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The impacts of road network density on motor vehicle travel: An empirical study of Chinese cities based on network theory

Shiguang Wang[a,d,e,f], Dexin Yu[a,e,f], Mei-Po Kwan[b,c,d], Lili Zheng[a,e,f,*], Hongzhi Miao[a], Yongxing Li[g]

[a] School of Transportation, Jilin University, Changchun, China
[b] Department of Geography and Resource Management, Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Hong Kong, China
[c] Department of Human Geography and Spatial Planning, Utrecht University, Utrecht, the Netherlands
[d] Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, Urbana, USA
[e] Jilin Research Center for Intelligent Transportation System, Changchun, China
[f] Jilin Province Key Laboratory of Road Traffic, Changchun, China
[g] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

A R T I C L E I N F O

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A B S T R A C T

This paper examines the impacts of road network density on motor vehicle travel through traffic flow and network analysis of cities in China from three perspectives: multi-city comparison with traffic flow data, multi-city and multi-period comparisons with structural characteristics. When we examine the correlation between road network density and traffic flow characteristics including the travel time and speed of 35 major cities in China, no correlation exists between them which may result from different network structures, dynamic traffic demands, traffic control plans, driving behaviors, and so on. It inspires us to explore the correlation between road network density and static travel indicators. Then structural characteristic of road networks can be treated as a fixed relatively attribute and becomes the next research emphasis of this work. Comparative analysis results of three current cities (Xiamen, Washington D.C., San Jose) indicate that the average travel distance in different cities with the similar land area will not increase significantly as road network density increases. Results of an analysis of road network evolution of Changchun, China show that the increase of road network density shortens the average road segment length as well as travel distance in general. This impact on average travel distance is also related to evolution periods or modes of urban road networks. These findings provide important empirical support for planners and policymakers to understand the impacts of road network density on transport performance and design more effective urban road networks.

1. Introduction

Transportation is one of the most important functions of a city, and urban structure is often significantly affected by the motion flow and the modes at the material level (Marshall, 2005). From a structural perspective, the operational performance of urban road networks is highly dependent on the network structure that shapes the traffic flows on a network (Wang et al., 2018a, 2018b, 2018c;

* Corresponding author at: No. 5988 Renmin Street, Changchun 130022, China.
E-mail addresses: wsg_its@163.com (S. Wang), yudx@jlu.edu.cn (D. Yu), mpk654@gmail.com (M.-P. Kwan), lilizheng@jlu.edu.cn (L. Zheng), honmgee@foxmail.com (H. Miao), liyx219@163.com (Y. Li).

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Duan and Lu, 2013; Xie and Levinson, 2007). Recently, the planning concept of "denser road networks and smaller blocks" is widely applied to the design and planning of new areas in Chinese cities(e.g., the Chenggong District of Kunming City and the Yuelai District of Chongqing). The traditional planning method prioritizes motor vehicle travel, which leads to wide and sparse arterial roads, the lack of branch roads and too many lanes in existing road networks. But it still cannot meet the rapidly growing traffic demand, resulting in increased and more serious traffic congestion and uneven traffic flow distribution in the road network. Wide roads will bring inconvenience to pedestrians (e.g., increasing the distance and time for pedestrians to cross streets). The large-sized blocks brought about by sparse road networks are not conducive to efficient bus transfer and vehicle detours and at the same time increases the difficulty of traffic management and control.

Reviewing the proposal and development of the planning model of "dense road network and small blocks," as early as 1889, Sitte summarized the artistic principles of urban construction by investigating a large number of squares and streets in medieval European cities, and advocated narrow, winding urban street space of medieval styles, which had an important influence on the later new urbanism (Sitte, 2013). In 1961, Jacobs put forward the urban planning idea of "dense road network, small blocks and mixed functions" (Jacobs, 1961). In the 1990s, in the face of the sprawls of American urban suburbs and the decline of urban centers, Calthorpe et al. initiated the rise of new urbanism (Ellis, 2002). New urbanism selects and develops the planning mode of "dense road network, small blocks" and advocates the return to the spatial form of traditional European towns creating high-density grid networks and livable streets. From the perspective of the overall development of a society, a denser road network can facilitate pedestrians and bicyclists, increase community vitality, improve residents' happiness and ensure social harmony. But how does it impact transport performance, especially motor vehicle travel? The topic is seldom investigated in existing empirical studies. A large number of case cities and multi-source data are necessary to address the question. This study of Chinese cities is a preliminary examination that helps to draw more attention from researchers in different countries and disciplines to such issues due to a variety of development states of different cities. It focuses on the influence of road network density on transport performance.

Taking a simple road network (a square with 2 km on each side) in Fig. 1 as an example, the travel distance varies as the road network and density change. The intersections are seen as the origin and destination of a trip. The initial average travel cost of the road network in Fig. 1**(a)** between any two intersections is 1.60 km when we consider road segment distance as weight or impedance. After adding a road (the red dotted line) as shown in Fig. 1**(b)**, the average travel distance becomes 1.54 km which is slightly less than the initial road network. But when we add a road (the red dotted line) as shown in Fig. 1**(c)**, a new intersection is created and the new average travel cost among the six intersections is 1.62 km although the cost among the initial five intersections does not change. The famous Downs Law pointed out that newly built roads will induce new traffic volume in the absence of effective government regulation and control of urban traffic, and traffic demand always tends to exceed traffic supply (Downs, 2004). Under this circumstance, it's reasonable to add the new intersection as an origin or destination. Even the intersection is not considered as the start or endpoint of a trip, the average cost is still the same as the initial road network because the added road cannot change the shortest

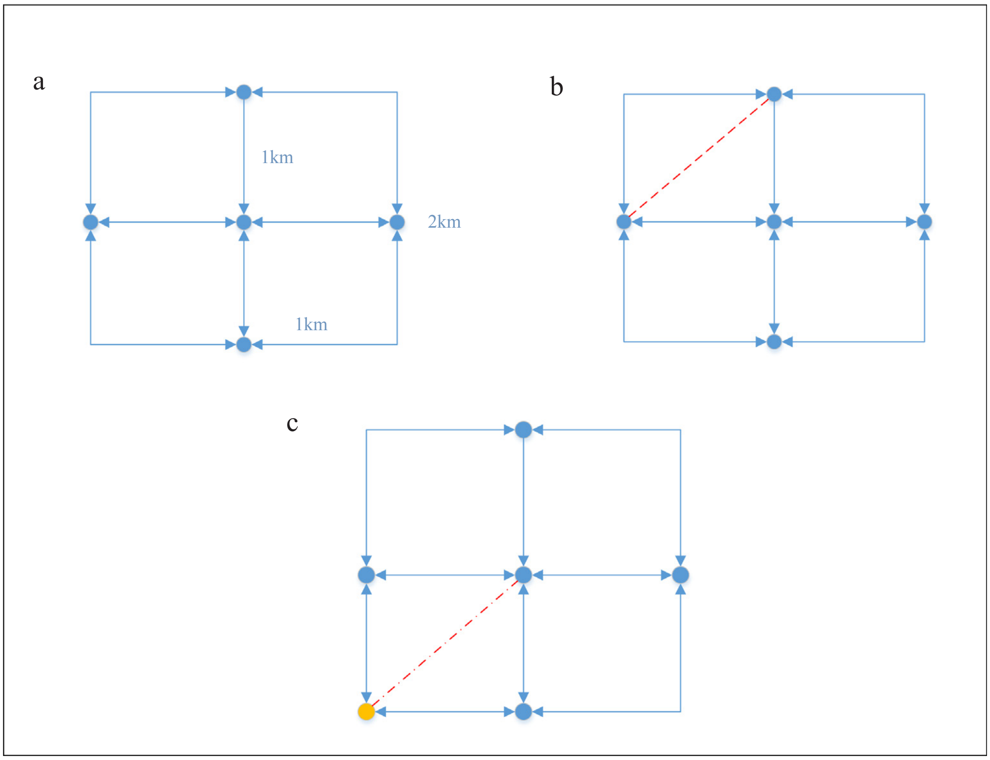

Fig. 1. A simple example to analyze travel cost variations. (a) Initial road network; (b) The first way to add a road; (c) The second way to add a road.

distance among existing intersections. Meanwhile, in the real road networks, city expansion and road network evolution are different from the simple example mentioned above. They usually have two prominent characteristics: densification and expansion. Theoretic modeling and deduction may not be enough to analyze the question. Therefore, the study aims to explore empirically whether road networks with different densities have an impact on motor vehicle travels.

2. Literature review

Many existing studies have analyzed the correlation between road density and transport performance. Safety and efficiency are the two key aspects of transport performance. As for the effects on safety, design of the roadway and development of different land uses can affect pedestrian road traffic injuries (Stoker et al., 2015), and some scholars even found that denser street networks with higher intersection counts per unit area are associated with fewer crashes for drivers and non-motorists (Zhang et al., 2015; Marshall and Garrick, 2011). During the development of cities, urban sprawls also become a risk factor of motor vehicle crashes (Ewing et al., 2014).

Besides safety, another aspect of the influence of road density on transport is the efficiency of travels, mobilities, and activities. Previous studies mainly focus on the pedestrian, bicycling, and other slow travel modes. Neighborhood density and street connectivity affect walking and other physical activities (Koohsari et al., 2014; Oakes et al., 2007). For example, the connectivity of the street network affects the distribution of pedestrians (Ozbil et al., 2011). Higher street connectivity and street network density are positively associated with much more walking and biking (Hajrasouliha and Yin, 2015; Marshall and Garrick, 2010). In particular, these associations are null (men) or inverse (women) in the CARDIA study (Hou et al., 2010). These studies are helpful to create a pedestrian-friendly environment. Meanwhile more compact street networks are also correlated with better health (Marshall et al., 2014). However, similar empirical studies in the field of motor vehicle travels are rarely conducted. Some studies found that increased street connectivity can reduce vehicle travel and tends to improve walking and cycling conditions (Marshall and Garrick, 2012; Ewing and Cervero, 2010). Meanwhile, community opening policy which originated from Benevolo (1980) is an effective solution to increase road network density, it is thus helpful to analyze the potential changes to street network accessibility. The government in China issued the community opening policy in 2016 which encourages more communities to be open to the public road system and put forward the planning concept of “narrow street and dense network” (The State Council of the People’s Republic of China, 2016). The planning concept of opening community has a significant impact on the development of modern city form. Results of street centrality analysis of Shenzhen, China after applying the policy (i.e., increasing density) indicate that the accessibility at some places increased, while it decreased at other places, and directness was generally improved (Yu, 2017). Research of four first-tier Chinese cities including Beijing, Shanghai, Guangzhou, and Shenzhen shows that open communities would increase the connectivity and accessibility of the current road network and decrease residents’ commuting time for short-distance travels (Yao et al., 2018). They are studies about the effects of network density on vehicular travel using network analysis.

In a word, new urbanism and the government in China both want to plan and construct cities with a dense road network, and many studies validated the benefits of a denser road network for safety, activities, and health. However, the correlation between density and transport, especially motor vehicle travels, has not been well analyzed from the perspectives of traffic flow and structural empirical analyses. If we understand the potential impacts of road network density on motor vehicle travels, it is likely to build a better road network more easily. This study thus seeks to answer the following research questions:

(1). In terms of traffic flow, does a denser road network lead to shorter travel time and faster travel speed for a city’s residents? To answer this question, the traffic flow and density data of 35 typical Chinese cities will be analyzed in Section 3.
(2). In terms of network analysis, how much motor vehicle travel will be affected by a denser road network in a comparative study of the present cities? If the increase in road density does not affect travel significantly, residents will tend to accept the planning concept and have a denser road network easier. To answer this question, we will undertake a comparative study of Xiamen, China and two American cities, Washington D.C. and San Jose in Section 4.2.
(3). In terms of network analysis, except the present cities, what is the impact of road density changes resulted from road network evolution in different periods for the same city on motor vehicle travel? Based on such network analysis, we may acquire knowledge about the impacts in advance before we build a denser road network in the real world. Changchun, China will be selected as the case in Section 4.3.

Please note that the three questions and corresponding data are independent, and they are different analysis dimensions on the impacts of road network density on motor vehicle travel. In the paper, we will first analyze the relationship between road network density and traffic flow parameters to explore whether the correlation between them exists.

3. Correlation between road network density and dynamic travel indexes

In this section, we will analyze whether any correlation exists between road network density and traffic flow parameters through the case of Chinese cities. Our data in this section are mainly derived from the annual report on road network density in major Chinese cities (2018) and traffic analysis reports for major cities in China (2017) of Amap. Because the analysis of road network density was conducted in 2017, the traffic flow data are also based on 2017 statistics.

Fig. 2. Selected Chinese cities for study in this section.

3.1. Selected Chinese cities and basic indicators

Considering the need for comprehensive analysis and data availability, we selected 35 major cities in China for this part of the study. These cities include four municipalities directly under the central government, five cities specifically designated in the state plan, and twenty-six capital cities. All selected Chinese cities are shown in Fig. 2. These cities involve all provinces except Xizang (or Tibet) and Taiwan due to the lack of traffic flow data for the provinces.

The definitions of different indicators analyzed in this section are described as follows.

Road network density is the ratio of total road length and the urban area within a specific range:

$$D = \frac{l}{A} \tag{1}$$

where D is road network density, l is the total road length within a specific range, A is the corresponding urban area. The statistical range of road network density is based on central city built-up area proposed by the current urban master plan.

The congestion delay index (*CDI*) refers to the ratio of peak travel time and free flow travel time. The metric contains two time scales, i.e., peak periods of a day and the whole day:

$$CDI = \frac{T_p}{T_f} \tag{2}$$

where CDI is the congestion delay index, T_p is the peak travel time, T_f is the free flow travel time. The higher the index is, the greater the travel delay and more congestions are.

The congestion delay index compares the travel time of trips between real and free flow situations. Another traffic indicator is traffic speed, which may be based on three different periods (i.e., the peak period, the whole day, or under free flow condition). The statistical period of traffic flow parameters for analysis is January-December in 2017. All traffic flow parameters are annual average values.

3.2. Correlation analysis between road network density and traffic flow parameters

Table 1 shows the results of road network density and traffic flow parameters for the 35 selected Chinese cities. As major cities in China, most of these cities (91.43%) have a low road network density (< 8 km/km^2). The average density value is 5.95 km/km^2 which is more than that of 48.57% selected cities. The standard deviation of the density values is 1.24.

We use the Pearson correlation coefficient to analyze the correlation between density and traffic flow parameters. The correlation among different indicators is shown in Table 2. The first row of Table 2 shows that the absolute values of all correlation coefficients are less than 0.3, indicating the correlation between density and traffic flow parameters is not high. As for traffic flow parameters, congestion delay index is negatively correlated with traffic speed, and peak traffic speed is positively correlated with daily traffic

Table 1
Road network density and traffic flow parameters of different cities.

Cities	Density (km/km^2)	Peak *CDI*	Peak speed (km/h)	Daily *CDI*	Daily speed (km/h)	Free flow speed (km/h)
Beijing	5.59	2.033	22.17	1.692	26.65	45.09
Shanghai	7.10	1.878	23.18	1.580	27.53	43.53
Guangzhou	7.02	1.892	24.13	1.674	27.26	45.66
Shenzhen	9.50	1.751	27.08	1.554	30.49	47.41
Harbin	4.94	2.028	21.93	1.707	26.06	44.47
Chongqing	6.49	1.951	23.27	1.601	28.35	45.40
Hohhot	4.24	1.949	23.71	1.639	28.18	46.21
Hefei	6.61	1.881	23.36	1.568	28.04	43.95
Dalian	6.03	1.875	25.16	1.555	30.34	47.16
Changchun	5.33	1.861	23.69	1.555	28.34	44.08
Nanning	6.57	1.858	22.15	1.652	24.85	41.14
Kunming	6.72	1.851	24.37	1.636	27.58	45.11
Xi'an	5.49	1.850	24.57	1.625	27.96	45.44
Yinchuan	4.76	1.840	21.91	1.615	24.97	40.33
Haikou	5.41	1.829	21.25	1.599	24.29	38.86
Guiyang	6.12	1.823	25.93	1.570	30.12	47.28
Chengdu	8.02	1.811	24.89	1.603	28.12	45.08
Nanjing	5.55	1.801	24.28	1.529	28.58	43.71
Changsha	6.27	1.798	23.9	1.548	27.75	42.96
Shenyang	4.74	1.795	24.06	1.533	28.17	43.18
Xining	5.04	1.783	27.36	1.614	30.31	48.77
Shijiazhuang	5.15	1.767	26.75	1.520	31.10	47.25
Fuzhou	6.81	1.760	24.72	1.518	28.63	43.51
Jinan	4.68	2.067	21.12	1.717	25.44	43.65
Qingdao	5.35	1.744	27.88	1.466	33.16	48.62
Nanchang	6.12	1.736	24.76	1.516	28.3	42.98
Lanzhou	4.04	1.735	24.24	1.586	26.51	42.05
Zhengzhou	6.22	1.715	27.8	1.543	30.93	47.68
Wuhan	5.77	1.712	27.86	1.460	32.67	47.69
Hangzhou	6.9	1.699	24.15	1.559	26.31	41.04
Xiamen	8.45	1.681	25.81	1.441	30.08	43.38
Taiyuan	5.17	1.678	29.09	1.473	33.17	48.80
Tianjin	6.04	1.678	27.94	1.447	32.39	46.88
Ningbo	6.67	1.617	24.57	1.403	28.31	39.72
Urumqi	3.41	1.476	32.24	1.611	29.33	47.59

Table 2
Pearson correlation coefficients of analyzed indicators.

Coefficients	Density	Peak *CDI*	Peak speed	Daily *CDI*	Daily speed	Free flowspeed
Density	1	−0.0479	−0.0512	−0.2396	0.0929	−0.0644
Peak *CDI*		1	−0.7710	0.7090	−0.4961	−0.1124
Peak speed			1	−0.5108	0.8269	0.7121
Daily *CDI*				1	−0.6699	−0.0862
Daily speed					1	0.7956
Free flow speed						1

speed and free flow speed.

The significant correlation between road network density and traffic flow parameters does not exist in the case of the selected Chinese cities. It is partly because residents' travel is a kind of dynamic behavior. Corresponding traffic flow parameters are stochastic due to different traffic states, transport signal control plans and driving behaviors. Therefore, it inspires us to explore the correlation between road network density and static travel indicators. Structural indicators which are constant within a specific period from the perspective of network science are good measures for investigating the intrinsic characteristics of a road network. And then the study attempts to analyze the question from the following two perspectives based on network analysis: different cities and a city in different periods.

4. Correlation between road network density and static travel indexes

4.1. Model and network indicators

A network consists of nodes and edges in network science. The study uses the primal approach of network science to model the urban road center-line network, namely the intersection is regarded as the node, and the road segment is the edge (Porta et al., 2006;

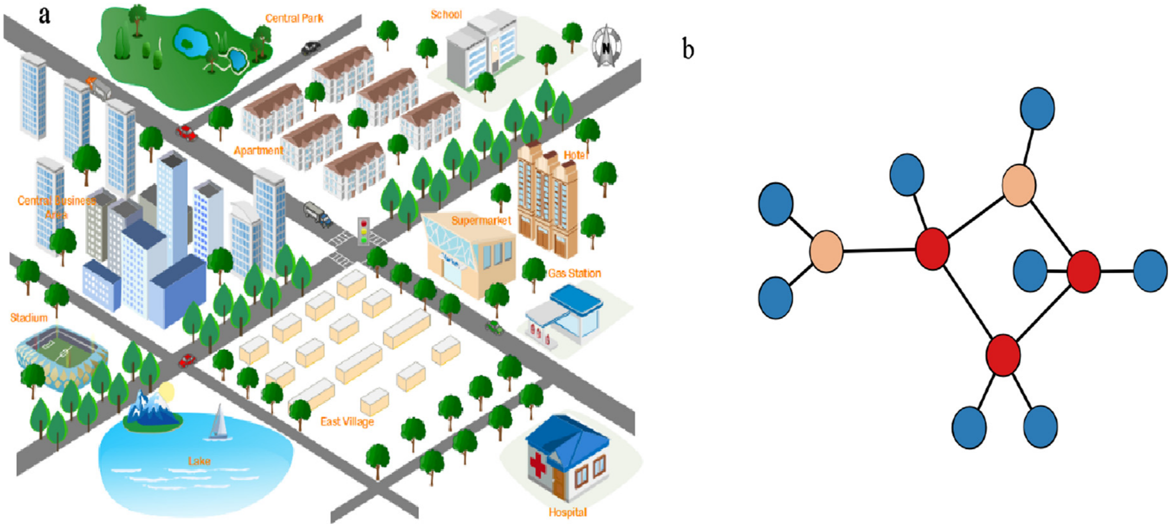

Fig. 3. Schematic diagrams of an urban road network: (a) real road network; (b) primal approach modeled network.

Wang et al., 2017). Fig. 3 is a schematic diagram of the primal approach.

Feature mining of road network structure with complex network theory and space syntax is a hot research topic at present (Derrible and Kennedy, 2011; Ducruet and Beauguitte, 2014). As a basic parameter to describe the characteristics of a complex network, the degree k_i of a node i is defined as the number of nodes connected to it (Newman, 2010). The greater the degree of a node, the more important it is. Average degree $\langle k \rangle$ is the average value of all node degree:

$$\langle k \rangle = \frac{\sum_{i=1}^{N} k_i}{N} \tag{3}$$

where N is the total number of nodes in the network.

In the network, the number of edges of a path which has the least number of edges between two nodes i and j is called the shortest path length d_{ij}. The average path length L is defined as the average distance between all node pairs:

$$L = \frac{1}{N^2} \sum_{j=1}^{N} \sum_{i=1}^{N} d_{ij} \tag{4}$$

In the undirected network, $d_{ij} = d_{ji}$, $d_{ii} = 0$, Eq. (4) is simplified as

$$L = \frac{2}{N(N - 1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} d_{ij} \tag{5}$$

If we consider road length as the weight of each edge, we can get the weighted average path length.

The clustering coefficient is the ratio of the number of connected edges to the maximum number of edges. Assuming that the node i is directly connected to k_i nodes in the undirected network, the maximum number of possible edges between the k_i nodes is $k_i(k_i - 1)/2$, while the actual number of edges is M_i, then the clustering coefficient C_i of the node i,

$$C_i = \frac{2M_i}{k_i(k_i - 1)} \tag{6}$$

Average clustering coefficient refers to the average value of clustering coefficients of all nodes in the graph.

$$\langle C \rangle = \frac{1}{N} \sum_{i=1}^{N} C_i \tag{7}$$

where $0 \leqslant \langle C \rangle \leqslant 1$. When $\langle C \rangle = 0$, all nodes are isolated nodes without connected edges. When $\langle C \rangle = 1$, the network is a complete graph of all nodes with connected edges between any two nodes.

Space Syntax is a theory on space which is based on geometric topology. It explores the logical relationship between space itself and each other, describes the space configuration quantitatively and finds the relationship between spatial form and human society (Hillier and Johnson, 1984).

The choice is a measure to calculate the probability or number of the shortest path of an axis or street from one space to all other spaces, that is the number space appears in the shortest topology path. If e_{ij} is an edge between the nodes i and j, then the choice

$$B_{ij} = \sum_{l \neq m} [n_{lm}(e_{ij})/n_{lm}] \quad (8)$$

where n_{lm} represents the number of shortest paths between the node l and m; $n_{lm}(e_{ij})$ represents the number of shortest paths that pass the edge e_{ij} between the nodes l and m. The choice is the same as the betweenness of network science.

The average depth MD_i represents the average distance between the node i and all other nodes.

$$MD_i = \frac{1}{N-1}\sum_{j=1}^{N} d_{ij} \quad (9)$$

where d_{ij} is the shortest distance between the nodes i and j, that is the total depth within the space region. It is consistent with the meaning of shortest path length in network science.

Integration I_i refers to the standardized distance from any space to all other spaces in the system. The distance from the starting space to all other spaces can be calculated with the following equation (Teklenburg et al., 1993).

$$I_i = \frac{(MD_i - 1)(N-1)}{N[\log_2((N+2)/3 - 1) + 1]} \quad (10)$$

4.2. Comparison of existing road networks

This section will describe and visualize the structural characteristics of urban road networks based on complex network and space syntax methods. These structural indicators will be used for analyzing the differences in transport performance between road networks with low and high densities from the perspective of small worldliness (Neal, 2018; Watts and Strogatz, 1998), network hierarchy (Huang et al., 2016; Jiang, 2009; Lammer et al., 2006; Wang et al., 2018a, 2018b, 2018c), and path length which mainly affect residents' travels when using motor vehicles.

The Chinese case selected for this part of the study is the low-density Xiamen road network which has been examined in previous studies (Wang et al., 2018a, 2018b, 2018c, 2017; Zhang et al., 2017). As for the high-density road networks, as the control, we first consider the economically developed American cities. Comparative cities should have similar attributes to Xiamen, China. Meanwhile, the density is the ratio of road length to the area, where the land area information is easy to obtain. So the land area is the first attribute that should be considered, Washington D.C with a similar area to Xiamen becomes the main comparative city here. To enrich the cases, San Jose in California with a similar population to Xiamen Island is also selected as the control. The basic information on these three cities is shown in Table 3. Xiamen Island is the core area of Xiamen city. Washington D.C. is the capital of the United States. San Jose is located in the southern part of the San Francisco Bay Area in California in the United States. This section mainly examines the structural characteristics of the road networks, so the specific social background is not considered. The vector road network file (.shp) and topological file (.graphml) for the two American cities were obtained from the open data of American urban studies by Dr. Geoff Boeing at the University of California, Berkeley (Boeing, 2017, 2018a). The number of nodes or roads and road length information are from the open data.

Clustering coefficient and average path length are two main indexes for determining the small worldliness of a network (Neal, 2018; Watts and Strogatz, 1998). If the network has a smaller average path length and larger clustering coefficient, it is a small-world network. Generally, it can be described as follows.

$$L \geqslant L_{random} \quad (11)$$

$$\langle C \rangle >> \langle C_{random} \rangle \quad (12)$$

where L_{random} and C_{random} represent the average path length and clustering coefficient of a random network with the same scale, which can be expressed as (Watts and Strogatz, 1998)

$$L_{random} = \ln N / \ln \langle k \rangle \quad (13)$$

$$C_{random} = \langle k \rangle / N \quad (14)$$

The clustering coefficient represents the average clustering degree of the network formed by the intersections and the adjacent

Table 3
Basic information on studied cities.

Cities	Land area(km^2)	Population(1 0 ^{4})	Population density(/km^2)
Xiamen Island[1]	157.76	105.30	6675
Washington DC[2]	158.20	68.09	4304
San Jose[2]	459.70	102.56	2231

[1] Data derived from Xiamen government, http://www.xm.gov.cn.
[2] Data derived from Wikipedia, List of United States cities by population, https://en.wikipedia.org/wiki/List_of_United_States_cities_by_population.

nodes in the urban road network, and it is a symbol of the width of the network. By calculation, the clustering coefficient of the Xiamen road network is about 0.053 which is a small clustering coefficient. In the urban road network, the average path length represents the depth of urban transportation, which requires two points in the network to be accessible through as few edges as possible. The average path length of Xiamen road network is about 11.43, which requires at least 11 road segments to connect any two intersections in the network. Considering the average segment length, the weighted average path length between any two nodes is 7.66 km. For the corresponding random network, $\langle C_{random} \rangle = 1.80 * 10^{-3}$, $L_{random} = 6.69$.The two indicators accord with determination conditions of Eqs. (11) and (12). Therefore, the Xiamen road network is a typical small-world network. In network science, a small-world network is regarded to have a better structure for travel than a network without small worldliness. The clustering coefficient of the road traffic network in Washington, D.C. is about 0.077. The average path length of its road network is about 47.29, which indicates that the distance between two nodes is relatively large, and an average of 47 road sections are needed to connect any two nodes in the network. Considering the average section length, the average length between any two points is 7.76 km. For the random network of the same size as Washington D.C., $L'_{random} = 7.91$ and $\langle C'_{random} \rangle = 3.20 * 10^{-4}$ which conform to the determination conditions of Eqs. (11) and (12). Therefore, the Washington DC road network is also a small-world network. The clustering coefficient of the San Jose road network is about 0.063, which has a small clustering coefficient. The average path length is 49.50. The distance between two nodes is relatively large and it takes an average of 50 road segments to connect any two nodes in the network. We could not obtain the weighted path length of San Jose road network due to the limited computation and storage ability of ArcGIS. For the random network of the same size as San Jose, $L''_{random} = 10.05$ and $C''_{random} = 1.28 * 10^{-4}$ which conform to Eqs. (11) and (12). Therefore, the road traffic network of San Jose is also a small-world network.

Higher choice values of space syntax show key roads which go through more shortest paths in different road networks. For example, the main roads in Xiamen include Xianyue Road, Hubin Road, Xiahe Road, and so on. Washington DC's main roads include Constitution Ave NW, 12th St NW, 9th St Expy and so on. The main roads in San Jose include W Valley Fwy, Monterey Rd, Almaden Expy, etc. When we use standardized choice for analysis, the results show that the proportions of road choice greater than the mean in Xiamen, Washington, and San Jose are 23.73%, 11.75%, and 10.94%, respectively. Although Xiamen's road network is more than the latter two obviously in proportion, the road lengths with higher choice values than the average are 166.16 km, 234.07 km, and 434.35 km respectively after considering the total road mileage. Travel is more convenient for residents of the latter two under identical travel demand and traffic conditions. Statistical information of choice is shown in Table 4.

Integration of different road networks shows a trend of gradual expansion from the middle to the surrounding areas, which can clearly show the hierarchy of the local roads in the road networks. Fig. 4 visualizes the integration of these road networks. The red area of Xiamen is an important commercial area. The red core area of Washington D.C. is near the White House and the United States Capitol. And the red core area of San Jose is near San Jose State University. Compared with Xiamen, Washington D.C. and San Jose have a clearer road network hierarchy. Statistical information of integration is shown in Table 5.

The structural indicators of the three cities are shown in Table 6. On the whole, the two American cities, Washington D.C. and San Jose, have significantly more intersections and road mileage than Xiamen and have a more mature road network structure. The current road density of Xiamen Island is 4.44 km/km^2 (road length/land area) which is smaller than those of Washington D.C. and San Jose. In particular, Strano et al. (2013) found the street density of the ten typical European cities with an average road length of 55.9–122.4 m was 7.23–23.91 km/km^2. The average street density of 6,857 American cities studied by Boeing was 9.74 km/km^2, and average road length was 143.66 m (Boeing, 2018a). Compared with European and American cities, Xiamen has large gaps in the road network. Average degree reflects the average value of different node degrees and can indirectly reflect the proportion of different types of intersections. There are a large number of dead ends in Xiamen Island and San Jose, resulting in average values less than or approximately equal to 3. The number of nodes and roads in Washington D.C. and San Jose was significantly higher than that of Xiamen Island. Although the average path length of Washington D.C. is four times more than that of Xiamen, the average segment length is shortened as the density increases. Thus, the weighted average path length of Washington D.C. is almost the same as that of Xiamen. Meanwhile, the average clustering coefficient of the former is greater than that of the latter, which indicates that the road intersections of the two American cities are more closely connected and the road connectivity and accessibility are better. From the perspective of the underlying road network structure, this example shows that the distance between two nodes of a denser road network does not increase significantly and has a limited impact on motor vehicle travel. However, more road segments along a specific route indicate that drivers usually experience more delay at the front of signal intersections. So in a denser road network, traffic control and travel information service become key optimization schemes for improving motor vehicle travel.

4.3. Comparison of road networks of multiple periods in a city

In a recent study, Boeing (2018b) found that modeling urban street networks as planar graphs can bias urban form analyses in

Table 4
Statistical description of choice in different road networks.

Cities	Maximum	Minimum	Mean	Standard Deviation
Xiamen	0.40595	0	0.01667	0.03660
Washington D.C.	0.53165	0	0.00495	0.02283
San Jose	0.46567	0	0.00434	0.02141

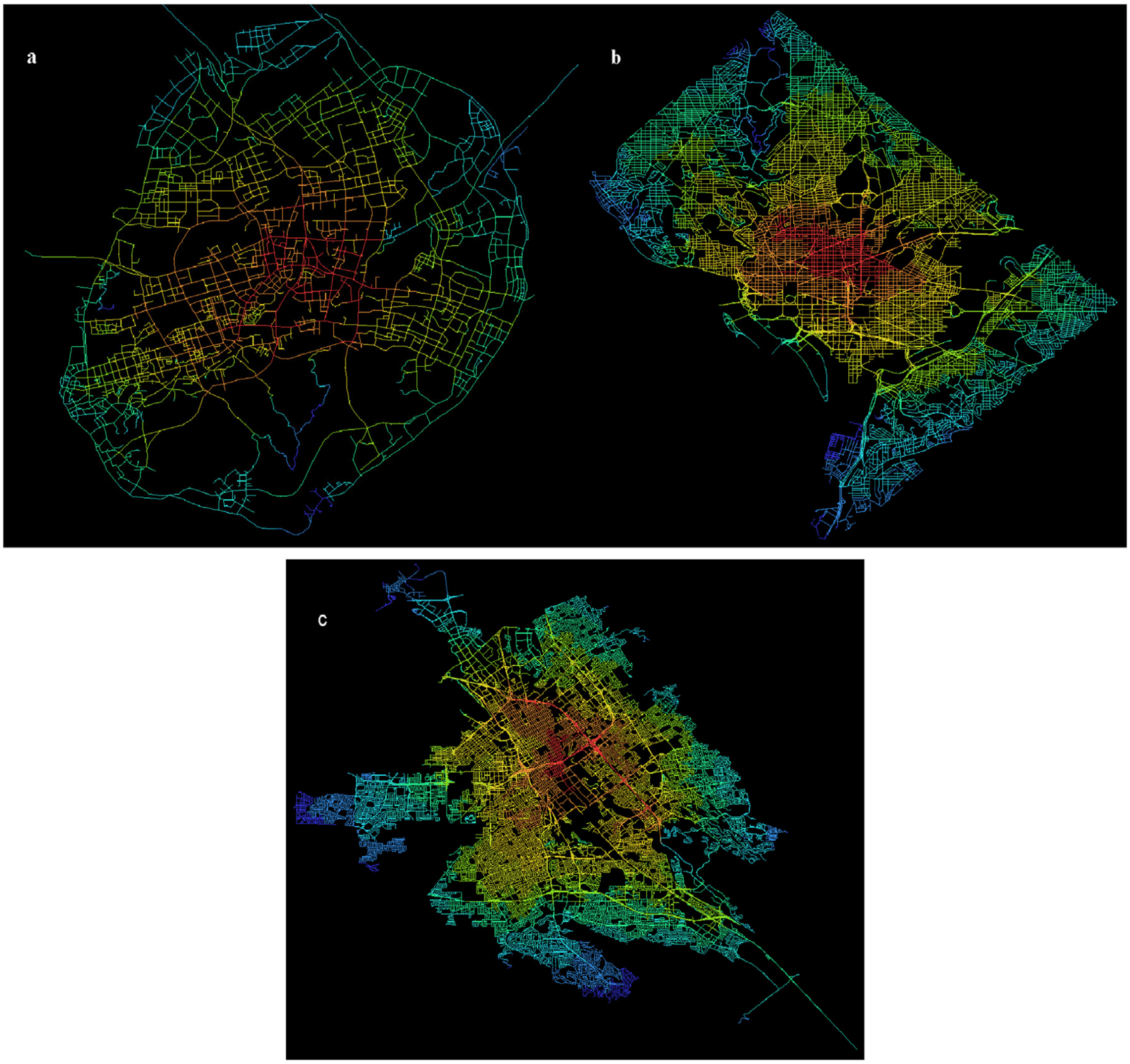

Fig. 4. Integration visualization of different road networks, (a) Xiamen, (b) Washington D.C., (c) San Jose. Values increase from blue to red.

Table 5
Statistical description of integration in different road networks.

Cities	Maximum	Minimum	Mean	Standard Deviation
Xiamen	0.33012	0.11236	0.23704	0.04512
Washington D.C.	0.13042	0.04492	0.09085	0.01786
San Jose	0.11327	0.03722	0.07644	0.01667

several ways: intersection counts are overestimated, average edge lengths are underestimated, and connectivity is misrepresented for topological studies. These phenomena may also exist in the comparative study of Chinese and American cities. More importantly, the intersections including T-junctions and four-way intersections are regarded strictly as the nodes, and road segments are also regarded strictly as the edges in the Xiamen road network. However, voluntary geography data such as OpenStreetMap has more artificial breakpoints to overcount intersections and underestimate street segment lengths. It is necessary to use the same modeling method for a city for getting more precise results. Next, we will model road networks of different periods of a city in uniform node-edge approach strictly.

This section chooses Changchun, China as a case city to analyze the temporal variation of the impacts of road density on travels in different historical stages. Road networks of Changchun in different years are shown in the Fig. 5. Changchun is one of the central cities in northeast China, an industrial base and a transportation hub. In 2017, the urban population of the city was 4.38 million, and it owned 1.59 million cars. Traffic maps of Changchun in different years were collected with the help of Changchun institute of urban

Table 6
Comparison of structural characteristics of studied cities.

Cities	Nodes	Edges	Road length (km)	Node density (/km^2)	Road density (km/km^2)
Xiamen	1691	2569	700.19	10.72	4.44
Washington DC	10,026	16,079	1946.53	63.38	12.30
San Jose	21,026	28,314	3885.10	45.74	8.64

Cities	Degree	Avg. path length	Cluster coefficient	Avg. segment length (m)	Weighted avg. path length (km)
Xiamen	3.038	11.43	0.053	271.64	7.66
Washington DC	3.207	47.29	0.077	123.47	7.76
San Jose	2.693	49.50	0.063	140.32	–

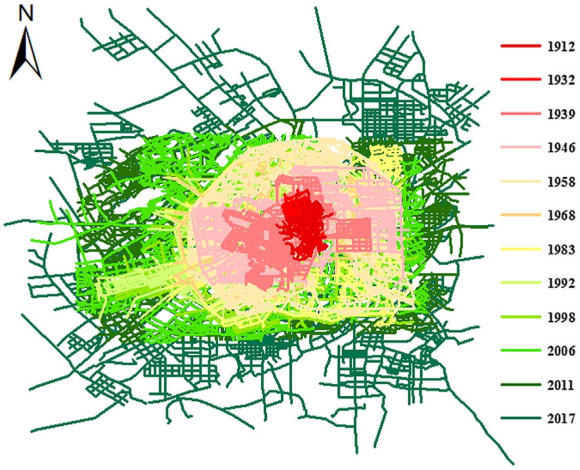

Fig. 5. Road network evolution in different historical periods in Changchun city, China (1912–2017).

planning and design. As a young city, these maps almost cover the whole historical periods of Changchun road evolution. Vector road networks were generated by ArcGIS to obtain road connection and length information. Then these data were imported into Gephi - a network visualization software to calculate various network indicators (Wang et al., 2019). Table 7 shows network indicators of different road networks. These values of path lengths and cluster coefficients show that all road networks of Changchun in different years are small-world networks.

When investigating the correlation between road network density and other network indexes in different periods of Changchun, we found that road network density presented a relatively negative correlation with functional indexes (e.g., average segment length, weighted path length, and weighted degree), as shown in the Fig. 6. That is to say, with the increase of road density, the length of each road segment and the distance between nodes tend to decrease approximately. This is the empirical evidence of the impact of road density on the physical impedance (travel distance or trip length) of residents' travel.

Except for the whole investigation of 1912–2017 road networks, we found the correlation between density and other indexes varies in different historical stages. It depends on the urban planning of specific historical periods. Changchun City is founded in 1800 by the Qing Dynasty government of China, and 19th century becomes its early period of urban construction. In 1912, the city had

Table 7
Structural indicators of Changchun road networks in different years.

Years	Nodes	Edges	Degree	Path length	Cluster coefficient	Segment length (m)	Weighted path length (km)
1912	187	284	3.02	8.69	0.089	529.12	2.38
1932	797	1284	3.22	18.25	0.057	195.84	1.99
1939	1015	1726	3.40	20.05	0.043	428.82	5.09
1946	2037	3559	3.49	25.80	0.030	391.21	6.44
1958	2923	4693	3.21	29.02	0.067	458.43	8.82
1968	459	744	3.24	12.54	0.067	977.21	6.21
1983	1285	2057	3.20	19.45	0.057	696.43	8.66
1992	2236	3757	3.36	23.36	0.041	246.07	7.23
1998	4534	7499	3.31	34.43	0.036	354.21	7.02
2006	4830	7920	3.28	31.85	0.036	459.15	9.38
2011	4505	7584	3.37	32.39	0.040	279.35	10.58
2017	4143	6648	3.21	28.86	0.031	358.26	12.37

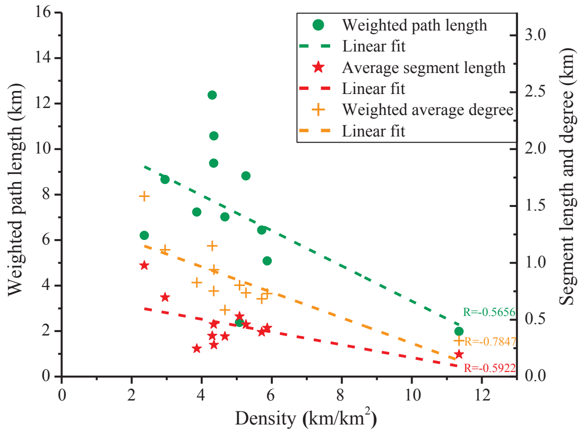

Fig. 6. Correlation among density, weighted path length, average segment length, and weighted degree.

merely 161 intersections (26 dead ends) and 284 road segments. However, Changchun has not been constructed under the unified urban master planning until the period of Manchukuo. In 1932, the Japanese colonialists designed and planed the city landscape and road systems of Hsinking or Xinjing (Today's Changchun) which determines the basic form and layout of the city's future road networks. After the founding of the People's Republic of China, Changchun began to design the overall urban planning during 1952–1957. Thus, the city underwent two kinds of different urban planning and design ideas which exhibited various development modes. In terms of time, it can be divided into two periods: 1932–1958 and 1968–2017. Table 8 shows the correlation of different stages between density and other indicators. As shown in Fig. 5, the city developed within the scope of peripheral ring road before the year of 1958. The road network density exhibits an obvious negative correlation with functional indexes (weighted degree, average segment length, and weighted path length). In particular, the physical distance between OD pairs tends to shorten as road network density increases. But in the process of continuous outward expansion of the city from 1968 to 2017, the situation changed. With the increase of road network density, weight degree or average segment length still tends to shorten; however, the weighted path length which shows a positive correlation with density seems to increase gradually.

5. Conclusions and discussions

The influence of road network density on motor vehicle travel was investigated in this paper from the perspective of traffic flow and structural characteristics of the underlying road networks. First, we analyzed whether the correlation between traffic flow parameters and road network density exists or not. Thirty-five major Chinese cities were selected as research cases for this part of the study. The correlation between road density and traffic flow parameters including travel time and speed was measured by the Pearson correlation coefficient. The results show the correlation between the congestion delay index (i.e., travel time) and travel speed in the scale of peak periods and a day is significant, but there is almost no correlation between road network density and these travel indicators. That is probably because residents' travel is a dynamic process which may be affected by different road conditions, traffic sign or signal, and personal route selections and driving behaviors. Road network density, however, seems to be constant and static in the short term.

Then the study analyzed the structural correlation of road networks in the case of Chinese cities. The first is a comparative analysis of a low-density road network (Xiamen Island as an example) and high-density road networks (Washington D.C. and San Jose of USA). The results indicate that these cities conform to classic small-world conditions. Choice of space syntax is a symbol that high-density road networks have more roads going through the shortest paths. Integration analysis of space syntax and cluster coefficients both show high-density road networks are more closely connected and have better network hierarchy. Average travel distance between any nodes of denser road networks has not been greatly lengthened, which has a limited impact on motor vehicle travel. However, a driver may encounter more intersections resulting in spending more travel time due to more delay time at signalized intersections. Of course, if there is no traffic congestion and more signalized intersections in a city, a denser road network is surely better for motor vehicle travel and pedestrians. The traffic management department of a city must do a good job of traffic control and traffic information service in the process of making the road network denser. The second is a comparative analysis of road networks of Changchun, China in different years. The results show that the average travel distance between any OD pair tends to shorten as

Table 8
Correlation coefficients between density and other indexes in different historical stages.

Historical stages	Weighted degree	Avg. Segment length	Weighted path length
1932–1958	−0.9932	−0.9826	−0.8853
1968–2017	−0.8328	−0.8883	0.4739

density increases if the road network grows within a specific urban area. However, if the city continues to expand outward, the case exhibits the average travel distance tends to increase gradually as the road network density increases. All road networks of Changchun in different years are small-world networks.

According to the case analysis results of this study, the implementation of the planning concept to build a denser road network has not greatly reduced the benefit of motor vehicles, and residents' travel will not be significantly affected. The reasonable implementation of the concept will also reduce the waste of road resources and provide more space for the development of slow green traffic. Considering the evolution of road networks, we should determine the current historical period and planning modes of a city to apply the findings of the study. Is the road network of a city in the stage of densification or sprawl or a combination of the two? After that, we may try to improve network performance by adjusting the structural measures of the current road network based on our findings. For example, the increase in density (the ratio of road length and real land area) in the stage of densification will reduce the average travel distance for any OD pair. During the sprawl or the combination period, the increase in density tends to increase the average travel distance. Our findings provide important empirical support for planners and policymakers to understand the impacts of road network density on motor vehicle travels and design more effective urban road networks. However, this paper has some limitations. On the one hand, the research conclusions need to be verified through more case studies. On the other hand, it is difficult to conduct in-depth, comprehensive and thorough analysis due to the limitation of existing data and technical requirements considering the complexity of urban transportation systems. More comprehensive and rigorous theoretical extrapolation still needs to be completed in future research. At the same time, in the practice of the planning concept of "narrow road, dense road network", it is still necessary to explore solutions to problems such as the reasonable connection between road network areas and the coordination control of traffic signals caused by the increase of the number of intersections.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2019.11.012. And the data used in the paper is available for public use at http://www.shiguangwang.org/en/.

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