

Using Bi-level Multi-Objective Programming in Passenger Structure Optimization for Comprehensive Transportation Channel

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Abstract—The economic structure is the lifeblood of national economic development. Passenger structure within comprehensive transportation channel (CTC) is the key to play a higher efficiency and to operate normally of an integrated transport system. This paper analyzes the ideas of PTS optimization within CTC using bi-level planning strategies. And then a bi-level multi-objective programming model is established in this paper, in which the upper level takes the builders and government's concern into account, such as system efficiency, transport capacity, capital investment. The lower level is a network equilibrium model based on a generalized cost function, while Channel saturation entropy index is introduced in the response function. A particle swarm optimization algorithm is designed to efficiently solve this NP-hard model. Finally, numerical implementations based on Beijing-Shanghai Channel are carried out to account for the performance of our model and algorithm.

Index Terms—Comprehensive Transportation Channel, Passenger Transport Structure, Optimization, Bi-level Multi-objective Programming, Particle Swarm Algorithm

I. INTRODUCTION

CTC is a multi-level and multi-mode integrated transport system which connects main distributing points of passenger and freight across widespread area, and takes large scale and stable traffic flow among different distributing points. Passenger structure optimization focuses on the adaptability between transport capacity and demand within CTC. In other words, investigate the composition of various modes inside transport industry, and the required proportion relationship to reach a reasonable division of labor.

CTC plays an important role in the process of social and economic development, and it has become hot issue received from international and domestic common concerns in recent years, for now the main studies include: Li Degang started from user effect to define CTC

structure based on travel demand and supply characteristics within CTC in reference [1]. Luo Xia proposed integrated processing method of 'path-way', passenger transport sharing ratio outside the region in reference [2]. Reference [3] proposed to build passenger structure allocation by the principle of max entropy. Reference [4] applied the idea of balancing urban traffic distribution network to propose passenger flow distributing model of multi-mode of traffic of regional transport Channel, which is based on network. Reference [5] applied the idea of uncertain programming to improve war drop principle and establish passenger transport capacity sharing model with optimal passenger flow and system. Si Bingfeng built a separation model and solution algorithm of traffic mode under the condition of integrated transport, which is based on random user balance theory and chaos theory in Reference [6]. Lejoon Chang researched and proposed prediction model for passenger transport market share of regional competitive transport Channel, which is based on network model in reference [7].

What we see from above mentioned are as follows: those studies either define passenger structure of CTC, or divide passenger structure of CTC based on network model and drawing on balance idea of urban traffic, or apply integrated processing method of 'path-way' and the theory of max entropy to reach reasonable allocation for passenger structure of CTC. All of the above studies only started from the perspective of traveler, they did not consider how traffic planners and government decision-making behavior will impact reasonable allocation for passenger structure of CTC. This paper introduces the idea of bi-level programming, the upper model covers such issues as system efficiency, transport capacity and investment which traffic planners and government concern about. The lower level covers network balance issue based on generalized cost function and the response function of the upper and lower level models introduces

saturated entropy index. And then it figures out how to reach reasonable allocation for passenger structure of CTC.

The rest of this paper is organized as follows. In the next section, the idea of Bi-level programming (BLP) for optimization of PTS within CTC is described and developed. We present the symbol definitions used in optimization of PTS within CTC in Section 3. The BLP optimization model for PTS within CTC is formulated in Section 4 and its solution algorithm is in Section 5. In section 6 the proposed model and algorithm is tested by Beijing-Shanghai (China) real Channel and its solution efficiency is analyzed. In the last section, we draw our conclusions, as well as the future research directions.

II. IDEA OF BI-LEVEL PROGRAMMING FOR THE OPTIMIZATION OF PTS WITHIN CTC

For the optimization of PTS within CTC, the conflict between system objectives of traffic planners and passenger travel choice has always been working. From a perspective of actual traffic operation rules, it is almost impossible to reach the optimal system benefits automatically by individuals' behavior of travel mode choice, only if all travelers cooperate each other and try to optimize the network system. In fact, 'selfish' natures of those travelers have always forced them to follow the principle of winning the best interests of themselves when they choose a travel mode.

But it is sure that this inevitable conflict between system objectives of traffic planners and passenger travel choice can be reconciled. Traffic planners can leverage transport supply properly within CTC to influence individual travel choice based on system analysis, good design and maximize system benefits while a traveler make decision of travel mode following the principle of winning the best interests. This situation can be considered a win-win situation. First, traffic planners achieve the dream of optimal system benefits. Secondly, travelers also can determine the optimal travel mode in full accordance with their wish of travel modes, thus balance the interests between system and user.

For the optimization of PTS within CTC, it is a complex system decision-making which involves many factors actually. On the one hand, traffic planners and government department make a programming for CTC, and invest heavily for construction and management of Channel resource to maintain CTC under normal operation so as to provide passenger travel service and meet the growing traffic demand. In other words, the maximization of social benefits is their ultimate objective. On the other hand, traveler makes a decision of travel choice based on traffic service provided by government whether to travel or not, detailed travel mode and so on. Travelers only care about their own interests and the ultimate objective of less travel costs. The whole optimization process is a typical master-slave hierarchical decision-making issue which involves their interactions and multi-level, top-down, hierarchical structure joint decision-making behavior between government department and public, so Bi-level programming idea can

be considered to optimize modeling for PTS within CTC. What the basic idea is introducing system evaluation to the upper level programming, and travel mode choice to the lower level programming model. The basic mathematical form for Bi-level programming (BLP) issue can be expressed as:

$$\begin{aligned} & \min F(x, y(x)) \\ & S.T. \quad G(x, y(x)) \leq 0 \\ & \min f(x, y) \\ & S.T. \quad g(x, y) \leq 0 \end{aligned} \tag{1}$$

III. NOTATION AND SYMBOL DEFINITIONS

In this section, we provide the notations that are used throughout the paper. This is followed by the key concepts associated with the research.

q_{ij}^k —transport capacity (persons) of k traffic mode from origin i to destination j within the Channel

E_{ij}^k —transport efficiency of k traffic mode from origin i to destination j within the Channel, dimensionless

t_{ij} —travel time of the shortest route from origin i to destination j , this paper defines the time of shortest route as what is actually in existence

t_{ij}^k —travel time of k traffic mode from origin i to destination j

C_{ij}^k —transport capacity (persons/day) of k traffic mode from origin i to destination j within the Channel

V_k —transport speed of k traffic mode, km/h

G_{ij}^k —function of construction and operation costs per km of k traffic mode from origin i to destination j

l_{ij}^k —route length of k traffic mode from origin i to destination j

G —upper limit of investment funds for construction and operation of transportation system within CTC

EC_p^k —function of total amount of emissions, k traffic mode for p pollutant within CTC

EC_p —the limit of total amount of emissions, p pollutant within CTC

ENC^k —function of energy consumption, k traffic mode within CTC

ENC —the limit of energy consumption sharing within CTC

c_{ij}^k —the generalized travel cost of k travel mode between point i and point j in the Channel

$C_{ij(\min)}$ —under the balance condition, minimum generalized travel cost between point i and point j in the Channel

f —the generalized cost function of travel mode

$t_{ij}^k(0)$ —the ideal generalized cost of k travel mode between point i and point j in the Channel

T_{ij}^k — k travel mode speed value between point i and point j in the Channel

P_{ij}^k — k travel mode economy values between point i and point j in the Channel

F_{ij}^k — k travel mode comfort value between point i and point j in the Channel

E_{ij}^k — k travel mode convenience value between point i and point j in the Channel.

θ_t —weight coefficient for service property of t .

α —undetermined parameter

β —undetermined parameter

III. OPTIMIZATION MODEL FOR PTS WITHIN CTC

The proposed problem for PTS within CTC can be formulated as a mathematical programming model, given as follows:

$$MaxZ_1 = \sum_i \sum_j \sum_k q_{ij}^k E_{ij}^k \quad (2)$$

$$MaxZ_2 = \sum_i \sum_j \sum_k C_{ij}^k \cdot V_k$$

$$(3) MinZ_3 = \sum_i \sum_j \sum_k G_{ij}^k l_{ij}^k \quad (4)$$

$$E_{ij}^k = \frac{t_{ij} \sum_{k=1}^n q_{ij}^k}{\sum_{k=1}^n t_{ij}^k q_{ij}^k} \times 100 \quad (5)$$

$$G_{ij}^k = f(C_{ij}^k) \quad (6)$$

Subject to

$$\sum_i \sum_j \sum_k G_{ij}^k l_{ij}^k \leq G \quad (7)$$

$$\sum_k EC_p^k(X) \leq EC_p \quad (8)$$

$$\sum_k ENC^k \leq ENC \quad (9)$$

Where X is determined by solving the user equilibrium, given as follows:

$$\begin{aligned} \min Z(q_{ij}^k) &= \sum_k \int_0^{q_{ij}^k} f(x) dx \\ s.t. \sum_k q_{ij}^k &= Q_{ij} \end{aligned} \quad (10)$$

$$q_{ij}^k \geq 0$$

$$c_{ij}^k(q_{ij}^k) = t_{ij}^k(0) [1 + \alpha (\frac{q_{ij}^k}{C_{ij}^k})^\beta] \quad (11)$$

$$t_{ij}^k(0) = -(\theta_1 T_{ij}^k + \theta_2 P_{ij}^k + \theta_3 F_{ij}^k + \theta_4 E_{ij}^k) \quad (12)$$

$$H(f_{ij}^k) = -\sum_i \sum_j \sum_k B(f_{ij}^k) \ln[B(f_{ij}^k)] \quad (13)$$

$$B(f_{ij}^k) = \frac{f_{ij}^k}{C_{ij}^k} \quad (14)$$

Expression (2) describes the first objective function namely Max efficiency for system structure within CTC. The level of transport efficiency is an important basis measuring the developing level of Channel transport. Max efficiency for system structure means that makes Channel system structure efficiency maximum by distributing transport capacity in a certain way within CTC with the co-existence of multi-mode transport.

Expression (3) describes the second objective function namely Max transport capacity for system structure of CTC. One of the purposes to optimize PTS is to improve transport capacity within a Channel, and meet passenger travel demand to the greatest extent, see Ref. [8].

Expression (4) describes the third objective function namely least for construction investment and operating costs. We often encounter the bottleneck of shortage in construction funds during the construction of CTC, so construction investment returns a factor required to consider during optimizing PTS.

Expression (5) shows the calculation of transport efficiency. This paper considers structure efficiency from the perspective of time. Time is not only the factor required considering when provider makes investment decision, as the primary means for improving market competitiveness, but also the indicator required to weight when passenger makes a travel mode decision. It also reflects transport quality further. This indicator can reflect the gap between actual and optimal traffic situation within each origin-destination of the Channel, and describe the efficiency of transport structure effectively.

Expression (6) defines the calculation of construction investment and operating costs.

Expression (7) describes the first constraint function namely total construction investment funds. Total construction and operation funds is a constraint for the optimization of PTS, the decision-making variable of the upper level issue of optimization model must meet the constraint of total construction and operation funds

Expression (8) describes the second constraint function namely traffic environment pollution. From the perspective of sustainable development, the total amount of environmental pollution from CTC should not exceed the corresponding capacity limit.

Expression (9) describes the third constraint function namely Energy consumption. Energy consumption is another aspect of sustainable development, and the total amount of energy consumption from CTC should not exceed the corresponding limit.

Expression (10) is the user equilibrium problem.

Expression (11) describes the calculation of c_{ij}^k

Expression (12) describes the calculation of t_{ij}^k

Expression (13) describes the calculation of Channel saturation entropy. We do not want long-term emergence of transport capacity greater than traffic demand and do not want to see traffic demand larger than transport capacity either. The former transport system will lead to depression and decline, which will result in the transport block, impact on social activities and economic production. View from social and economic balance of transport demand and supply, this balance is dynamic, socio-economic development process in every stage of transportation demand and supply should be balanced. Channel saturation entropy is selected in this paper to describe the supply-demand balance factor. Channel saturation entropy is attracted by a variety of passenger transportation resources in their degree of saturation within the entropy description. When a Channel arrived maximum entropy saturation, the transport structure within this comprehensive transportation Channel reaches dynamic equilibrium. During the transition from imbalance to balance, the difference of saturation between any two modes becomes narrow and the Channel saturation entropy changes from small to big at the same time. While balance situation reached, the saturation of every mode is almost equal.

Expression (14) describes the calculation of $B(f_{ij}^k)$.

IV. DESIGN OF PARTICLE SWARM OPTIMIZATION ALGORITHM FOR MODEL SOLUTION

Solving Bi-level programming model is very difficult. Especially non-linear bi-level programming model is a strongly NP hard problems. The more variables, the more difficult to find the global optimal solution.

Although an algorithm which can ensure to find the very strict optimal solution has not be found yet. But some better algorithms have been found to search the optimal solution, such as bi-level programming problem. Literature [9] proposed using particle swarm optimization algorithm for solving bi-level programming model and has received good results.

This paper proposes to use particle swarm optimization algorithm and the ideas through hierarchical iteration to solve bi-level multi-objective programming model. In other words, the upper level programming is solved by using particle swarm optimization algorithm, and the lower level programming is solved by using traditional

optimization methods. Then run iterations between the upper and lower levels, finally approach the optimal solution for bi-level multi-objective programming, whose steps are as follows:

Step1 (Initialization) Initialize the parameters of PSO algorithm. Generate initial solution (required to meet the constraints) randomly. Initialize particle position in particle swarm $X_i(C_{ij}^k)$ and speed V_i randomly, $i \in [1, m]$. m represents population size (i.e. particle number). Set P_i as i particle current position of the particle, and set P_g as the position of the best particle in initial population.

Step2 For all particles in particle swarm, execute the following operations:

① Update speed and position according to the following formula:

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 (P_i^k - X_i^k) + c_2 r_2 (P_g^k - X_i^k) \quad (15)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (16)$$

$$\omega = \omega_{Max} - iter \times \frac{\omega_{Max} - \omega_{Min}}{iter_{Max}} \quad (17)$$

② (Solving lower level programming) Substitute position X_i of particle i (i.e. the solution for upper level model) into lower level model, use traditional method to solve lower level model, and get the solution $y_i^*(q_{ij}^k)$ of lower level model.

③ Substitute X_i , y_i^* into response function, and calculate the fitness $F(X_i, y_i^*)$ of particle i , $i \in [1, m]$.

④ If the fitness of particle i is better than particle P_i 's, update P_i to current position X_i of the particle. The optimal solution y_{P_i} of lower level corresponding to P_i updated to y_i^* .

⑤ If the fitness of particle i is better than particle P_g 's, update P_g to current position X_i of the particle. The optimal solution y_{P_g} of lower level corresponding to P_g updated to y_i^* .

Step3 Determine whether the algorithm meets convergence criteria, if meet, go to Step 4, else goes to Step 2.

Step4 Output the optimal solutions P_g and y_{P_g} of bi-level programming model, and the algorithm ends.

V. MODEL APPLICATION

A. Beijing-Shanghai Channel Data Collection and Analysis

For related parameters of passenger traffic between all OD points within Beijing-Shanghai Channel and service attributes of all transport modes, see Table I. In this table, A represents civil aviation, C represents highway, R1 represents the existing railway, R2 represents inter-city railway. Although travel vehicles on the highway include buses and owned vehicles, this paper only

considers buses when taking into account of basic data investigation and collection. There are ordinary train, fast train, express train and CRH train in a Channel, this paper only defines two species. One is ordinary train and fast train as existing railway. The other is express train and CRH train as inter-city railway. And it only focuses the trains whose original and terminal stations are the same with target city, which exclusive of the crossing trains.

TABLE I.
RELEVANT PARAMETERS OF PASSENGER VOLUME AND SERVICE ATTRIBUTES

Attributes	Traffic mode	Beijing-Tianjin	Beijing-Jinan	Beijing-Nanjing	Beijing-Shanghai	Tianjin-Jinan
Rapidity T/min	A	N	50	120	150	N
	C	180	380	840	900	360
	R ₁	90	280	690	780	200
	R ₂	70	210	N	600	N
Fare P/Yuan	A	N	320	800	700	N
	C	35	115	200	340	91
	R ₁	30	110	250	300	85
	R ₂	51	170	N	N	70
Comfort F	A	N	0.448	0.64	0.522	N
	C	0.302	0.160	0.16	0.254	0.370
	R ₁	0.258	0.154	0.2	0.224	0.345
	R ₂	0.440	0.238	N	N	0.285
Convenience E	A	N	0.414	0.509	0.370	N
	C	0.206	0.054	0.073	0.062	0.357
	R ₁	0.265	0.228	0.418	0.247	0.643
	R ₂	0.529	0.304	N	0.321	N
Transmission Capacity/Person/day	A	N	1100	800	4500	N
	C	3500	1300	200	250	500
	R ₁	12000	3500	2500	1500	1500
	R ₂	17000	2300	N	16000	N
Total OD demand/Person/day		35000	8200	5800	16400	5800
Travel Distance/km		137	495	1162	1463	357
Attributes	Traffic mode	Tianjin-Nanjing	Tianjin-Shanghai	Jinan-Nanjing	Jinan-Shanghai	Nanjing-Shanghai
Rapidity T/min	A	100	110	60	85	N
	C	N	720	500	660	250
	R ₁	600	210	420	550	190
	R ₂	N	N	N	N	N
Fare P/Yuan	A	600	700	450	600	N
	C	N	286	180	200	80
	R ₁	230	130	135	180	55
	R ₂	N	N	N	N	N
Comfort F	A	0.723	0.627	0.588	0.612	N
	C	N	0.256	0.235	0.204	0.593
	R ₁	0.277	0.117	0.177	0.184	0.407

	<i>R2</i>	N	N	N	N	N
Convenience E	<i>A</i>	0.857	0.692	0.510	0.510	N
	<i>C</i>	N	0.106	0.061	0.066	0.432
	<i>R1</i>	0.143	0.202	0.429	0.424	0.568
	<i>R2</i>	N	N	N	N	N
Transmission Capacity/Person/day	<i>A</i>	600	850	600	1100	N
	<i>C</i>	N	120	120	120	1480
	<i>R1</i>	0	1100	0	1100	14400
	<i>R2</i>	N	N	N	N	N
Total OD demand/Person/day		3500	4700	3500	4700	49000
Travel Distance/km		1024	1325	667	968	301

Note:

1. Transport capacity of civil aviation was derived from China Communications Yearbook and passenger load factor.
2. Transport capacity of highway was derived from long distance bus timetables around cities, based on 40 persons per bus, and passenger load factor.
3. Transport capacity of railway was derived from train timetables and the passenger load factor of 1,100 persons per existing train and 600 persons per inter-city train.

B. Model Parameter Design and Results Analysis

As the government has made massive investment for infrastructure in recent years, the investment of construction and operation is no longer the most important condition for restricting transportation development. With worldwide sustainable development strategy research and development, environmental pollution, energy consumption will highlight their role of restriction in the future. This paper will not consider the restriction from the investment of construction and operation, but only focus the restriction from environmental pollution and energy consumption. Environmental pollution load limit of external passenger transport of main cities including Beijing, Tianjin, Jinan, Nanjing and Shanghai along Beijing-Shanghai Channel in

target year is (6.04 4.12 2.24 2.28 6.87) [108g/day] respectively, see reference[10] to[12]. And total energy consumption limit is (7.39 5.05 2.74 2.79 8.41) [107MJ/day] respectively, also see reference [10] to [12].

Use Matlab language to program, in the process of calculation, take population number as 1,000, iterations as 1,000, learning factor as 2, the upper limit of weighted coefficient as 0.9, and the lower limit as 0.1. The upper limit of different traffic modes positioned on different OD pairs depend on environmental pollution load limit and total energy consumption limit, and the lower limits are set to 0. Then figure out passenger capacity allocation for all modes of transport on the basic sections of Beijing-Shanghai Channel, see Table II and Figure 1 for details.

TABLE II.
RESULTS OF PASSENGER STRUCTURAL OPTIMIZATION

Interval section	Section length	Optimized configuration Result million persons / year				Optimized PTS(%)			
		<i>A</i>	<i>C</i>	<i>R1</i>	<i>R2</i>	<i>A</i>	<i>C</i>	<i>R1</i>	<i>R2</i>
Beijing-Tianjin	137	689	4166	5414	3896	4.86	29.41	38.22	27.50
Tianjin-Jinan	357	419	2193	1347	N	10.59	55.38	34.03	N
Jinan-Nanjing	667	479	3085	504	N	11.78	75.82	12.40	N
Nanjing-Shanghai	301	463	2751	4817	5753	3.36	19.96	34.95	41.74

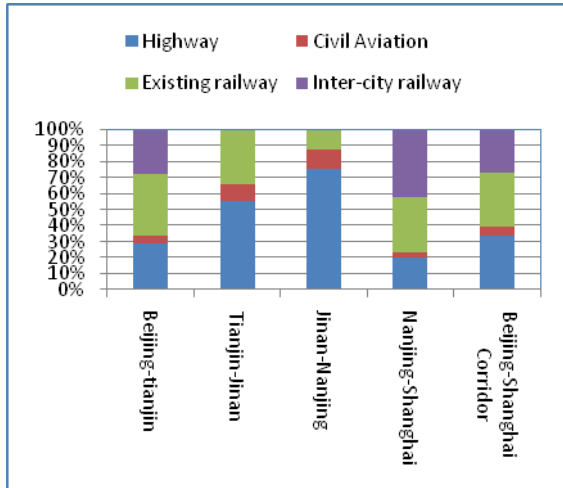


Figure 1. Results of Passenger Structural Optimization

C. Reasonable Development Measures for PTS Allocation of Beijing-Shanghai Channel

The following conclusions can be drawn from the above optimized results:

1) For section distance less than 300 km (such as Beijing-Tianjin, Nanjing-Shanghai), to reach optimal allocation of PTS, passenger transport share by highway should account for around 25%, railway around 70%, of which inter-city railway should accounted for around a half. For the shorter section within CTC, it is necessary to meet high efficiency, high quality and high service level requirements. And it is the mega trend to develop inter-city passenger transport lines.

2) For longer section distance (such as Tianjin-Jinan, Jinan-Nanjing), which have not built inter-city railways yet, to reach optimal allocation of PTS, passenger transport share by highway should account for around 50%, railway around 20%, civil aviation above 10%. Obviously, highway accounts for a bigger share. For the reasons, one side is that the traffic capacity of the existing railways around the two sections is smaller which cannot meet larger passenger transport demands. The other side is that highway passenger transport is convenient and flexible. There is no other choice while they cannot afford the huge costs of aviation and were forced to choose highway travel. With social and economic development, people's living levels improvement, if inter-city railway or highway railway is built around the two sections in future, it is not difficult to foresee that a large number of passengers will change their travel modes from highway to inter-city railway or high-speed railway.

3) For the whole Beijing-Shanghai Channel, passenger shares of the three traffic modes of the existing railway, inter-city railway and highway present the situation of three pillars. On the one hand, although the separation of railway passenger and freight is the mega trend, the existing railway will exit passenger transport market gradually, although it still holds a considerable passenger transport share with the advantages of low transport cost and large transport capacity. Market desalination is a process and that will take some time. On the other hand,

inter-city railway has shown its up-and-coming strength and attracted a certain number of passengers with the advantages of high speed, safety and reliability. Finally, the highway plays the advantages of mobile, flexible and through transportation to distribute passengers for railways and other traffic modes. The three traffic modes have almost divided up the entire Beijing-Shanghai Channel passenger transport market.

VI. CONCLUSION

This paper has established a PTS allocation optimization model within CTC with taking max saturation entropy of Channel as response function of upper and lower level from the perspective of bi-level multi-objective programming. And it proposed to use particle swarm optimization algorithm and ideas of hierarchical iteration to solve this model. The allocation results show that the method can shorten the saturation gap of all transport modes on the basic sections within Channel and avoid a certain mode of transport's too saturated while another is underutilized. Accordingly, to reach effective matching of capacity and traffic, this paper has also introduced environmental pollution load limits and total energy consumption limits to the constraints, and makes them rigid restriction for the upper limit of allocation capabilities of all transport modes, which reflects sustainable development of CTC.

However, this paper only considers bus system among highway mode during data collection and investigation, whose consequence would be more errors for short highway travel share analysis like Beijing to Tianjin. In addition, the author has taken ordinary train, fast train, express train and CRH train together among railway traffic modes into consideration, even if take the same parameters, which failed to show their differences. How to solve these problems above will be the main direction for author's further research.

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