus to measure the actual travel time between origin and destination. Taking a journey by rail as an example, the door-to-door approach involved in calculating the total time cost can be divided into four parts (Figure 2): (1) the driving time from the point of origin to the railway station; (2) the transfer time at both railway stations, including time penalties as those caused by switching from road to railway travel mode and the frequency of service and line changes (Pérez, Quintana, & Pastor, 2011); (3) the traveling time between the initial and final railways stations; and (4) the driving time from the railway station to the destination.

Therefore, the total travel time calculation based on the door-to-door approach for the railway travel mode can be described as follows:

\[ T_{\text{rail}} = T_{\text{os}} + T_{\text{ss}} + T_{\text{id}} + T_{t}, \]  

(1)

where \( T_{\text{os}} \) is the travel time from the origin to the railway station, \( T_{\text{ss}} \) is the travel time by railway between stations, \( T_{\text{id}} \) is the travel time from the railway station to the destination, and \( T_{t} \) refers to the transfer time at both railway stations, which is set as 1 h (Martín et al., 2004), that is, a half hour per station.

2.3. Layered cost distance method

The ArcGIS ‘Cost Distance’, a spatial analysis tool, is efficient in measuring the accumulative cost from each cell to the target cell based on raster datasets (Dannenberg, Kunze, & Nduru, 2011). However, this tool cannot directly be applied to closed expressway and railway travel modes. Instead, a layered cost distance (LCD) method was introduced to modify the function of this tool, making it suitable for these travel modes. The LCD method processes different travel modes by ‘Cost Distance’ in different layers (Figure 3) and then creates a composite raster result. It consists of
four steps: (1) creating buffer zones at both sides of expressways (Figure 3(b)) and railways (Figure 3(c)) as impediments; (2) assigning a time cost to each cell which represents the cost per unit distance for moving through the cell; (3) calculating the cost distance of different travel modes in different layers; and (4) combining these results to produce a minimum cost raster map of hybrid travel mode.

The study area was divided into regular raster grid cells with a spatial resolution of 100 m × 100 m, and each cell was assigned a related time cost as an attribute. The time cost of the cells refers to the traffic section (i.e., road and railway) according to the characteristics of the transport modes, and is calculated as:

\[
\text{Cost} = \frac{100}{V} \times 60, \tag{2}
\]

where cost units (min/100 km) is the travel time (min) per unit distance (100 km) for moving through the cell, and \( V \) units (km/h) is the velocity of the transport mode, which was assigned the following values (based on the Chinese ‘Technical Standard of Highway Engineering’ and ‘Design Specification for Highway Alignment’): expressway, level I highway, level II highway, level III highway, level IV highway, and sub-national standards highway, have average speeds of 110, 80, 70, 35, and 20 km/h, respectively. The average speed of conventional railways was set at 120 km/h, and the average speeds for HSR lines were set at 250, 200, and 160 km/h based on the design speeds of 350, 250, and 200 km/h.

Highways of normal level (Figure 3(a)) are open and can be entered at any section, but expressways and railways are closed except for expressway entrances and railway stations. Therefore, buffer zones with a certain width were set at both sides of expressways (Figure 3(b)) and railways (Figure 3(c)), where the minimum access speed (0.1 km/h) was assigned; and a high traffic speed (110 km/h) was assigned to expressway entrances. In the same way, buffers with five-grid-cell distance surrounding the railway stations (Figure 3(d)), were set a speed of 1 km/h in order to realize the average half-an-hour transfer time (100 m × 5/1 km/h = 0.5 h).

In order to cover the entire area of Jiangsu province, we assigned the cost to all cells of the study area, including the non-traffic area. For the cells corresponding to non-traffic areas, the strategy for value assignment was as follows: the cells of river bodies were assigned a speed of 1 km/h (Jiang, Xu, & Qi, 2010; Wang, Xu, Zhu, Qi, & Xu, 2010), since the river bodies have some traffic capacity but are obviously slower than land travel; the non-traffic

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**Figure 1.** Chronology of HSR operations in Jiangsu over the period 2010–2030.

**Figure 2.** Schematic diagram of the door-to-door approach for (a) highway travel mode and (b) railway travel mode.
areas of mountains were also assigned a speed of 1 km/h; and all of the other unassigned cells were set at 15 km/h.

Isochrone maps display areas of similar travel time to one selected point on the map (Spiekermann & Wegener, 1994). In this paper, we aim to present isochrone maps of Nanjing city impacted by the HSR network development, and therefore we chose the seat of Nanjing government as the fixed starting location of the door-to-door approach. To create isochrone maps by the LCD method, we first created a series of cost raster maps at the starting location for highways of normal level, all highways, and highway and railway travel modes. Next, we combined these maps to produce a minimum cost raster map of hybrid travel mode by using the ‘Mosaic to New Raster’ tool with ‘MINIMUM’ mosaic parameters. Finally, multphased isochrone maps were produced using the ‘Raster Calculator’ tool, and we reclassified all of these maps using an interval of 1 h.

3. Results

The isochrones map using the LCD method (Figure 4(a)) was compared with those produced using isochrone mapping methods (Figure 4b) without considering the transfer time (Jiang et al., 2010; Wang et al., 2010) by railway travel mode. As is shown in Figure 4(a) and 4(b), on this regional scale there is a large difference in travel time measurement between cities using different methods in Scenario 2. Further, using validation by Google Maps and Baidu Maps (Figure 4(c)), the standard deviations of the differences between the LCD results and those of the online maps are 6.8 min (4.6%) for the road model and 11.7 min (8.7%) for the HSR model. Therefore, the result using the LCD method is much closer to the actual travel time.

The color gradient from green to orange in the maps of Scenarios 1, 2, 3, and 4 (Map D–G) illustrate the increasing travel time from different locations to Nanjing city. We used two indicators, ‘accessible area’ and ‘accessible counties’, to analysis changes in the isochrone maps with the development of the HSR network. These two indicators describe the size of the area and the number of the counties in Jiangsu province can be reached from Nanjing city within different travel time limits. The results are shown in Table 2.

The results demonstrate that in 2010–2030, the ‘accessible area’ within 1–2 h and 2–3 h will expand from 13,422 and 24,297 km² to 15,450 km² (15.1%) and 35,890 km² (47.7%), respectively; whereas there will be only minor changes (6.0%) in areas within 1 h. The results from the ‘accessible counties’ indicator have several features in common with the ‘accessible area’ indicator: the most significant benefits will occur in the 1–2 h interval, with a considerably increased number from 25 to 38 (52.0%). In other words, by 2030 most of the area and counties in Jiangsu province will be accessible from Nanjing city within 3 h.
Map Scenarios 2/1, 4/2, and 4/1 (Map H–J) illustrate the absolute changes in travel time between different scenarios. It seems that the development of the HSR network will have little or no effect on saving travel time between Nanjing and neighboring cities, such as Zhenjiang, Yangzhou, and Taizhou. In contrast, the greatest improvements will occur in peripheral northern and southeastern regions, where the travel time to Nanjing will be reduced by more than 30 min both in Scenarios 2/1 and 4/2. In particular, the travel time between Xuzhou and Nanjing will decline drastically from 248 to 146 min (41.1%) in Scenario 4/1, followed by Suzhou (26.4%) and Lianyungang (24.0%).

4. Conclusions

Highly detailed accessibility analyses are important for the accurate evaluation of transport plans and should be of significant interest to transport departments and policy-makers. For this purpose, we produced a series of isochrone maps which demonstrate the utility of the LCD method for Nanjing to other cities in Jiangsu province.
of the LCD method for quantifying improvements in the accessibility of Nanjing city in Jiangsu province over the period of 2010–2030. The LCD method clearly provides a significant improvement in the accuracy of travel time measurements.

The results demonstrate that over the period of 2010–2030 the travel time between Nanjing and other cities in Jiangsu province will gradually shorten with the evolution of the HSR network. Both the ‘accessible area’ and the ‘accessible counties’ within a travel time of 1 h will rarely change, since clearly the transfer time is considered to be more significant relative to the travel time in the case of short journeys. However, significant changes will occur in the case of areas within 1–3 h, especially for the peripheral northern and southern zones. As the HSR network continues to develop, the contour lines of isochrone maps will move outwards along the HSR lines, but the ‘corridor effects’ are not particularly obvious as the road network is relatively well-developed in Jiangsu province.

Software
The maps presented in this paper were organized, managed, processed and analyzed using ESRI ArcGIS 10.2.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This work was supported by National Natural Science Foundation of China [grant number 41171325], [grant number 41471068], [grant number 41230751]; Program for New Century Excellent Talents in University [grant number NCET-12-0264].

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