Traffic System Optimization Model Based on Travel Demand of Multi-mode Traffic Network

Xinzheng Yang¹,2,a, Kang Zhou¹,*,b, Xiao Peng¹

¹Key Laboratory of Advanced Public Transportation Science, China Academy of Transportation Sciences, Beijing, China, 240 Huixinli, Chaoyang District, 100029
²School of Automobile Engineering, Chang’an University, Xi'an, China
Middle-section of Nan'er Huan Road, 710064

*a1583552819@qq.com
*b Corresponding author: wszhka@163.com

Abstract—The urban multi-mode traffic system, which is composed of rail transit, bus and trolley bus, taxi (including online car Hailing), bicycle and walking, provides the basic guarantee for the daily travel of urban residents. Based on the analysis of urban multi-mode transportation system and network characteristics, the directed network diagram of multi-mode transportation system is constructed. Based on the research methods of related fields at home and abroad, aiming at the characteristics of urban residents’ travel, especially commuting travel, a multi-objective optimization model of urban residents’ travel scheme analysis from the perspective of travel time, travel cost, etc. is constructed. Considering the non-linear characteristics of the model, the multi-objective model is transformed into a single objective model, and the model is solved by CPLEX optimization software. Finally, the applicability and reliability of the model are verified by an example.

1. Introduction
In the process of urban development and urban spatial structure evolution, urban transportation system has always played a very important role. Urban development and urban transportation are interrelated, promoted and influenced each other. Urban spatial structure and land use form determine the occurrence, attraction and distribution of urban traffic. The development of urban traffic makes the adjustment and expansion of urban spatial structure and land use possible, which reflects the interactive and recursive relationship. The urban multi-mode transportation system is formed and evolved gradually under the interaction between the two.

By analyzing the research results of multi-mode traffic at home and abroad, we can see that urban multi-mode traffic network is widely used in the formation of travel chain and the analysis of relevant characteristics. The state variables of multi-mode traffic network can reasonably express the time, distance, cost and other parameters of combined mode travel, which plays an irreplaceable role in describing the behavior of combined mode travel. Xi Zeng and Ciguang Wang (2007) used graph theory to further differentiate the travel chain in multi-mode traffic network into in riding chain and transfer chain, and described the node added state variables. Based on the analysis of commuting traffic characteristics, a multi-mode commuting traffic network diagram is constructed [1]. Liyin Xiong and Feng Lu (2008) proposed a description method of urban multi-mode traffic network and its connectivity.
based on the concept model of road network space and GDF logical data model [2]. Jianwei Zhang, Feixiong Liao (2011) constructed and verified a multi-mode traffic network model based on advanced travel information system. In this model, the network is divided into public network and private network, and then the super network is constructed by using transfer link. The validity of the model and algorithm is verified by research [3]. Tiangang Qiang, Mingming Zhao, et al. (2019) used the original mapping method to build the urban multi-mode traffic network model, which consists of car network, ground bus network and rail transit network, and proposed the robustness analysis index of urban multi-mode traffic network, and compared the stability of the traffic network when it is attacked [4]. In terms of travel options, Yuan Li et al. (2014) considered the impact of transfer times on the travel time of passengers and the route cost including walking time, waiting time, travel time, transfer time and transfer penalty, constructed a stochastic user equilibrium model to describe the distribution of urban public transport O-D demand on the network [5]. Qing Song (2017) and others proposed the construction method of urban bicycle network based on OpenStreetMap and the mathematical model of multi criteria bicycle path optimization based on it, and gave an optimal multi criteria path planning method based on clustering to solve the model [6].

With the continuous progress of urbanization in China, the scale of urban multi-mode traffic network is increasing, and the structure of multi-mode traffic network is improving. How to optimize and adjust the multi-mode traffic network according to the travel needs of urban residents is of great significance. Based on the urban multi-mode traffic network, combined with the directed graph, this paper constructs an analysis model of urban residents' travel plan. On this basis, the urban traffic network can be optimized and the urban traffic infrastructure can be improved according to the urban characteristics and development positioning.

2. Characteristics of urban multimodal transportation system and network

Multi-mode traffic system is a significant feature of urban transportation system. The cooperation of various transportation modes serves people's travel together, which embodies the dynamic functional relationship of people's production and life. Urban multi-mode traffic system mainly includes transportation system (operation of traffic behavior), road (rail) system (passage of traffic behavior) and traffic management system (control of traffic behavior). Among them, the transportation system is the traffic behavior that directly serves the transportation demand, the road system serves for the transportation system to complete the traffic behavior, and the traffic management system is the guarantee of the normal and efficient operation of the whole transportation system.

With the continuous improvement of transportation infrastructure, the urban traffic network is becoming more and more complex. With the expansion of the city scale, a comprehensive urban traffic network consisting of bicycle, car, conventional bus, subway and intercity railway is gradually established. In the multi-mode traffic network, each single traffic mode operates according to its own rules. Travelers can connect each traffic sub network through the transfer behavior to realize the dynamic transfer of traffic demand between different traffic sub networks. A reasonable multi-mode traffic network has a positive role in promoting urban residents' travel and urban development.

In this paper, bicycle, public transport and private car travel are the main modes of urban residents' travel, OD points of residents in the region and stations (including transfer points) on the transportation network are the nodes of multi-mode traffic network, and the arc connecting all nodes in the region is the travel path. The specific network structure is shown in Figure 1 (the data on the connecting arc in the figure is the travel cost and time between nodes, with the unit of yuan and min respectively). For the same traffic mode, it is assumed that the path time and cost from the starting point to the first node and the last node to the destination are the same (the optimal road).
3. Construction of travel demand analysis model

3.1 Problem Description
In the urban multi-mode traffic network, urban residents can have different options for travel. For urban residents, reasonable choice of different travel schemes according to their needs can save travel costs and travel time consumption. For urban traffic management and planning departments, according to different demand characteristics of residents' travel and urban development positioning, urban traffic system can be optimized and traffic infrastructure can be improved. Suppose that the residents of a certain area arrive at the destination $d$ from the departure $o$, and the travel path is composed of the road sections with different modes of transportation and the medium conversion passenger nodes between the travel modes. There are bicycle, public transport or private car connections between any two nodes connected, and there are $q$ alternative paths between each od. At the transfer node, residents can transfer between different modes of transportation, which requires extra time and cost. The whole travel process is also constrained by line capacity and transfer times. Passengers have certain requirements for the time spent on the route and travel cost. On the premise of assuming the safety and reliability of all kinds of travel modes, taking travel cost and travel time as the evaluation elements of the route, a multi-objective model with the minimum travel cost and travel time is constructed. According to the passenger flow situation under different demand characteristics, the node of each route, the best road section between nodes and the combination of travel modes on the road section are finally selected, and based on this, the traffic network and infrastructure will be improved and optimized.

3.2 Modeling Assumptions
Before modeling, the following assumptions need to be made:
- In the process of travel, for two adjacent nodes, residents can only choose one traffic mode and one travel section.
- The starting point of each path is the starting point of residents, and the ending point is the destination, each path has and only has one starting point and one destination.
- Residents' transfer between different modes of transportation can only occur at the nodes, and at most one transfer between bicycle and public transport can be conducted at each node, regardless of the transfer within a public transport or between different modes of public transport.
- When residents choose only one way to travel, there is only one optimal route.
3.3 Parameters Setting

The multi-mode traffic network is represented by directed graph \( G = (N, A) \), and the traffic mode is reflected in the road section \([7, 8]\). \( N \) is the set of nodes on the path, node \( a \) satisfies \( i \in N \); \( A \) is the joint arc set of nodes, \( A = A' \cup A'' \), \( A' \) is the set of link arcs between nodes. \( P \) is defined as the set of all effective travel paths, \( p \) is a path within the set of paths, which satisfies \( p \in P \), \( A^p \) is the collection of transfer arcs at the node, \( a \in A \); \( o \) and \( d \) are the departure and destination of residents' travel (\( O \) is the first node on the path, \( D \) is the last node on the path), \( O \) and \( D \) are the set of departure and destination respectively, \( o \in O \), \( d \in D \). \( T \) is the unit travel cost on the connected arc \( a \); \( \gamma^p_{od} \in \{0, 1\} \), if the residents between \( o \) and \( d \) choose path \( p \), then \( \gamma^p_{od} = 1 \), otherwise \( \gamma^p_{od} = 0 \); \( \delta^p_{od} \in \{0, 1\} \), if the p-th route selected by residents between \( o \) and \( d \) includes link arc \( a \), then \( \delta^p_{od} = 1 \), otherwise \( \delta^p_{od} = 0 \); \( \tau^p_a \) is the travel time of the connecting arc on the route (including the travel time on the road section and the transfer time between different traffic modes); \( \zeta \) is the monetary value of residents' travel time; \( \omega^a \) is the flow rate on the joint arc \( a \); \( m^a \) is the maximum traffic (transport) capacity on the combined arc \( a \); \( \Delta \) is the maximum positive number.

\( x^p_{od} \) is the decision variable, which represents the passenger flow allocated on the path \( p \) between \( o \) and \( d \) in the decision cycle.

3.4 Objective Function and Constraints

\[
\min \ C = \sum_{o \in O} \sum_{d \in D} \sum_{p \in P} x^p_{od} \delta^p_{od} x^p_{od} c_a \quad (1)
\]

\[
\min \ T = \sum_{o \in O} \sum_{d \in D} \sum_{p \in P} \sum_{a \in A} x^p_{od} \delta^p_{od} x^p_{od} \tau^p_a \zeta \quad (2)
\]

\[
\omega^a = \sum_{o \in O} \sum_{d \in D} \sum_{p \in P} \delta^p_{od} x^p_{od}, \forall a \in A \quad (3)
\]

\[
\omega^a \leq m^a, \forall a \in A \quad (4)
\]

\[
x^p_{od} \geq 0, x^p_{od} \leq \Delta \gamma^p_{od}, \forall o \in O, d \in D, p \in P \quad (5)
\]

Among them, equation (1) is the objective function to calculate the minimum travel cost of residents; equation (2) is the objective function to calculate the minimum travel time of residents; equation (3) is the flow constraint of the connecting arc on the path to calculate the connecting arc; formula (4) is the capacity constraint, and the passenger flow on joint arc \( a \) should be less than the maximum capacity on the road section; formula (5) is the relationship constraint between passenger flow and path, when \( \gamma^p_{od} = 1 \), the passenger flow on the path will be allocated.

4. Model solution

4.1 Model Processing

For multi-objective model, in order to facilitate the solution and analysis, it is usually transformed into a single objective model. In this paper, two objective functions are transformed into a single objective model by using weight factors. Given that \( \sigma \) is the travel cost weight factor and \( \theta \) is the travel time weight factor, and \( \sigma + \theta = 1 \), \( 1 \geq \sigma > 0, 1 \geq \theta > 0 \) is satisfied, the objective functions (1) and (2) are transformed into
\[
\min C_1 = \frac{1}{\theta} \sum_{\omega \in D} \sum_{d \in D} \sum_{p \in P} \sum_{a \in A} y_{\omega}^{p} \delta_{\omega}^{p} x_{d}^{p} c_{a} + \frac{1}{\theta} \sum_{\omega \in D} \sum_{d \in D} \sum_{p \in P} \sum_{a \in A} y_{\omega}^{p} \delta_{\omega}^{p} x_{d}^{p} t_{a}^{p} \zeta
\]  

(6)

4.2 Solution Method

Based on the existing multi-mode traffic network, the initial feasible travel network is generated, and then the optimal travel scheme is determined by the given analysis model to analyze the travel choice of urban residents in different needs. Based on the processing of model, ILOG CPLEX is used to solve the problem.

**Step 1** determine the feasible initial network according to the different traffic modes of the OD arc segment. When the initial network is large, the initial network is divided into several blocks through the traffic area division, and analyzed separately [9].

**Step 2** label the initial path and its arc segment, and calibrate the parameters of the labeled initial network.

**Step 3** the model is solved using ILOG CPLEX. In the set representation of CPLEX code, the relationship matrix is used to represent the path and arc segment, the path and passenger flow, and the arc segment on the path and the cost and time.

5. Case study

Taking the road network in Figure 1 as an example, the network includes three starting points, two end points and 27 nodes (three bicycle and public transport transfer points, private car travel does not consider transfer, assuming that the travel time cost of private car and taxi is the same). Table 1 shows the OD of residents' travel in a certain hour. Due to the influence of weather, physical reasons, inability to take public transportation or cycling and other special circumstances, there will be certain random uncertainty in the OD of travel. Before using the model for analysis and calculation, first use the random function (0-12%) to calculate and process the travel demand of different modes among OD. Table 2 shows the capacity of different modes of transportation after deducting the transit passenger flow outside the region from the OD of multi-mode transportation network (the transfer capacity of bicycle and public transportation is not restricted) and the monetary value of residents' travel time. Due to the space limitation, the capacity and other parameters on the joint arc of each road section are not listed one by one.

**TABLE 1 OD of urban residents**

| Origin-Destination | Number of People |
|--------------------|------------------|
| \( o_1 - d_1 \)    | 1000             |
| \( o_2 - d_1 \)    | 1500             |
| \( o_3 - d_1 \)    | 1300             |
| \( o_1 - d_2 \)    | 1200             |
| \( o_2 - d_2 \)    | 1300             |
| \( o_3 - d_2 \)    | 1500             |

**TABLE 2 Characteristic parameters of multimodal traffic network**

| Monetary Value of Travel Time (RMB/min) | Bicycle | Public | Private car |
|----------------------------------------|---------|--------|-------------|
| 0.2                                    |         |        |             |
| 0.3                                    |         |        |             |
| 0.3                                    |         |        |             |
### 4.3 Solution Results

Based on the above model and parameters, the solution is calculated by ILOG CPLEX optimization software, and the results are shown in Table 3. Without considering the influence of travel time, cost and random factors respectively, the optimization results as shown in Table 4 and Table 5 are obtained.

| Origin-Destination | Traffic capacity (vehicle / h) | Traffic capacity (person / h) | Traffic capacity (pcu/h) |
|--------------------|-------------------------------|-------------------------------|---------------------------|
| o1-d1              | 900                           | 650                           | 800                       |
| o1-d2              | 600                           | 600                           | 700                       |
| o2-d1              | 800                           | 900                           | 700                       |
| o2-d2              | 500                           | 600                           | 1000                      |
| o3-d1              | 800                           | 800                           | 600                       |
| o3-d2              | 500                           | 700                           | 1000                      |

| TABLE 3 Calculation results |
|-------------------------------|
| **Origin-Destination** | **Travel Mode** | **Traffic Flow** | **Origin-Destination** | **Travel Mode** | **Traffic Flow** |
|----------------------------|-----------------|------------------|-----------------------|-----------------|------------------|
| o1-d1                      | Bicycle         | 28               | o2-d2                 | Bicycle         | 156              |
|                            | Public transport| 609              |                       | Public transport| 592              |
|                            | Private car     | 363              |                       | Private car     | 552              |
| o1-d2                      | Bicycle         | 64               | o3-d1                 | Bicycle         | 89               |
|                            | Public transport| 583              |                       | Public transport| 753              |
|                            | Private car     | 553              |                       | Private car     | 458              |
| o2-d1                      | Bicycle         | 80               | o3-d2                 | Bicycle         | 173              |
|                            | Public transport| 823              |                       | Public transport| 691              |
|                            | Private car     | 597              |                       | Private car     | 636              |

| TABLE 4 Solution results without considering travel time |
|-------------------------------|
| **Origin-Destination** | **Travel Mode** | **Traffic Flow** | **Origin-Destination** | **Travel Mode** | **Traffic Flow** |
|----------------------------|-----------------|------------------|-----------------------|-----------------|------------------|
| o1-d1                      | Bicycle         | 900              | o2-d2                 | Bicycle         | 500              |
|                            | Public transport| 100              |                       | Public transport| 600              |
|                            | Private car     | 0                |                       | Private car     | 200              |
| o1-d2                      | Bicycle         | 600              | o3-d1                 | Bicycle         | 800              |
| Origin-Destination | Travel Mode | Traffic Flow | Origin-Destination | Travel Mode | Traffic Flow |
|--------------------|-------------|--------------|--------------------|-------------|--------------|
| $o_1-d_1$          | Bicycle     | 0            | $o_2-d_2$          | Public transport | 300          |
|                    | Public transport | 200         |                    | Public transport |              |
|                    | Private car   | 800          |                    | Private car     | 1000         |
| $o_1-d_2$          | Bicycle     | 0            | $o_3-d_1$          | Public transport | 700          |
|                    | Public transport | 500         |                    | Public transport |              |
|                    | Private car   | 700          |                    | Private car     | 600          |
| $o_2-d_1$          | Bicycle     | 0            | $o_3-d_2$          | Public transport | 500          |
|                    | Public transport | 800         |                    | Public transport |              |
|                    | Private car   | 700          |                    | Private car     | 1000         |

### 4.4 Result Analysis

Through the above calculation results, it can be clearly found that travel time and travel cost have a very important impact on the choice of residents’ travel mode, which are important considerations for the optimization of urban multimodal transportation system.

Although the calculation example sets the cost weight as 0.7, hoping that the residents can choose the bicycle and public transport mode with lower cost and more environmental protection, but due to the relatively high time value of bicycle commuting travel, the proportion of car travel is still large under the public transport capacity restriction (mainly reflected in congestion). Relatively speaking, public transport is relatively low in travel cost and time, accounting for the largest proportion of the three modes of travel. In view of the long transfer time between bicycle and public transport given in this paper, there is no passenger flow between bicycle and public transport. According to the results of the case study, the multi-mode traffic network in the region needs to improve the public transport service capacity from the aspects of increasing the density of the public transport network and improving the public transport capacity. The specific improvement scheme can be considered according to the passenger flow distribution results on each line.

In addition, without considering the impact of travel time, residents are more willing to choose public transport and bicycle travel with lower cost. Without considering the impact of travel cost, residents are more willing to choose private car travel with the shortest time. However, in the actual travel, due to the limitation of road capacity and public transport capacity, it is difficult for residents to choose the travel mode simply according to the travel time or cost. When optimizing the urban multi-mode traffic system, the urban traffic development orientation should be fully considered while considering the travel needs of urban residents. For example, for cities that encourage the development of green travel, the weight of travel time should be appropriately reduced to make residents prefer to...
choose green travel modes such as public transport and bicycles. On this basis, the line can be optimized and the infrastructure can be improved according to the results of passenger flow distribution. For the new small and medium-sized cities, the proportion of car travel can be increased appropriately under the premise of urban land use planning permission. The analysis of travel scheme can provide some data support for urban road optimization, in order to facilitate the reconstruction and expansion of traffic infrastructure according to urban characteristics and travel demand.

6. Conclusion

- Based on the background of urban multi-mode traffic system, the travel schemes of residents with different needs under the urban multi-mode transportation network are analyzed.
- Based on the analysis of the relevant factors that affect the travel of urban residents, a multi-objective travel analysis model with the goal of the minimum total cost and the shortest time is constructed.
- The multi-objective model is transformed into a single objective model by setting the weight factor. On this basis, the model is solved by ILOG CPLEX optimization software.
- For large-scale multi-mode traffic network, the large-scale traffic network can be divided into several block networks by traffic area division, and then be solved and analyzed separately.
- According to the calculation results of different travel needs, the urban traffic system can be optimized from the macro and micro perspectives.
- In this paper, the traffic network of bicycle, public transport and private car travel modes is studied, but other modes and complex issues such as mutual transfer are ignored. It is necessary to further analyze in the next study. In addition, with the increase of the number of private cars on the road, the road congestion is gradually intensified, and the travel time of private cars is gradually longer, which limits the residents to choose private cars for travel. Therefore, the relationship between road congestion and travel time, the impact on residents' travel, and the sensitivity analysis of travel cost and time need to be further studied.

Acknowledgment
This study was supported by the National Key Research and Development Program of China (No. 2018YFB1600900).

References
[1] X. Zeng, C. G. Wang. Improvement of Logit model and its application in forecasting the distribution ratios of passenger flows on Cheng-Yu intercity railroad, Journal of Changsha Communications University, vol. 23, pp. 50-53, December 2007.
[2] L. Y. Xiong, F. Lu, C. B. Chen. Connectivity model for multi-model urban transportation networks, Geomatics and Information Science of Wuhan University, vol. 33, pp. 393-396, April 2008.
[3] J. W. Zhang, F. X. Liao, T. Arentze, et al. A multimodal transport network model for advanced traveler information systems, Procedia Computer Science, vol. 38, pp. 912-919, May 2011.
[4] T. G. Qiang, M. M. Zhao, Y. L. Pei. An analysis of characteristic of complex network and robustness in Harbin multi-mode traffic network, Journal of Transport Information and Safety, vol. 37, pp. 65-71, February 2019.
[5] Y. Li, B. F. Si Si, X. B. Yang, et al. A stochastic user equilibrium model and algorithm for urban transit network with transfer cost, Systems Engineering — Theory & Practice, vol. 34, pp. 2127-2134, August 2014.
[6] Q. Song, X. L. Li, M. Li. OpenStreetMap based modeling and multi-criteria routing of urban cycleway Network, Journal of Transportation Systems Engineering and Information Technology, vol. 17, pp. 143-149, June 2017.
[7] K. Zhou, S. W. He, R. Song, et al. Decision scheme optimization for empty pallets dispatching based on pallet pool mode, Control and Decision, vol. 30, pp. 2009-2013, November 2015.
[8] K. Zhou, S. W. He, R. Song, et al. Optimization model of railway empty pallet dispatching based on the mode of pallet pool [J]. Journal of Beijing Jiaotong University, vol. 38, pp. 22-26, June 2014.

[9] B. H. Wang, S. W. He, R. Song, et al. Multi-modal express shipment network routing optimization model and algorithm, Journal of the China Railway Society, vol. 31, pp.12-16, April 2009.