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Urban Density, Accessibility and Energy Consumption in the Transport Sector: Analysis of 30 Cities in China

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Abstract: The growth and diversification of transport demand accompanied with social and economic development led to increasing energy consumption in transport sector. In order to find a way that can not only contribute to reducing transportation energy consumption but also fully meet the transport demand, the research firstly formulated three indicators. Urban density implies population size and intensity of social and economic activities that is related to transport demand. Accessibility is defined by per capita road area and average bus numbers of ten thousand people and reflects transport conditions of private and public traffic. Per capita energy consumption in transport sector was used to characterize environmental effects. The data of urban density and accessibility was collected from the National Statistical Yearbook, while the data of transport energy consumption was obtained by conversion of DMSP/OLS (Defense Meteorological Satellite Program/Operational Lines-can System) night lighting data which is a sign of human activity. Secondly, considering the different levels of transport infrastructure and economic development in different regions of China, only 30 provincial capital cities were selected to analyze the relationships of the three indicators mentioned above. Based on relationship analysis, 30 cities were divided into three patterns. It was founded that the first pattern would be optimal because of a good match of transport demand and supply coupled with low energy consumption. The second pattern is non-ideal, since it is at high level of energy consumption and less balanced between transport demand and supply. The third pattern should improve accessibility and reduce energy consumption. Finally, some suggestions about urban transport development that are suitable to local conditions were proposed for different urban patterns.

Keywords: urban density; energy consumption; accessibility; regional analysis

1. Introduction

Transportation plays a key role in smart and green cities. Rapid economic growth and urbanization increase the service demand of urban private transport and public transport, and consequently raise the energy consumption in transport section dramatically [1-2]. Therefore, it is necessary to find a way that can not only contribute to reducing transportation energy consumption but also fully meet the transport demand, which has become a focused issue about achievement of social sustainable development. China is in a stage of rapid development of urbanization [3-5].

Related studies showed that relationship between urban density and energy consumption in transport is generally considered a negative correlation, namely more compact city, much easier to reduce energy consumption in transportation [5-8]. However, accessibility that represents demand of passenger did not get enough attention among relationship above. In order to fully explore the interreaction among urban density, transportation user's benefits (accessibility) and environmental benefits (energy consumption in transportation section), the paper will build a three-dimensional coordinate including urban density, accessibility and transportation energy consumption.

Considering the regional differences in China resulting from different levels of transport infrastructure and economic development, 30 provincial capital cities were selected in order to analyze the relationship of urban characteristics, transport accessibility and energy consumption in transport sector. Furthermore, 30 cities were divided into different patterns in order to provide references for the reasonable measures of urban transport development that are suitable to local conditions.

2. Data and Methods

2.1. Urban density

Urban density implies population size and intensity of social and economic activities that is related to transport demand, characterized by urban population density. Urban population density from the Statistical Yearbook is usually the ratio of urban population to area of administrative regions. This definition would be biased to truly reflect the urban population density for some cities with large administrative regions but smaller built-up area, like Beijing and Shanghai. Accordingly, the ratio of urban population and built-up area will be chosen to indicate urban density as following.

$$DEN = \frac{P}{A} \tag{1}$$

DEN: urban density; *P*: urban population; *A*: urban built-up area.

2.2. Accessibility

Accessibility means ease of reaching destination and involves urban transport infrastructure/ conditions of private and public traffic, which can be reflected by per capita road area and average bus numbers of ten thousand people (*Source: 2012 National Statistical Yearbook*). Considering urban rail system plays a more and more important role in city transport and resident accessibility, passenger capacity of railway transport will be added into accessibility by conversion to bus capacity as follows:

$$B = b \cdot \frac{p_t}{p_b} \quad (2)$$

B: revised average bus numbers of ten thousand people;

b: average bus numbers of ten thousand people;

p_t: total urban passengers;

p_b: passengers by bus.

In order to merge per capita road area and average bus numbers of ten thousand people into one direct indicator, we regarded these two values of Beijing as the standard and use ratios between each city's values and Beijing's values as multipliers in next step. So accessibility is defined by per capita road area multiplying revised average bus numbers of ten thousand people above.

$$ACC = \frac{R}{R_J} \cdot \frac{B}{B_J} \quad (3)$$

ACC: urban accessibility;
R: per capita road area;
B: revised average bus numbers of ten thousand people;
R_J: per capita road area in Beijing;
B_J: revised average bus numbers of ten thousand people in Beijing.

2.3. Energy Consumption in Transport Sector

Per capita energy consumption in transport sector was used to characterize environmental effects. Data of transportation energy consumption for each province is originated from the *China Energy Statistical Yearbook*. In order to obtain data of transportation energy consumption in city level, DMSP/OLS (Defense Meteorological Satellite Program/Operational Lines-can System) is used as multiplying factor. DMSP/OLS can detect low-intensity lighting from the Earth surface activities, even including small-scale urban residential lighting and traffic, etc [8-9]. Therefore, DMSP/OSL has become a good source as characterizing the impact of human activities and monitoring human activity [10]. The more frequent the human activity is, the brighter the corresponding area in DMSP/OSL image shows at night, the higher the lighting value is. In addition, the amount of energy consumption and frequency of human activity are regarded as positive correlation. Therefore, the study will choose ratio of city lighting data and corresponding data in province level as important basis for converting transportation energy consumption into city. Per capita energy consumption in transport sector can be defined as follows:

$$EC = \frac{EC_p \cdot \alpha}{P} \quad (4)$$

$$\alpha = \frac{L_c}{L_p} \quad (5)$$

EC: per capita energy consumption in transport sector;

EC_p: energy consumption in transport sector in province level;

α: ratio of city lighting data and corresponding data in province level;

P: urban population;

L_c: night lighting value in city;

L_p: night lighting value in province.

3. Results

Considering the different levels of transport infrastructure and economic development in different regions of China, only 30 provincial capital cities were selected to analyze the relationships of the three indicators mentioned above. Through data selection and calculation, research obtained the results of their connection.

Firstly, urban density and accessibility are negatively related in Figure 1, namely the higher density, relatively lower accessibility. Densely populated city leads the larger the traffic demand. In the same level of traffic infrastructure, transportation supply cannot meet the demand unlike the low population density city.

Secondly, urban density and energy consumption in transport section are overall negatively correlated (Figure 2), consistent with previous research conclusion [4]. Similar to the law of diminishing returns in economics, it states that in all productive processes, adding more of one factor of production, while holding all others constant will at some point yield lower incremental per-unit returns. Likewise, population growth will decrease the marginal cost of transportation energy consumption.

However, there is no apparent correlation between the accessibility and transportation energy consumption (Figure 3), namely high level of transportation infrastructure do not result to high energy consumption. Energy consumption in transport section may relate with land use, traffic structure, traffic management and road construction. Improvement of accessibility embodies in improvement of transport quality and increase of transport quantity. Quality improvement may reduce energy consumption, but increase the amount of investment, construction and post operation will increase energy consumption.

Figure 1. Urban density and accessibility.

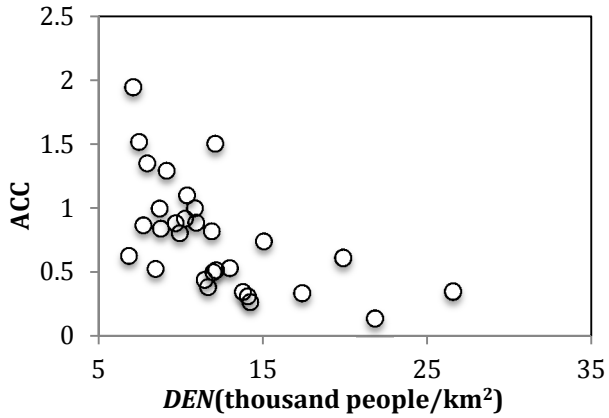


Figure 2. Urban density and energy consumption.

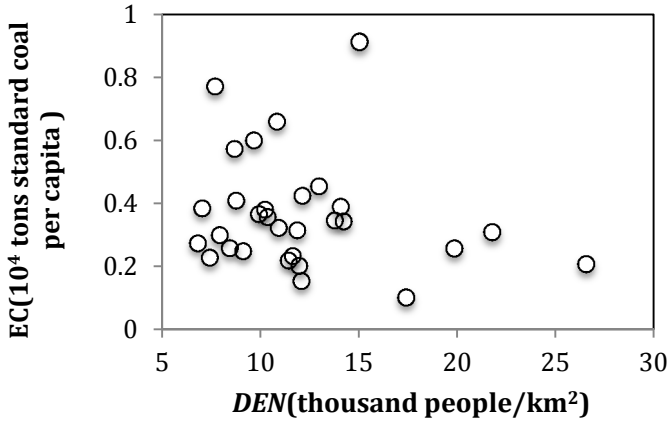
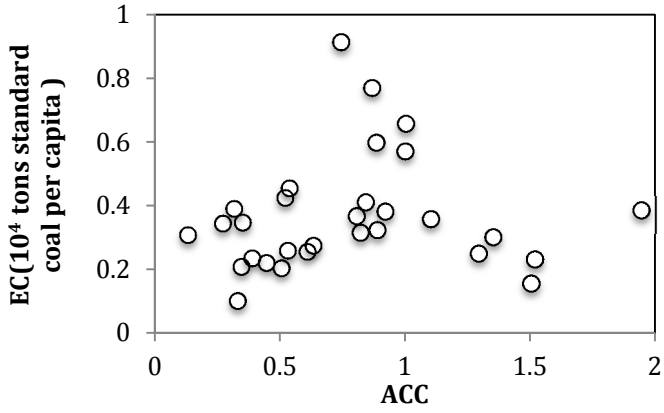


Figure 3. Accessibility and energy consumption.



Based on relationship analysis of urban characteristics, transport accessibility and energy consumption, 30 cities were divided into three patterns in table 1. The first pattern is defined that urban density and accessibility are high-high or low-low at low level of energy consumption. High or low is relative to average level of the 30 cities. The second pattern is at high level of energy consumption and less balanced between transport demand and supply——high urban density corresponding to low accessibility or inverse. The third pattern should improve accessibility and reduce energy consumption.

3.1. Pattern I: Balance between transportation supply and demand with low energy consumption

The balance between traffic supply and demand coupled with low energy consumption is the most ideal for city development and transportation system. That both the urban density and accessibility are at high or low level means the basic balance of transport demand and supply. At the same time, energy consumption in transport section maintains at a relatively low level. This kind of city is defined as the first pattern, such as Shijiazhuang, Hangzhou etc. The city paid attention to the necessary investment in transportation infrastructure during the urbanization integrated the development of economy, population and society. With the high demand-high supply of Hangzhou as an example, the development of public bicycle in Hangzhou plays a leading role in the country; meanwhile, Hangzhou reduced vehicle energy

consumption, relieved the traffic pressure and increased the accessibility through promoting the non-motorized vehicles travel in the city.

Table 1. Three patterns of cities.

	Pattern I		Pattern □				Pattern □	
Urban density	High	Low	High	Low	High	Low	High	Low
Accessibility	High	Low	High	Low	Low	High	Low	High
Energy consumption	Low		High		Low		High	
Number	2	5	2	1	6	5	4	5
Cities	HH: Shijiazhuang, Hangzhou LL: Taiyuan, Harbin, Lanzhou, Xining, Urumqi		HH: Fuzhou, Kunming LL: Nanning		HL: Nanchang, Zhengzhou, Haikou, Chengdu, Guiyang, Xi'an LH: Changchun, Jinan, Nanjing, Hefei, Yinchuan		HL: Tianjin, Shanghai, Chongqing, Shenyang LH: Beijing, Wuhan, Changsha, Guangzhou, Hohhot	
Comments	Ideal: a good match of transport demand and supply coupled with low energy consumption.		Balance of supply and demand but high energy consumption		No balance between supply and demand in spite of low energy consumption		Non-ideal: less balanced between transport demand and supply at high level of energy consumption.	
Suggestions	Maintain transportation supply and better environmental benefits.		Reduce energy consumption		Increase transportation supply		Pay attention to manage urban transport systems and control energy consumption.	

In contrast, relatively low urban density and low accessibility present low transportation demand and supply. Accordingly, both also reached equilibrium. The urban population pressure in smaller cities is also smaller. Residents there travel in a short distance, so the contradiction between traffic pressure and demand of life is not prominent. Besides, limited by economic conditions, not high proportion of residents have private cars and public transport and bicycles are still occupies a very important position. So, energy consumption in transport section is low compared with large city, which means little negative impact on environment. In the small city with low population density, high accessibility that means large road area per capita and many bus numbers of ten thousand people will cause waste of public infrastructure and energy, so the traffic supply and demand balance guarantee the sustainable development of city. For example, Yinchuan, Lanzhou, Xining and Urumqi are less developed areas in northwest of China. Less population agglomeration and lower level of people life demand less traffic

infrastructure than the eastern developed regions; in the areas with low level of economic development, city transportation facilities are underdeveloped but enough to meet the needs of city traffic demand along with the low transportation energy consumption natural.

3.2. Pattern II: Imbalance of supply and demand or high energy consumption

Some cities are classified into the second pattern, performing well either in balance of transportation supply and demand or low energy consumption. It includes cities where balance of supply and demand but high energy consumption and cities where imbalance between supply and demand with low energy consumption. The former needs to mainly reduce energy consumption and the latter should increase transportation supply.

Cities with high traffic energy consumption in spite of the basic balance of supply and demand of transportation bring negative environmental benefit. For example, Nanning city's urbanization is relatively backward, belonging to the early stage of city expansion with low population density. Although existed transportation facilities could meet the basic passenger travel demand, energy consumption in transport section is high and bad for environment benefits. The sprawl of city development is the key factor that affects the sustainable development of Nanning city transportation. Guangxi province including Nanning city covers a vast territory and sparsely populates. However, urban expansion recklessly not only increases the travel distance for passengers, but due to the travel distance increasing transportation energy consumption also grows. Therefore, in order to achieve sustainable development of the urban transportation, government or management department should control the size of city and configure various urban function, utilize the land rationally and guide the city to the development of multi center structure to reduce travel distance for passengers; strengthen the construction of public transport to improve passenger's travel mode; at the same time increase the technical inputs and promote clean energy use in public transportation.

Another phenomenon is low energy consumption but transportation supply often cannot meet the travel demand. For example, in Xi'an City with relatively dense population and a higher level of economic development, city road density is not high and therefore limited development of public transport and passenger accessibility. So transportation infrastructure needs to be improved. These cities could achieve the sustainable development of transportation through following strategies. Maintain a reasonable scale of the city and increase the investment of transportation infrastructure construction, like a modest increase in the proportion of city road traffic and increase public railway construction; improve the awareness of residents from the motor vehicle and private mode converted to non motor vehicle and public mode during the development of economic and urbanization; promote utilization of clean energy in advance to achieve the sustainable development of transportation.

3.3. Pattern III: Unbalance between supply and demand with high energy consumption

The third pattern is defined with cities that have unbalanced transport demand and supply coupled with negative environmental impact. These cities are non-ideal for city sustainable development. Unbalanced transport demand and supply includes two circumstances: demand outpaced supply and supply exceeded demand.

In the cities where demand outpaced supply, more intensive urban population leads more traffic demand, but under-developed transportation infrastructure cannot keep pace with increase of demand. In addition, the high energy consumption in transport section is also an obvious problem in these cities. Both environmental benefit and passenger benefit are limited to sustainable development of the city. Tianjin, Shenyang, Shanghai, Chongqing is in high density, at the same time, the economic development and urbanization are also rapid. The low accessibility is mainly originated from the reason that city construction speed cannot follow the speed of the population growth rate. On the one hand, the existing transport facilities cannot meet the needs of residents travel; on the other hand, the traffic congestion causes more drama energy consumption. So reasonable city planning and construction are the key methods to improve the city environment benefit and user benefits. In addition, strengthening the construction of infrastructure such as roads and public transport during the rapid urbanization, will improve the residents proportion of transit trip by public transportation.

On contrary, in the cities where supply exceeded demand, urban population density is low but with high transport infrastructure, and as a result energy consumption is high. It's unreasonable transportation planning that leads to waste of resources. These cities have a good match between development of urbanization and transportation facilities construction. Beijing, Wuhan and Guangzhou have developed railway transportation, so urban transport infrastructure has been improved and accessibility has increased; but because of the large size of the cities, residents need to spend a longer time to their destination. Rich residents at a growing level of economic development tend to travel by comfortable and convenient private cars. Increase in private traffic prompted the transportation energy consumption growth. At the same time, the rapid development of urbanization appeals a great number of migrants to cities, therefore all of urban transport pressure, traffic congestion, time –consuming and energy consumption would increase. Such cities should pay attention to manage urban transport systems through proper transportation facilities to configure and control in order to achieve reducing energy consumption and improving resource utilization efficiency.

4. Conclusions and Discussion

The research firstly formulated urban density, accessibility and energy consumption three indicators to characterize population size, transport infrastructure and environmental effects respectively. Then considering the different levels of transport infrastructure and economic development in different regions of China, only 30 provincial capital cities were selected to analyze the relationships of the three indicators mentioned above. Based on relationship analysis of urban characteristics, transport accessibility and energy consumption, 30 cities were divided into three patterns. We obtained some results as following:

(1) Urban density and accessibility are negatively related; likewise, urban density and energy consumption in transport section are overall negatively correlated; but there is no apparent correlation between the accessibility and transportation energy consumption.

(2) The first pattern is the most ideal for city development and transportation system where the balance between traffic supply and demand coupled with low energy consumption.

(3) Some cities are classified into the second pattern, performing well either in balance of transportation supply and demand or low energy consumption. It includes cities where balance of supply

and demand but high energy consumption and cities where imbalance between supply and demand with low energy consumption. The former needs to mainly reduce energy consumption and the latter should increase transportation supply.

(4) Finally, the third pattern is defined with cities that have unbalanced transport demand and supply coupled with negative environmental impact. These cities should pay attention to construction of transportation infrastructure to meet passenger demand and control energy consumption in transport section at the same time.

The research explored the relationship among the traffic demand, traffic supply and energy consumption at the macroscopic level. However, the connection between transportation infrastructure and transportation energy consumption is still a problem that is worth discussing. The growing level of transportation infrastructure will increase energy consumption? The improvement of transportation infrastructure, such as increase of road area, will product new energy consumption like more cars running; but if not, the energy consumption caused by traffic congestion and other energy consumption are not surely lower than those new energy consumption. In other words, the level of transportation infrastructure will educe energy consumption for congestion, but at the same time will increase the energy consumption of the vehicle operation. So the relationship between transport infrastructure and transport energy consumption also need to be researched through the temporal changes of city, and this relationship may be different in different cities due to the economic foundation and other factors.

Conflict of Interest

The authors declare no conflict of interest.

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