Citation: QIN Peng, XIAO Liang, CHEN Jiankai. Deficiency of Classic Trip Distribution Models and Exploration of the New Theory [J]. Urban Transport of China, 2019 (05): 84–90, 104.

Deficiency of Classic Trip Distribution Models and Exploration of the New Theory

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Abstract: Due to the deficiencies in the classic trip distribution models, the Origin Destination (OD) matrices obtained from these models lack scientificity and their accuracy is still open to question. To solve this issue, we should explore and develop a new trip distribution theory and establish a scientific and reasonable trip distribution model. This paper analyzes the deficiencies of several trip distribution studies and classic trip distribution models, such as the Growth Factor Model and the Gravity Model, and proposes that the essence of trip distribution forecasting is to deeply understand the inherent logic among travelers, travel modes, origins, and destinations, which are related to travelers' characteristics. The paper discusses the relationship among the key factors, including land use, travelers, and travel modes, and explores the inherent relationship between these key factors and trip distribution. Based on the study above, the paper proposes a new trip distribution theory based on the key factors and a general idea for developing trip distribution forecasting models. Finally, the paper establishes a conceptual trip distribution model based on the new theory and points out the necessity to promote the research on the forecasting of urban development and the travel behavior of different groups. **DOI:** 10.13813/j.cn11-5141/u.2019.0513-en

Keywords: transportation forecast; trip distribution; OD matrix; group attribute; transportation mode selection

1 Overview of trip distribution forecast

The birth of transportation planning theory is marked by "Chicago Area Transportation Study" published by the City of Chicago in 1962 [1]. At present, the common forecasting method of travel demand in transportation planning practice is the four-step method, in which trip distribution is aimed at forecasting the trip exchange volume among Traffic Analysis Zones (TAZs), and the result is presented in the form of Origin Destination (OD) matrices [2]. The OD matrices obtained from the step of trip distribution and the shares obtained from the step of mode split are the basis for the calculation of traffic volume on each road segment in the step of traffic assignment, so trip distribution is a key step in the four-step method.

Since the birth of transportation planning theory, a vast amount of studies have been conducted on trip distribution. However, the fact is that the trip distribution results are often inaccurate or even incorrect in practice. As pointed out in past studies, there are serious deficiencies in classic trip distribution models (i.e. growth factor models and gravity models), so it is necessary to explore improvements and new theories for trip distribution. Previous studies mainly focused on the improvement and development of general trip distribution models [3–6], the calibration of model parameters [7–9], the application of big data in trip distribution [10–15], the forecast of trip distribution based on trip chains [15–16], the improvement of trip distribution models considering land use [17–21], and the evaluation and analysis of the accuracy and effectiveness of trip distribution forecasts [9,22–23]. In Reference [4], a fuzzy gravity model was established based on the fuzzy mathematical theory to overcome the fuzzy problem in trip distribution. In Reference [7], it was pointed out that the average impedance between TAZs could be taken as the constraint in the calibration of parameters. Reference [14] studied the method to extract individual trip chain information based on mobile sensor data, which was helpful to analyze the spatial distribution of trips. Based on the trip chain information extracted from household survey data, Reference [16] analyzed the key factors that affected the trip chains of different travelers. Cross-classification was conducted to obtain typical populations with similar travel characteristics, and a model was developed to forecast the generation and distribution of trip chains for these typical populations. In Reference [18], a combined model of trip distribution and traffic assignment was proposed based on the distribution function of the land-use trip rate. In Reference [20], information entropy was introduced to build a entropy model of the land structure, and entropy parameters were introduced to build a generalized gravity model, realizing the connection between urban land use planning and transportation

Received: 2019-06-24

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planning. Reference [21] established a relationship model of land use pattern, population, and trip generation. It classified and decomposed the types of trip chains and forecast trip distribution according to the trip purpose and the corresponding land use type.

The past research was fruitful, which improved the forecasting method of trip distribution to a certain extent by integrating land use types and big data into trip distribution forecasting. However, it failed to deeply reflect the internal relationship among trip distribution, land use, and other key factors. For a new trip distribution theory, the deficiencies of classic trip distribution models are briefly analyzed first in this paper. Then the internal logic relationship among trip distribution, land use, and other key factors (e.g. traveler attributes and transportation mode attributes that internally reflect road network layout) is discussed. Finally, a conceptual trip distribution model based on the key factors is established preliminarily.

2 Deficiencies of existing trip distribution models

Classic trip distribution models refer to the growth factor model and the gravity model. The growth factor model includes the method of average growth rate, the Detroit method, the Fratar method, and the Furness method. The gravity model involves the unconstrained model, the single constraint model, the double constraint model, etc. In the improved gravity model, the main improvements include the parameter calibration method and the impedance function [4,8–9]. Trip distribution models based on land use mainly take the factors such as the land area and the floor area ratio into consideration to calculate trip distribution probabilities among different zones [21–23].

2.1 Deficiencies of classic trip distribution models

2.1.1 Growth factor model

The classic growth factor model forecasts the future trip exchange volumes among TAZs based on current OD matrices, the results of future trip generation, and growth rate functions. The essence of the growth factor model is that the trip exchange volumes among TAZs (i.e. each cell in the OD matrix) are related to the trip production and attraction volumes of each TAZ in the region. The growth factor model is commonly expressed as follows:

$$t_{ij} = t_{ij0} \cdot f(i, j) , \tag{1}$$

where t_{ij} is the future trip volume from TAZ i to TAZ j; t_{ij0} is the current trip volume from TAZ i to TAZ j; and $f(i, j)$ is the growth rate function for trips from TAZ i to TAZ j.

The growth factor model directly forecasts future OD matrices based on the growth rates obtained from the current OD matrices and forecasts of future trip generation, which is not reasonable. In essence, t_{ij} is not determined by the current OD or the future production and attraction of each TAZ. This model does not consider the internal mechanism of trip distribution in depth and fails to reflect the essence that the trips from TAZ i to TAZ j. At the same time, this model cannot work when the current OD matrix is sparse, because it needs to calculate the growth rates based on the current OD matrix.

2.1.2 Gravity model

The classic gravity model calculates the travel impedance matrix according to the generalized cost (including one or several factors, such as travel time, distance, and cost) among the TAZs in the future, which is used to calculate the trip exchange probabilities among TAZs. These probabilities are then combined with the forecasting results of future trip generation to calculate the OD matrices of future trip distribution. The essence of the gravity model is to consider the trip exchange volumes among TAZs as a function of travel cost. Its general expression is

$$t_{ij} = k \cdot \frac{P_i \cdot A_j}{F(P_i, A_j, k) \cdot R(i, j)} , \tag{2}$$

where k is a general adjustment coefficient; P_i is the total trip production of TAZ i; A_j is the total trip attraction of TAZ j; $f(P_i, A_j, k)$ is a coefficient function of P_i, A_j, and k; $R(i, j)$ is the travel impedance (i.e. generalized cost) function between TAZ i and TAZ j.

Compared with the growth factor model, the gravity model does not need the current OD matrix. However, the gravity model considers the trip exchange volumes among TAZs only as a function of travel cost. It does not really reflect the nature of trip distribution because t_{ij} is essentially not determined by the travel cost among TAZs. At the same time, the trip exchange volume will increase too fast when the travel cost is zero (or very low) according to the classic gravity model.

2.2 Deficiencies of other trip distribution models

2.2.1 Improved gravity model

The improved gravity models discussed in this section refer to the gravity model with improved parameter calibration and the gravity model based on land use. The essence of the first improved gravity model (i.e. with improved parameter calibration) is to improve the method of parameter calibration, which does not overcome the essential problems of the classic gravity model. Therefore, this type of improved gravity models has similar deficiencies as the classic gravity model.

As to the second improved gravity model (i.e. based on land use), its essence is to calculate the attraction intensity of various land use types between TAZs according to development intensity. It is then used to calculate attraction probabilities to obtain the trip distribution among TAZs, i.e., the trip OD matrix. Its general expression is as follows:

$$t_{ij}=p_{ij}\cdot k\cdot\frac{P_i\cdot A_j}{F\left(P_i,\,A_j,\,k\right)}\,, \tag{3}$$

where p_{ij} is the association intensity of TAZ i and TAZ j calculated based on its land use association.

In fact, the association intensity between TAZs is not entirely determined by the nature of the land use, because different types of travelers could exist in lands with the same nature, and different types of travelers would have various trip purposes which lead to different trip distribution patterns. Therefore, this improved gravity models only focuses on the nature of land use and fails to deeply reflect the internal mechanism of trip distribution.

2.2.2 Distribution models based on advanced technology

The distribution model based on advanced technology discussed in this section mainly refers to the distribution model of trip chains based on big data. Currently, the big data used in most big-data-based trip distribution studies are mobile signaling data, which are used to extract the travelers' trip chain information and track travelers' trip distribution patterns to propose trip distribution models.

As for the distribution model of trip chains based on mobile signaling data, the mobile signaling data only contains the travel information of current travelers and the mobile signaling data for future travelers is not available, so the mobile signaling data can be used to validate the current trip distribution. If this model is combined with land use, different trip chains can be developed according to the types of land use, and the relationship between the future land use types and trip chains can be studied to forecast trip distribution.

In essence, there are still deficiencies in the trip distribution model established by associating land use with trip chains obtained from mobile signaling data. This model only considers trip chains and land use together superficially. Like most of the improved gravity models based on land use, it simplifies the relationship between land use and trip chains. Trip chains among the zones with the same land use relationship could be different because the travelers are different, which means that the trip distribution model should not be developed simply based on the land use type.

3 Relationship between key factors and trip distribution

Many factors can affect trip distribution, such as land use, road network accessibility, the cost of the transportation mode, choice behaviors of the travelers and so on. The key factors include travelers, land use layout, and transportation modes, among which travelers are the basic key factors and the basis of secondary key factors, i.e., land use layout and transportation modes.

3.1 Travelers and trip distribution

Travelers have an impact on trip distribution, which is reflected in the research on trip chains [16–17]. For example, Reference [16] classified the trip chains of different travelers and studied their key influencing factors. Travelers constitute the core of travel, because the purpose of travel is for a traveler to reach the destination to complete a certain task by one or several modes of transportation. Therefore, travelers are the basis of travel and different travelers have various travel needs, which is directly reflected in different trip distribution patterns. This fact also inherently requires that transportation should be people-oriented.

From a certain point of view, the trip purpose of a traveler is determined by the traveler's own attributes. Travelers with different attributes have varied trip purposes, such as walking and shopping for the elderly and going to work and school for the young. Since trip purposes are different, trip destinations would be also different. Similarly, the spatial distribution of trip origins (residence) selected by travelers with different attributes is also changing, leading to different spatial distribution of trips. Therefore, the logical relationship between travelers and trip distribution can be expressed as follows: Travelers' attributes inherently determine or affect their trip purposes as well as trip origins and destinations, then the possible spatial distribution of trips, and finally trip distribution together with the factors of land use and the transportation mode.

Travelers' attributes mainly include generalized income and expenditure ratio, occupation, age, family structure, education background, trip purpose, value of other assets (non-income assets), etc. These attributes are interrelated. It is therefore necessary to identify the key attributes to clearly reflect the relationship between travelers' attributes and trip distribution. In this paper, generalized income and expenditure ratio, value of other assets, occupation, etc. are identified as the key attributes. This paper also defines the attribute category: Travelers in each attribute category have similar travelers' attributes and similar travel decision-making behaviors, which is an economic classification of travelers. In trip distribution, travelers make decisions based on external factors and their own attribute category.

3.2 Transportation modes and trip distribution

It is easy to understand that transportation modes affect trip distribution, which is also proven in relevant studies [24–26]. For example, Reference [24] showed that the interaction between the transportation mode and the mode of trip chains was significant. A traveler always need one or several modes of transportation to travel, so the availability, generalized cost, and other attributes of the transportation mode will significantly affect which mode(s) a traveler will choose.

Because different modes of transportation have their own suitable travel distances and possible service areas, transportation modes will indirectly affect the trip origins and destinations of a traveler when the traveler's attribute category is fixed. Therefore, the relationship between transportation modes and trip distribution can be expressed as follows: Given travelers' attribute category, travelers will consider their own attributes, transportation modes' attributes and other factors to choose the transportation modes, determine the possible spatial distribution of trip origins and destinations, and finally the trip distribution.

The attributes of a transportation mode mainly include availability (or accessibility) and generalized cost. The availability of a transportation mode has two meanings: 1) whether the transportation mode is provided between the origin and the destination of a trip. For example, if rail transit is not provided, the mode of rail transit is not available; 2) the acceptability of the logical sequence of the riding points of the transportation mode and the origin and destination of the trip. For example, rail transit is provided, but the nearest rail station is 1.2 km away from the trip origin and 0.8 km away from the trip destination, and both stations are located in the opposite direction of the trip. Then rail transit is not considered as available if the trip distance is only 2.2 km since it does not make sense to use rail transit in this hypothetical example. The second meaning can also be considered together with the travel cost of the transportation mode. The generalized travel cost of the transportation mode generally includes time consumption, money consumption, loss of safety and comfort, and other elements.

It should be noted that the influence of the transportation network on trip distribution is inevitable [27]. There is an internal relationship between the transportation network and the transportation mode, namely that there are no transportation mode without the support of transportation network (including aviation). Therefore, the attributes of transportation modes intrinsically contain transportation networks, namely that transportation modes are the embodiments of transportation networks. It is then more in-depth to discuss the impact of the transportation mode on trip distribution directly.

3.3 Land use layout and trip distribution

It has been widely recognized by the industry that land use has a significant impact on trip distribution [18–22]. For example, in Reference [2], trip distribution was studied by analyzing the scale factors of regional agglomeration based on the land use type. However, the key to studying the relationship between land use and trip distribution is how to present the impact from the essence.

On the surface, the relationship between land use and trip distribution is the interaction of land use; in a deeper sense, it is the combination of various types of land use and land development intensity, regional location, supporting facilities, etc., which provides sufficient conditions for trip production and attraction. Therefore, it is t_{ij} rather than t_{ik} or t_{kj}. The attributes of land use layout include land use type, location (including supporting facilities), and development intensity. Lands with different locations, land use types, and development intensities attract travelers in various attribute categories. Travelers will select their trip destinations according to their own attributes, the attributes of transportation modes, and other factors, which is finally manifested as trip distribution.

Therefore, the logical relationship between land use layout and trip distribution can be expressed as follows: Lands with various land use types in different TAZs attract potential travelers in different attribute categories (i.e. choice of the trip origin) through development intensity and location factors. Travelers select the transportation mode and the trip destination according to their own attributes, the attributes of the transportation mode, and other factors (i.e. choice of the transportation mode and the trip destination), which is manifested as trip distribution affected by land use layout.

Only by deeply understanding the interaction of lands in TAZs with different land use layouts and the relationship among attributes of land use layout, traveler attributes, and transportation mode attributes, can we scientifically and reasonably analyze the essential relationship among land use layout, travelers, transportation modes, and trip distribution can be analyzed, . This is the basis of establishing a distribution model of scientific trip.

4 Development of preliminary model

4.1 Basic ideas of model development

Since no research is found to simultaneously consider the impact of the key factors discussed above on trip distribution, and the research on the model development in this area is almost blank, this paper attempts to initiate a trip distribution model based on land use layout attributes, traveler attributes, and transportation mode attributes. The basic ideas of model development are as follows:

The first step is to develop TAZs according to land use planning and transportation planning.

The second step is to calculate the number of people accommodated by lands with various land use types (based on land development intensity) in each TAZ and determine the availability of various transportation modes for each TAZ.

In the third step, based on the results of the second step and the Urban Development Forecasts (UDF), the spatial distribution of lands and travelers in various attribute categories are studied.

In the fourth step, based on the results of the third step and the UDF, the trip purposes of the travelers in various attribute categories are forecast, which is conducted for lands with various land use types in each TAZ.

In the fifth step, based on the results of the fourth step, land use planning, and the availability of each transportation mode, the possible spatial distribution of the trip destinations for travelers in various attribute categories are forecast, which is conducted for lands with various land use types in each TAZ. In the meantime, the generalized travel cost (including time consumption and money consumption) of each combination of transportation modes among TAZs are calculated based on the availability of the transportation mode and the definition of TAZs. Finally, the probabilities of trip destinations are calculated (including the probabilities of transportation modes for each route).

In the sixth step, based on the results of the fifth step, the trip destinations and transportation modes of travelers in various attribute categories are determined, which is conducted for lands with various land use types in each TAZ.

The seventh step is to obtain the trip distribution results (including the route results).

The basic ideas of the model development proposed in this paper are shown in Figure 1. The meaning of each symbol in Figure 1 is explained as follows.

A1 is the UDF. A2 is the number of travelers in various attribute categories. A3 is the spatial distribution of lands and travelers in various attribute categories. A4 represents travelers in various attribute categories from lands with various land use types in each TAZ, as well as their trip purposes (generally referring to career choice). A5 is the most possible trip purpose based on A4.

B1 is the planning and layout of land use. B2 is the development of TAZs. B3 is the number of people accommodated by lands with various land use types in each TAZ (based on land development intensity). B4 is the number of travelers in various attribute categories who are accommodated by lands with various land use types in each TAZ. B5 indicates the trip purposes of travelers in various attribute categories who are accommodated by lands with various land use types in each TAZ. B6 is the possible spatial distribution of trip destinations for travelers in various attribute categories who are accommodated by lands with various land use types in each TAZ. B7 is the determination of trip destinations and transportation modes for travelers in various attribute categories who are accommodated by lands with various land use types in each TAZ.

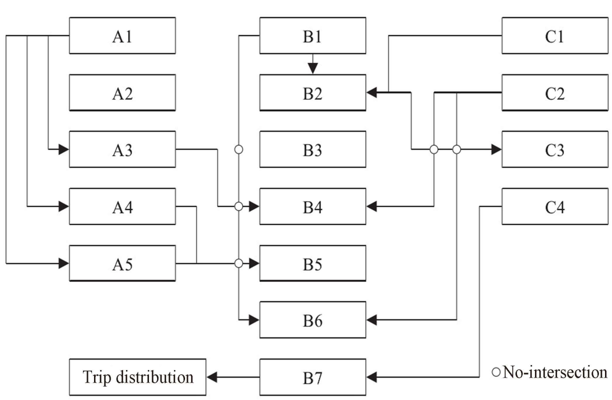

Figure 1 Model structure

C1 represents various types of transportation planning. C2 is the availability of each transportation mode. C3 is the generalized travel cost (including time consumption and money consumption) of each combination of transportation modes among TAZs. C4 manifests the relative probabilities of each combination of transportation modes among TAZs (these probabilities inherently include the probabilities of available routes).

4.2 Significance of research on UDF

In this paper, the research on Urban Development Forecasts (i.e. UDF) refers to the research and forecast of various elements about future urban development, which is to forecast the future based on the current situations. The UDF should include the forecasts of various urban development indicators (such as level of urbanization, area of urban construction land, GDP, household income and expenditure ratio, and value of other non-income assets) and the forecasts of the relationship among various urban development elements (such as people, cars, air, land, water, industries, various resources, and policy system).

The socio-economic data provided by the UDF is the basis of model development, so UDF is of great significance. For the data needs of the development of the trip distribution model, the UDF studies should include, but not limited to, the following: 1) the proportion of travelers in different attribute categories in a city (traveler attributes include many factors, but the factors that have the most direct impacts are the income and expenditure ratio, the value of other assets, etc.); 2) the sensitivity of travelers in different attribute categories to the generalized cost of each transportation mode; 3) the dependence of travelers in different attribute categories on supporting facilities; 4) the sensitivity of travelers in different attribute categories to house prices; 5) the spatial distribution of lands and travelers in different attribute categories; 6) the forecasts of travelers in various attribute categories who are accommodated by lands with different land use types in each TAZ and their trip purposes.

4.3 Basic assumptions and preliminary model development

As mentioned above, this paper is only to establish a preliminary conceptual model due to the lack of relevant research. The preliminary model makes the following assumptions:

1) Trip distribution has inertia: For travelers, their trip distribution is basically fixed over a long period of time, namely that it has certain inertia.

2) The trip distribution model proposed in this paper essentially includes all four steps of the traditional travel demand modeling: trip generation (i.e. production and attraction), trip distribution in the traditional concept, mode split, and traffic assignment. Therefore, this model could be used to describe the entire travel process: who chooses which starting point, what transportation modes (which include the travel path internally), and arriving at which ending point.

Since trip distribution is the joint effect of the key factors such as land use attributes, traveler attributes, and transportation mode attributes. Trip distribution is dependent on the key factors, which is an independent variable, and the formula could be expressed as follows:

$$d_k = R(l,\ m,\ p_k)\ , \tag{4}$$

where d_k is the trip distribution result of travelers in attribute category k; R is the mapping from key factors to d_k; l is the independent variable for land use attributes; m is the independent variable for transportation mode attributes; p_k is the independent variable for travelers in attribute category k.

The independent variable for land use attributes (l) is a key factor of trip distribution, and it is a function of location, land use type, facilities, etc. l can be expressed as

$$l = F_l(r,\ u,\ d)\ , \tag{5}$$

where F_l is the mapping from land use attributes to l; r is the location; u is the land use type; d is the development intensity.

The independent variable for transportation mode attributes (m) is another key factor of trip distribution, and it is a function of accessibility, travel cost, etc. m can be expressed as

$$m = F_m(a,\ c)\ , \tag{6}$$

where F_m is the mapping from transportation mode attributes to m; a is the accessibility of the transportation mode; c is the travel cost of the transportation mode.

The independent variable for travelers in attribute category k (p_k) is the basic key factor of trip distribution. It is a function of travelers' income and expenditure ratio, value of other non-income assets, occupation, etc. p_k can be expressed as

$$p_k = F_k(e,\ o,\ j)\ , \tag{7}$$

where F_k is the mapping from traveler attributes to p_k; e is the traveler's generalized income expense ratio; o is the value of other non-income assets; j is the traveler's occupation (may be a dummy variable).

According to the trip distribution results of the travelers in each attribute category, the trip distribution of all travelers can be obtained (including the travel paths). The key to getting the trip distribution results is to calibrate the mapping relationship presented in Formulas (4) to (7), which can be obtained through a large number of empirical studies.

5 Conclusions

The problem of trip distribution is essentially a decision-making problem that reflects the choice behaviors of the population. The in-depth study of trip distribution needs to clarify the influencing factors of trip distribution and understand their impacts. Based on the analysis of the deficiencies in traditional trip distribution models, this paper proposes that the essence of trip distribution is the choice behaviors of travelers in attribute categories under different land use and transportation mode conditions. This paper also points out that the study of travelers' choice behaviors needs to be integrated with the research on the Urban Development Forecasts (UDF) to obtain the basic data and the mapping relationship. The analysis of the essential relationship between trip distribution and key factors presented in this paper is significant to the development of a scientific trip distribution theory based on the UDF.

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(Translated by QIN P)

