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Research on the optimal density of highway network

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Abstract

The density of highway network is an important evaluating indicator in highway network planning. Due to the lack of depth researches and discussions, some negative factors affect the density of highway network, e.g. huge occupation of land and fund consumption in highway network construction. In this background, this dissertation proposes improved methods to study the optimal density of highway network from the perspective of land output based on existing researches. Through analyzing the relationship between highway network density and land output, this dissertation establishes a model on the optimal density of highway network based on land output.

Keywords: highway network planning; highway network density; land output; optimal density; diminishing marginal benefit law

1. Introduction

Highway network density is a reflection of the highway construction quantity within a certain region. This index is mostly cited to research the development of highway network in status assessment, development strategy, and post evaluation. The formation and expansion of highway network depends on the highway traffic demands stemming from regional economy and social development. However, highway construction brings negative influences, such as occupying a large amount of land (especially the agricultural cultivated land), thus causing certain environmental pollution in the construction process. Therefore, for the development of regional economy, higher highway network density is necessarily desirable. There is an optimal density that fits to economy development. If current highway network density is lower than optimal value, it will lead to the increase of highway transportation cost in the total social production cost, and transportation resources shift to other transportation modes. Then other transportation capacity will be insufficient. In case the capacity of the whole

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transportation system is imbalanced with social need, highway network will hinder social economy development eventually. If current highway network density is higher than optimal value, it will cause many serious consequences, such as lower network efficiency, longer investment recovery period for many toll roads, excessive occupancy of construction funds, and land resources waste. Therefore, grasping the optimal density of highway network has practical significance in efficiently supporting national economy development and ensuring sustainable development of highway transportation.

In finding out a solution approach for highway network optimal density, this article starts with a land research closely related to highway. Hopefully it will have some guidances for highway network planning.

2. Concepts of highway network density and land output

The highway network density is the highway mileage owned by unit land area or unit population, which usually expressed by highway lengths owned by per thousand square kilometers of land or by per thousand population (Cong Li, 2000). To reflect regional nodes' accessibility and to express how different grades of highway adapt to traffic demand, it is better to adopt equivalent highway network density (YunFeng Yang, 1995). It means converting highway mileage into equivalent highway mileage according to certain standards and conversion coefficient. Then equivalent highway network density can be calculated. The calculation process is as follows:

$$D_s = \frac{\sum L_i \times w_i}{S} \tag{1}$$

In which, D_s is equivalent highway network density of the average area, L_i is the actual length of certain grade highway, w_i is the corresponding conversion coefficient, and S is the area.

Earlier researchers have solved highway network reasonable density problem in the view of cost. One solution was to minimize highway construction cost and highway transportation cost to determine the reasonable density (Yunfeng Yang, 1995; Ling Huang, 1996).The other way considered the generalized highway cost, which is calculated by highway construction cost plus highway transportation cost minus the sum of direct and social economic benefit of highway network (Yulong Pei & HongRen Chen, 1995). The two methods above were based on minimizing highway construction cost. The models were straightforward, but the coefficients were hard to determine. Till now, there aren't any projects determining highway network reasonable density using these models. Today, the more widely used method is to determine the reasonable density by working backward from the reasonable highway total length. Total length predictions can be divided into direct predictions and indirect predictions. Direct predictions, such as time sequence method, gray prediction model and regression analysis method, use time as a parameter or other factors including industrial and agricultural production value, population, car ownership, consumer spending and so on, to build and calibrate model coefficients. Indirect predictions use passenger and freight transportation volume of highway network as parameters (Han Bai, LingXiang Wei, et al., 2012; Tao Wang & HangFei Lin 2011; Jiancheng Sun, Xia Li, et al., 2008). Foreign researchers were also focused on highway network reasonable scale, rarely only on highway network density (ShuQing Li, ReQing Tang, 2000).

Recent researches referring to highway network density, the influential factors are more complicated, such as regional natural geography condition, the level of economic development, population density, the resource industry structure, traffic demand, highway network construction history, and national policy strategy and so on.

There are many influential factors, which are relevant to each other. If taking all these factors as the independent variables in studying reasonable highway network density, it will increase difficulty and lose accuracy.

Land is the foundation of human survival and livelihood, which has three major functions of carrying, producing and resourcing (ChaoKe Li, ShiFang Song & ZhenYing Hao, 2001). It is said that there isn't any human, human survival, and human development without land. In certain depth and height of land, there are many production capacities that create everything on earth, which are the basic conditions of earth life grow and reproduce. Human doing material goods production needs not only biological resources but also large amount of non-living resources (such as construction materials, mineral resources, etc.). Without these resources, human can not live and develop either. Human production activities must also be carried out while attached to land. From another point of view, as a most basic production factors, land can only carry out production process while combined with other factors. That means land has not any output. Land output is obtained through other production and living activities. The value of land is transferred to the production activities that attached to land during production process. How to measure the results of human uses land has always been a question that is worth studying. Measures of land development, utilization, and protection are in order to better use land. Utilize land is the purpose of human occupied land, and land output is the result of utilize land.

Human put labor, material, fund, etc., into land to obtain effective products or services. Therefore, in this article land output is defined as the total production output of all human production and living activities. In other words, land output is the result of human activities, the result of human using land, and also the benefits brought to human by using land from economic angle. Studies highway network density from the angle of land output, not only reflects the close relationship between highway network and social economic development, but also makes it more reasonable because highway construction is using land.

If considers land output as the production yields of the combination of many production factors, then how many of these production factors and how these factors combined will impact the result of land output. Take investment as an example, the intensity of investment has closely related to how much the land output is. Different utilize situation of land also great impacts land output. Based on the expression of production function, this article describes land output function as following equation.

$$F = f(x_1, x_2, x_3, \cdots, x_n) \tag{2}$$

In which, F is land output, x_i is the amount of all kinds of investment factors.

3. Research of relationship between highway network density and land output

3.1. Impacts from increasing highway network density to land output

3.1.1. Positive impact

First, the increase in highway network density is always the result of highway construction, which has direct effect on land output. Second, the increase in highway network density boosts industrial structure adjustment. Third, highway network density increase brings potential economic benefits, which includes reducing transportation costs, accelerating commodity circulation, boosting the development of industrial belt along the line etc., and thus influences land output.

3.1.2. Negative impact

The negative impact of highway network density increase to land output means the unexpected negative effects to highway users and non-users during highway construction and use, such as occupation of land during construction process, air and noise pollution during use process. Besides, highway construction must invest large amount of human, material and financial resources. Investment amount is large, time consumption as well as investment recovery period is long. When highway network density is too high, transportation resources lean to highway. It would cause the excess capacity of the entire transportation system, and eventually lead to the waste of transportation resources.

3.2. Impact from land output to highway network density

The rapid development of the economy produces large highway transportation demands, forces highway infrastructures to transform and develop rapidly, and requires highway network density to be further increased. Land output increase is the expression of economic growth and social progress within regional land scope. That is to say the increase of land output leads to and stimulates the increase of highway network density. In addition, land output situation reflects regional economic power, and directly impacts highway construction investment amount.

4. Research method of highway network optimal density based on land output

4.1. Optimal states of highway network density

Based on previous definition, land output is the total amount of all human production and living activities on the land, and also the result of comprehensive utilization of self contained factors and other input factors in certain land. Highway is one of the most important infrastructures in operating highway transportation activity, as well as a significant part of the transportation system. It is an input factor of land output, following the law of diminishing marginal returns. At the time when highway network density is fairly small, single route has limited traffic capacity, which can easily reach saturation state by traffic requirement deriving from economy and social development. At this moment, building new route links makes highway network transform from tree shape to net shape. It can reduce large number of traffic circuitous phenomenon. And increased highway network density brings benefits to regional economy development. When highway network density reaches certain scale, in other words, when it can satisfy the requirement of social economy development, marginal benefits brought by new highways decrease gradually, or even became negative numbers. According to diminishing marginal benefit law, with the assumption that the proportion of other investment factors rather than highway remains the same, when the marginal benefits of land output deriving from increased highway network density reaches zero, land output reaches maximum. At this time, highway network density reaches optimal value.

4.2. Effective land and effective land output

It can be seen from the definition of land output, not any piece of land has output. For example, an isolate land has no land output, even though there are wild animals or natural minerals. Because it is inaccessible by human beings, these animals or minerals can not be transformed into economically valued resources, or bring human society any economic satisfaction. This particular land obviously has no output. Similarly, land occupied by highway generally can no longer be used to other purposes. Highway construction can not bring any land output. Benefits can only be released by highway utilization. Therefore, highway itself has no value, but its benefits are achieved by it transferring to other industries. In a word, land occupied by highway itself does not create any value, or any land output. Therefore, for the convenience of researching, the land is divided into effective land and ineffective land.

Ineffective land can further be divided into 2 types: unused land and highway occupied land. Unused land (hereinafter referred to as the first category ineffective land) mainly refers to land except agriculture land and construction land, that are not be used by now, or very difficult to use. Highway occupied land (hereinafter referred to as the second category ineffective land), mainly refers to land that is occupied by highway construction, which includes cultivated land, forest land, pasture land, house site land, waste land, mountain land, and tidal land. Only borrow pit outside occupation site, temporarily occupied land, and development and management purpose occupied land can be said as non highway occupation land (Ning Lei, 2007).

Effective land means whole region area minus ineffective area, which can be calculated as follows:

$$S' = S - S_0 \tag{3}$$

$$S_0 = S_0^1 + S_0^2 = S_0^1 + \sum L_i V_i = S_0^1 + ax \tag{4}$$

In which, S' is effective land area, S is whole region area, S_0 is ineffective land area, S_0^1 is the first category ineffective land area, S_0^2 is the second category ineffective land area, L_i is the length of certain grade highway, V_i is the width of this grade highway, x is equivalent highway network density, a is the land occupation coefficient accordingly.

4.3. Research model for highway network optimal density based on land output

4.3.1. Assumptions

First, technology level remains the same, which means production technology does not experience major reformation. Second, the ration of investment factors in land output, except for highway, remains unchanged. Third, highway construction is well funded. In other word, the fund of highway network construction is not limited.

Although technology advances fast, technology breakthrough dose not happen anytime. Technology advances in intermittent mode, only after a certain period of preparation can major breakthrough occurs. Once certain technology level forms, there’s always a fairly stable period, no matter in agriculture or industry. This is called technology level remain period. Therefore, first assumption is valid in a certain period. It is also valid in a fairly stable period that the ration of investment factors in land output except for highway remains unchanged. Ratio of investment factors changes anytime in reality. Only after a certain period of preparation, major breakthrough can occur. Therefore, second assumption is valid in a certain period too.

4.3.2. Research model

Based on above assumptions and equation (2), land output can be described as follows:

$$F = \varphi(x) \tag{5}$$

In which, φ is a new function relationship, and x is highway network density.

According to diminishing marginal benefit law, while other factors remain unchanged, total production amount is increased with one factor increases at first, and then begins to decrease when it reaches certain level. Highway network density increase has similar pattern to land output: before reaching optimal point, the speed and scale of highway construction do not satisfy transportation requirement of regional economic development, land output has space to ascend, and investing in highway could drive land output increasing. At the point when highway network density have reached optimal point, the speed and scale of highway construction have already satisfied transportation requirement of regional economic development, land output reaches maximum. After reaching optimal point, negative impact of continuing highway network construction becomes more and more obvious, and land output decreases.

Use a figure to represent the relationship between highway network density x and land output F.

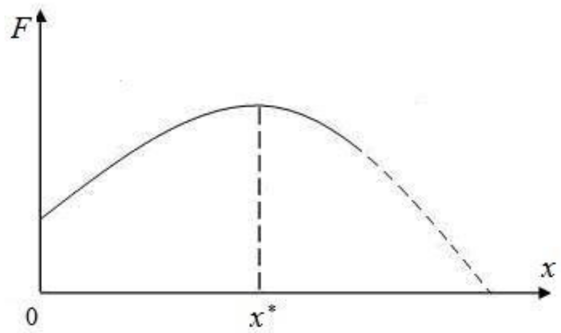

Fig.1 relationship between highway network density and land output

When x equals to zero, i.e. there is no highway, land output equal to a value larger than zero. This is because there are other transportation methods. Before reaching extreme point x^*, marginal output of highway network density is larger than zero. Land output is at an increasing stage. In this stage, the superiority of highway network is fully expressed. The contribution of highway network to land output changes from time to time, but positive impact is always larger than negative impact. When x equals to x^*, the marginal output of highway is zero, land output reaches maximum. If highway network density is larger than x^*, marginal output is smaller than zero. At this moment, the negative impact of highway network begins to emerge, and land output begins to decrease. In theory, if all land transforms into highway, i.e. no other industrials, land output equals to zero. However, this is an extreme condition that does not exist in reality.

Average effective land output is used to better describe the negative impact of highway network density increase to effective land decrease. Based on previous equations, regional average effective land output is the output on unit area of effective land. As there is no output on ineffective land, whole regional land output equals to effective land output within this region. It can be concluded that average effective land output equals to the ration of land output and effective land area. The equation is shown as follows:

$$f' = \frac{F'}{S'} = \frac{F}{S'} \tag{6}$$

In which, f' is the average effective land output, F' is the effective land output, S' is the effective area, and F is the land output.

The relationship between highway network density x and average effective land output f' is as follows:

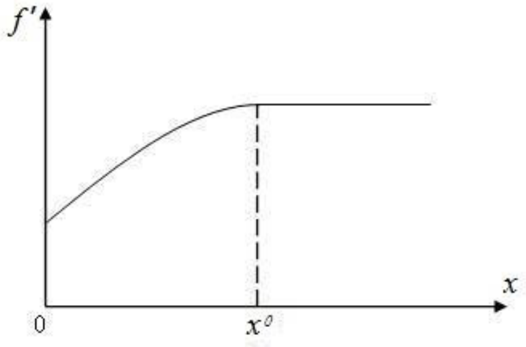

Fig.2 relationship between highway network density and average effective land output

If highway network density equals to zero, average effective land output is equal to or higher than zero as there are other transportation methods. When x reaches point x^0 from point zero, f' is a monotonic increased curve. When $x>x^0$, f' stops increase. Because under these assumptions above, when highway network density increases from zero, average effective land output increases due to circulation enlargement. Highway network density increases to some point will has not any enhancing effect or declining effect. The reason is that average effective land output is not affected by the major negative impact of land output, which is highway land occupation. Under the circumstances that technology level and ration of other investment factors remain unchanged, it is impossible to increase average effective land output relying only on highway network density increasing. That is to say, under the assumptions of this article, when highway network density increases to certain point, average effective land output remains unchanged.

Combining the two figures above, the relationship between x^* and x^0 is as follows. When $x>x^0$, the increase of x does not lead to the increase of f'. However, the effective area S' is declining, causing F to decline accordingly. Therefore, x^0 is larger than x^* ($x^0>x^*$); When $x\leq x^0$, the increase of x leads to the increase of f'. However, the effective area S' is declining, causing F to have both ascending and declining phases.

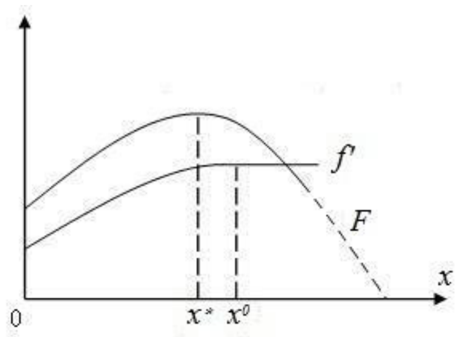

Fig.3 relationship between highway network density and two types of land output

Based on above analysis, at the interval of 0 to x^0, f' is monotonic increased, set to $f(x)$.

$$F = F' = f' \times S' = f(x) \times (S - S_0) = f(x) \times (S - S_0^1 - ax) \tag{7}$$

In which, S_0^1 is the first category ineffective land area, S_0^2 is the second category ineffective land area, x is highway network density, a is the area convert coefficient, ax is the occupied land area at highway network density x.

From this point of view, land output F is the one variable multiple function of highway network density x. x^* can be derived by finding the extreme point between 0 and x^0. The solving process is as follows: first, finds out the expression of $f(x)$ between 0 and x^0; Calculate regional average effective land output f' and equivalent highway network density x in known years. In which, $f'=F'/S'=F/S'=F/(S-S_0)$, data of S and S^0 are easy to get, data of F can be replaced with regional GDP. Then, the expression of $f(x)$ can be derived by regression method using relevant software; second, the expression of F can be derived using equation (7). Now, land output F is the one variable multiple function of highway network density x. Through solving the extreme value of F, it will get the optimal density of highway network.

Although these assumptions can not be fully achieved in reality, data similar to the assumptions can be found to do regression analysis. For example, observe the investment ration of all industries from regional statistical year book to acquire data from fairly stable periods. Then test the data by using econometric methods such as stationary analysis and causal analysis. Due to limited length of this article, the research on optimal density of highway network is restricted to theoretical model, and specific cases are not involved.

5. conclusions

The optimal density of highway network research in this article based on land output angle can be concluded as follows:

First, the increase of highway network density boosts economic development, but there still exists negative impacts due to highway land occupation etc. Therefore, there is an optimal density of highway network that contributes most to social economic development.

Second, in this article, land output is defined as the total production output of all human production and living activities. In addition, as an important indicator of regional highway development situation, highway network density has a close relationship with land output: highway network is the major guarantee of land output; the increase of highway network density contributes a lot to land output; highway construction has negative impacts on land output as well. Land output also drives, stimulates, and determines highway network density. Highway network density and land output should have corresponded and coordinated.

Third, based on diminishing marginal benefit law, and the assuming that the proportion of other investment factors rather than highway remains unchanged, when the marginal benefits of land output deriving from increased highway network density reaches zero, land output reaches maximum. At this time, highway network density reaches optimal value. On the basis of valuing effective land and effective land output, this article has exploratory proposed highway network optimal density model and has found out the solving method.

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