Urban Transport Structure Evolution Mechanism and Optimization Strategy

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Abstract
The urban transportation contradiction between supply and demand becomes outstanding increasingly. To solve this problem, this study put forwards an overall thinking and specific way to optimize the urban transport structure. Firstly, from the angle of urban transport structure evolution, the urban transport structure dynamic evolution model is presented to describe the competition among any transport modes. Secondly, the stability of the proposed model is analyzed to show that, reducing the transport competition as well as improving the public transport competitiveness is efficient to optimize the urban transport structure. Finally, two methods from the point of land use utilization and externality are proposed for optimizing urban transport structure and promoting urban transport sustainable development.

Key words: Sustainable Development, Urban Transport Structure Optimization, Dynamic Evolution, Land-use, Externality

1. INTRODUCTION

The theory about urban transport sustainable development is increasingly perfect and it points out that urban transport structure optimization contributes to promoting developing urban transportation. The transportation structure optimization research mainly focus on two kinds of problems, the first problem is which transport structure mode is the most reasonable, and the second problem is what is the dynamic mechanism of transportation structure evolution, namely how to guide the transport structure reasonably. Based on the concept of sustainable development, and combined with situation: large population, less land, ecological environment is fragile, the idea about the urban transport structure that promoting bus priority policy is pointed in( Goldman,Gorham2006; Gwilliam2003;Kelly 2006) .(Li 2007)divided urban traffic mode into two types: ‘private car dominated mode’ and ‘public transport dominated mode’, and put forward that the sustainable city traffic patterns should be useful to meet the travel demand, improve the ecological environment, reduce the social total cost, optimize the resource utilization, as well as guide the urban rational layout. Obviously, our country should choose ‘public transport dominated mode. (Thomson, 1982) divided urban traffic pattern into five types based on the relationship between land use and urban transportation: full development of car, limitation of urban center, maintain a strong urban center, low cost, restrict traffic. It also pointed out that the characteristics of land use and urban transportation under each traffic pattern. Article in journal (Goldman and Gorham 2006) examined the concept and implementation of sustainable transport. The goal of sustainable transportation may be better served by a number of the organic innovations in transportation practice that are occurring in the field.

Once the evolution goals of transport structure are determined, then the remaining problem is how to achieve it. Up to this day, many scholars have conducted a lot of researches on how to promote the urban transport structure optimization. These researches focus on qualitative and quantitative analysis about the relationship between urban traffic system and land use, because the land use pattern determines the trip generation, trip distribution, trip mode choice and so on. Study in articles (Shaw and Xin 2003;Wan 2002) put forward that the change of city traffic patterns reflects service area and transport speed, and different service areas and transport speeds will affect urban layout, transport structure and traffic scale. Also some scholars studied the effect of the residents travel mode from the aspects of residential density and employment density. The relationship between urban land use and transport structure were widely recognized as follows:(i) high-density urban land use is fit for the public transport, increasing land use density combined with urban land use function can reduce the private car usage and its trip distance (presented in articles (Pushkarev and Zupan 1977;Schimek 1996)); (ii) The urban land use density and employment density influence on transport mode selection, and finally influence on urban transport structure (presented in articles (Messenger and Ewing...
1996; Ewing and Halilur 1994; Kockelman 1997)); (iii) There is an analysis about the relationship between the urban transport systems of thirty-two cities with urban land-use, and the results shows there is a high correlation between low-density use land and highway traffic development (presented in articles (Newman and Kenworthy 1989; Newman and Kenworthy 1996; Newman and Kenworthy 1989)); What’s more, the urban transport structure optimization based on energy consumption is studied in paper (Lu and Wang 2004). Study in article (Xu 2003) pointed out that technical and economical characteristic of transport mode, traveler characteristic, travel behavior characteristic and transport supply characteristic are all important elements in analysis the regularity about people’s selection about the transport modes. And then method determining the urban transport structure is studied associated with qualitative and quantitative analysis.

This paper make some effects to discuss the urban transport structure optimization problem, analyze the urban transport structure evolution mechanism, identify the key elements influencing the transport structure and its effect pattern, and on this basis, this paper put forwards the overall thought about the urban transport structure optimization for achieving sustainable development of urban transport.

The remainder of this paper is organized as follows. The first part discusses the mechanization of urban transport structure optimization. The urban transport structure dynamic evolution model is presented in the second part. And the general ideal of urban transport structure optimization is promoted in the third part. The forth part concludes this study.

![Figure 1. The general idea to solve urban traffic problems](image)

2. Urban Traffic Structure Optimization

Urban transport structure in this study means the probability of urban residents choosing any mode of transport, namely, the proportion of the total urban passenger trips shared by each transport mode. Urban residents’ traffic mode selections are quite different in different periods and regions under the influence of traffic management, urban natural environment and some other factors. Currently, the main components of urban transport are walking, bicycle, subway, regular public transit, taxi, car, private car, motorcycle and so on.
The urban transport structure is not immutable, we can change some factors to make it more reasonable for achieving certain goals. This is main idea of urban transport structure optimization. Realize that the unreasonable urban transport structure is the main cause of prominent urban transportation problem, it is very feasible and necessary to optimize the urban transportation structure. The importance of urban traffic structure optimization in solving traffic problem is shown in the following figure 1.

From an overall perspective, the object of urban traffic structure optimization is to balance the relation among urban transport system, energy resources as well as ecological environment. On the individual level, the object is prioritizing public transportation, encouraging non-motorized transport model, restricting private car ownership, and promoting coordinate development among all traffic modes.

3. URBAN TRANSPORT STRUCTURE EVOLUTION DYNAMICS MODEL

The essence of the urban transport structure evolution is the consequence of people’s transportation selections following their personal travel utility maximization principle. Level of productive forces, traffic demand, natural system, and some other regulation policies are the crucial elements influencing on personal travel utility when people select the traffic modes. People’s individual behavior will influence the overall probability of traffic mode selection, showing out urban transport structure evolution eventually.

Based on the ‘rational man’ hypothesis in economics, traveler will select the traffic mode which can bring maximum travel utility, and then the travel utility is effected by regulation policy, traffic demand and others elements. As a consequence, the effects of these elements on urban transport structure are shown in traffic modes’ average travel utility. Apart from artificial uncontrollable elements, planner can take measures to make the traffic mode which is expected for further development more effective than others, and to improve the traveler choice probability, and ultimately to optimize the urban transport structure. The urban transport structure evolution dynamic model is shown as figure 2.

Figure 2. The urban transport structure evolution dynamic model

Apart from objective factors, urban transport structure dynamic evolution will be guided by travelers’ subjective intentions since people’s transportation choices are decided by personal travel utility maximization principle: the more personal travel utility, the more often it will be selected. On the background of urban process to accelerate, the social economy develops rapidly, but the ecological environment is damaged seriously and the natural resources are exploited excessively. People can guide the urban transportation structure by means of urban traffic planning, land use planning, traffic control measures, and formulate relevant policies and regulations to achieve the sustainable development of economy, society and ecology.

More specifically, land use planning decides the characteristics of traffic demand; traffic planning and traffic control measures decide the characteristics of traffic supply; and then relevant policies and regulations are designed to guide the combination between them. The above-mentioned three aspects elements decide the travel utility, and influence on urban traffic structure evolution ultimately. At the same time, once the urban traffic structure is formed, it will have reverse strengthening on traffic supply and demand. This is the urban traffic structure dynamic evolution mechanism.

Urban transport structure evolution dynamic model gives out its optimization elements, then the paper below will build model about competition between public transport and individual motorized transport, to clear out the matters requiring attention in the gross of urban traffic structure optimization.
3.1 Building competition model between transportation modes

Urban traffic structure evolution is a competition process between two transportation modes. Human powered vehicle cannot meet fast and long distance movement traffic demand, and it only acts as a supplementary transportation mode now. Public transport and private car may supple each other in some kind of degree, so the competition between them decide the future direction of urban traffic structure evolution.

Urban transport is limited to urban resources and ecological environment. The competition between public transport and private car is reciprocal. Supposing that the development scale of public transport is \( \alpha_1 \), and the scale of private cars is \( \alpha_2 \), the maximum traffic development scale is \( \sigma \), then the threshold value of public transport development scale is \( \sigma - \alpha_1 \). The maximum traffic development scale is \( \sigma - \alpha_2 \). It can reduce the revenue gap with private cars by improving public transport technical index such as comfort, speed, convenience, punctuality rate. The public transport cost advantage is more obvious after external costs internalized. And then part of the traveler will shift towards public transportation. On the other hand, with 'vehicle-oriented' city plans, building transportation infrastructure can make the private cars advantage such as flexibility, convenience, fast and comfort stand out more, and then part of the traveler will shift towards private cars. Supposing that it is a linear competitive relationship between the public transport and the private cars, the competition coefficient of private car is \( \beta_2 \), and its competitiveness is \( \beta_2 \alpha_1 \). Similarly, the competition coefficient of public transport \( \beta_1 \), its competitiveness is \( \beta_1 \alpha_2 \).

Let’s assuming that the public transport growth rate at some point is \( \delta_1 \), the private car growth rate at some point is \( \delta_2 \), and their nature growth rates are \( \mu_1, \mu_2 \) respectively. Then we can build the growth rate model based on the above hypothesis. The model is shown as follows:

\[
\begin{align*}
\delta_1 &= \mu_1 \alpha_1 \left(1 - \frac{\alpha_1}{\sigma - \alpha_2} \frac{\beta_2 \cdot \alpha_1}{\sigma}\right) \\
\delta_2 &= \mu_2 \alpha_2 \left(1 - \frac{\alpha_2}{\sigma - \alpha_1} \frac{\beta_1 \cdot \alpha_2}{\sigma}\right)
\end{align*}
\]

(1)

3.2 The model stability analysis

Formula (1) is a two-dimensional nonlinear system, its variables are the development scale of public transport \( \alpha_1 \), and the scale of private cars \( \alpha_2 \). Supposing that the urban transportation is consist of the public transport and the private cars only, and the maximum transport development scale is \( \sigma \), which is a constant value. When the public transport or the private car has the absolute superiority, then the urban transport structure remains stationary, and the corresponding coordinates are \( \phi_1(\sigma, 0) \) and \( (0, \sigma) \). Realizing that the proposed model (1) is a high order multi-parameter equation set, this paper qualitatively analyzes the competitive situation using stability theory of ordinary differential equation.

Let

\[
g(\alpha_1, \alpha_2) = 1 - \frac{\alpha_1}{\sigma - \alpha_2} \frac{\beta_2 \cdot \alpha_1}{\sigma}, \quad f(\alpha_1, \alpha_2) = 1 - \frac{\alpha_2}{\sigma - \alpha_1} \frac{\beta_1 \cdot \alpha_2}{\sigma}.
\]

Set \( f(\alpha_1, \alpha_2) = 0 \), \( g(\alpha_1, \alpha_2) = 0 \), Two curve lines can be drew, as shown as figure 3, and then the evolution tendency of \( \alpha_1, \alpha_2 \) can be analyzed in this figure. The values of \( \beta_1 \) and \( \beta_2 \) will influence the final judgment, so four cases are discussed as follows according to different values of \( \beta_1 \) and \( \beta_2 \).

(a) \( \beta_1 > 1, \beta_2 > 1 \)

(b) \( \beta_1 < 1, \beta_2 < 1 \)
\begin{figure}[h]
\centering
\begin{subfigure}{0.4\textwidth}
\centering
\includegraphics[width=\textwidth]{fig1a.png}
\caption{$\beta_1 > 1, \beta_2 < 1$}
\end{subfigure}
\begin{subfigure}{0.4\textwidth}
\centering
\includegraphics[width=\textwidth]{fig1b.png}
\caption{$\beta_1 < 1, \beta_2 > 1$}
\end{subfigure}
\caption{$\alpha_1, \alpha_2$ stability analysis}
\end{figure}

(1) $\beta_1 > 1, \beta_2 > 1$

(2) $\beta_1 < 1, \beta_2 < 1$

(3) $\beta_1 > 1, \beta_2 < 1$

(4) $\beta_1 < 1, \beta_2 > 1$

\textbf{3.3 The enlightenment}

The stability analysis of urban transport structure provides theoretical support for transport structure optimization. Furthermore, competitive intensity among transport modes and their competitive powers are the two main factors influencing urban transportation structure stability, which must be considered in taking measures to keep dynamic equilibrium between the public transport and the private cars.

(1) Limiting the competitive intensity

The above analysis shows that when $\beta_1 > 1, \beta_2 > 1$ or $\beta_1 < 1, \beta_2 < 1$, or $\beta_1 < 1, \beta_2 > 1$, the ultimate result of urban transportation evolution is that one of these two traffic modes will be eliminated thoroughly, which goes against the system equilibrium theory.

Every sort of transportation has its unique technical economy character, only by combing all sorts of transportation, we can realize maximum in overall utility. Therefore, the competitive intensity between different transport modes should be limited so as to building reasonable urban transportation.

The perfect condition is that the public transport and the private cars become complementary and each of them makes the most effective contribution. The corresponding urban transportation growth model is shown as formula (2):
\[
\begin{align*}
\delta_i &= \mu_i \alpha_i \left(1 - \frac{\alpha_i}{\sigma - \alpha_i}\right) \\
\delta_i &= \mu_i \alpha_z \left(1 - \frac{\alpha_z}{\sigma - \alpha_z}\right)
\end{align*}
\] (2)

The results of this differential equation set is that, no matter what the original values of the public transport and the private cars are, it will realize dynamic equilibrium, as long as the overall scale of them is equal to the maximum threshold which ecological environment can support. In this case, the ecological environment bearing capacity can be fully used.

(2) Improving the competitiveness of the public transport

The way to build the public transport dominated urban transport structure is to improve the competitiveness of the public transport $\beta_2$. Because of some objective reasons such as huge upfront investment, social public welfare, its natural growth rate $\mu_1$ is less than the private cars' $\mu_2$. If the competitiveness of the public transport cannot be improved, people will not select it as trip mode, and it will be eliminated as time passed.

3.4 Analysis of examples

In order to reflect the relationship between the various kinds of transportation modes, this section design a numerical experiment to show the evolution trajectories about two transport modes (private car vs Public transport). Supposing that the initial scales for these two modes are $\alpha_1 = \alpha_2 = 0.5$. The experiment results are shown as fig 4.

<table>
<thead>
<tr>
<th>(a) $\beta_1 = 1.2 (&gt;1), \beta_2 = 1.1 (&gt;1)$</th>
<th>(b) $\beta_1 = 1.1 (&gt;1), \beta_2 = 1.2 (&gt;1)$</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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<tr>
<th>(c) $\beta_1 = 0.8 (&lt;1), \beta_2 = 0.6 (&lt;1)$</th>
<th>(d) $\beta_1 = 1.2 (&gt;1), \beta_2 = 0.9 (&lt;1)$</th>
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<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
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**Figure 4.** The evolution Track between cars and public transport

The results reveal that the evolution process cannot keep stable if there exists fierce competition between private cars and public transport ($\beta_1 > 1, \beta_2 > 1$, as shown in figs 4(a), (b)). The less competitive transport mode will be eliminated from transportation market, and this is consistent with the abovementioned theoretical analysis.

Figure 4(C) confirms that the transportation market will converge to a stable state, if the competition between cars and public transport is reasonable ($\beta_1 < 1, \beta_2 < 1$). Note that the dynamic system shown in Fig
4(c) suffers a fluctuation process before it arrives at the ultimate stable state, this is mainly because the proposed dynamic evolution is nonlinear.

As shown in fig 4(d), the urban transport system will also be out of balance and the scale of the public transport will decrease to zero since the private car has a stronger competitiveness than the public transport. Compared with fig 4(a), the evolution rate in this case is faster obviously, this indicates that the larger competitiveness difference between transport modes, the weaker one will be eliminated faster.

4. THE GENERAL IDEAL OF URBAN TRANSPORT STRUCTURE OPTIMIZATION

The formation of the urban transport structure result from two aspects: on the macroscopic it is the competition between all kinds of transportation modes and on macroscopic point it is people’s transportation options following personal travel utility maximization principle. So for optimizing the urban transport, the government should encourage TOD model and bus priority in order to increase the public transport utility and improve the public transit trip share rate. On the other hand, it is unscientific to take administrative enforcement measures to limit the private cars, the administrative enforcement measures only works in short-term, and it is enormously expensive for managerial supervision.

The government should realize that it is the travelers that determine the transport structure. And then the idea of urban transport structure optimization can be summarized as follows:

(1) Urban land-use
Urban land-use decides the characteristic attribute of traffic demands which further affect traffic generation, traffic attraction and traffic distribution. This means urban land-use will play a crucial role in the formation of urban transport structure. On the contrary, to establish the required traffic structure dominated by a specific transport mode, the key is to form a conformable land utilization pattern.

The reasonable traffic structure should be dominated by the public transport and supplemented by other transport modes. If the role of land-use planning cannot work, it will be hard to form the required traffic structure, and it is less effective than expected. What’s more, the public transport with large capacity can promote the urban traffic sustainable development, if the land use intensity is weak, the total traffic demand is low and the distribution is disperse, the public transport cannot take its advantages, that is, the carrying rate is low, and the other performance indexes such as the average energy consumption, the average road resource usage and the average e, are all lower than the private cars, and then the social benefit is poor. On the other hand, the construction of public transport, especially for the rail transit, needs heavy investment in the early stage, which cannot be recovered without large passenger volume. So its deficiency in economic performance is not benefit to promote the public transport.

Furthermore, the transport mode which dominates the transport structure needs the corresponding traffic facilities, and affecting urban land-use further. In turn, urban land-use affects the formed transport structure, so it is difficult to change the present transport structure because it is complicated system engineering.

Therefore, based on the combination of land-use and urban traffic structure optimization, the designated land-use pattern can change the corresponding traffic utility with the result of trip mode rate changing.

(2) Optimization ideas from externalities
Under individual utility maximization principle, the traffic mode selection will go awry for the externalities of transport resource allocation, and then transport structure will lost its balance finally. So eliminating externalities, which can change the present transport utility, is another way to guarantee urban transport structure evolution to be more reasonable.

5. CONCLUSION

The urban transport structure is changing with the influence of productivity level, traffic demand, natural environmental system as well as relevant regulations. From the micro perspective, it is people traffic mode selection based on individual utility maximization that influencing the urban transportation structure.

This study shows that individual utility is the key element to affect people trip decision, which is therefore the fundamental impetus of urban transport structure evolution. Under the market mechanism without externalities, the optimized resource allocation can be achieved. However, the urban transport with public properties cannot meet the hypothesis. So eliminating externalities is another way to promote urban transport structure evolution.

This paper put forwards the objective about the urban transport structure optimization, namely promoting the public transportation, establishing non-motorized traffic system, and limiting the private car development scale, to guarantee that all transport modes coordinate with each other, and ultimately make sure that the whole transportation market is harmonious and sustainable between urban transport with natural system and socioeconomic system. Based on this, this study also proposes an urban transport structure dynamic evolution model, and analyzes the stability of competition model between all transport modes. The analysis results show
that lowering the competitive intensity and improving the competitiveness of the public transport was useful to optimize the urban transport structure. And finally, this study emphasizes that the urban transport structure optimization based on land-use or externalities is the integral mentality.

CONFLICT OF INTERESTS

The author(s) confirm that this article content has no conflicts of interest.

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