



Analysis of the Impacts of Passenger Demand on the Profitability of Different Types of Urban Rail Transit

Qi ZHOU¹, Baohua MAO², Sairong PENG³, Junsheng HUANG⁴, Peining TIAN⁵

Original Scientific Paper
Submitted: 26 May 2022
Accepted: 10 Jan. 2023

¹ 18114062@bjtu.edu.cn, Key Laboratory of Transport Industry of Big Data, Application Technologies for Comprehensive Transport, Beijing Jiaotong University

² Corresponding author, bhmao@bjtu.edu.cn, Key Laboratory of Transport Industry of Big Data, Application Technologies for Comprehensive Transport, Beijing Jiaotong University

³ 18120246@bjtu.edu.cn, Signal & Communication Research Institute, China Academy of Railway Science

⁴ 19114037@bjtu.edu.cn, Key Laboratory of Transport Industry of Big Data, Application Technologies for Comprehensive Transport, Beijing Jiaotong University

⁵ 20120900@bjtu.edu.cn, Key Laboratory of Transport Industry of Big Data, Application Technologies for Comprehensive Transport, Beijing Jiaotong University



This work is licensed
under a Creative
Commons Attribution 4.0
International License.

Publisher:
Faculty of Transport
and Traffic Sciences,
University of Zagreb

ABSTRACT

With the rapid development of urban rail transit (URT) in China, a contradiction between high costs and low passenger demand becomes prominent. Complete analysis of the impacts of passenger demand on the profitability of URT can be difficult to conduct, due to the multifaceted impact of passenger demand with multidimensional characteristics. To this end, we propose a strategy that helps to analyse the profitability of different types of URT, taking into account the spatial and temporal characteristics of demand. Based on data of the Shunde (SD) district in China, the profitability of metro, light rail transit (LRT), monorail and tram was evaluated. Results show the profitability under different demand levels. Tram might be the best choice at low demand levels. At medium demand levels, LRT and monorail are competitive. At high demand levels, LRT with medium to high capacity and low cost is a good alternative to metro, though the capacity of metro is higher. Utilizing the URT with high capacity under insufficient demand can aggravate the burden of depreciation, and make it hard to achieve profit. The spatial characteristics of the demand described in this paper reflect the problem of insufficient demand in marginal areas due to the diversified construction of URT.

KEYWORDS

urban rail transit; profitability; light rail transit; passenger demand; spatial characteristic.

1. INTRODUCTION

Urban rail transit experienced rapid development worldwide due to its advantages in reducing traffic congestion, greenhouse gas emissions and improving accessibility [1–3]. By the end of 2020, the total mileage of the urban rail transit (URT) in the world reached 33,346 km, and the total mileage in the mainland of China reached 7,970 km, ranking first worldwide. However, the URT expansion in China exposed problems of high capital cost with low passenger demand [4]. In China, the capital cost per mile of the metro has risen from 0.5 bn ¥ in 2000 to 0.8 bn ¥ in 2015 [5], and even exceeded 1 bn ¥ in 2019. While a huge investment brings social benefits such as land value enhancement and urban attractiveness improvement [6], ticket revenue from passengers is always one of the most important ways to justify the upfront investment of URT

[7]. However, in China, statistics show that the average passenger intensity of URT only reached 7,100 pass/km-day in 2019 [8], which is much lower than the 13,100 pass/km-day in Japan [9] and 14,400 pass/km-day in Korea [10]. The ticket revenue with low passenger demand can hardly cover the operating costs, causing a heavy financial burden on the government. This reflects the waste of resources caused by the mismatch between supply and demand.

As the demand for transportation infrastructure in urban areas increases, the financial pressure on governments will further increase [11]. Moreover, decision-makers need data on the cost and profitability of different systems [12], especially in the trend of coordinated development of various URT systems in China. Therefore, it is necessary to study the impacts of passenger demand on the profitability of different types of URT. Profitability refers to the ability to make a profit in a period of time [13]. The main business of the URT is to provide transportation services for the public. Generally, the profitability of URT involves three aspects, which are the operator, the URT system and the passenger demand. The operator is in charge of management strategies, the URT is the carrier that provides services, and the passengers are the objects served by the operator and system simultaneously. In this paper, we focus on the aforementioned two aspects which are the passengers and the URT systems, aiming to provide help to the governments in the selection of the URT systems.

Most of the studies that focus on the economics of different transportation modes are based on the pioneering studies of Meyer, Kain and Wohl [14]. They were the first to define total social cost in order to integrate the operator cost and user cost, and they compared the social cost of the railway, bus and car based on a typical commuter corridor in the United States of America. They found that the social cost of transportation modes depends on the passenger demand of the corridor.

Later studies focused on enriching the connotation of the costs and the types of transportation modes. Brand and Preston [15] added the external cost to social cost and developed a stand-alone spreadsheet model to evaluate the social costs of 15 modes of transportation, and a more detailed integrated model using the software Vips and Contram to compare the user benefits. Li [16] improved the spreadsheet cost model developed in [15] by revising the speed-flow and passenger waiting time equations in mixed traffic. Similarly, Grimald [17] developed a parametrical socio-economic cost-benefit analysis of the stylised model to evaluate the cost and benefit of the conventional bus and LRT in an urban corridor. Tirachini [18] compared the total costs (operator and user cost) of heavy rail transit, LRT and bus rapid transit (BRT) from three perspectives, namely the minimisation of the total cost and the maximisation of the profit and the welfare. Manoratna [19] proposed an assessment model of social costs and environmental costs. Moreover, the city Colombo was taken as a case to assess the travel time saving and environmental impacts, in which the monorail is introduced in the transportation system. Tam [20] developed social cost models for conventional bus, BRT, monorail, metro, car, motorcycle, taxi and Uber at a strategic level, and compared the average social cost of eight modes with a case study of Hanoi, Vietnam, to provide a basis for the transportation technology selection of low-income countries. Avenali [21] compared the social economic costs associated with the bus and rail in Italy, the comparison was carried out by considering a given level of exogenous demand. The service production costs, infrastructure usage costs and externalities impacts are all included in the social costs. In these studies, passenger demand was assumed to be an exogenous variable of the operator cost, the impact of the passenger demand on the URT system scale was ignored, and the impact of the system scale on the operator cost was likewise ignored.

Wang [22] followed the approach of Meyer et al. [14] as well as Keeler and Small [23] and considered the passenger demand when measuring the system scale of various transportation modes in the cost model. Then the full costs of metro, LRT, bus, BRT, car and bicycle were compared. However, the relationship between the passenger demand and system size might not correspond exactly. In reality, URT projects are often criticised by many scholars and planners for demand overestimation [24–26], reflecting the discrepancy between actual and expected passenger demand (system size), and this discrepancy leads to the waste of resources.

In general, the previous studies focused on the comparison between URT and other transportation modes such as bus, private car and bicycle. However, URT contains seven systems [27]. Different types of URT provide more options for small and medium-sized cities to develop rail transit. This study extends the existing literature in three respects.

- 1) The spatial and temporal characteristics of passenger demand are further considered, and different types of traffic corridors are simulated by the proposed strategy.
- 2) The impacts of passenger demand on two different aspects, the revenue and the operator cost are taken into account. The passenger demand affects the ticket revenue, but from the aspect of cost, passenger demand also affects both the system scale and the operational workload. The impacts on the two aspects can be different.
- 3) This paper describes the differences between various URT systems, such as metro, LRT, monorail and tram. The more scientific delineation of the passenger demand applicable range of URT systems contributes to the decision-making for governments in terms of selection of different types of URT.

The remainder of this paper is organised as follows. In Section 2 we propose the strategy to evaluate the profitability of different types of URT systems. In Section 3 case studies considering various passenger demand scenarios are conducted. The summary of the obtained results is presented in Section 4. In Section 5 we describe the conclusion of the paper and provide ideas for future studies.

2. METHODOLOGY

The process and components to analyse the profitability of URT systems are shown in *Figure 1*. Iterative calculations are performed for different passenger demand levels and URT modes, and final results can be generated for various scenarios.

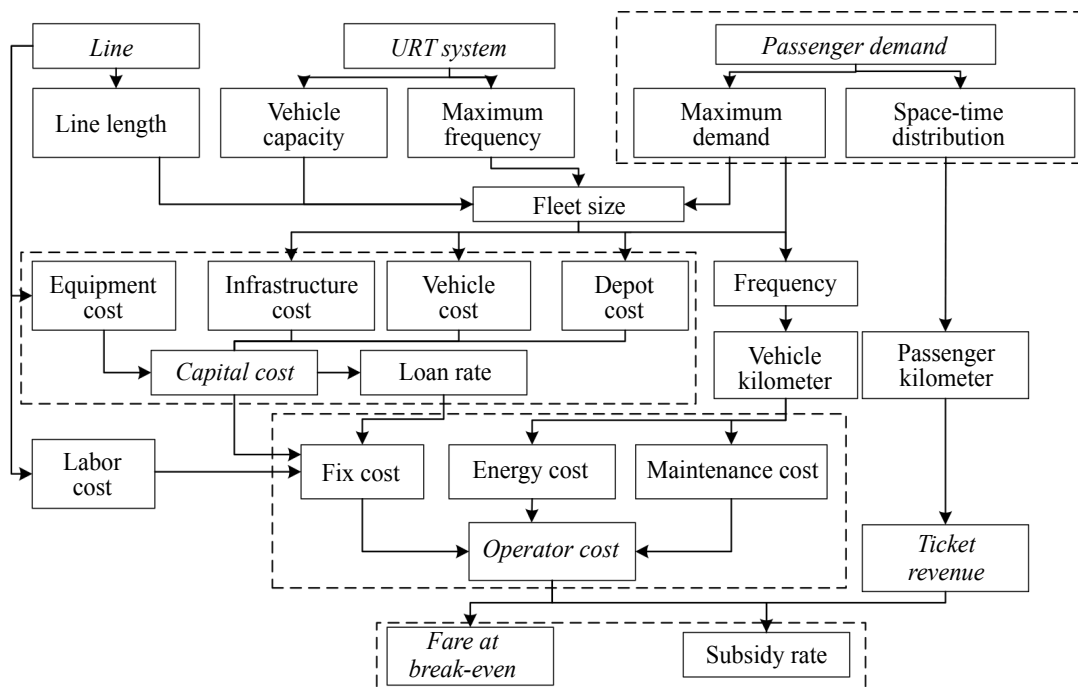


Figure 1 – The procedure to analyse the profitability of URT considering passenger demand characteristics

The analysis on profitability in this paper is based on an independent urban corridor, and only one URT system with independent right-of-way operated on the corridor. There is a ring-travel model developed by Anas and Moses [28] that created a circular city with radial highways connecting the central business district (CBD) and suburbs. In the cities of China, radial corridors are important for daily commuting. We assume

that URT is on a radial corridor connecting the CBD and suburbs, which is consistent with the situation that a large number of residential communities are distributed along a radial corridor connecting the CBD [29].

We analyse the profitability of different types of URT based on the same corridor. In China, operator loss is always subsidized by the government. The subsidy rate at a fare level is used to indicate the profit and loss. The fare at break-even status (BEF) is used to indicate profitability. The subsidy rate and BEF for the k th system at the j th level of demand can be respectively expressed by *Equations 1 and 2*

$$B_{j,k} = \frac{O_{j,k} - I_j}{O_{j,k}} \tag{1}$$

$$T_{j,k}^b = \frac{O_{j,k}}{Q_j L} \tag{2}$$

where $B_{j,k}$, $T_{j,k}^b$ denote the subsidy rate and the BEF. The $O_{j,k}$ denotes operator cost. The I_j denotes the ticket revenue. The $Q_{j,k}$ denotes the passenger transport intensity for a day (PIT). The L denotes the length of the corridor.

2.1 Passenger demand

Passenger demand can be characterised by time and space [30]. The spatial characteristics refer to the distribution in each station or section. To calculate the frequency of departures, the model requires the value of peak passenger demand per hour, for the most load section (MLS). We assume that demand in the radial corridor conforms to the pattern given by Shang [31], and it varies with time. The temporal characteristics of passenger demand refer to the distribution in different periods. The PIT can be expressed as

$$Q_j = \frac{\sum_{s=1}^S \left[\int_0^L P_{0,j}^s (1 - e^{-(\partial/y)\beta}) dy \right]}{L} \tag{3}$$

where the s denotes the period, for $s \in \{1, 2, \dots, S\}$. The $P_{0,j}^s$ denotes the peak demand per hour for s th hour for MLS. Considering the technical constraints of URT, the range of passenger demand should be within the system capacity, $P_{0,j}^s \leq C_{k,max}$, the $C_{k,max}$ denotes the maximum capacity of the k th system. The y denotes the distance from MLS. The ∂ and β denote the demand parameters.

2.2 Ticket revenue

The revenue of the operator may be diversified [32]. However, ticket revenue is an important factor of profitability, which can be expressed as

$$I_j = Q_{j,k} L T_{j,k} \tag{4}$$

where $T_{j,k}$ denotes the fare.

2.3 Operator cost

Operator cost can be classified into fixed cost and variable cost depending on their relation to the operation workload. Fixed cost refers to the relatively fixed expenditure that does not change with the operation workload during the operation process, such as the depreciation cost, finance cost and staff payment [33]. Variable cost refers to the expenses that directly change with the change of operation workload in the operator cost, including the operation energy consumption and maintenance expenses of vehicles [34]. Due to the small proportion of working capital loan interest in finance cost [35], we consider long-term loan interest. Operator cost can be expressed as

$$O_{j,k} = \lambda_k L P_l + Z J_{j,k} + \frac{t(1+t)^p}{(1+t)^p - 1} C_{j,k}^r + (M_k + G_k E) V_{j,k} \tag{5}$$

where λ_k denotes the number of laborers per km and P_l denotes the annual income per person. $ZJ_{j,k}$ denotes the depreciation of fixed assets and $C_{j,k}^r$ denotes interest during the construction period. The t denotes the interest rate per year and p denotes the repayment year. M_k and G_k denote the maintenance cost and traction energy consumption per vehicle-kilometre (vkm). E denotes the price of electricity. $V_{j,k}$ denotes vehicle-kilometre. Considering the lowest level of service constraint, $V_{j,k}$ can be expressed as

$$V_{j,k} = 365 \cdot 2n_{j,k}L \sum_{s=1}^S f^s t^s, \quad f^s = \left\lceil \left[\begin{array}{l} \frac{P_{0,j}^s}{C_{v,k}na} \Big| h_{min} \leq \frac{60}{f^s} < h_{max} \\ \frac{60}{h_{max}}, \quad \frac{60}{f^s} \geq h_{max} \end{array} \right. \right\rceil \quad (6)$$

where $n_{j,k}$ denotes the fleet size and f^s denotes frequency for s period. The t^s is the duration for the s th period. The h_{max} denotes the maximum departure interval, usually 10 min and h_{min} denotes the minimum departure interval. The $C_{v,k}$ denotes the vehicle capacity when the standing density is 6 person/m² onboard. The vehicle capacity can reach maximum when the standing density is 7 person/m². The a denotes the ratio of $C_{v,k}$ to the maximum vehicle capacity, usually 1.2 [36, 37].

Depreciation of assets

Depreciation of assets is calculated by the straight-line method. The original depreciable value includes the capital cost of the URT system and the interest on the loan during the construction period [35]. Assuming that each loan is used in the middle of the year and no other financing costs are considered, depreciation and interest for construction can be expressed as

$$ZJ_{j,k} = \frac{1-c}{z}(C_{j,k} + C_{j,k}^r) \quad (7)$$

$$C_{j,k}^r = \sum_{i=1}^I \left(\sum_{x=1}^{i-1} (C_{j,k}^x \delta + C_{j,k}^{r,x}) + \frac{\delta C_{j,k}^i}{2} \right) t \quad (8)$$

where c denotes salvage value percent and z denotes asset life. $C_{j,k}$ denotes capital cost. $C_{j,k}^r$ denotes the interest in construction. The notations i and x denote the construction period, for $x \in \{x \mid 0 < x < i\}$ and $i \in \{1, 2, \dots, I\}$. $C_{j,k}^x$ and $C_{j,k}^i$ denote the capital cost of the year x and i . δ denotes the loan ratio. $C_{j,k}^{r,x}$ denotes the interest in year x .

Capital cost

The capacity and capital cost of the URT depend on the maximum passenger demand during peak hours for MLS. The fleet size can be expressed as

$$n_{j,k} = \left\lceil \frac{\mu P_{max,j}}{C_{v,k} a f_{max,k}} \right\rceil \quad (9)$$

where μ denotes capacity reserve ratio. $P_{max,j}$ denotes the j th expected maximum demand per hour for MLS and $f_{max,k}$ denotes the maximum departure frequency of the k th system.

The capital cost considered by the model contains four sections: vehicle acquisition, infrastructure (stations and line), equipment and depot which can be expressed as

$$C_{j,k} = c_k n_{j,k} (1 + \gamma) Y_{j,k} + \sum_{m=1}^M (P^m U_k^m M_{j,k}^m + L_k^m W_k^m) + (L_{j,k}^t + L_{j,k}^l) W_k^d \quad (10)$$

where c_k , γ denote the price and the spare ratio of the vehicle, γ is usually 6%. $Y_{j,k}$, P^m denote the number of vehicles and stations. m denotes the laying method for $m \in \{1, 2, \dots, M\}$. U_k^m denotes the unit area cost of the station. $M_{j,k}^m$ denotes the area of the station platform which can be calculated according to [38]. L_k^m denotes the corridor length by mode m . W_k^m , W_k^d denote the unit cost of line and equipment, and the parking lot and the vehicle inspection depot. $L_{j,k}^t$, $L_{j,k}^l$ denote the length of the parking lot and the inspection depot, which can be expressed as

$$L_{j,k}^t = [(L_{j,k}^c + \varepsilon_k)N_k^t + (N_k^t - 1)d_k^t + L_k^t](bY_{j,k}n_{j,k}/N_k^t) \tag{11}$$

$$L_{j,k}^l = [(L_{j,k}^c + \varepsilon_k)N_k^l + (N_k^l - 1)d_k^l + L_k^l](bY_{j,k}n_{j,k}/N_k^l) \tag{12}$$

$$Y_{j,k} = \frac{2L \cdot 60}{v_k} + t_k \cdot \frac{P_{max,j}}{C_{v,k}n_{j,k}} \tag{13}$$

where $L_{j,k}^c$ denotes the length of the train, ε_k denotes parking error. N_k^t and N_k^l denote the number of train spaces in the parking lot and inspection depot. d_k^t and d_k^l denote the distance between train spaces of the parking lot and the inspection depot. L_k^t and L_k^l denote the additional distance and b denotes the proportion of trains stopped and inspected, usually 20%. v_k, t_k denote the traveling speed and turnover time.

According to the model, the operator cost is decided by the passenger demand Q , the capacity of URT system C_v and the capital cost C . Moreover, the capital cost is decided by the passenger demand Q , the capacity of the systems C_v and the economic characteristics of systems K . The relationship between operator cost and capital cost can be expressed as

$$O(\rho Q, C_v, K) = \delta C(Q, C_v, K) + \varphi V(\rho Q, C_v) + \tau \tag{14}$$

where δ, φ and τ are constants that are independent of the passenger demand. The ratio between actual and expected passenger demand is expressed by the difference coefficient $\rho, \rho \in (0, 1]$. The larger the ρ , the closer the actual demand is to the expected demand.

3. CASE STUDY

We use the data of one particular district in China in this case, which is termed as Shunde (SD) district and located in Foshan (FS) city in southern China. Among the administrative regions at the same level, the SD district contributes the most to the gross domestic product (GDP) of China. Currently, the SD district has only one metro passing through the northwest corner, and the local government is interested in building a straddle monorail line with 33 kilometres across the southeastern central city.

3.1 Data description

The line and passenger demand data are mainly from the SD Transport Bureau. The average distance between stations is 1.1 km, the maximum peak demand for MLS is 16,300 pass/h with an average daily turnover of 2.5 million passenger kilometre (pkm). The operating hours of URT are 6:00-24:00, therefore the full-day operating hours are set to 18 hours.

The capital cost parameters of different URT systems are obtained from the official construction reports of URT in China, and the operation parameters are mainly obtained from the China Association of Metros, see Table 1. The unit cost of the parking lot and inspection depot of each system is around 180.2 million ¥/km. According to the vehicle parameters and the maximum fleet size that can be achieved in reality, the maximum capacity of the four types of URT is 72,000, 49,500, 38,000 and 15,000 pass/h, respectively.

Cost parameters are derived from public data presented by the government. The data on labour costs are obtained from [40] and the annual labour cost is 109,800 ¥. The electricity and fare of URT are obtained from the rail transit operating company of the city FS. The price of electricity is 0.6840 ¥/kWh and the fare is 0.32 ¥/pkm. The construction period is generally four years. According to [41], the total investment in the project shall not be less than 40% of the financial funds, which means that the loaning ratio is about 60% of the capital cost. According to [42], the life span of the civil construction works, the vehicles and the equipment are about 100 years, 30 years and 25 years, respectively. Moreover, the residual value rate is derived from the financial reports of the operating companies, and the residual value rates of the three are 5%, 3% and 3%, respectively. The annual interest rate of the loan is 4.9%.

Table 1 – Parameters of URT systems

Parameters	Description	Metro	LRT	Monorail	Tram
U_k^m	Cost of station [$10^4\text{¥}/\text{m}^2$]	1.20	0.72	0.71	261.72*
W_k^m	Cost of line and equipment [$10^8\text{¥}/\text{km}$]	2.07	1.41	1.22	0.66
c_k	Price of vehicle [$10^4\text{¥}/\text{veh}$]	650	600	840	1,170
c_{vk}^a	Capacity of vehicle [pass/veh]	250	215	165	81
ε_k^b	Length of parking error [m]	1	1	2	1
d_k^b	Distance of train space in parking lot [m]	12	12	6	6
d_k^l	Distance of train space in inspection depot [m]	5	5	12	5
L_k^l	Additional distance of parking lot [m]	21	21	12	12
L_k^l	Additional distance of inspection depot [m]	21	21	21	12
h_{min}^c	Minimum departure interval [min]	2	2.5	2.5	3
G_k^c	Traction energy consumption [kWh/vkm]	2.03	1.33	1.84	0.77
M_k	Maintenance cost [$\text{¥}/\text{vkm}$]	3.8	3.8	5.7	3.3
λ_k	Number of labourers [person/km]	60 ^d	40 ^e	57 ^f	13 ^c

* The unit is $\text{¥}10^4/\text{km}$, ^a from [39], ^b from Technical Standard for Vehicle Base Engineering of Urban Rail Transit CJJ/T306, ^c from China Association of Metros, ^d from Scientific Research Institute of the Ministry of Transportation and Communications, ^e from Light rail transit design standards GB/T51263, ^f from Monorail traffic design standards GB50458.

3.2 Result analysis

Table 2 presents the BEF and subsidy rates for the various URT for the passenger demand level in the SD district. It can be seen that the LRT is the best choice with the lowest BEF and subsidy rate at the current fare, while the monorail comes close. The straddle monorail does not show the best profitability for three main reasons. First, the transport capacity of the monorail is smaller than the LRT and the metro. Therefore, facing the same passenger demand the monorail needs a bigger system scale (e.g. more trains and a bigger scale of depot and platform). Second, in China, there are only 2 monorail lines (line 2 and line 3) in the city of Chongqing, and 2 monorail lines are newly in operation in the city of Wuhu. The data of the monorail come from the monorail lines in Chongqing, which have relatively higher energy cost than ordinary systems due to the bigger slope and curve radius of the lines, and relatively higher PIT than other systems. Third, without a widely used and standardised industry chain in China, the maintenance cost of equipment and facilities can be expensive.

Table 2 – System profitability indicators in case scenarios

	Unit	Metro	LRT	Monorail
BEF	[$\text{¥}/\text{pkm}$]	0.90	0.65	0.84
Subsidy rate	[%]	61.89%	45.80%	58.61%

In fact, by now, 44 cities in China are planning to build monorails. Some monorail stakeholders tend to compare the types of URT systems from different perspectives. For example, some believe that the capital cost of the monorail is less than the metro, but such cost is not based on the same system scale. Meanwhile, some policymakers believe that constructing monorails could attract investment and contribute to building local monorail industries. However, the competition among cities to develop the local rail transportation industry may lead to local protectionism, which is not conducive to integrated development and is more likely to form duplicate construction and waste of resources. Moreover, the scale of monorail operation in one city is not enough to support a complete monorail industry.

Based on the above conditions, the profitability of URT under different passenger demand levels is further analysed. *Figures 2 and 3* show the BEF and subsidy rate for different types of URT with peak demand from 3,000 to 70,000 pass/h and demand difference coefficient ρ from 0.2 to 1. The BEF and subsidy rates decrease as the peak demand and the ρ increase. For example, when the peak demand changes from 20,000 to 70,000 pass/h and ρ is 0.8, the BEF of LRT changes from 0.81 to 0.42 ¥/pkm, and the subsidy rate decreases from 60.29% to 23.42%. As ρ changes from 0.2 to 0.8 while the peak demand is 30,000 pass/h, the BEF decreases from 2.37 to 0.62 ¥/pkm, and the subsidy rate decreases from 86.51% to 48.78%.

In this paper we compare the calculation results with the data presented by Bian et al [43]. Note that the [43] was adopted by the Opinions on Strengthening the Management of Urban Rail Transit Planning and Construction [44]. Results show that the BEF calculated by the model under the same basic corridor conditions and capital cost is between 0.34 to 0.43 ¥/pkm, which is a little higher than the 0.3 ¥/pkm in [43]. The reason for that is the operator cost which in this paper includes interest of the construction and depreciation of equipment, and the non-operator income is not included in the revenue. It can be estimated that the results of this paper have certain reliability.

The profitability changes with the change of passenger demand in *Figures 2 and 3*. Since the peak demand is an important factor affecting the scale of the URT system, the variation reflects the mechanism that passenger demand affects profitability by influencing system scale. Therefore, we set $\rho=1$ to analyse the impacts of peak demand on different types of URT.

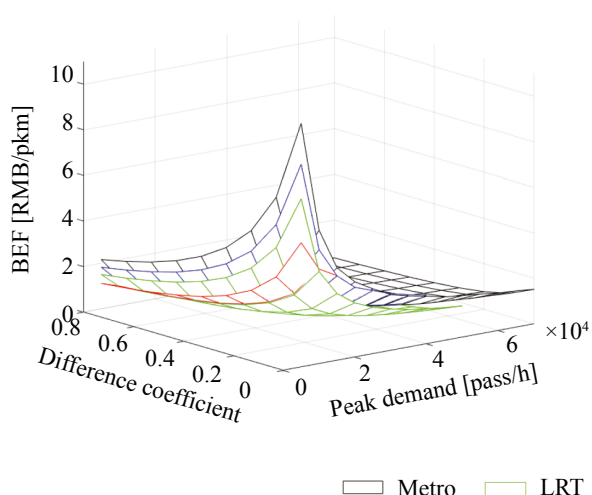


Figure 2 – The BEF for different demand levels

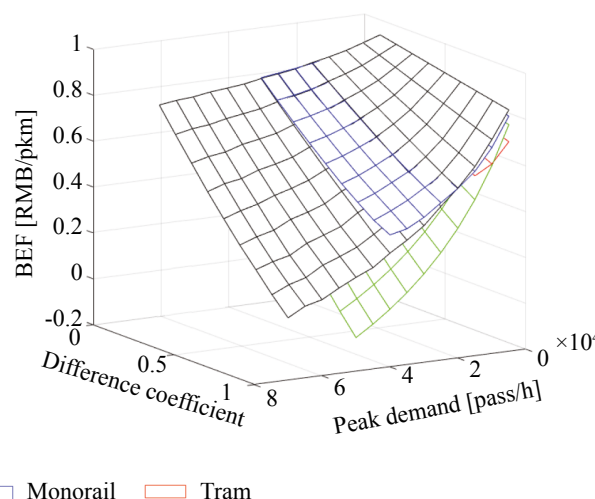


Figure 3 – The subsidy rate for different demand levels

From *Figures 4 and 5*, we know that the tram shows the lowest BEF and subsidy rate when the peak demand is below 10,000 pass/h, the LRT shows the highest profitability when the peak demand exceeds 10,000 pass/h. The profitability of the metro is higher than monorail when the peak demand is higher than 22,000 pass/h. The difference between the profitability curves is mainly caused by the mismatch between the capacity of URT and the passenger demand. As the passenger demand increases, less capable systems require more investment, such as larger train fleet size and more workload, resulting in higher operator cost and lower profitability.

Passenger demand is a factor that not only determines the investment but also affects the revenue of the operator. According to the model in this paper, for the passenger demand, there may be some differences between the revenue side and expense side, which can be depicted by the difference coefficient of demand. Meanwhile, there are different spatial distributions of passenger demand under different types of corridors.

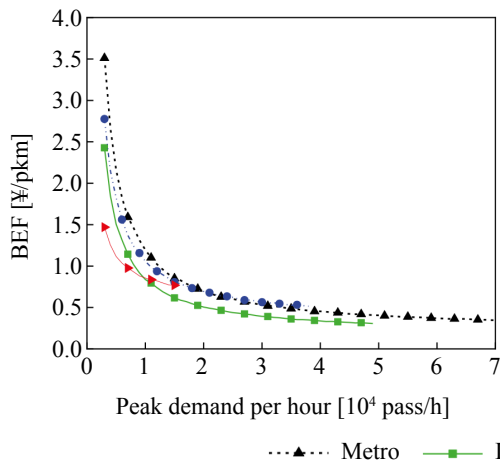


Figure 4 – The BEF for different peak demand

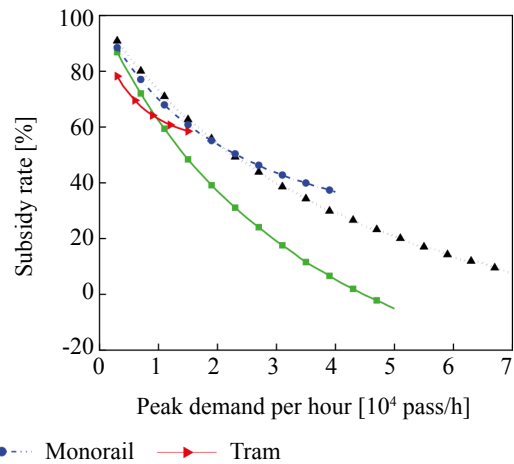
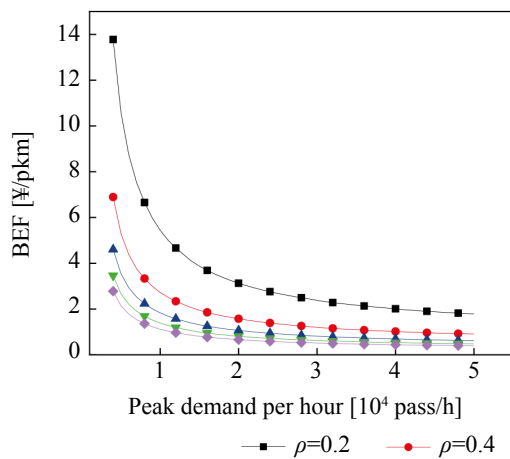


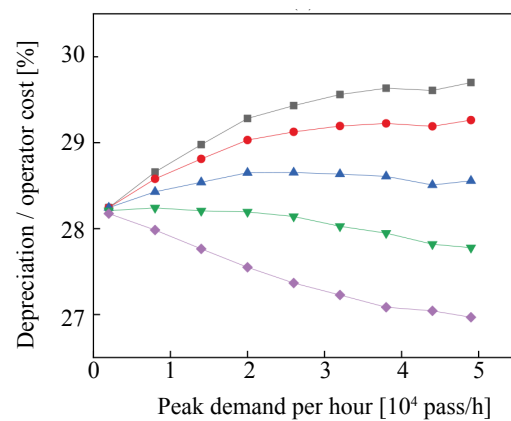
Figure 5 – The subsidy rate for different peak demand

3.3 The influence of demand difference coefficient

Figure 6a shows the BEF of LRT for different demand difference coefficients. We can see that at the same level of system size (capital cost), the greater the ρ , the progressively smaller the reduction in the BEF gets. Due to the sunk cost characteristic of URT, when the demand is relatively low, the minimum service level constraint leads to the actual operator cost being higher than the theoretical operator cost that corresponds to the actual demand level, which also leads to higher BEF. With the increase of ρ , the growth rate of passenger demand is higher than the corresponding growth rate of the operator cost, and the decrease in BEF rate is narrowed.



a) The BEF



b) The percentage of depreciation

Figure 6 – The influence of difference coefficient

In fact, the demand difference coefficient ρ reflects the waste of resources due to the mismatch between supply and demand. As shown in Figure 6b, the proportion of depreciation to operator cost increases as ρ decreases, and the gap between the proportions of depreciation to operator cost grows gradually with the increase of the demand for different values of ρ . For example, when the peak demand is 20,000 pass/h, the proportion of depreciation to operator cost of LRT increases from 27.38% to 29.50% as ρ changes from 1 to 0.2. Similarly, when the peak demand is 70,000 pass/h, the proportion of depreciation to operator cost increases from 26.62% to 30.06%. We can see that utilising the URT system with capacity that exceeds the passenger demand can aggravate the system depreciation burden, which directly affects the operator cost

[45]. Therefore, one should focus on the adaptability of the URT system and passenger demand of the corridor in the planning stage to avoid wasting resources.

3.4 The influence of the spatial distribution of demand

The radial corridors can be classified into three types, namely diameter corridor, long-distance radial corridor and short-distance radial corridor. The diameter corridor crosses the downtown area from one suburb area to another suburb area, see the cases presented in Sections 3.2 and 3.3 in this paper. For the short-distance radial corridor, one end connects the city centre and the other end connects the periphery of the centre and is 11 km in length. A long-distance radial corridor refers to a corridor with one end connecting the city centre and the other end connecting the suburb and is 22 km in length. Figure 7 shows the spatial distribution of passenger demand of the three types of corridor when the peak demand is 30,000 pass/h.

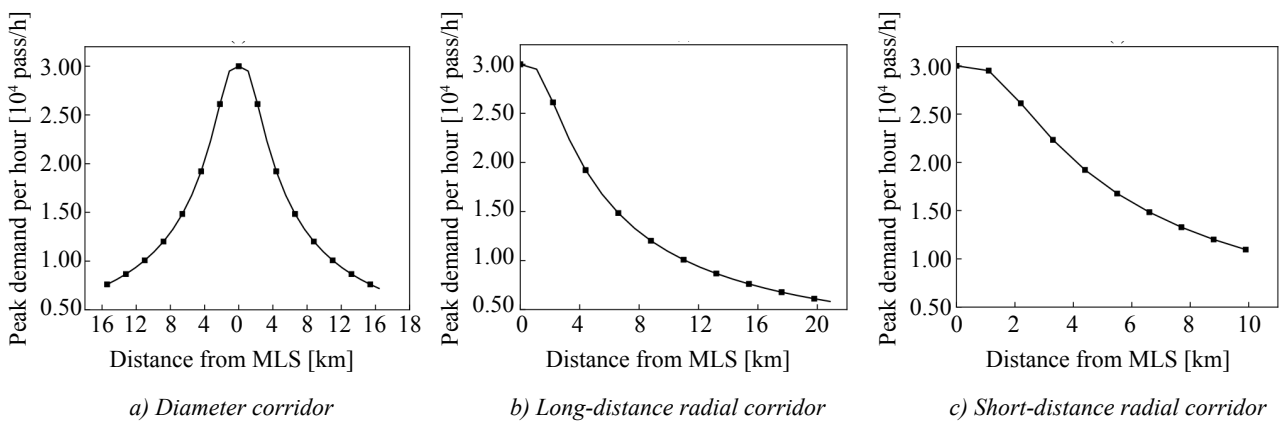


Figure 7 – Spatial distribution of passenger demand for different route types

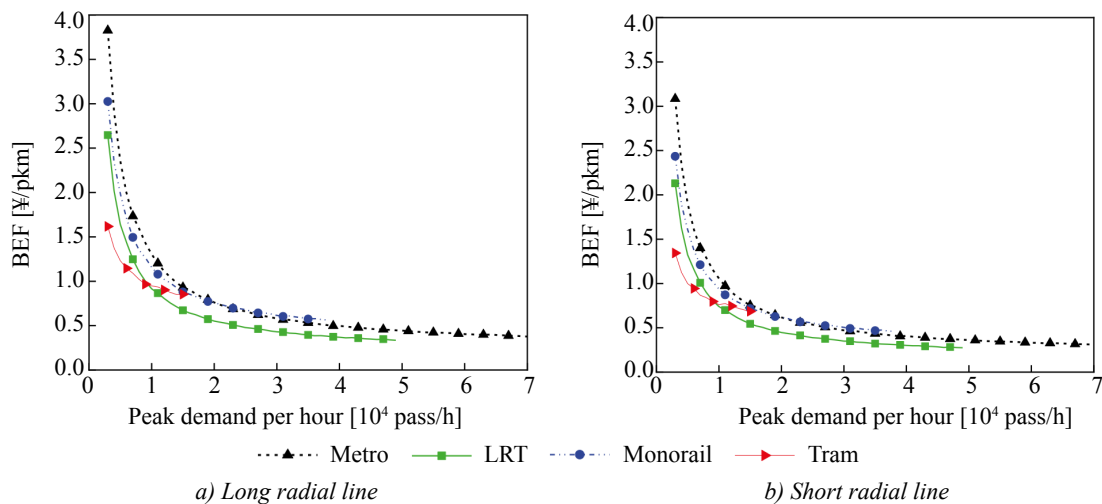


Figure 8 – The BEF of different route types

We analyse the BEF of different types of corridors by fixing the value $\rho=1$. The diameter corridor is shown in Figure 4, and the long-distance radial corridor and short-distance radial corridor are shown in Figure 8. It can be seen that the spatial distribution of demand does not affect the relationship between the BEF and the demand, and the relative magnitude between the profitability of the various systems. However, the value of the BEF has changed. Under the three demand distributions, the average changes in BEF of the four URT systems are 10.80%, 10.81%, 10.74% and 10.15%, respectively. We can see that the average

change of LRT is the biggest, while that of the tram is the smallest. The change degree in BEF is mainly influenced by the proportion of variable operator cost under different passenger demand levels.

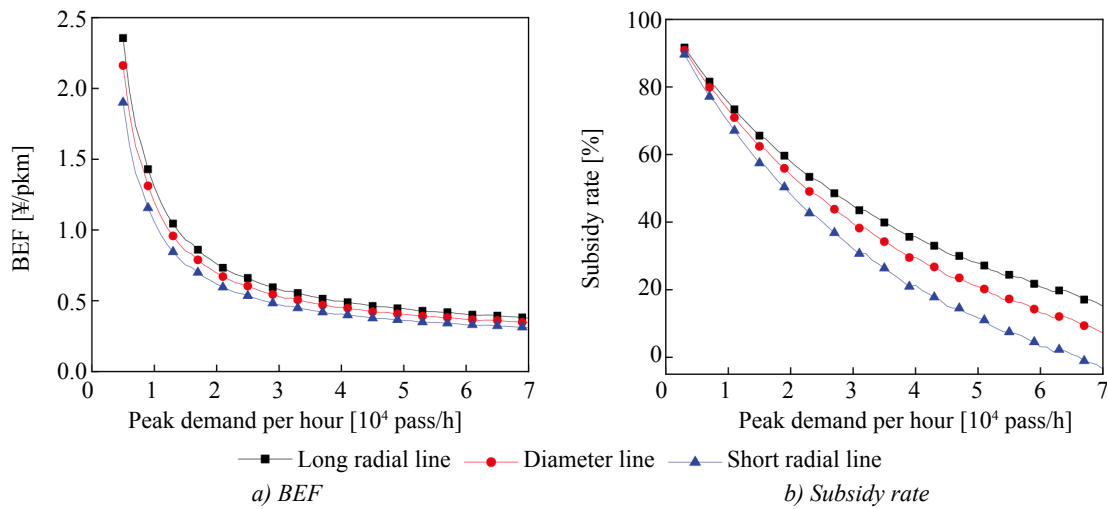


Figure 9 – BEF and subsidy rate of metro systems under different line types

Figure 9 shows the BEF and subsidy rate of the metro under different corridors. We can see that under the same peak demand the profitability of the short-distance radial corridor is the best, the second is the diameter corridor. The essential difference between the corridors is the PIT, therefore such a result demonstrates the mechanism by which the spatial distribution characteristics of passenger demand can influence profitability through the PIT. In practice, to serve more urban residents, more and more cities choose to extend rail transit lines to the edge of cities or suburbs. However, if the passenger demand in the extended part is relatively low, it will result in a more uneven spatial distribution of passenger demand along the corridor.

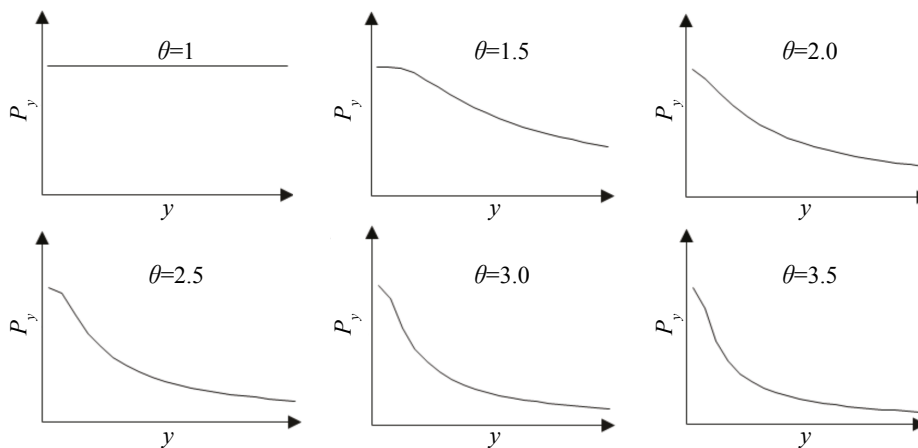


Figure 10 – Spatial distribution of passenger demand for different sectional uneven coefficients

The sectional uneven coefficient $\left(\theta = \max \{ P_1, P_2, P_3, \dots, P_M \} \cdot M / \sum_{m=1}^M P_m \right)$ can be used to describe the uneven degree of passenger distribution, P_m denotes the passenger of the m th section and M denotes the number of sections. Taking the long radial line as an example, the passenger distribution under different sectional uneven coefficients is shown in Figure 10.

Table 3 shows the profitability under different sectional uneven coefficients. Since the capacity of trams cannot reach 30,000 pass/h, only metro, LRT and monorail are shown here. It can be seen that the BEF increases linearly with the increase of the θ . The balance degree of demand distribution has a connection with

the location of the line. Therefore, to improve profitability, it is important to consider the spatial distribution of passenger demand and keep reasonable lengths of the lines when planning the URT. Comprehensive land development along the line shall also be considered to enhance the passenger attraction of the line.

Table 3 – The BEF under sectional uneven coefficients (¥/pkm)

θ	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Metro	0.41	0.62	0.82	1.03	1.24	1.44	1.66
LRT	0.31	0.46	0.61	0.77	0.92	1.07	1.23
Monorail	0.44	0.66	0.87	1.1	1.32	1.53	1.77

4. CONCLUSION AND FUTURE WORK

This paper designed an assessment model for the profitability of different types of URT systems. The spatial and temporal characteristics of passenger demand were considered. Case studies are carried out based on a realistic urban corridor, and the conclusion on developing URT at a strategic planning level was made.

First, to select proper types of URT for cities is essentially a matter of matching supply and demand. The mismatch between the URT capability and the passenger demand can cause at least two bad consequences. First, the burden of depreciation of the system can be aggravated even worse, which is not consistent with the passenger demand. This makes it hard to achieve financial balance. Second, the operator cost is increased and the operator losses can be worse. Therefore, selecting a reasonable URT system is necessary in the planning stage, but if the imbalance already exists, it is necessary to focus on improving the operational management to reduce costs by optimising transportation organisation measures.

Second, tram shows the best profitability at low demand levels due to the advantages of low costs, though the capacity is relatively small. This may explain why the tram is popular in small and medium-sized cities. But when the demand increases, the scale of the tram system needs to be severely enlarged and it will no longer be advantageous in terms of profitability, thus the LRT turns out to be a better choice. In the context of the poor cost-effectiveness of the existing URT development model, considering the lower cost and good performance of LRT in passenger attraction, there is hopefully a renaissance of LRT in China, as LRT has been developed in the past in some developed countries such as the United States [46]. However, the monorail is controversial in China. It is widely acclaimed for its small turning radius and climbing ability, but it is not yet standardised in China, leading to the risk that cities will face higher marginal costs when facing the manufacturers. In terms of profitability, the monorail is only more competitive than the metro at medium demand levels.

Third, in terms of profitability, the metro might be a competitive choice when the demand is lower than 50,000 pass/h but not the best, despite the capacity advantage. Sometimes metro (elevated rail) is considered the best choice at high demand levels [20]. However, in China, 88% of the metro is built underground even in land-rich areas, resulting in high costs. In addition, due to the excessive pursuit of large capacity, China has formed the URT network dominated by metro, with 78.81% of the operating mileage of metro and only 9.8% of LRT, monorail and tram. Although the metro does alleviate the traffic congestion problems in some cities, such a developing model did not work well. In fact, 70% of the cities did not reach the predicted passenger demand during the operating period, and 96% of the operators faced losses.

Fourth, the balance between the profitability of the operator and the public welfare of transportation services deserves attention, and the line length should be reasonably controlled in developing URT to safeguard the service level and operational efficiency. The spatial distribution characteristics of passenger demand portrayed in this paper reflect the phenomenon of insufficient demand in marginal areas due to the diversified construction of URT in China. The unbalanced spatial distribution of demand will affect the PIT of the lines and further affect the profitability, especially for metro, LRT and monorail which have higher costs.

It is necessary to note the limitations of this study and illustrate several logical extensions for future work.

- 1) The passenger demand is assumed to be exogenous in this paper. This assumption ignores the preference of passengers for alternative transport modes, which means that the difference of endogenous demand caused by the difference of URT service quality is not considered. Future research can develop the endogenous demand through the elasticity of passenger demand to travel time and crowding.
- 2) The proposed model is based on an independent corridor and the URT systems are assumed to have independent right-of-way. However, sometimes there may be no independent right-of-way for some types of URT systems. For example, trams in many cities only have semi-independent right-of-way. In this case, the train operation can be disturbed in the mixed traffic environment. The operating efficiency and cost are likely to be affected by traffic congestions or other uncertainties. Therefore, the operator cost model in mixed traffic can be improved in the future.
- 3) This paper mainly considers the operator cost. However, during the operation of URT systems, the noise, vibration, carbon emissions, etc. are the external costs that deserve attention. Future research can consider quantifying the external cost and internalising it to comprehensively compare the operation efficiency of different transit modes.
- 4) Only metro, LRT, monorail and tram were considered in this paper. With the social development and technological progress, URT will develop in the direction of multi system. The maglev, heavy rail transit, automated guideway transit and other rail transit modes can be studied in the future.

ACKNOWLEDGEMENT

This study was supported by the Fundamental Research Funds for the Central Universities (2021YJS095) and the National Natural Science Foundation of China (71971021). The authors deeply appreciate the support.

REFERENCES

- [1] Shen Q, Chen P, Pan H. Factors affecting car ownership and mode choice in rail transit-supported suburbs of a large Chinese city. *Transportation Research Part A: Policy and Practice*. 2016;94:31-44. DOI: 10.1016/j.tra.2016.08.027.
- [2] Kelly FJ, Zhu T. Transport solutions for cleaner air. *Science*. 2016;352(6288):934-936. DOI: 10.1126/science.aaf3420.
- [3] Wen S, Shi J, Zhang W. Impact of urban rail transit network on residential and commercial land values in China: A Complex Network Perspective. *Complexity*. 2021;2021:11-15. DOI: 10.1155/2021/8849066.
- [4] Guerra E, Cervero R. Cost of a ride: The effects of densities on fixed-guideway transit ridership and capital costs. *Journal of the American Planning Association*. 2011;77(3):267-290. DOI: 10.1080/01944363.2011.589767.
- [5] Sohu. *The project costs per km of heavy rail transit in Beijing are more than one billion CNY*. <http://news.sohu.com/20150630/n415908777.shtml> [Accessed 18th May 2020].
- [6] Ransom MR. The effect of light rail transit service on nearby property values. *Journal of Transport and Land Use*. 2018;11(1):387-404. DOI: 10.5198/jtlu.2018.1096.
- [7] Zhao J, et al. Cost of an urban rail ride: A nation-level analysis of ridership, capital costs and cost-effectiveness performance of urban rail transit projects in China. *Journal of Transport and Land Use*. 2018;11(1):1173-1191. DOI: 10.5198/jtlu.2018.1292.
- [8] China Association of Metros. *Annual Report. 2019*. <https://www.camet.org.cn/tjxx/5133> [Accessed 24th May 2022].
- [9] Ministry of Land, Infrastructure, Transport and Tourism. *Annual report of railway statistics. 2019*. https://www.mlit.go.jp/tetudo/tetudo_tk2_000053.html [Accessed 9th Aug 2022].
- [10] Korea Bureau of Statistics. *Comprehensive urban railroad indicators. 2019*.

- https://kosis.kr/statisticsList/statisticsListIndex.do?vwcd=MT_ZTITLE&menuId=M_01_01 [Accessed 9th Aug 2022].
- [11] Hensher DA, Ho C, Mulley C. Identifying preferences for public transport investments under a constrained budget. *Transportation Research Part A: Policy and Practice*. 2015;72:27-46. DOI: 10.1016/j.tra.2014.12.002.
- [12] Bokor Z. Cost calculation model for logistics service providers. *Promet – Traffic&Transportation*. 2012;24(6):515-524. DOI: 10.7307/ptt.v24i6.1198.
- [13] Hall M, Weiss L. Firm size and profitability. *The Review of Economics and Statistics*.1967; 319-331. DOI: 10.2307/1926642.
- [14] Meyer JR, John F, Wohl M. *The Urban Transportation Problem*. London: Oxford University Press; 1965.
- [15] Brand C, Preston J. *The software tool: Specification and case study validation*. Transport Studies Unit, University of Oxford. TSU Working Paper (Ref. 948), 2003.
- [16] Li XC, John P. Assessing the financial and social costs of public transport in differing operating environments and with endogenous demand. *Transportation Planning and Technology*. 2015;38(1):28-43. DOI: 10.1080/03081060.2014.976981.
- [17] Grimaldi R, Laurino A, Beria P. *The choice between bus and light rail transit: A stylised cost-benefit analysis model*. Munich Personal RePEc Archive; 2010. https://mpira.ub.uni-muenchen.de/24872/1/MPRA_paper_24872.pdf [Accessed 16th August 2022].
- [18] Tirachini A, Hensher DA, Jara-Díaz SR. Restating modal investment priority with an improved model for public transport analysis. *Transportation Research Part E: Logistics and Transportation Review*. 2010;46(6):1148-1168. DOI: 10.1016/j.tre.2010.01.008.
- [19] Manoratna DA, Kawata K, Yoshida Y. Environmental impact and travel time savings of a new monorail system in colombo’s commuting traffic. *Transportation Research Part D: Transport and Environment*. 2017;51:122-128. DOI: 10.1016/j.trd.2016.12.003.
- [20] Vu T, Preston J. Assessing the social costs of urban transport infrastructure options in low and middle income countries. *Transportation Planning and Technology*. 2020;43(4):365-384. DOI: 10.1080/03081060.2020.1747202.
- [21] Avenali A, et al. Rail versus bus local public transport services: A social cost comparison methodology. *Transportation Research Interdisciplinary Perspectives*. 2020;7:100200. DOI: 10.1016/j.trip.2020.100200.
- [22] Wang R. Autos, transit and bicycles: Comparing the costs in large Chinese cities. *Transport Policy*. 2011;18(1):139-146. DOI: 10.1016/j.tranpol.2010.07.003.
- [23] Keeler TE, Small K. *The full costs of urban transport part III: Automobile costs and final intermodal cost comparisons*. Monograph No. 21. University of California, Berkeley: Institute of Urban and Regional Development; 1975.
- [24] Flyvbjerg B, Skamris Holm MK, Buhl SL. How (in) accurate are demand forecasts in public works projects?: The case of transportation. *Journal of the American Planning Association*. 2005;71(2):131-146. DOI: 10.1080/01944360508976688.
- [25] Kain JF. The urban transportation problem: A reexamination and update. In: Gomez-Ibanez J, Tye WB, Winston C. (Eds.) *Essays in transportation economics and policy: A handbook in honor of John R. Meyer*. Washington, DC: Brookings Institution Press; 1999. p. 359-401.
- [26] Pickrell DH. *Urban rail transit projects: Forecast versus actual ridership and costs*. Final report. Urban Mass Transportation Administration, United States. Report number: UMTA-MA-08-9021-89-1, 1990.
- [27] Ministry of Construction of the People's Republic of China. CJJ/T 114-2007. *Classification standard of urban public transport*. Beijing: China Architecture and Building Press; 2007.
- [28] Anas A, Moses LN. Mode choice, transport structure and urban land use. *Journal of Urban Economics*. 1979;6(2):228-246. DOI: 10.1016/0094-1190(79)90007-X.
- [29] Monson K. String block vs superblock patterns of dispersal in China. *Architectural Design*. 2008;78(1):46-53. DOI: 10.1002/ad.608.
- [30] Wang M, et al. Determining the level of service scale of public transport system considering the distribution of service quality. *Journal of Advanced Transportation*. 2022;2022. DOI: 10.1155/2022/5120401.

- [31] Shang B, Zhang X. Passenger-flow spatial distribution model of urban rail transit. [城市轨道交通客流空间分布模型]. *Journal of Southwest Jiaotong University* [西南交通大学学报]. 2013;48(03):539-545. DOI: 10.3969/j.issn.0258-2724.2013.03.023.
- [32] Sharma R, Newman P. Urban rail and sustainable development key lessons from Hong Kong, New York, London and India for emerging cities. *Transportation Research Procedia*. 2017;26:92-105. DOI: 10.1016/j.trpro.2017.07.011.
- [33] Kot S. Cost structure in relation to the size of road transport enterprises. *Promet – Traffic&Transportation*. 2015;27(5):387-394. DOI: 10.7307/ptt.v27i5.1687.
- [34] Nurcahyo R, et al. Mass rapid transit operation and maintenance cost calculation model. *Journal of Advanced Transportation*. 2020;2020. DOI: 10.1155/2020/7645142.
- [35] Zhu Y, Zhang XQ, Jin Y, Liao Y. Research on construction condition of intercity railway based on financial analysis [基于财务分析的城际铁路建设条件研究]. *Journal of Railway Engineering Society* [铁道工程学报]. 2011;28(08):116-120. DOI: 10.3969/j.issn.1006-2106.2011.08.022.
- [36] Jiang Z, et al. Reinforcement learning approach for coordinated passenger inflow control of urban rail transit in peak hours. *Transportation Research Part C: Emerging Technologies*. 2018;88:1-16. DOI: 10.1016/j.trc.2018.01.008.
- [37] Zhu Y, et al. A bi-level model for single-line rail timetable design with consideration of demand and capacity. *Transportation Research Part C: Emerging Technologies*. 2017;85:211-233. DOI: 10.1016/j.trc.2017.09.002.
- [38] Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB50157-2013. *Code for design of metros*. Beijing: China Architecture and Building Press; 2013.
- [39] Li YH, et.al. Research on the quantitative method of multi-level and multi-mode rail transit system selection in metropolitan areas [都市区轨道交通多层次各制式量化选择方法研究]. *Railway Standard Design* [铁道标准设计]. 2020;64(06):9-16. DOI: 10.13238/j.issn.1004-2954.201907280002.
- [40] National Bureau of Statistics. *Annual Average Wages of Employed Persons by Industry and Position in 2020*. http://www.stats.gov.cn/xxgk/sjfb/zxfb2020/202105/t20210519_1817691.html [Accessed 12th May 2022].
- [41] The People's Republic of China. *Opinions of the general office of the State Council on further strengthening the management of urban rail transit planning and construction*. Beijing: the Office of the State Council; 2018.
- [42] Ministry of Construction of the People's Republic of China. JB1004-2008. *Construction standards for urban rail transit engineering projects*. Beijing: China Planning Press; 2008.
- [43] Bian Y, Yang Y, Zhou X. Study on construction condition index of urban rail transit project [城市轨道交通项目建设条件指标研究]. *Urban Rapid Rail Transit* [都市快轨交通]. 2015;28(6):1-5. DOI: 10.3969/j.issn.1672-6073.2015.06.001.
- [44] People's Republic of China. *National Development and Reform Commission on Strengthening Urban Rail Transit Notice of planning and construction management*. Beijing: National Development and Reform Commission; 2015.
- [45] Li WX, Yin S. Analysis on cost of urban rail transit [城市轨道交通成本构成分析]. *Journal of Transportation Systems Engineering & Information Technology* [交通运输系统工程与信息]. 2012;12(02):9-14. DOI: 10.3969/j.issn.1009-6744.2012.02.002.
- [46] Kuby M, Barranda A, Upchurch C. Factors influencing light-rail station boardings in the United States. *Transportation Research Part A: Policy and Practice*. 2004;38(3):223-247. DOI: 10.1016/j.tra.2003.10.006.

周琪¹, 毛保华², 彭赛荣³, 黄俊生⁴, 田佩宁⁵

¹ 18114062@bjtu.edu.cn, 北京交通大学综合交通运输大数据应用技术交通运输行业重点实验室

² 通讯作者, bhmao@bjtu.edu.cn, 北京交通大学综合交通运输大数据应用技术交通运输行业重点实验室

³ 18120246@bjtu.edu.cn, 中国铁道科学研究院通信信号所

- ⁴ 19114037@bjtu.edu.cn, 北京交通大学综合交通运输大数据应用技术交通运输行业重点实验室
- ⁵ 20120900@bjtu.edu.cn, 北京交通大学综合交通运输大数据应用技术交通运输行业重点实验室

客流对不同城市轨道交通制式盈利能力的影响研究

摘要

随着城市轨道交通的迅猛发展，成本高昂与客流不足的问题日益突出。然而，由于客流需求具有多维特征导致其对盈利能力的影响分析具有一定难度。为此，本文在考虑客流需求时空特性的基础上，提出一种分析不同城市轨道交通制式盈利能力的策略，评估单一走廊下地铁、轻轨、单轨、有轨电车的盈利能力。结果表明：低需求水平下，有轨电车是最优选择；中等需求水平下，轻轨和单轨具有竞争力；高需求水平下，即使地铁运能更大，具有中高运能和低成本的轻轨仍是一个很好的选择。在客流规模不足的条件下使用超出需求的系统，将增加与客流规模不相符的系统折旧负担，提高实现运营财务平衡的条件。本文对客流空间分布特征的刻画体现了中国因城市轨道交通多元化建设导致的边缘区客流不足的现象。

关键词

城市轨道交通；盈利能力；轻轨；客流需求；空间特征