Rational scale of urban rail transit network based on system dynamics *

LIU You-jun†, JING Xiao ‡, GUO Qian-wen

School of Civil Engineering and Mechanics, Huazhong University of Science & Technology, Wuhan 430074, P. R. China

Received 30 December 2010; received in revised form 21 January 2011

Abstract: Urban rail transit (URT) has been playing an important role in urban sustainable development with its advantages of high speed, large capacity, high efficiency and low pollution. Estimating URT network scale is the key to ensure the scientificity and feasibility of its construction. The existing studies on rational scale of URT network have not dealt with the interaction of supply and demand. This paper describes the establishment of a system dynamics model of rational URT network scale determination, considering the interaction between URT construction and city social economic development as well as the dynamic equilibrium of capital supply and traffic demand, and the verification of the model validity by applying it to the case of Wuhan City’s URT construction.

Keywords: urban rail transit (URT); network scale; city economy; system dynamics

1 Introduction

With the high speed of China’s economic development and increasing urbanization and motorization, metropolitan traffic congestion and traffic accidents are getting more and more serious as well as pollution problems. Urban rail transit (URT) has played an important role in urban sustainable development with its advantages of high speed, large capacity, high efficiency and low pollution. The rational scale of a URT network is not only the macro-control variable of the network planning but also is a vital investment basis.

URT construction in developed countries started early, and the network systems have been well developed. However there have been only a few studies reported to have addressed the scales of those URT networks, and most of them are just conceptual. Nevertheless, research in China focuses more on the rational scale of a URT network.

Bollinger and Ihlanfeldt [1] put forward that the scale of a URT network is restricted by city size, urban economic strength and other factors. Zhu et al. [2] discussed a model of URT network scale based on qualitative and quantitative analysis, and used the structure model method in system engineering to establish a hierarchy structure of factors affecting the URT network scale. Some independent factors were selected to construct a multi-factor model by stepwise linear regression. Geometric method has also been used in the determination of network scale. Yang and Zhang [3] set up a model to estimate the rational route network scale based on the analysis of rational walk region and rational traffic region of URT stations. In the model, the weighed average feeding distance and converted coefficient of attraction scope were calculated to reckon the rational attraction scope of different URT stations. Thus the rational route network scale can be forecasted according to the suitable route network
shape of different regions. Both supply and demand should be considered in URT construction. Based on the characteristics of resident traveling demand and urban planning strategy, Jin et al. [4] put forward the demand and mechanisms of URT networks involving gradient effect, elasticity effect, equilibrium effect and integration effect, and also evaluated the optimization scheme of URT network scale considering the restriction variables of the urban economy, environmental resources, etc. Nevertheless the study did not tackle the dynamical changes in every time period. There are also some special methods to analyze URT network scale. For instance, Ma and Wang [5] put forward a new model based on the connectivity between passenger distributing centers, to compute the rational scale of rail transit network. An et al. [6] set up a computation model based on traffic demand overflow. The model predicted that a road network could provide traffic service at certain service level in the future. The overflow of total traffic demand contrasted with road network capacity was computed, and the overflow was transported by rail transit so that the rational scale of the rail transit network could be confirmed.

URT demand and supply actually are in a dynamic equilibrium process; so the rational scale is relative, and varies with different development stages [7]. Nevertheless, the existing research methods of determining URT scale fail to consider the dynamic characteristics of supply and demand. Whether the URT network scale is reasonable or not should be tested by a dynamical model. The mutual promotion of URT construction and economic development is the leading reason that drives the dynamical changes of the rational scale. In this paper, the rational scale in every period is simulated considering the interaction between URT construction and economic development based on system dynamics.

2 System dynamics modeling

2.1 Theory

System dynamics is a simulation method which was established by Professor Forrester of American Massachusetts Institute of Technology in the 1950s [8]. Being used to research highly nonlinear, multi-variable and multi-complex feedback systems, this kind of quantitative method was put forward based on the system theory, the cybernetics, the information theory, and large-scale system theory. At present, system dynamics is widely utilized in the fields of urban economy development, management and operation of enterprise, safety control, etc. [9]. Because of the comprehensive purpose in each kind of complicated dynamic systems, the paper attempts to apply the principle of system dynamics to analyze the interaction between URT construction and economic development so as to determine the rational scale of URT network in every period. The steps to analyze system dynamics problems are shown in Fig. 1.

\[ \text{Aim of modeling} \rightarrow \text{Feedback loop of causality} \]

\[ \text{Analysis of feedback and drawing flowchart of system} \rightarrow \text{Equation of system dynamics} \]

\[ \text{Flowchart running} \rightarrow \text{Simulation and analysis} \]

Fig. 1 Steps of analyzing problems

2.2 Analysis of system dynamics applicability

2.2.1 URT construction

URT is playing an increasingly significant role in stimulating domestic demand and promoting social and economic development, and it is a main driving force for sustainable development [10]. URT promotes economic development in direct and indirect ways. Its direct effects refer to the direct impacts on related industries during URT construction and operation, for instance, economic benefits on construction, design, supervision, building materials, machinery manufacturing, electronics, metallurgy and other industries, as well as its own boarding charge and advertising revenue. Indirect effects of URT construction play in terms of external effects. These external effects act on the industries and social groups which do not have direct relationship with the main part of URT construction, such as real estate, environmental protection, tourism, entertainment and e-commerce [11].

URT construction is conducive to economic development, but on the other hand, the scale of URT network is not limitless. In addition to a set ceiling of the
traffic demand, it is restricted by economic development which is the control variable of capital investment. Construction of URT must be adapted to economic development. Moreover, economic development can also promote the URT passenger flow demand.

Therefore, URT construction and economic development promote each other with dynamical relationships.

2.2.2 Methodological analysis

System dynamics method can be well applied to studying the complexity of an urban rail transit system, which generally focuses on the system of society, economic, ecology, etc. The system of URT construction is exactly an ideal object of system dynamics research because the interactions between the factors both inside and outside the system can be clearly recognized and reflected through system dynamics.

System dynamics method can be well applied to studying the dynamical relationships of urban economic development and URT construction because system dynamics deals with the dynamic process of system development under internal causal feedback loops. Through system dynamics, dynamic development and trends can be concluded, and long-term strategic quantitative analysis of dynamic studies can be made.

System dynamics method can also be well applied to studying problems without enough historical data. Though it occurs frequently that data lack or some of them are difficult to quantify during modeling, the system can also be calculated and analyzed using causal relationships among various factors, limited data and certain structure via system dynamics method. Therefore, the system dynamics method is just appropriate to the URT construction system problem which may lack some statistical data.

From the above analysis, it is obvious that using system dynamics to simulate the development of URT and economy can be a new effective method to determine the rational scale of the URT network.

2.3 System analysis

2.3.1 Determination of system boundary

System dynamics analysis of system behaviors is based on the interaction of internal elements, and assumes that changes in the external environment do not essentially impact system behaviors, and are not controlled by internal factors of the system. So the system boundary specifies what is included in the model. A conceptual model and variables inside the boundary which have significant relationships with the targeted dynamical problem should be included in the model; on the contrary, factors outside the boundary should be excluded.

By studying the intrinsic relationship between the URT network scale with the regional population, land area, economic development, transport demand and other factors, we can select the key factors mainly affecting the rational URT network construction scale from a large number of factors, and identify correlations between different factors \[12\]. The system boundary of this study is elaborated as follows.

In the aspect of economic system, GDP (gross domestic product) is used to denote the local economic development aggregates, and relevant factors include city employment, fiscal revenues, investment from financial revenue, URT operation revenue, annual URT investment for new projects, etc.

In the aspect of URT construction, the total length of URT network is used to denote the URT network scale, and the relevant factors include total length of new URT lines beginning to be constructed during a year, construction cycle, URT passenger volume, etc. \[13\]

2.3.2 Causality analysis

System dynamics research focuses on feedback mechanism problems. To study the feedback structure of the system, the first step is to analyze the relationship between the parts and macrocosm of the system, then explore the relationship between the cause and the effect, and lastly re-link them together to set up loops. System dynamics commonly uses system causality graph to express the concepts of feedback loops.

The causality between construction of URT network and economic development is shown as Fig. 2.

The causality graph indicates that, increase in the scale of URT network will drive the local GDP growth, promote employment, and increase operation revenues, all of which can increase the capital investment in URT construction \[14\]; while the costs of operating URT will rise with the increasing scale of URT network, which can reduce the amount of investment; moreover, city employment, passenger volume and URT operation
revenue all have positive effects. The main feedback loops are shown as follows.

1) Positive feedback loop 1: Total length of URT network $\rightarrow \uparrow \text{GDP} \rightarrow \uparrow \text{Fiscal revenue} \rightarrow \uparrow \text{URT investment from financial revenue} \rightarrow \uparrow \text{Annual investment for new construction} \rightarrow \uparrow \text{Annual length of URT lines beginning to be constructed} \rightarrow \uparrow \text{Total length of URT network}$

2) Positive feedback loop 2: Total length of URT network $\rightarrow \uparrow \text{URT passenger volume} \rightarrow \uparrow \text{URT operation revenue} \rightarrow \uparrow \text{Annual investment for new construction} \rightarrow \uparrow \text{Annual length of URT lines beginning to be constructed} \rightarrow \uparrow \text{Total length of URT network}$

3) Positive feedback loop 3: Total length of URT network $\rightarrow \uparrow \text{City employment} \rightarrow \uparrow \text{Fiscal revenue} \rightarrow \uparrow \text{URT Investment from financial revenue} \rightarrow \uparrow \text{Annual investment for new construction} \rightarrow \uparrow \text{Annual length of URT lines beginning to be constructed} \rightarrow \uparrow \text{Total length of URT network}$

4) Positive feedback loop 4: Total length of URT network $\rightarrow \uparrow \text{City employment} \rightarrow \uparrow \text{URT passenger volume} \rightarrow \uparrow \text{URT operation revenue} \rightarrow \uparrow \text{Annual investment for new construction} \rightarrow \uparrow \text{Annual length of URT lines beginning to be constructed} \rightarrow \uparrow \text{Total length of URT network}$

5) Negative feedback loop 5: Total length of URT network $\rightarrow \uparrow \text{URT operation costs} \rightarrow \downarrow \text{Annual investment for new construction} \rightarrow \downarrow \text{Annual length of URT lines beginning to be constructed} \rightarrow \downarrow \text{Total length of URT network}$

2.4 System flowchart setting

The factors are quantified according to the system causality, and the flowchart of system dynamics is developed using the software of Vensim_PLE (www.vensim.com/venple.html) as shown in Fig. 3.

The system consists of 4 subsystems: economic subsystem measured by GDP, employment subsystem measured by city employment, URT network subsystem measured by length of URT network, and passenger volume subsystem measured by URT proportion. In the system, stream level variables include total length of URT network, URT passenger volume and city employment. Table functions include natural GDP value function of time, URT construction investment proportion function of time, cost proportion of URT operation revenue function of time and total public transportation passenger demand function of time. Constants include natural increasing rate of employment, initial increasing rate of passenger volume, ticket price, construction cycle, proportion of capital funds, and new URT-construction cost per kilometer; and there are some auxiliary variables.

---

![Fig. 2 Causality graph of the system where GDP is gross domestic product and URT is urban rail transit](image)
2.5 Equation setting

\[
\text{GDP} = \text{Natural GDP value} + \text{Increased GDP value caused by URT} \quad (1)
\]

Increased GDP value caused by URT = Annual added URT length \times Increased GDP value caused by 1 km URT \quad (2)

Annual added employment population = Natural increasing rate of employment + Increased employment caused by URT \quad (3)

Increased employment caused by URT = Annual added URT length \times Increased employment caused by 1 km URT \quad (4)

Annual added passenger volume = URT passenger volume \times Initial increasing rate of passenger volume \times Multiplier of passenger volume change \quad (5)

Multiplier of passenger volume change = 1 − \frac{\text{ticket price/acceptable limit of ticket price} + \text{Population of city employment}/a + \text{Total length of URT network}/b}{a + b + (\text{Total length of URT network})/b} \quad (6)

Herein \(a\) and \(b\) are parameters.

Annual length of URT lines beginning to be constructed = Annual investment for new construction/Cost of building 1 km URT \quad (7)

Annual investment for new construction = URT investment from financial revenue/Proportion of capital funds + URT operation revenue \times Cost proportion of URT operation revenue + amounts of bank loan − URT operation cost \quad (8)

Fig. 3 The flowchart of system dynamics
URT investment from financial revenue = Fiscal revenue × URT construction investment proportion

URT operation revenue = URT passenger volume × Ticket price × (1 + proportion of other revenues) × transfer coefficient

2.6 Model examination

Shanghai City has the longest URT network in the world with 12 lines of a 431 km total length [15]. Its substantial historical data can be used to examine the model accuracy. We used the data from Shanghai statistical yearbook [16] of years from 1995 to 2010 with the basic initialization of year 1995. The variables being examined included total length of URT network, GDP, city employment and URT passenger volume. The examination results show that the relative error was lower than 15% for all different periods, suggesting that the model is acceptable and valid. The calculated scales of URT network in Shanghai City in different years are listed in Table 1.

Table 1 Simulated length of Shanghai URT network compared with corresponding historical data from Shanghai statistical yearbook [16].

<table>
<thead>
<tr>
<th>Year</th>
<th>Historical length/km</th>
<th>Simulated length/km</th>
<th>Relative error/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>36.4</td>
<td>36.4</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>136.7</td>
<td>117.0</td>
<td>14</td>
</tr>
<tr>
<td>2003</td>
<td>153.9</td>
<td>142.0</td>
<td>7</td>
</tr>
<tr>
<td>2005</td>
<td>187.6</td>
<td>210.0</td>
<td>11</td>
</tr>
<tr>
<td>2007</td>
<td>301.6</td>
<td>279.0</td>
<td>7</td>
</tr>
<tr>
<td>2009</td>
<td>392.0</td>
<td>424.0</td>
<td>8</td>
</tr>
<tr>
<td>2010</td>
<td>431.4</td>
<td>450.0</td>
<td>4</td>
</tr>
</tbody>
</table>

3 A case study of URT network in Wuhan

After system dynamics model setting and examination, the URT scale of every time period can be simulated dynamically and the ratio of URT network supply and URT demand can be obtained through changing the annual investment. Hence the rational URT network scale can be obtained considering both economic support and passenger flow demand via system simulation. We took the URT construction of Wuhan city as the case study to demonstrate the simulation of a dynamical system.

3.1 Determination of parameters

The first phase of Wuhan city’s URT Line 1 was completed in September 2004, but it failed to function well as a single line without scale effect. From 2004 to 2010, the second phase project of Line 1, the first phase project of Line 2 and the first phase project of Line 4 were under construction with an investment of 2,372 × 10^10 yuan. In July 2010, the whole line of Line 1 began to operate with a total length of 28.945 km [17], which is currently the longest light rail line in P. R. China. Newly appearing efficiency has impelled Wuhan city into an actual URT era.

In simulation, the initial year was assumed to be 2005, which is 5 years before the entire Line 1 being put into operation, and the data of the year 2005 were taken as the initial values. According to the actual situation of Wuhan City, the main parameters were defined as follows.

1) Prediction of fiscal revenues

We used software of SPSS (www.spss.com/) to analyze the history data [18] of fiscal revenue, GDP and the city employment from 2000 to 2009, and obtained the function of fiscal revenue as follows.

Fiscal revenue = \(-1,695.51 + 0.053 \times GDP + 4.158 \times \text{City employment}\)

2) Annual added URT length

The construction cycle was assumed to be 5 a. The value of new URT-construction cost per kilometer was assumed to be 600 million yuan, covering the costs of station building, demolition around the project areas and vehicle purchase.

Annual added URT length = Annual investment for new construction / 6

As delay exists in the period from starting construction to operation, the function of DELAY1I in the software which denotes the delay in material flow is used as follows.

Annual length of URT lines beginning to be constructed = Annual investment for new construction / 6

3) Annual investment for new construction
Annual investment for new construction = URT investment from financial revenue / Proportion of capital funds + URT operation revenue × Cost proportion of URT operation revenue – URT operation cost

In the case of a given fiscal revenue, URT investment from financial revenue is decided by URT construction investment proportion, which is a decision variable in the simulation. The cost proportion of URT operation revenue in this case was assumed to be 90%, as most of the URT operation revenue should go into the operation and construction cost [19]. According to Wuhan URT construction investment status, proportion of capital funds was assumed to be 40%; the URT operation cost including maintenance, operation and repayment fare was assumed to be 80 million yuan per kilometer.

4) Natural GDP

Natural GDP can be predicted through regression analysis of historical data from 2000 to 2009, as before 2009, URT in Wuhan hardly brought benefits.

\[ \text{GDP} = 1411.76 - 80.5 \times (\text{Time} - 2000) + 48.184 \times (\text{Time} - 2000)^2 \]

5) Natural increasing rate of employment

The average employment increasing rate from 2000 to 2009 was assumed to be 1%, as before 2009, URT in Wuhan had little impact on employment.

6) Quantification of increased GDP and employment caused by URT

Relevant studies and estimates show that each additional unit of investment can spur GDP to add 2.63 units of volume directly and 7.83 units of comprehensive benefits totally, and can also create more than 8,000 jobs [20]. In other words, GDP can increase by \(4.5 \times 10^9\) yuan and the employment population can increase by 48 thousand by each additional kilometer of URT lines.

7) URT passenger volume

The initial value of URT passenger volume was assumed to be the passenger volume of Line 1 in 2010, the first year for the whole line to be put into operation. The initial increasing rate of passenger volume was assumed to be 10%.

\[ \text{Multiplier of passenger volume change} = 1 - \sin \left( \frac{\text{Ticket price}}{\text{Acceptable limit of ticket price}} + \frac{\text{City Employment}}{a} + \frac{\text{Total length of URT network}}{b} \right) \]

Acceptable limit of ticket price was assumed to be 8 yuan; the transfer coefficient was assumed to be 1.5. And \(a\) and \(b\) were assumed to be 1000 and 500 respectively.

8) Prediction of total public transportation passenger demand

Total public transportation passenger flow has been improving steadily in recent years with an annual increase rate of around 4% [21], which was used to predict the total demand on public transport. The initial annual volume was assumed to be \(2 \times 10^9\).

3.2 Simulation

Simulation was carried out with an initial time of the year 2005, final time of the year 2040 and a time step of 1 a. URT construction investment proportion from Wuhan government was taken as the decision variable. Annual URT proportion in the total public transportation passenger volume was the control variable.

Based on related studies, it is reasonable that URT investment from the government shares a proportion in total fiscal revenue of less than 8% [22]. So, the investment proportion parameter in each year was tested within the limit of 8%.

From the simulation, we discovered that in the early period of URT construction, the network scale is mainly limited by the fund supply; while in the later period, when the fiscal revenue is over \(1 \times 10^{11}\) yuan, the rational scale is based on the URT demand targeted for a share over 60% in the total public traffic passenger volume in future years; and the investment proportion could be decreasing from then on. After several times of simulation, URT construction investment proportion in a year was assumed to be 8% for the period from 2005 to 2020, 5% from 2020 to 2025, 3% from 2025 to 2030, and 2% from 2030 to 2035. After 2035, no more investment from government would be needed for constructing new lines.

The simulation shows that the URT network would reach a total length of 530 km and passenger volume would be up to 4,500 million accounting for 65% of the total public transport passenger volume in 2040. Results of the rational URT network scale in different years are listed in Table 2.

The simulated pattern of the rational URT network scale evolving over time and the proportion of URT passenger volume in the total of public passengers are illustrated in Figs. 4 and 5, respectively.
Table 2 The rational URT (urban rail transit) network scales of the key years

<table>
<thead>
<tr>
<th>Year</th>
<th>Rational total length of URT network/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>51</td>
</tr>
<tr>
<td>2015</td>
<td>88</td>
</tr>
<tr>
<td>2018</td>
<td>152</td>
</tr>
<tr>
<td>2020</td>
<td>204</td>
</tr>
<tr>
<td>2025</td>
<td>287</td>
</tr>
<tr>
<td>2030</td>
<td>368</td>
</tr>
<tr>
<td>2035</td>
<td>438</td>
</tr>
<tr>
<td>2040</td>
<td>533</td>
</tr>
</tbody>
</table>

4 Conclusions

This paper describes the establishment of a system dynamics model to determine the rational URT network scale, through research on the interaction between URT construction and local economic development, taking into consideration the equilibrium between capital supply and URT passenger flow demand. The system dynamics model examination with historical data of URT construction during the period from 1995-2010 of Shanghai city shows that the estimates produced by the proposed model are of a relative error lower than 15%, demonstrating that the model is acceptable and valid. Wuhan city’s URT construction is applied to illustrating the empirical simulation procedure. With the assumed value of URT construction investment proportion within a control limit of 8%, rational scales of URT network in different years are obtained from the simulation. Simulation results suggest that, the whole network will be completed before the year 2040 with a total length of 530 km, and an annual passenger volume of 4 500 million accounting for 65% of the total public transport volume.

It should be noted that the value-taking of some parameters in this study needs further improvement; for instance, consideration of the gradient effect of URT construction may be necessary. Investment and financing approach of URT construction need to be studied further to improve the model.

References


Wikipedia. Shanghai Metro [EB/OL]. 2011-2-1 [cited 2011-2-20]. http://en.wikipedia.org/wiki/%E4%B8%8A% E6%B5%B7%E8%BD%A8%E9%81%93%E4%BA% A%4%E9%80%9A.


Edited by LUO Min