

Evolution mechanism of demand for comprehensive transportation system based on metabolic ecology

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Abstract: The metabolic evolution model of transportation demand for comprehensive transportation systems is put forward on the basis of a metabolic theory of ecology. In the model, the growth rates or changing rates of transportation volumes for the various transportation modes of a city are determined not only by the GDP per capita which reflects the size of the city itself, but also by the relationship of competition and cooperation among transportation modes. The results of empirical analysis for Chinese cities show that the allometric growth exponent in the equation for the variation rate of passenger demand volume on rail is greater than the predicted value of 1/4 in metabolic ecology, whereas the allometric growth relationship is not so evident in the equation for the variation rate of passenger demand volume on road. The changing rate of road transportation is thus mainly affected by the relationship of competition and cooperation among transportation modes for Chinese cities.

Key words: comprehensive transportation system; system evolution; metabolic; allometric growth relationship

Most theoretical models for the evolution of the transportation system are developed upon the ecological evolution model; e. g., Qiu and Chen^[1] studied the adaptive dynamics of comprehensive transportation corridor's evolution based on the model from ecology. In general, evolution models for transportation demand study the relationships between transportation and the national economy, as well as society. To study the demand evolution of the transportation system, we can begin with the dynamic pattern of the demand for various transportation modes respectively, especially with the relationship between transportation and the economy. In this paper, we propose a metabolic demand evolution model of the comprehensive transportation system (CTS) based on the theory of metabolic ecology. The demand evolution of the CTS is tackled with the allometric growth relationship between the economy and transportation, combining the competition and cooperation relationships between transportation modes, thus providing a new angle of view for the evolution of transportation demand.

1 Evolution Model of Demand for CTS

1.1 General model of metabolic ecology theory

The metabolic rate determines almost every rate of biological activity, while the main factors influencing metabolic

rate are the size of the individual, temperature, chemical component or stoichiometry. Kozłowski et al.^[2] discovered that the basic metabolic demand of the individual is proportional to the power of three quarters of the size of individual. West et al.^[3] derived that the theoretical values of the allometric growth rate between the size of the individual M and some characteristic parameters of the organisms, such as metabolic rate, growth rate, and death rate, are integer times a quarter. Enquist et al.^[4] argued that the resource utilizing rate, i. e. the metabolic rate, of individual plants is approximately proportional to the power of three quarters of its mass M . They proved that the energy metabolic law follows from the biological individual to the whole ecological system based on the individual metabolic theory, which is supported by a great deal of laboratory data. Enquist et al.^[5] utilized the corresponding metabolic theory to predict and prove that there is an allometric relationship between the size of an individual and the metabolic rates of molecule and cells. Gillooly et al.^[6-8] also prognosticated and testified that there is an allometric relationship between the evolution rate of DNA and the size of the individual.

1.1.1 Individual size vs. metabolic rate

In the early twentieth century, Huxley pointed out that the relationship between the variation of biological characteristics and the size of an individual can be represented by the following allometric equation:

$$Y = Y_0 M^b \quad (1)$$

where Y is the metabolic rate, the time of growth, the growth rate of a population, or the evolution rate of molecule etc.; M is the size of an individual; Y_0 is the normalization constant; b is the allometric growth exponent which is derived by the theoretic mechanic model for the branching organization, and b is the integer times 1/4, not times 1/3 derived by the Euclidean geometry model.

1.1.2 Temperature vs. metabolic rate

There is an exponential relationship between temperature and almost all biological activities such as biochemical reactions and metabolic rates. These relationships can be represented by the Boltzmann factor as

$$Y \propto e^{-\frac{E}{kT}} \quad (2)$$

where E is the activation energy, k is the Boltzmann constant, and T is the absolute temperature. The Boltzmann factor reflects how temperature affects the rates of various biological reactions; therefore, it can describe the relationships between temperature and the metabolic rate from mono-celled microbes to many-celled propagations, including even the relationship between temperature and the growth rate of individuals and populations; this includes growth time and organism lifespan. In addition, researches indicate that the activation energy of these processes is quite similar, and typ-

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ical metabolic biochemical reactions are observed in that scope, which proves that the metabolic rate dominates most of the biological rate.

1.1.3 General relationship

To sum up, combining the impact of the size of the individual and temperature on the metabolic rate, the model can be represented as

$$I = I_0 M^b e^{-\frac{E}{kT}} \quad (3)$$

where I is the metabolic rate, and I_0 is the normalization constant.

1.2 Demand evolution model of transportation volume based on theory of metabolic ecology

To assure the validity of the analogy, the key to applying metabolic ecology theory to research on transportation demand evolution of the CTS lies in the choice of research object and the variables.

First, the growth rate, or more precisely the variation rate of transportation demand volume for various transportation modes within the CTS can be viewed as the metabolic rate of the CTS. Because from the view point of substance and energy processes, the demand evolution of various transportation modes is the main driving force that directly promotes the development of various transportation modes within the CTS. The rise and fall of a transportation mode directly embodies the rise and fall of its demand volume.

Secondly, we need to determine the corresponding variables regarding the size of a population or individual when researching the demand volume of the CTS. We know that transportation demand is a derived demand, mainly determined by the level of the economy. Taking macro economy as a whole, the economic income of every economic individual, or more specifically speaking, the GDP per capita of a city or region, can be used as the proxy variable for the size of the population or individual. Obviously, the higher the GDP per capita, the bigger the size of the population or an individual of a city or region in the sense of economic level.

Finally, we should choose a corresponding variable for temperature. From a systems point of view, one of the two decisive factors of metabolic rate which metabolic ecology emphasizes is from the system itself, i. e. the size of the individual; the other is from its environment, i. e. temperature. As to the demand volume evolution of various transportation modes within the CTS, the environment mainly refers to the competition and cooperation among transportation modes, which can be represented by the function of the transportation volume of the various transportation modes.

Negative exponential distribution is a kind of mathematical sign between simplicity and complexity. On the one hand, in contrast with the Gaussian distribution, the exponential distribution is the distributional characteristics of complex systems; on the other hand, compared with the power law distribution, the exponential distribution is the behavioral sign of simple systems. In fact, as a complex system, the CTS can be represented by a set of the exponential scale law and the power law for the moment. Combined with the theory of metabolic ecology, we can build the metabolic evolution model of the transportation volume demand as follows:

$$\frac{dx_i}{dt} = x_0 Y^b E(\mathbf{x}) \quad (4)$$

where x_i is the demand volume of a kind of a transportation mode for a city or a region, and x_0 is the normalization constant for the variation rate of the transportation volume demand; Y is the GDP per capita of a city or a region, and b is the allometric growth exponential; \mathbf{x} is the vector of the transportation demand of a city or a region, and $E(\mathbf{x})$ is the competition and cooperation environment function that a transportation mode of the city or the region faces.

Without loss of generality, we first consider the passenger transportation demand evolution of two kinds of transportation mode of a city or a region, and we might as well suppose that the term reflecting the competition and cooperation $E(\mathbf{x})$ take the exponential function form, i. e. ,

$$E(x_i, x_j) = \frac{1}{x_0} \left[C_i - \sum_j \exp(k_{i,j} x_j) \right] \quad i, j = 1, 2 \quad (5)$$

where $k_{i,j}$ is the net competition or cooperation effect coefficient of the j -th kind of transportation mode on the i -th kind of transportation mode, and C_i is the normalization constant, reflecting the restrictions that resources and supply put on demand.

Thus, the metabolic evolution equation of passenger transportation demand for two kinds of transportation modes within a city or a region is

$$\frac{dx_i}{dt} = Y^b \left[C_i - \sum_j \exp(k_{i,j} x_j) \right] \quad i, j = 1, 2 \quad (6)$$

Because of the introduction of the term C_i , the restriction that resources and supply put on demand assures the existence of the equilibrium variation rate for transportation volume demand, which can be solved as

$$C_i - \sum_j \exp(k_{i,j} x_j) = 0 \quad i, j = 1, 2 \quad (7)$$

Moving the size of individual term Y in Eq. (6) to the left of the equation, and taking the logarithm on both sides, we obtain

$$\ln\left(\frac{dx_i}{dt} Y^{-b}\right) = \ln\left[C_i - \sum_j \exp(k_{i,j} x_j)\right] \quad i, j = 1, 2 \quad (8)$$

The superiority of Eq. (8) lies in that the relationship between the transportation volume of various transportation modes of the city or the region and the demand volume variation rate of the transportation mode revised by the size of the individual term Y can be determined directly, and according to $k_{i,j}$, the net competition or cooperation effect coefficient of the j -th kind of transportation mode on the i -th kind of transportation mode can be obtained. Likewise, multiplying both sides of Eq. (8) with the reciprocal of $C_i - \sum_j \exp(k_{i,j} x_j)$, and taking the logarithm, we obtain

$$\ln\left\{\frac{dx_i}{dt} / \left[C_i - \sum_j \exp(k_{i,j} x_j)\right]\right\} = b \ln Y \quad i, j = 1, 2 \quad (9)$$

Eq. (9) corresponds to the relationship between the GDP per capita of the city or the region and the variation rate of demand volume of a transportation mode of the city or the region revised by the net competition or cooperation effect.

2 Example

According to the statistical data from *Chinese City Statistical Annual* of 2006 and 2007, we take 226 cities with rail and road passenger transportation data out of 269 cities as samples and use the demand variation rate of the transportation mode as the dependent variable, and the GDP per capita of the city or the region as well as the passenger transportation volume of rail and road as the independent variable. By making regression analysis on Eq. (6) with the nonlinear least square method, we can obtain the following results as shown in Tab. 1.

Tab.1 Regression analysis results of equations for variation rates of passenger demand volume

On road				On rail			
<i>b</i>	<i>C</i> ₁	<i>k</i> _{1,1}	<i>k</i> _{1,2}	<i>b</i>	<i>C</i> ₂	<i>k</i> _{2,1}	<i>k</i> _{2,2}
0.047	2.035	3.032	-8.717	0.308	2.011	-0.570	8.547

The regression analyses show that there exist allometric growth relationships between the rates of variation for demand volume of some kind of transportation mode in a city or a region and the GDP per capita. The allometric growth exponent in the equation for the variation rate of passenger demand volume on rail is a little greater than the predicted value of one quarter in metabolic ecology, whereas the allometric growth relation is not so evident in the equation for the variation rate of passenger demand volume on road, which reflects that the variation rate of passenger demand volume on road has a certain rigidity and is not mainly restricted by the GDP per capita in that region, but by the resource and supply together with its own passenger demand quantity. In the meantime, the variation rate of passenger demand quantity for a transportation mode is negatively correlated with the transportation volume of another transportation mode, which shows the impact of the competition from another kind of transportation mode.

The above analysis shows that the demand evolution of the CTS, especially that of its rail passenger transportation subsystem, complies with a law similar to that which governs the evolution of population of the ecological system, which conforms to the general rule of evolution of the complex system. There is an allometric growth relationship between the economic system and the CTS. Based on this allometric growth relationship, better predictions about demand evolution of the

transportation system under the self-organization condition can be anticipated.

3 Conclusion

In this paper, a metabolic evolution model of transportation volume demand for the CTS based on the theory of metabolic ecology is proposed. The demand evolution of the CTS is studied by looking into the allometric growth relationship between transportation and the economy combined with the competition and cooperation among transportation modes. The results from positive analysis of Chinese cities show that there is an allometric growth relationship between the growth rates or changing rates of railway transportation volumes and the GDP per capita of the city in China, while the changing rates of road transportation are mainly affected by the relationship of competition and cooperation among transportation modes for Chinese cities.

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基于代谢生态学的综合运输体系需求演化机制

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摘要:在代谢生态学理论的基础上,提出了综合交通运输体系运量需求的代谢演化模型.模型中城市各种交通方式的运量增长率或变化率不仅依赖于反映城市自身规模的人均GDP,而且受到运输方式间的竞争与合作关系的制约.对中国城市的实证分析结果表明:铁路旅客交通需求量变化率方程中的异速增长指数略大于生态代谢理论中预测的1/4值,而公路旅客运输需求量变化率方程中的异速增长关系并不明显,中国城市公路交通需求的变化率主要受到运输方式间竞争与合作关系的影响.

关键词:综合运输体系;系统演化;新陈代谢;异速增长关系

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