

Article

Analysis of Intercity Transportation Network Efficiency Using Flow-Weighted Time Circuity: A Case Study of Seven Major City Clusters in China

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Abstract: Enhancing the efficiency of intercity transportation networks is crucial for sustainable regional transport development, significantly impacting travel behaviors and energy consumption. The transportation infrastructure within the city cluster is rapidly developing to accommodate the increasing traffic demand, necessitating substantial investments. It is imperative to investigate the effectiveness of intercity traffic within urban clusters, to evaluate the influence of transportation infrastructure enhancements on regional traffic efficiency. Circuity is a conventional metric used to assess the efficiency of transportation networks, primarily emphasizing distance, while overlooking factors such as travel time and traffic flow. In this study, the concept of circuity has been redefined in terms of travel time and has been referred to as the transportation network travel speed. Subsequently, the amalgamation of travel speed within the transportation network and traffic flow culminates in the proposition of Flow-Weighted Time Circuity (FWTC). Real-time intercity navigation data, offering accurate travel time estimations, are utilized to analyze the spatial distribution of intercity transport efficiency in the seven major city clusters of China, via both automobile and train modes of transportation. The results indicate that (1) as the travel distance extends, the speed of transportation within the network typically increases, albeit with increasing fluctuations, especially in the case of intercity train travel; (2) concerning the efficiency of intercity automobile travel, most city clusters demonstrate satisfactory performance, with the exception of the Guanzhong Plain. The Yangtze River Delta and Beijing–Tianjin–Hebei regions stand out for their superior performance. In terms of intercity train efficiency, the Yangtze River Delta, Beijing–Tianjin–Hebei, and Mid-Yangtze River regions exhibit higher levels of efficiency in intercity train transportation, while the Guanzhong Plain city cluster falls behind in this aspect. On the whole, the efficiency of intercity travel using automobiles surpasses that of train travel, indicating a pressing need for improvement in the latter.

Keywords: city cluster; intercity traffic efficiency; flow-weighted time circuity; navigation data

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1. Introduction

1.1. Background

The economic cluster has become a crucial model for global economic development, due to the rapid pace of globalization, urbanization, and spatial reconstruction [1]. In contrast to the historically isolated growth of individual cities, the formation of city clusters is intended to enhance resource efficiency through the consolidation of production factors and the establishment of well-connected spatial structures among cities [2]. This developmental approach places increased requirements on the intra-regional transportation infrastructure. However, the construction and operation of the road network are accompanied by a large amount of energy consumption [3] and cannot be built indefinitely. Consequently, assessing

the effectiveness of transportation networks at the city cluster level emerges as a crucial issue in fostering efficient interconnectivity among urban clusters [4].

For an extended period, road transportation has been the primary mode of intercity transportation in China, primarily due to the absence of efficient long-distance transportation options [5]. The rapid expansion of transit systems in China is being driven by a large population, rapid economic growth, and policy reforms [6]. High-speed railways (HSRs) are experiencing rapid development and construction globally, as a novel mode of transportation [7]. To date, HSRs have become a more competitive mode of intercity transportation, offering economic advantages, environmental friendliness, and superior ride quality, compared to road transportation. The investment in HSRs forms an integral component of China's national development strategy, designed to meet the rapidly increasing transportation needs, particularly for intercity travel [8]. The construction of HSRs has a significant impact on both medium- and long-distance passenger and cargo transportation, as well as on the spatial organization of cities and regions [9]. Concurrently, significant advancements have been achieved in highway construction. By the conclusion of 2021, the total length of highways in China had extended to 177,300 km. Rail transit and road transportation have emerged as the predominant modes of intercity transportation in China.

The significant impact of substantial investments in transportation infrastructure on the effectiveness of intercity transportation within regions has garnered considerable attention from scholars. The significant cost associated with them raises a question that is of considerable interest to proponents and detractors of transport infrastructure alike. There exists a plethora of studies examining mobility and the extensive effects of developing transport infrastructure. Europe [8], Japan [10], and the United States [11] have conducted comprehensive and valuable studies on their potential, offering exemplary cases in various fields to the global community. Previous research conducted on developed economies can provide valuable insights regarding theories and analytical approaches. These studies have explored various fields, such as intercity travel time, cost, and distance [12,13]; network connectivity [14,15]; spatial accessibility [5,16]; and agglomeration effects [17]. However, the majority of these studies concentrated on specific cities, provinces, or countries. There is a limited amount of research available on city clusters, despite their significance as a primary driver of economic development in the current stage. Therefore, there is an urgent need to investigate the present state of intercity traffic efficiency in light of the ongoing development of traffic infrastructure, which serves as the impetus for this study.

Trade-offs exist among coverage, accessibility, connectivity, and directness within transportation networks [14]. It is important to note that high-density transport infrastructure does not guarantee efficient operations. Elevated levels of indirectness intensify trip detours, consequently diminishing traffic efficiency. Circuity is commonly defined as the ratio of network distance to Euclidean distance [18]. This metric has been extensively utilized to assess the linearity of journeys and the effectiveness of transportation infrastructures [19]. In addition to network performance evaluation, circuity is utilized for network design [20] and route selection in transportation networks [21]. The original concept of circuity assesses the efficiency of transport networks based on Euclidean distance, but it overlooks the various modes of travel and traffic volumes associated with different origin–destination (OD) pairs within the region.

To address this issue, the circuity framework incorporates travel time and travel volume, leading to the successive proposal of transportation network travel speed and Flow-Weighted Time Circuity (FWTC). The aforementioned concepts are employed for the accurate evaluation of the operational effectiveness of the intercity transportation network within China's seven major city clusters, utilizing the most recent intercity navigation data. The transportation network's travel speed attempts to quantify circuity in terms of travel time rather than distance. In the definition of FWTC, the migration of populations between various cities is considered. A city exhibiting identical transport network structures, yet with varying passenger flow distributions, may manifest different efficiencies, which can

be elucidated through the utilization of the new indicator, as opposed to conventional methods. The traffic flow weight factor is derived from calculations generated using the gravity model.

1.2. Literature Review

1.2.1. Definitions of Circuity

In previous research, quantitative studies on transportation efficiency have concentrated on the following three approaches: (1) analyzing the topology of the transportation network [22–24], which examines the overall network efficiency of information and transportation; (2) comparing the actual time spent with the theoretical minimum commuting time [25,26], which focuses on the balance between job and housing locations or excessive commuting; and (3) investigating the geometric characteristics of the spatial network [27,28], with circuity being a prominent area of study. The initial two studies focus on evaluating the effectiveness of transportation operations within urban areas and may not be entirely relevant when considering efficiency metrics on broader regional levels. In contrast, the latter approach is suitable for conducting studies on a larger scale.

For a road or transit network, circuity is commonly described as the ratio between the network distance and Euclidean distance [18]. Network distance, whether representing the movement trajectories of people or goods, denotes the overall length of the physical route or the shortest path from the point of origin to the destination, within a specific transportation network. Euclidean distance refers to the direct distance between two points in the XY coordinate plane. Due to the extensive scope of the study, the great circle distance, upon which the network was constructed—an approximately spherical surface—proves to be more accurate than Euclidean distance [29]. Therefore, certain studies employ the great circle distance to quantify the level of indirectness in the transportation network.

Circuity, as defined originally, pertains to the comprehension of networks based on spatial distance. As research progresses and the road network expands, the number of available travel routes between nodes increases. This leads to real-time updates of optimal routes, posing challenges in accurately determining the actual route length. However, this calculation method is not suitable for scenarios involving various modes of transportation in real traffic conditions. The phenomenon of equating the same value of circuity to different traveling times, due to the utilization of various modes of transport, can lead to an erroneous assumption of uniform efficiency across networks with equivalent actual distances. The central concept underlying all traffic analyses is the aspiration to minimize travel time. The evaluation of a transportation system's worth is predominantly contingent on the benefits accrued by users through time saved during travel. This underscores the ongoing efforts to enhance technology for achieving higher traffic velocities and reduced travel distances [30]. Travel time is widely recognized as an intuitive indicator of a passenger's perception of distance impedance [31], with individuals showing a greater focus on travel time over distance [20]. Hu [14] initiated experimentation regarding the ratio of the actual travel time to the theoretical minimum time, as a metric for circuity. However, the concept of theoretical minimum time has not been firmly established as a calculation method. However, it offers an efficient method to utilize travel time for studying the effectiveness of transportation networks.

1.2.2. Circuity in the Efficiency of Transportation Networks

The investigation of circuits plays a crucial theoretical role in the disciplines of transport planning, network design, and urban planning. When the circuity is analyzed in relation to travel time, the initial focus on the spatial arrangement of the road network evolves into a broader assessment of transport efficiency. This encompasses the effectiveness of various modes of travel within their respective networks.

The existing literature on the effectiveness of various modes of transportation, in terms of circuity, primarily falls into the following two categories: (1) investigations into efficiency across different transportation modes and (2) examinations of its correlation with travel

distance patterns. From varying transportation modes' perspectives, distinctions exist in their individual transportation efficiencies. Public transportation commonly adheres to predetermined routes [20], leading to increased circuitry. When opting for travel by car, as opposed to public transportation, the vehicle typically prioritizes selecting the quickest route over the shortest route. When faced with traffic congestion or complex road conditions in urban areas, private vehicles frequently opt to take detours [32]. From the standpoint of travel distance, the efficiency of automobile travel is inversely related to Euclidean distance, with an intercept [33]. In terms of bicycle travel, a study conducted in Ohio (United States) indicates that there is a positive correlation between the degree of detour and the distance traveled [34].

1.2.3. Collection of Traveling Time in Relevant Studies

In conventional travel behavior theory and existing empirical studies, travel time is considered a fundamental factor in the selection of travel mode [31,35]. However, the majority of studies employing this indicator have relied on inaccurate travel time approximations, particularly in the case of public transportation. Further investigation is warranted to enhance the accuracy of travel time calculations to align more closely with real-world scenarios.

In current efficiency studies, traffic data are primarily sourced from the following four outlets: (1) The sources involve utilizing cell phone signaling data [36], which necessitates a thorough process of cleaning, mining, and extraction to acquire high-quality data. This process is relatively complex. (2) Public historical data can be acquired in large quantities directly from institutions or websites [26,37]. However, it frequently lacks timeliness and may have gaps in information. (3) The process entails performing calculations or simulations utilizing algorithms such as Dijkstra and Floyd, following the acquisition of accurate travel location details [28,38,39]. (4) The real-time intercity navigation data across various modes of transportation are obtained using online mapping technology [5,16]. This approach offers advantages because of the continuous updates of real-time data provided by different mapping software such as Baidu Map and Tencent Map. The system efficiently mirrors the real transportation network operational status and computes interchange durations among various modes by leveraging extensive data from public transportation systems. Consequently, it offers highly accurate estimations of travel time [14]. This method has garnered growing popularity in research applications due to its advantages in data accuracy, availability, and timeliness.

1.3. Research Objectives and Structure

The literature review reveals that numerous scholars have dedicated their efforts to investigating the effectiveness of intercity transportation networks, providing the groundwork for this study. However, there are still disadvantages in certain areas, primarily in the following areas:

(1) The conventional distance-based circuitry remains predominant in the realm of transportation network efficiency research [18,20,28,29]. However, this indicator fails to account for the travel mode and the volume of travel. While there have been efforts to broaden its scope by incorporating travel time, the methodology remains underdeveloped and is unable to provide an accurate assessment of the effectiveness of intercity transportation networks.

(2) Contemporary research on travel efficiency predominantly employs aggregation techniques to assess the travel efficiency of a particular transportation mode within an urban area [16,19,26,28,33]. Alternatively, the operational efficiency of a specific road network type at the national level is taken into consideration [14,20,29]. At this stage, urban agglomerations' economy has emerged as the predominant mode of economic development. The absence of thorough efficiency studies comparing various modes of transportation within city clusters hinders the advancement of intercity transport in city clusters towards a more sustainable and cost-effective direction.

In summary, this study provides a new definition of distance-based circuitry by incorporating travel time considerations. Subsequently, it was integrated with the gravity model to introduce a novel framework for assessing the efficiency of intercity transportation. Taking into account the travel mode and traffic flows, this approach can provide a more accurate description of the effectiveness of the intercity transportation network. The efficiency examined in this research emphasizes the significance of the intercity transportation network within a local area, for the functioning of the intercity transportation network across the entire urban cluster, as opposed to solely assessing the accessibility or convenience of a specific road segment.

Subsequently, real-time navigation information for car and train travel between cities is acquired using Amap's API. This study examines the spatial distribution of transportation efficiency among various intercity travel modes within seven major city clusters in China. By comparing the traffic efficiency of different regions, the effectiveness of infrastructure construction can be verified, so as to ensure the low energy consumption of the whole process of the construction and operation of the transportation network to the maximum extent.

The analysis is carried out at the level of city clusters and the research results are also accompanied by a discussion of their policy implications. The subsequent sections of the paper are structured as follows: In Section 1, the background, the related studies, and the main work of this research have been introduced in detail. The methodology and the techniques for data processing and data acquisition are presented in Section 2. The results are outlined in Section 3, which is followed by a discussion in Section 4. Section 5 serves as the conclusion of this study.

2. Methodology

2.1. Transportation Network Travel Speed Model

The circuitry refers to the ratio of the actual travel path distance to the Euclidean distance along the path between the origin (O) and destination (D) points of a trip. The circuitry can be determined as follows:

$$c_{ij} = \frac{a_{ij}}{d_{ij}} \quad (1)$$

where c_{ij} is the circuitry of the trip from the city i to the city j ; a_{ij} denotes the actual travel path distance of this trip; and d_{ij} is the Euclidean distance between the city pair.

The original concept of circuitry solely considers the arrangement of the transportation network from the perspective of travel distance, while disregarding the influence of travel mode and transportation conditions. However, for intercity travel, passengers pay more attention to travel time than travel distance [14,20,31]. The passengers prefer trips with shorter travel duration rather than shorter distance. To overcome this constraint, this study redefines the notion of circuitry, by introducing the ratio of the Euclidean distance between the origin and destination points to the actual travel time. This novel metric is referred to as the transportation network travel speed.

$$v_{ij} = \frac{d_{ij}}{t_{ij}} \quad (2)$$

where v_{ij} is the transportation network travel speed of the travel process between the city pair starting from city i to city j , and t_{ij} is the average travel time of the travel path. A larger value of v_{ij} corresponds to a faster travel speed within the transportation network.

2.2. Approach for Travel Time Measurement

2.2.1. Train Travel Time Measurement

For the measurement of train travel time, a model is developed based on Salonen's approach to measuring intercity travel time by train [31]. The total travel time by train between two cities consists of five parts (Figure 1) and it can be calculated as follows:

$$T_{ij}^{rail} = T_{iI} + T_{wI} + T_{IJ} + T_{wJ} + T_{Jj} \quad (3)$$

where T_{ij}^{rail} is the total travel time from city i to city j ; T_{iI} and T_{Jj} stand for the travel time using intracity public transport from the origin to the optimal train station and from the optimal to the destination, respectively; T_{IJ} is the travel time by train between two stations; T_{wI} is the transfer waiting time at the train station I , including the time of entering the station, security check, and waiting for the train; and T_{wJ} is the waiting time at the train station J , including the time of exiting the station and queueing for public transport.

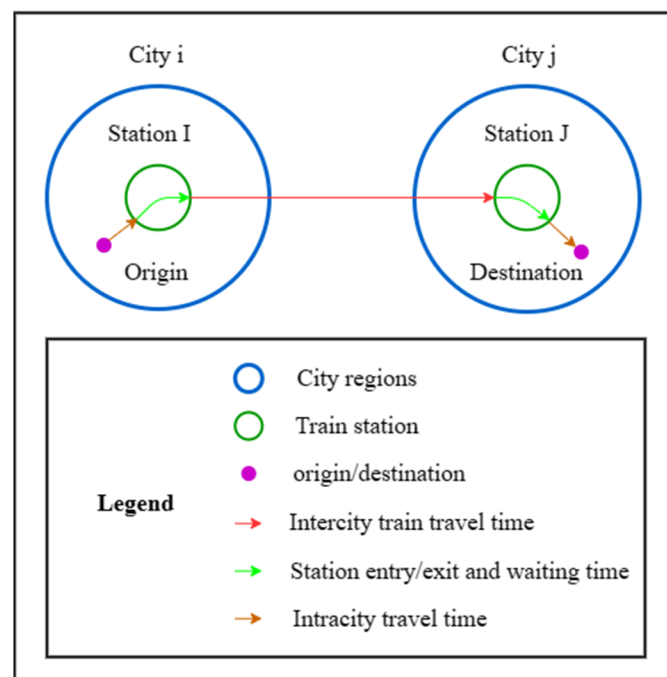


Figure 1. Schematic diagram for calculating intercity travel time.

T_{IJ} and T_{wI} were retrieved from the National Railway Customer Service Website (<https://www.12306.cn>, accessed on 1 April 2023). T_{iI} , T_{wJ} , and T_{Jj} are the components of intracity travel, derived from the simulated query module of public transportation on Amap (<https://ditu.amap.com>, accessed on 1 April 2023). Amap is able to automatically calculate the time spent on intracity transport using public transportation. It will include real-time data on walking and transfers during this process. The API built in this study can be used to export these data. This is a typical advantage of utilizing online mapping technologies. It is recommended to arrive at the station at least 30 min prior to departure to allow for ticket verification by the China Railway Customer Service Center.

However, due to the online mapping technology, the train travel mode encompasses both high-speed rail and regular train services, making it difficult for us to obtain real-time navigation data separately for each. In China, most domestic online mapping software applications face this limitation. Consequently, the train travel data utilized in this study encompasses both HSRs and regular train journeys.

2.2.2. Automobile Travel Time Measurement

Automobile intercity travel time is relatively simple. The passengers do not need to travel to a station to obtain an automobile service, nor do they need to transfer from a station to another mode of transportation to reach their destination. As a result, complicated formulas are needed. Therefore, this study utilizes the API to simply export the data directly.

2.3. Intercity Efficiency Model

Zhai [26] and Dong [36] introduced a methodology to assess the effectiveness of transportation networks by integrating population density with circuitry. Incorporating the actual population distribution as a factor in the circuitry weight leads to varied transportation efficiencies in regions with similar network structures, but differing population distributions. Therefore, this indicates that these networks possess varying degrees of importance in enhancing the overall transportation efficiency within the city, aligning with typical trends.

The calculation of the new model relies on the traffic flow between various city pairs. However, obtaining population data with high precision presents a challenge and serves as a bottleneck. Due to the expansive geographical coverage of city clusters, obtaining accurate statistics on passenger flows between city pairs is challenging, costly, and time consuming and might not be available in less-developed areas. Numerous studies utilize digital traffic data mining techniques to estimate passenger travel flow. However, the application of this method to extensive and intricate regions is presently hindered by limitations in data availability and computational capabilities. This study references the works of Geertman [40] and Yan [41] and posits that the likelihood of traveling from city i to city j is directly related to the appeal of city j to city i . Variations in resource allocation and industrial distribution among cities within the urban agglomeration result in distinct interrelationships between each pair of cities. The intensity of these interrelationships directly influences the distribution pattern of intercity passenger flows [42].

The gravity model [43] combines the spatial distribution of different regions with their attributes, to measure the level of connectivity between these regions. It represents the prevailing model utilized in research concerning the extent of spatial ties and predicting travel distribution. The basic principle states that the strength of spatial connection is assumed to be directly proportional to the product of the masses of two cities and inversely proportional to the square of the distance between them. This model is characterized by its simplicity and broad adaptability. Consequently, this study employs the gravity model to forecast intercity travel distribution within urban agglomerations. Its calculation formula is as follows:

$$A_{ij} = \frac{\sqrt{P_i \cdot GDP_i} \times \sqrt{P_j \cdot GDP_j}}{d_{ij}} \quad (4)$$

where A_{ij} is the attractiveness of city i to city j ; P_i and P_j are regional demographic indicators for the two cities, usually expressed in terms of total population; and GDP_i and GDP_j denote the gross product of the two cities. This study collects pertinent data at the prefecture-level city level, which is then aggregated to the city cluster scale. The primary data utilized comprise economic and social indicators, such as population and GDP. The data are sourced from the China Urban Statistical Yearbook, China Regional Economic Statistical Yearbook, as well as provincial and municipal statistical yearbooks.

Therefore, the movement of traffic between cities can be expressed as follows:

$$q_{ij}^a = q_i^a \cdot \frac{A_{ij}^a}{\sum_{j=1, j \neq i}^{n_a} A_{ij}^a} \quad (5)$$

where q_{ij}^a is the passenger traffic flow from city i to city j in city cluster a ; n_a is the number of cities in city cluster a ; A_{ij}^a is the attractiveness of city i to city j and it can be calculated using

the gravity model; and q_i^a is the total passenger traffic flow in city i , which represents the total number of passengers departing from that city in a given period of time. To simplify the calculation, this study uses the total population of the city as a proxy [26].

Therefore, the calculation model of intercity travel efficiency is given as follows:

$$\sigma_{ij}^a = \frac{q_{ij}^a}{\bar{q}} \cdot \frac{d_{ij}^a}{t_{ij}^a} \quad (6)$$

$$\bar{q} = \frac{\sum_{a=1}^7 \sum_{i=1}^{n_a} \sum_{j \neq i}^{n_a} q_{ij}^a}{\sum_{a=1}^7 \sum_{i=1}^{n_a} \sum_{j \neq i}^{n_a} 1} \quad (7)$$

where σ_{ij}^a is the intercity travel efficiency of the city pair starting from city i and ending at city j in city cluster a . The larger its value, the more efficient the intercity travel becomes for this city pair and the more prominent its role in the transportation network within the city cluster; $\bar{q}$ is the average value of the passenger traffic flow of each city pair in the seven major city clusters; and d_{ij}^a and t_{ij}^a are the Euclidean distance and average travel time of the city pair, respectively.

From the perspective of city clustering, the city is regarded as a node within the intercity transportation network system. The efficiency of the intercity transportation network can be assessed using the following method [14]:

$$\sigma_i^a = \sum_{j=1, j \neq i}^{n_a} \sigma_{ij}^a \quad (8)$$

where σ_i^a is the intercity efficiency of city i in city cluster a .

By integrating each city within a city cluster [36], the intercity efficiency of the entire city cluster can be obtained as follows:

$$\sigma^a = \frac{1}{n_a} \sum_{i=1}^{n_a} \sigma_i^a \quad (9)$$

where σ^a is the intercity efficiency of the city cluster a .

2.4. Study Data

In 2018, a governmental report [44] outlined plans to advance the integrated development of key national and regional strategies within various major city clusters in China's forthcoming urban landscape. These regions encompass the Yangtze River Delta, Pearl River Delta, Beijing–Tianjin–Heibei, Chengdu–Chongqing, Mid-Yangtze River, Central Plain, and Guanzhong Plain. This study focuses on seven highly representative urban agglomerations in China as the research area.

The data pertaining to county-level administrative areas are predominantly incomplete, less reliable, and challenging to access. This study primarily aims to analyze the efficiency of intercity transportation networks within prefectural cities across different city clusters.

The study gathers data at the prefectural city level and subsequently consolidates it to the level of city clusters. The primary data utilized comprise economic and social indicators, as well as the intercity travel time between each pair of cities.

Economic and social data are gathered from sources such as the China City Statistical Yearbook, China Regional Economic Statistical Yearbook, as well as provincial and municipal statistical yearbooks. The travel time between two cities by car is acquired through the Amap route planning module via API.

To calculate the intercity travel time, the initial step entails identifying the location information. Urban agglomerations involve a large area with a large number of city pairs. It is impractical to visit a large number of points within each city to establish mobility OD data. Secondly, train travel time necessitates the use of the National Railway Customer Service Website, which involves a considerable workload. Thirdly, acquiring travel data in certain underdeveloped areas of prefecture-level cities presents challenges, with the possibility of encountering a scarcity of accurate satellite maps. Therefore, following a review of the relevant studies [5,38], this paper selects the seat of the city government as one of the criteria for determining OD points.

In order to further supplement, we choose pinpointing the area within the city with the highest concentration of points of interest as another criterion for OD points, denoted as point E. This represents the bustling economic center of the city.

Following this, two modes are chosen—government–government and point E–point E—which symbolize the linkage between the political and economic hubs of each city and their respective counterparts in other cities. These two OD standards define the general area. This particular area accommodates the highest population density in the city and, thus, represents intercity travel for the majority of city residents.

The dataset analyzes the regular travel time patterns of intercity travel, focusing on the shortest travel times between 2686 city pairs by both train and car. Data are collected hourly from 8:00 a.m. to 8:00 p.m. during the entire month of April 2023, for the selection of time nodes. Two configurations of starting and ending points are examined across a 30 d period. The average travel time for each city pair in the city cluster is calculated based on these two configurations, leading to the creation of a comprehensive travel time matrix encompassing all city pairs within the cluster. It is important to highlight that the train travel time matrix and the car travel time matrix are computed independently.

3. Results

3.1. Spatial Pattern of Transportation Network Travel Speed

The circuitry concept has been extended to include the speed of travel within transportation networks, thereby overcoming its previous limitations in accounting for the varying speeds of different modes of transportation and road conditions. Emphasis has been placed on integrating travel time as a critical parameter for capturing the circuitousness of transportation networks. The research case focuses on the seven major city clusters in China. The real-time navigation data for automobile and train travel modes are obtained through API, which is provided by Amap. Based on the models and data presented, the travel speed of the transportation network between the intercity nodes within each city cluster is calculated and illustrated in Figure 2.

As the Euclidean distance between the cities of origin and destination increases, there is an upward trend in the average travel speed of the transportation network. However, the level of data dispersion also intensifies. The statement suggests that long-distance journeys typically involve fewer detours; however, significant variations exist in travel conditions across different regions.

From the perspective of various modes of transportation, average of the transportation network travel speed using automobile is faster than those of train, over the same distance. Moreover, the standard deviation in its numerical distribution indicates a higher level of data concentration. This suggests that passengers face relatively minor differences in the transportation network travel speed of automobiles across varied city clusters, when traveling the same distance. Consequently, we conclude that car travel is generally more efficient than train travel.

As the Euclidean distance between the origin and destination cities increases, the average of the transportation network travel speed by train increases quickly, while the efficiency gap between train and car travel diminishes. Between 0 km and 200 km, traveling by car demonstrates a clear advantage; however, beyond the 300 km mark, train transportation in certain regions starts to outperform cars. This phenomenon is likely attributable to

the availability of relatively abundant high-speed rail services in these city pairs, resulting in significantly faster train travel compared to automobile journeys.

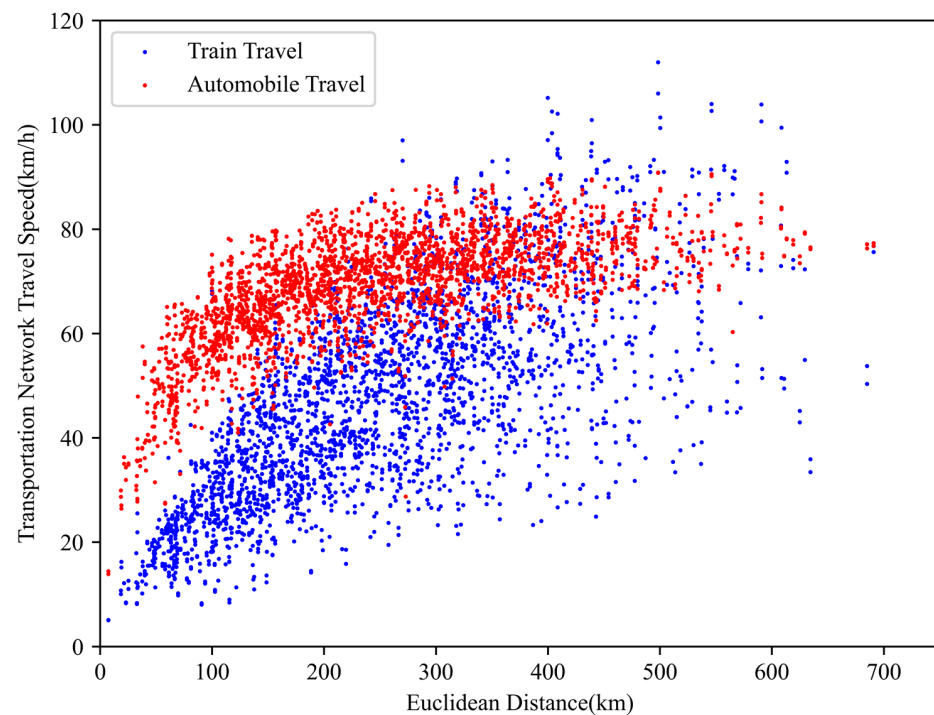


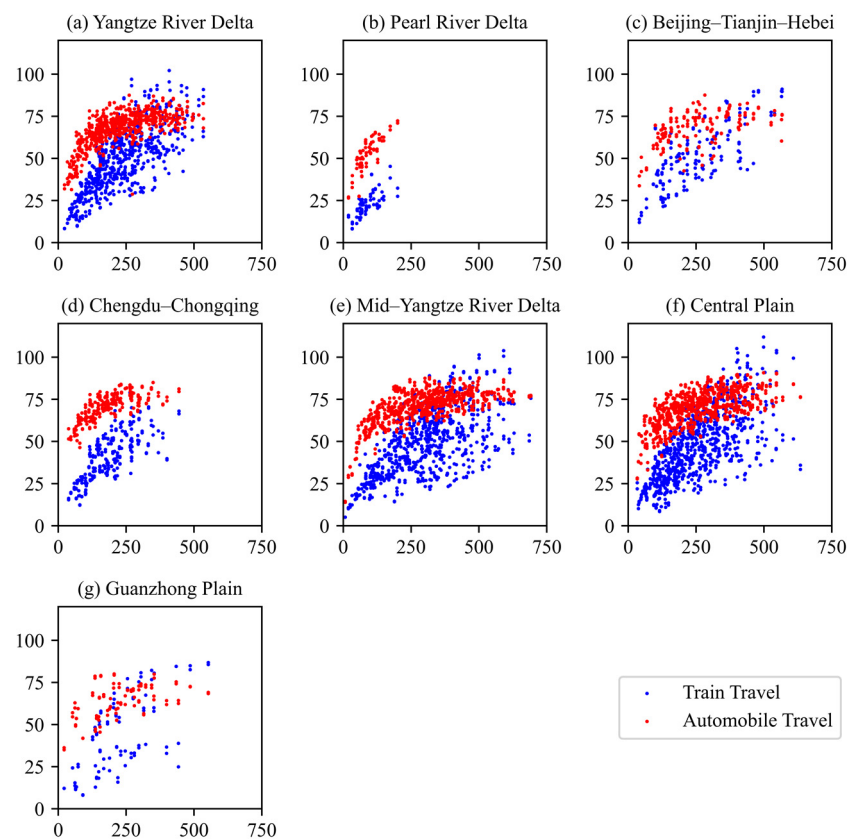
Figure 2. Scatter diagram of transportation network travel speed and the Euclidean distance between the cities of origin and destination.

To investigate the variations in travel speed within transportation networks concerning the Euclidean distance separating the origin and destination cities across various city clusters, scatterplots are generated for each city cluster (Figure 3). The horizontal axis of the scatter plot denotes the Euclidean distance between OD pairs, while the vertical axis represents the speed of travel within the transportation network. In Figure 3, the speed of travel in the transportation network by automobile exceeds that of the train, for most Euclidean distances between the origin and destination cities within each city cluster. This trend is particularly noticeable for short- and medium-distance journeys. Furthermore, when considering the standard deviation of travel speeds within transportation networks by car, as presented in Table 1, it can be inferred that the efficiency of travel within intercity highway networks across different city clusters is relatively consistent.

In the context of train travel, the speed of transportation networks in the Yangtze River Delta and Beijing–Tianjin–Heibei regions exhibit higher values and a lower level of dispersion. This suggests that the majority of cities within these clusters can leverage the advantages of the “time–space contraction effect” facilitated using HSR networks. The Pearl River Delta region features a higher number of detours for intercity travel, leading to a slower transportation network travel speed. However, the distribution of travel speeds across the transportation network as a whole, for the same Euclidean distance between OD pairs, exhibits similarities to those observed in the three aforementioned city clusters. The slower transportation network travel speeds in this city cluster are primarily limited by the shorter intercity Euclidean distances between prefectural-level cities. The Guanzhong Plain exhibits a slower transportation network travel speed and significant fluctuations, which could be associated with regional development polarization. In comparable regional areas with a similar number of affiliated cities, the transportation network travel speed and the fluctuation of train travel in the Mid-Yangtze River and Central Plains regions exhibit relatively close similarities. The aforementioned conclusions align with those presented in Table 2.

Table 1. Number of city pairs in each cluster.

City Cluster	The Number of City Pairs
Yangtze River Delta	702
Pearl River Delta	72
Beijing–Tianjin–Hebei	156
Chengdu–Chongqing	240
Mid–Yangtze River Delta	756
Central Plain	650
Guanzhong Plain	110
sum	2686

**Figure 3.** Scatter diagram of transportation network travel speed and the Euclidean distance between the cities of origin and destination in different city clusters. (a–g) represent different city clusters, respectively.**Table 2.** Statistical analysis of transportation network speed of different transportation modes in city clusters.

City Cluster	Transportation Network Travel Speed by Train (km/h)		Transportation Network Travel Speed by Automobile (km/h)	
	Average	S.D.	Average	S.D.
Yangtze River Delta	49.218	18.405	67.440	9.962
Pearl River Delta	22.764	7.186	51.719	10.374
Beijing–Tianjin–Hebei	46.729	12.739	64.014	9.872
Chengdu–Chongqing	44.036	13.735	68.897	7.881
Mid–Yangtze River Delta	48.184	18.638	65.769	9.439
Central Plain	47.896	20.193	66.797	10.194
Guanzhong Plain	41.627	23.054	61.307	11.228

3.2. Intercity Efficiency Analysis

Table 3 displays the top ten cities with the most efficient intercity transportation across various modes, for each city node. The analysis indicates that the efficiency of intercity transportation in core cities exceeds that of other cities. Within the framework of the comprehensive development of the urban cluster as a whole, the central cities demonstrate rapid progress in transportation infrastructure and make use of the majority of the transportation resources at their disposal.

Table 3. Top 10 cities with the best intercity traffic efficiency under different travel modes.

Ranking	Train Intercity Travel	Automobile Intercity Travel
1	Shanghai	Shanghai
2	Beijing	Beijing
3	Hangzhou	Shenzhen
4	Tianjin	Hangzhou
5	Zhengzhou	Tianjin
6	Wuhan	Chongqing
7	Chongqing	Chengdu
8	Shenzhen	Guangzhou
9	Hefei	Zhengzhou
10	Chengdu	Wuhan

Once the transportation efficiency for each city is determined, the overall efficiency of the entire city cluster is computed utilizing Equation (9). In Figure 4, the efficiency of intercity travel by automobile consistently surpasses that of train travel within each urban cluster. In the realm of intercity transportation efficiency for automobiles, most city clusters demonstrate a high performance, with the exception of the Guanzhong Plain (67.70), which shows a subpar efficiency. The Yangtze River Delta (115.21) and Beijing–Tianjin–Hebei (120.13) regions demonstrate higher levels of intercity automobile efficiency in comparison to other city clusters. In the context of intercity train efficiency, the Yangtze River Delta (84.04), Beijing–Tianjin–Hebei (87.44), and Mid–Yangtze River Delta (76.78) demonstrate a superior performance, leveraging their extensive train networks to achieve this objective. However, the Guanzhong Plain (44.87) continues to fall behind, necessitating further development and enhancement of its train transportation infrastructure.

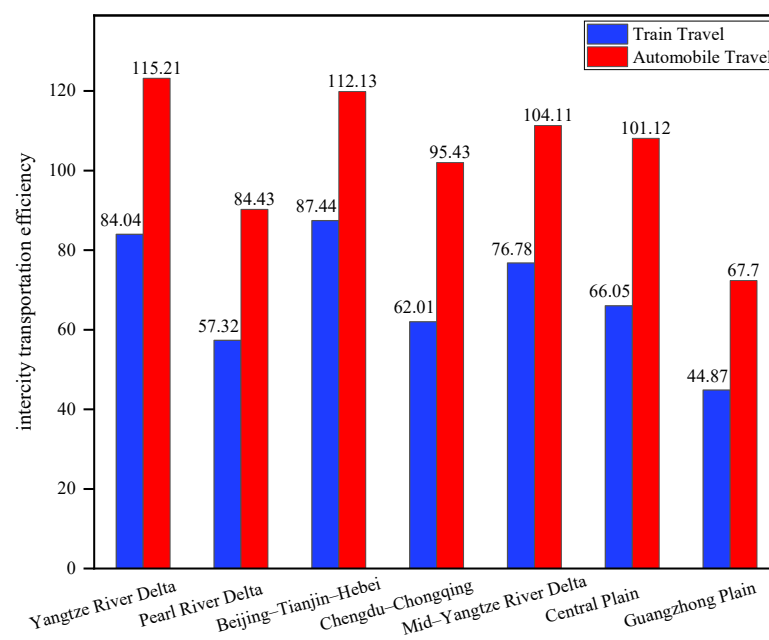


Figure 4. Comparison of intercity efficiency of city clusters.

4. Discussion

Circuitry functions as a metric for assessing the appeal of trip routes and is well suited for the analysis and comparison of cities and urban regions. The original concept of circuitry overlooks traffic patterns and flow, which are essential factors in assessing traffic efficiency. To address this issue, the circuitry framework includes considerations of travel time and travel volume, leading to the subsequent introduction of transportation network travel speed and FWTC. These concepts are employed to assess the effectiveness of intercity traffic within urban clusters. Additionally, different from real-time traffic time, the transportation network travel speed and FWTC can effectively take into account the factor of travel distance, allowing for a comprehensive comparison and analysis of travel efficiency across various city pairs. In contrast, real-time traffic data solely facilitates comparing the efficiency of different traffic modes between the same city pair.

Compared to original circuitry, transportation network travel speed and FWTC not only better reflect the preference of the majority of riders, but also accommodate different travel modes. Original circuitry uses route distance to calculate intercity travel efficiency, which leads to the same efficiency for travel paths with the same route distance, but different travel times taking varied transportation modes. This phenomenon is evidently unreasonable. The issue does not apply to transportation network travel speed and FWTC, because they use travel time to define efficiency. Therefore, with the rise of multimodal transportation, transportation network travel speed and FWTC are widely used.

It is important to note that the transportation network travel speed, technologically rational traffic speeds, and real average travel speed of a transportation mode are related, but not equivalent. From the perspective of calculation method, transportation network travel speed is the ratio of the whole journey time to the European-style distance of OD, traffic speed is instantaneous values with the unit of distance traveled per unit time, while average travel speed represents the average traffic speed of the entire route. The essence of transportation network travel speed and FWTC is the time cost of travel, taking varied modes of transportation. Travel technology does not directly influence transportation network travel speed and FWTC. Instead, it affects transportation network travel speed and FWTC by influencing travel time. Generally speaking, modes of transportation with higher technologically rational traffic speed tend to complete the same displacement in shorter time durations. However, there are many factors affecting the travel time, such as the operating speed of each section, the layout of the transportation network, and the transfer time. These factors are taken into account by the transportation network travel speed and the FWTC.

The transportation network's travel speed by automobile offers the advantage of increased connectivity within a 200 km radius, while also ensuring centralized data distribution. This phenomenon could be associated with varying proportions of HSR and conventional trains in different regions. In developing regions, intercity travel is predominantly facilitated by conventional trains, whereas developed regions have the option to utilize HSR for more efficient transportation. This discrepancy results in significant variations in travel speeds within the transportation network, despite covering the same Euclidean distance.

Variations in travel speeds exist within transportation networks across various city clusters. The variations stem from the geographical separation of prefecture-level cities and the distinct developmental circumstances of transportation networks. Therefore, it is imperative to strategically determine the allocation of investment in transportation modes, based on the distances between prefecture-level cities within city clusters. Within each urban cluster, the primary cities dominate the majority of the road network resources, indicating a polarized scenario.

From the standpoint of urban agglomerations, the effectiveness of intercity car travel is evidently greater than that of train transportation. The variation in travel times can be ascribed to the lengthy transfers required in public transportation, along with the inconvenience stemming from the remote positioning of train stations from the central

city area. Intercity travel by automobiles is made more convenient through the presence of urban expressways and highways. This obviates the necessity for intermodal transfers, thereby enhancing the efficiency and continuity of intercity travel. Regions are actively advocating for the use of public transportation, specifically focusing on rail transit. Rail transit frequently serves as a vital component of both freight and passenger transport networks. The development of HSRs is expected to induce a substantial reduction in time and space constraints for the neighboring cities. This effect is anticipated to enhance regional transportation efficiency and ecological sustainability. Therefore, addressing the inefficiencies in transfers and intracity public transportation during intercity train travel is imperative.

This study introduces a methodology for the efficient computation and comparison of circuitry values across various transportation modes and city cluster scale levels. The efficacy of developing extensive transportation infrastructure can be illustrated by examining the enhancement in intercity transportation efficiency within a specific timeframe, thereby establishing a foundation for forthcoming development initiatives. The definition of FWTC is predicated on the traffic flow between various city pairs. However, obtaining population data with high precision presents a challenge and serves as a bottleneck that hinders additional research progress. The situation may differ when utilizing high-precision population data for conducting comparable analyses.

Additionally, this study gathered travel time data based on the shortest trip rather than the preferred route. The calculation and comparison of circuitries along the preferred route may yield varying results, potentially leading to greater disparities. However, the process of choosing the optimal route is complicated by numerous subjective factors, which hinder the efficient collection of statistical and informational data. To advance research effectively, it is crucial to have ample access to data and computational resources to address these issues.

5. Conclusions

In light of the growing focus on China's transportation network development and city cluster economy, this research investigates the spatial distribution of intercity transportation efficiency for automobiles and trains within China's city clusters. The study focuses on the scale of the city cluster, aiming to address the existing research gap in this area. This contribution can offer theoretical insights for future urban planning endeavors. The variations in transportation network density, diverse geometric properties of networks, and differences in population distribution among various cities result in discrepancies in transportation efficiency across urban areas.

An extended concept of circuitry is proposed to address the limitations of the original circuitry, which primarily emphasizes the distance dimension, while overlooking the speed of different modes of transportation and road conditions. It encompasses the temporal aspect and is commonly known as the speed of the transportation network. FWTC is proposed through the integration of transportation network speed and the gravity model. This approach aims to provide a more accurate assessment of intercity transportation efficiency. Furthermore, the study focuses on seven major city clusters in China; data on navigation for automobile and train travel modes are collected using Amap's API. Real-time data enables the analysis of travel time between city pairs, facilitating an examination of spatial patterns in intercity transportation efficiency for both automobile and train travel modes within China's city clusters. The results indicated the following:

- (1) As the Euclidean distance between the origin and destination cities increases, there is a rising trend in the average of transportation network travel speed. However, the level of fluctuation also intensifies. From the standpoint of various transportation modes, as the Euclidean distance between the cities of origin and destination expands, the discrepancy in travel speed within the transportation network between train and automobile gradually decreases. In the context of variability, train travel demonstrates

more significant fluctuations, while automobile travel shows a higher level of stability, characterized by more concentrated data points.

(2) In terms of the city cluster scale, the speed of automobile travel within the transportation network is faster and more evenly distributed, resulting in fewer disparities among various city clusters. In terms of transportation network travel speed by train, the Yangtze River Delta and Beijing–Tianjin–Hebei regions demonstrate a relatively superior performance compared to the relatively inferior performance of the Pearl River Delta and Guanzhong Plain.

(3) The intercity efficiency of automobile travel is typically high within each city cluster, with the exception of the Guanzhong Plain. The Yangtze River Delta and Beijing–Tianjin–Hebei regions exhibit a particularly noteworthy performance in this regard. From the standpoint of intercity train travel efficiency, the Yangtze River Delta, Beijing–Tianjin–Hebei, and Mid-Yangtze River regions demonstrate significant efficiency owing to their interconnected train networks. In contrast, the Guanzhong Plain exhibits a relatively lower efficiency in its train traffic, highlighting the necessity for additional development and enhancement.

Overall, the benefits of intercity travel by car are more pronounced when considered on a city cluster scale. While intercity train travel presents a significant advantage in regions where the Euclidean distance between the originating and destination cities exceeds 300 km, there is still a need for overall improvement in its efficiency.

The study has several limitations. Firstly, the selection of the origin and destination for intercity travel typically focuses on the most representative locations within the city, rather than employing an extensive sampling of points to accurately simulate real travel conditions. Secondly, to calculate travel flows between city pairs, this study has to simplify the process by employing a gravity model to make predictions. The assessment of intercity attractiveness is limited by using the Euclidean distance as the sole measure of evaluation. This approach overlooks important factors such as travel costs, geographic terrain, and other variables that can significantly influence the actual travel willingness of passengers. These simplifications of the model cause some of the error. With the continuous innovation of information technology and computing technology, the emergence of digital footprints (geo-located data collected using electronic equipment) offers an efficient data source for gathering travel data and OD data. This data source boasts a higher penetration rate and lower usage bias, compared to social media data and statistical data. Through the mining of these electronic data, we can effectively collect real-time travel data and OD data. It provides accurate and timely data support for further exploring the travel efficiency of the intercity transportation network.

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