Optimization for train plan of full-length and short-turn routing under variable marshalling conditions

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Abstract. According to the imbalance characteristics of passenger flow in station section in urban railway transit, optimization for train plan of full-length and short-turn routing under variable marshalling conditions is developed. The cost composition and basic constraints of the two entities of passengers and enterprises in this context are analyzed in detail. The multi-objective mixed integer nonlinear programming of the train plan is developed. And the decision variables are train formation plans and positions of turn-back stations. Convert multi-objective models into single-target models by converting costs to total costs and solve the model with MATLAB. The validity of the model is verified by a case and the sensitivities of full-length and short-turn Routing trains’ numbers are also analyzed. The results show that the operation of full-length and short-turn routing mode during peak hours can improve the passenger flow service level of the central section; the optimization of full-length and short-turn routing can further reduce the operating costs of enterprises.

1. Introduction
With the rapid development of cities, urban rail transit as the main framework of urban traffic has attracted more and more attention. Usually, urban rail transit runs single route trains. This method does not consider the spatial imbalance of passenger flow. In view of this situation, it is necessary to adjust the train plan according to the demand of passenger flow and improve the operation efficiency.

Many scholars have studied the problem of variable marshalling of the long and short routes train plan. Wang Yuanyuan[1]establishes a mixed integer non-linear programming model considering passenger travel cost and enterprise operation cost. Rong Yaping[2] takes the train marshalling plan and departure frequency as decision variables, and studies the optimization of train operation plan. Xu Dejie[3] build a model considering the train variable marshalling under the long-short route operation plan, and achieves better results. This paper only considers through passenger flow. In view of interchange passenger flow, Ruijia[4] studied the long-short route train operation scheme, and solved the optimal operation scheme of each route. Dai Cunjie[5] considers the unbalanced arrival time of passengers. Based on the dynamic passenger flow, it designs the improved NSGA-II algorithm to solve the train diagram, which has higher practical significance.

This paper studies the optimization for train plan of full-length and short-turn routing under variable marshalling conditions, aiming at optimizing the balance between supply and demand of passenger flow and improving the service level of enterprises.

2. Basic assumptions of model
To facilitate the modeling in this paper, the following assumptions are made:
1) passengers take trains that arrive first and can directly meet the transportation needs.
2) Each train runs at the same time and stops at the same time, and stops at each station.
3) Trains on different routes run independently and the train stocks are not exchanged with each other, and only one marshalling scheme is adopted in the same route.
4) In order to ensure the generality of the method, this paper assumes that all station have turnaround conditions.

3. Problem Description and Parameter Definition of the long and short routing operation

3.1. Model Description of the long and short routing operation

There are N stations on the line. The station set \( H = \{1, 2, 3, ..., N\} \) corresponds to the section set \( Q = \{(1, 2), (2, 3), ..., (N-1, N)\} \). The long routing trains run through the whole line. The long routing stations set \( H_1 = H \), and the section set \( Q_1 = Q \); The short routing trains run between the \( s \) and \( e \) stations, and the short routing trains stations set \( H_2 = \{s, s + 1, s + 2, ..., e\} \) and \( H_2 \subseteq H \), the section set \( Q_2 = \{(s, s + 1), ..., (e-1, e)\} \) and \( Q_2 \subseteq Q \). \( |T| \) is the length of the study period. \( p_{ij} \) represent passengers get on at i station and get off at j station. \( i < j \) represent the upstream passenger flow and \( i > j \) represent the downstream passenger flow; \( f_1 \) and \( f_2 \) are the train departure frequency on the long and short routes respectively, the frequencies of up and down trains are the same. \( m = f_2 / f_1 \) and \( m < R + \).

According to hypothesis 1, passenger flow \( M_1 \) getting on or off in section \([1, s] \) or section \([e, N] \) choose the large-scale transit train. For the passenger flow \( M_2 \) traveling in the section \([s, e] \), there is no difference for the passenger flow \( M_2 \) to choose the two types of trains. The passenger flow \( M_2 \) will be evenly distributed according to the departure ratio of the two types of trains and will be divided into \( \theta \) proportion by the long routing trains and \( 1-\theta \) proportion by the short routing transit trains. To sum up, the total passenger flow of large-route trains is \( M_1 + \theta \cdot M_2 \), and that of small-route trains is \( (1-\theta) \cdot M_2 \).

4. Establishment of model

The train operation plan is a comprehensive result of balancing passenger demand and transport supply. The cost composition of both sides should be analyzed in detail when establishing the model.

4.1. Enterprise Cost

Enterprise Cost mainly includes operation cost and fixed cost.

4.1.1. Operating costs. Operating cost is related to the running consumption of train and the number of crew. The formulas for calculating train running costs is as follows.

\[
\min Z_1 = \sum_{k=1}^{N-1} I_k \cdot f_1 \cdot C_1 + \sum_{k=s}^{e-1} I_k \cdot f_2 \cdot C_2
\]  

Formula: \( Z_1 \) is the total running kilometers of the long and short route trains; \( I_k \) is the length of section \([k, k+1] \); \( C_1 \) is the number of long route trains and \( C_2 \) is the number of short route trains.

The formulas for calculating the number of crew is as follows.

\[
\min Z_2 = \frac{f_1 \cdot T_{t1}^l} {\lvert T \rvert} + \frac{f_2 \cdot T_{t2}^z} {\lvert T \rvert}
\]

Formula: \( Z_2 \) is the number of crew, \( T_{t1}^l \) is the turnaround time of the long route trains and \( T_{t2}^z \) is the turnaround time of the small route trains.

4.1.2. Fixed cost. Fixed cost mainly considers the average train stocks’ cost of the long and short route trains. The formulas for calculating the number of train stocks is as follows.


\[ \min Z_3 = \left[ \frac{f_1 \cdot T^1_z}{T} \cdot C_1 + \frac{f_2 \cdot T^2_z}{T} \cdot C_2 \right] \]

Formula: \( Z_3 \) is the use of the number of train stocks, \([ \ ] \) represents an upward rectification.

4.2. Passenger Travel Cost

Passenger travel cost mainly considers passenger travel time. According to hypothesis 2, train running time and stopping time are the same. Therefore, only the passengers waiting time is considered. Passenger waiting time is related to the passenger flow and the average waiting time. More scholars have suggested that the average waiting time can be considered as half of the departure interval. Therefore, passenger waiting time can be expressed by equation 4.

\[ \min Z_4 = \left( \sum_{i=1}^{N} \sum_{j=1}^{N} p_{i,j} - \sum_{i=s}^{s} \sum_{j=1}^{N} p_{i,j} - \sum_{i=s+1}^{N} \sum_{j=1}^{N} p_{i,j} \right) \cdot \frac{|T|}{2f_1} + \left( \sum_{i=s}^{s+1} \sum_{j=1}^{N} p_{i,j} + \sum_{i=s+1}^{N} \sum_{j=1}^{N} p_{i,j} \right) \cdot \frac{|T|}{2(f_1 + f_2)} \]

4.3. Constraints

\[ C_n \leq M \quad (m = 1, 2) \]

\[ f_1 \geq \max \left( P^1_x, P^2_x \right) \cdot \frac{1}{C_1 \cdot V \cdot \beta} \quad k \in \{1, 2, \ldots, s-1, e-1, N-1\} \]

\[ f_2 \geq \max \left( P^1_x, P^2_x \right) \cdot \frac{1-\theta}{C_2 \cdot V \cdot \beta} \quad k \in \{s, s+1, \ldots, e-1\} \]

\[ P^1_k = \sum_{i=1}^{s} \sum_{j=k+1}^{N} p_{i,j} \quad P^2_k = \sum_{i=s+1}^{N} \sum_{j=1}^{N} p_{i,j} \]

\[ \theta = \frac{f_1 \cdot C_1}{f_1 \cdot C_1 + m \cdot f_1 \cdot C_2} = \frac{C_1}{C_1 + mC_2} \]

\[ m = \frac{f_2}{f_1} \]

\[ f_1 + f_2 \leq \frac{|T|}{f_{\min}} \quad (f_1, f_2 \in Z^+) \]

Where: \( V \) is the vehicle capacity; \( \beta \) is the design full load rate, \( M \) is the maximum numbers of organized group, and \( P^1_k, P^2_k \) is the upstream and downstream section passenger flow in the interval.

Formula (5) indicate that the maximum numbers of organized group limit; formula (6) (7) indicate that maximum section passenger flow limit trains departure frequency; formula (9) indicate the ratio of passenger flow shared by the two types of trains in small transit sections; formula (10) indicate the relationship between the two types trains departure frequency. formula (11) indicate maximum flow capacity limitation.

4.4. Solution Method

The above model establishes multiple objectives and it is a mixed integer non-linear programming
model (MINLP). Each cost can be transformed into total cost by weighting the time cost, so the multi-objective problem can be transformed into a single objective problem.

\[
\min Z = \sigma \cdot Z_1 \cdot V + \alpha \cdot Z_3 + \phi \cdot Z_3 + \gamma \cdot Z_4
\]  

(12)

In formula: Z is the total cost; \(\sigma\) is the passenger operating cost; \(\alpha\) is the crew travel time cost; \(\phi\) is the average use cost of the train stocks; and \(\gamma\) is the waiting time per passenger cost.

5. Case study

5.1. Parameter Settings

Using the data of a certain line in a city, include the length of each section and the travel time, the OD data of the morning and evening rush hour passenger flow. The value of \(\gamma\) is 1.5 yuan/person minute, \(\alpha\) is 10.8 yuan/person hour, and \(\sigma\) is 0.0765 yuan/person kilometer; the train travel speed is 35 km/h. The value of the \(l_{\text{min}}\) is 2 minutes, and \(M\) is 8, \(\phi\) is 700 yuan/vehicle hour, \(V\) is 310. The return time of each return station is 2 minutes and the value of \(\beta\) is 1.2.

5.2. Solution Process

The decision variables include the return station and the numbers of organized group. This paper uses MATLAB to traversal through all feasible solutions. The optimal solution is presented in Table 1.

| Operational period | Route | Marshalling (long/short) | departure frequency (long/short) | Passenger waiting time (min) | train stocks number | running kilometer | Crew Working time (min) | target value (yuan) | change rate of Passenger waiting time | change rate of train stocks number | change rate of running kilometer | change rate of Crew Working time | change rate of target value |
|--------------------|-------|--------------------------|---------------------------------|-----------------------------|--------------------|-------------------|----------------------|------------------|----------------------------------|---------------------------------|-----------------------------|-----------------------------|---------------------------|
| fixed morning rush hour | 6A — 14 — | 332310 | 37 | 2367 | 732 | 579355 | |
| long and short route | 4A 6A 11 7 | 360203 | 26 | 1541 | 689 | 461075 | +8.4 | -29.7 | -34.9 | -5.9 | -20.4 |
| 6A 4A 7 11 | 509698 | 25 | 1498 | 545 | 526099 | +53.4 | -32.4 | -36.7 | -25.6 | -9.19 |
| fixed evening rush hour | 6A — 14 — | 343692 | 37 | 2367 | 732 | 585047 | |
| long and short route | 4A 6A 10 8 | 379575 | 27 | 1621 | 696 | 554560 | +10.4 | -27.0 | -31.5 | -4.9 | -17.4 |
| 6A 4A 7 11 | 487824 | 27 | 1636 | 604 | 1427.1 | +41.9 | -27.0 | -30.9 | -17.5 | -8.0 |

As can be seen from the table above:

1) Compared with single route, the model can improve the turnover efficiency of the train stocks, significantly reducing the running cost and the operation cost of the train stocks, thus reducing the overall cost by 20.4%.

2) The model matches the supply and demand balance of passenger flow better. For passengers traveling outside the short routing section, the frequency of trains is reduced and passenger waiting time can be increased.

3) Reducing the marshalling number of the trains can increase the frequency of train departure, can reduce the passengers waiting time, and further reduce the comprehensive operation cost of the plan compared with the fixed marshalling.

6. Sensitivity analysis for variable marshalling

6.1. The number of the small route train marshaling

After setting optimal return station, the supply of train transport capacity can be determined by passenger flow demand. Transport supply is the product of train departure frequency and train marshaling number, how the adjustment of train marshaling number will affect the comprehensive
operation cost is illustrated by setting sensitivity experiments, as shown in figure 1.

![Figure 1. The influence of the number of small-route trains on the indicators.](image)

From figure 1, it can be seen that when fixing return station and the long route train marshaling number, the increase of the number of the short route train marshaling will increase the passenger waiting time, reduce the number of crew, and the other costs will remain unchanged. Therefore, enterprises can reduce the number of the small route train marshaling so as to improve the comprehensive social benefits of transportation organizations.

6.2. The number of the large route train marshaling
When fixing trains routing intersection and the short route train marshaling number. By adjusting the number of long route train marshaling, the changing trend of each cost is basically the same as that in figure 1, so no more explanation is given.

7. Conclusions
According to the unbalanced of passenger flow in different sections along urban rail lines, this paper proposes a model based on the combination of the long and short routing operation and variable marshalling operation mode. The feasibility of the method is verified by the case solution and analysis results, which can save about 20.4% of the overall cost compared with the single route scheme. Finally, sensitivity analysis is carried out on the number of the large and small route train marshaling. It is proposed that small marshaling train can reduce passenger waiting time and further improve comprehensive operation efficiency.

References
[1] WANG Y Y, NI S Q. (2013) Optimization of Train Schedules of Full-length & Short-turn Operation Modes in Urban Rail Transit. Journal of the China Railway Society. Commun., 35(7): 1-8.
[2] RONG Y P, ZHANG X C, BAI Y, et al. (2016) Optimization for train plan of urban rail transit based on hybrid train formation. Journal of Transportation Systems Engineering and Information Technology. Commun., 16(5): 117-122.
[3] XU D, MAO B H, LEI G L. (2017) Optimization for Train Plan of Full-length and Short-turn Routing in Urban Rail Transit. Journal of Transportation Systems Engineering and Information Technology. Commun., 17(1): 120-126.
[4] SHI J R, ZHENG M, YAO Z S. (2011) Optimization of Train Plan by Considering Conveying Capacity Utilization in Urban Rail Transit. Journal of Transportation Systems Engineering and Information Technology. Commun., 38(1): 169-189.
[5] DAI C J, LI Y Z, ZHAN S C, et al. (2018) Optimization of Train Operation Scheme for Urban Rail Transit Considering Dynamic Passenger Demand Full-Length & Short-Turn Routing Modes. Journal of the China Railway Society. Commun., 39(02):128-136.