Algorithm of Passenger Travel Route in Space-Time Service Network of Railway Transport

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Abstract
Passenger travel space-time route optimization algorithm based on railway transportation network is the core of passenger transport product planning and operation adjustment research. Firstly propose the train space-time service network construction method of passenger transport product design, and study space-time service arc costs on the basis of analyzing the time-space characteristic and choice behaviors of passengers’ high-speed railway trip. As passenger space-time route search algorithm must satisfy some constraint conditions such as passengers’ travel time window and transfer frequency, this article proposes a combinational algorithm constituted of time window search algorithm and improved Dijkstra algorithm to figure out the assemblage of reasonable passenger route in the train space-time service network. And at last the article uses the timetable of passenger train in Chinese high-speed railway network as the initial space-time service network, and applies MALAB programming to realize the passenger space-time route searching and to verify the validity of the algorithm.

Key words: Space-time Service Network, Passenger Travel Route, Reasonable Route Choice Set, Time Window Search Algorithm, Improved Dijkstra Algorithm.

1. INTRODUCTION
Passenger travel route is composed under the comprehensive orientation of railway transport organization and travel choice in space-time service network. Search algorithm of passenger route is the basic research of optimization of transport product planning, which is significant for timetable optimization and evaluation on the performance of network operation. The railway network scale in China is huge and complicated, which increases the difficulty in studying the search algorithm of passenger travel route in space-time train service network.

Scholars have made a great number of studies on the problem at present. (Connors and Sumalee, 2009) studies the optimization on the selection of travel route under the condition of uncertain road network. The perception time and perception probability of travelers are obtained by the nonlinear conversion of practical travel time and the probability value, which takes the maximum of the perception efficiency of passengers as the optimization objective and seeks for the optimal route. (Deng and Chen, 2012) proposes an improved Dijkstra algorithm to solve the shortest route problem, which includes the setting of two fuzzy parameters: addition principle of two edges and comparison of two routes which cover fuzzy-value edges. It introduces graded integration representation to improve the typical Dijkstra algorithm. (Mukherjee, 2012) develops a heuristic methodology for solving the Shortest route Problem, which aim to exploit tolerance for imprecision, uncertainty and partial truth to achieve tractability, robustness and low cost solution corresponding to the minimum-cost route or the shortest route. (Lozano and Medaglia, 2013) puts forward a kind of accurate algorithm for solving the shortest route problem with constraints. This algorithm is based on the idea of network pulse propagation, which manifests that the algorithm is better than the labeling algorithm of the shortest route verified by a road network with 40000 nodes and 80000 edges. The algorithm can solve any problem with column-generation structure, such as the design of road network of BRT and duty scheduling of multiple events. The solution efficiency is obvious superior to the current business linear solution software. (He and Song, 2014) proposes an improved branch-and-price algorithm is applied to solve the large scale integer programming problem. When dealing with the algorithm, a rapid branching and node selection for branch-and-price tree and a heuristic train time-space route generation for column generation are adopted to speed up the algorithm computation time. The computational results of a set of experiments on China's high-speed rail system are presented with the discussions about the model validation, the effectiveness of the general time-space route cost, and the improved branch-and-price algorithm. (Chen and Shen, 2014) constructs dynamic road network model to optimize the evacuation route for vehicles based on Dijkstra algorithm. It demonstrates that the model can provide relatively
superior evacuation route for vehicles and provides the decision maker with emergency evacuation strategies under three different cases. (Noda and Rodríguez, 2015) propose an exact method to solve the constrained shortest route (CSP) problem. The new approach takes advantage of the binary partition strategy of a recent K shortest routes (K-SP) algorithm that allows posing numerous additional route constraints in the model without extra difficulty. The method is compared with the current best algorithm to solve the CSP problem and produces significant speedups in a wide range of network configurations. (Tong and Nie, 2015) puts forward the generation method of alternative route set in multiple constraint conditions. K short routes is proposed based on layering network to generate the alternative route set of passenger flow and hybrid genetic algorithm to generate the alternative route set of passenger flow in format of origin-destination matrix in order to overcome the shortage of traditional Dijkstra algorithm. Then reasonable routes of passenger flow are selected from the alternative route set.

As far as we can summary from the current research status, domestic and foreign scholars have made few researches on railway passenger space-time route search algorithm, it requires to study the space-time service arc costs based on characteristics of railway passenger transportation products and passengers’ travel choice behaviors. In addition, considering that passenger space-time route must satisfy some constraint conditions such as passengers’ travel time window and transfer frequency, it requires to carry out researches on time window search algorithm and he generating algorithm of reasonable route assemblage in rain time-space service network.

2. NETWORK TOPOLOGY CONSTRUCTION

Complex train space-time service network: it refers to the space-time service network, which is formed by train timetable, and aims to provide passengers choices for travels with time-window constraint. The network is made up of service link and node and segment arc with space-time property. The optimization of space-time service network needs to accord with the property of dynamic demands of passengers’ travels and thus completes the general optimization of passenger transportation service product design.

![Time and space service network of passenger train](image)

Figure 1. Time and space service network of passenger train

Train Space-time service node is nodal point which is used for exchanging passenger flow. It is made up of operation trains with time sequence in the network and aims to provide choices for passengers in different space-time traveling properties. It includes train departure service space-time node, train stop space-time service node and train arrival space-time service node. The train space-time service arc is constituted by any connected
space-time service nodes.

Train space-time service route is a connected route in time and space with departure time strategies and OD traveling choices provided by one or more trains. It is made up of time and space in a sequence transactions from travelers’ departure place to waiting for train at the station, on the train, transference in different trains and arrival at destination. Train space-time route has service attributes such as time, expenses, transfer frequency and transfer time and so on.

Train space-time service arc is the foundation of time-space service route. A time-space service route is made up with many or several kinds of time-space service segment arcs. The service segment arc has all service attributes as the service route.

3. MODEL FORMULATION

On condition that given the planned timetable of train and space-time service network. The model of passenger travel routewith time window limitation assumes all the operational train in the space-time service network follows the dispatching command totally.

3.1. Definitions of the Basic Notations

$$G^T = (N^T, E^T)$$: Complex train space-time service network, which is composed by space-time service nodes and segment arc;

$$[0,T]$$: Time intervals of the planned research;

$$r^T$$: Train numbers which possess operation time and space information in the plan, and add operation time information on the basis of the passenger train operation scheme. $$r^T \in \mathcal{R}^T$$, $$\mathcal{R}^T$$ is the assembly of the operation train in the space-time service network;

$$N^T$$: Train space-time service node set, complex train space-time service network has nodes with passenger flow exchanging property, and is composed by the station node in the physical network and the departure time sequence of the connected train, among which any space-time service node is indicated with $$s$$,

$$n_i^j$$, $$n_i^i$$: The starting and ending point of the space-time service node which connects with space-time service segment arc $$e_i^j$$;

$$E^T$$: Train space-time service segment arc set, composed with two segment arcs between any two connected time-space service nodes, $$e_i^j$$ ($$e_i^j \in E^T$$) indicates the space-time segment arc $$\{n_i^j, n_i^i \in N^T\}$$ between train space-time service nodes $$n_i^j$$, $$n_i^i$$;

$$p(i) = \{j| (i, j) \in E^T\}$$: Predecessor connecting arc of the No. $$i$$ space-time service node;

$$s(i) = \{j| (i, j) \in E^T\}$$: Successor connecting arc of the No. $$i$$ space-time service node;

$$q_{k,i}^{(a)}(t)$$: Entering space-time service segment arc $$e_i^j$$ during time $$t$$ and arriving service node $$n_j$$ on time $$t + \tau$$, the $$\gamma$$ kind passenger flow volume of OD to $$\omega$$;

$$c_i(t)$$: The travel impedance when go through space-time service segment arc $$e_i^j$$;

$$v_i$$: The train technical speed to form space-time service segment arc;

$$c_i^{(a)}(n_i^j)$$: The total travel impedance from starting point to the service node $$n_i^j$$ of NO. $$\omega$$ of OD for $$\gamma$$ passengers when they choose No. $$k$$ space-time service route;

$$S_{k,i}^{(a)}(t)$$: No. $$\omega$$ OD for $$\gamma$$ passengers to choose No. $$k$$ route for traveling during the travel route set in time $$t$$;

$$\delta_{k,i}^{(a)}$$: The relational variable of space-time service segment arc $$e_i^j$$ and the riding scheme $$S_{k,i}^{(a)}(t)$$,

$$\delta_{k,i}^{(a)} = 0.1$$;

$$q_{k,i}^{(a)}(t)$$: Passenger flow volume of No. $$\omega$$ of OD when $$\gamma$$ passengers choose No. $$k$$ space-time service route during time $$t$$;

$$TS_{\gamma}^{(a)}(t),TD_{\gamma}^{(a)}(t)$$: The assignment starting and endingtime for $$\gamma$$ passengers flow volume $$q_{\gamma}^{(a)}(t)$$ of No.
of OD during time \( t \):

\[ \lambda^{(a)}_{\gamma} : \text{Priority coefficient of No. } \omega \text{ of OD for } \gamma \text{ Passengers assignment}; \]

\[ n_{k,d}^{(a)}: \text{The crossing service point of No. } k \text{ space-time service route for } \gamma \text{ passenger flow volume of No. } \omega \text{ OD and the No. } k \text{ space-time service route for } \gamma \text{ passenger flow volume of No. } \omega \text{ OD}; \]

\[ IS^{(a)}_{\gamma}(t), ID^{(a)}_{\gamma}(t): \text{The expected traveling departure and arrival service time window of No. } \omega \text{ OD for } \gamma \text{ passengers } q^{(a)}_{\gamma}(t) \text{ during time } t, IS^{(a)}_{\gamma}(t) = [t_a, t_b], ID^{(a)}_{\gamma}(t) = [t_c, t_d]; \]

\[ t_a, t_b, t_c, t_d: \text{The expected earliest and latest traveling departure service time window of No. } \omega \text{ OD for } \gamma \text{ passengers } q^{(a)}_{\gamma}(t) \text{ during time } t; \]

\[ t_a, t_b: \text{The expected earliest and latest traveling arrival service time window of No. } \omega \text{ OD for } \gamma \text{ passengers } q^{(a)}_{\gamma}(t) \text{ during time } t; \]

\[ H^{(a)}_{\gamma}(t): \text{The matrix of transfer time maximum of OD to } \omega \text{ for } \gamma \text{ passengers } q^{(a)}_{\gamma}(t) \text{ during time } t, \]

which is ascertained by its traveling distance mileage;

\[ C^{(a)}_{\gamma}(t): \text{The longest tolerance time of OD to } \omega \text{ for } \gamma \text{ passengers } q^{(a)}_{\gamma}(t); \]

\[ \omega_{\gamma}(t): \text{Time cost weight in total cost for } \gamma \text{ passengers}; \]

\[ vot_{\gamma}(t): \text{Time value of } \gamma \text{ passengers}; \]

\[ \omega_{\gamma}(t): \text{Fares spending weight in total cost for } \gamma \text{ passengers}; \]

\[ \omega_{\gamma}(t): \text{Congestion cost weight in total cost for } \gamma \text{ passengers}; \]

\[ T^{(a)}_{\gamma}(t): \text{Time cost for passengers from } n_{\gamma} \text{ to } n_{\gamma} \text{ when adopts space-time service route } S^{(a)}_{\gamma}(t); \]

\[ C^{(a)}_{\gamma}(t): \text{Tangible cost consumption for passengers from } n_{\gamma} \text{ to } n_{\gamma} \text{ when adopts space-time service route } S^{(a)}_{\gamma}(t); \]

\[ C^{(a)}_{\gamma}(t): \text{Intangible cost consumption caused by crowd or psychological elements for passengers from } n_{\gamma} \text{ to } n_{\gamma} \text{ when adopts space-time service route } S^{(a)}_{\gamma}(t); \]

\[ \omega_{\gamma}(t): \text{The transformed intangible cost weight by psychological expectation for service time by } \gamma \text{ passengers in space-time service network}; \]

\[ \rho^{(a)}_{\gamma}(t): \text{The transformed intangible cost function by psychological expectation for service time by } \gamma \text{ passengers in space-time service network.} \]

### 3.2 Model of Passenger Travel Route

During the given time, consider that the passenger travel from the departure point to the destination, with the departure point signed as \( n_{\gamma} \) and the destination signed as \( n_{\gamma} \), the passengers arrive at destination through space-time service route \( S^{(a)}_{\gamma}(t) \). The choice of passengers in choosing which space-time service route in the departure point is connected with the general cost of this space-time service route. Assuming that the function of the general cost of this space-time service route in the space-time service network is:

\[ C^{(a)}(n_{\gamma}) = \omega_{\gamma}(t)\text{vot}_{\gamma}(t)T^{(a)}_{\gamma}(t) + \omega_{\gamma}(t)C^{(a)}_{\gamma}(t) + \omega_{\gamma}(t)\rho^{(a)}_{\gamma}(t) \]

\( \rho^{(a)}_{\gamma}(t) \) is non negative function, assuming that during \( t \) period, the expected service time for departure for \( \gamma \) passengers \( q^{(a)}_{\gamma}(t) \) in No. \( \omega \) of OD is \( IS^{(a)}_{\gamma}(t) = [t_a, t_b] \), if the departure time for passengers’ traveling \( TS^{(a)}_{\gamma}(t) \in IS^{(a)}_{\gamma}(t) \), then \( \zeta^{(a)}_{\gamma}(t) = 0 \) , if the departure time for passengers’ traveling \( TS^{(a)}_{\gamma}(t) \notin IS^{(a)}_{\gamma}(t) \), then \( \zeta^{(a)}_{\gamma}(t) = 1 \). Assuming that during \( t \) period, the expected service time for destination for \( \gamma \) passengers \( q^{(a)}_{\gamma}(t) \) in No. \( \omega \) of OD is \( ID^{(a)}_{\gamma}(t) = [t_c, t_d] \), if the arrival time for passengers’ traveling \( TD^{(a)}_{\gamma}(t) \in ID^{(a)}_{\gamma}(t) \), then \( \xi^{(a)}_{\gamma}(t) = 0 \) , if the arrival time for passengers’ traveling \( TD^{(a)}_{\gamma}(t) \notin ID^{(a)}_{\gamma}(t) \), then \( \xi^{(a)}_{\gamma}(t) = 1 \). Here:

\[ \rho^{(a)}_{\gamma}(t) = \omega_{\gamma}(t)\zeta^{(a)}_{\gamma}(t) + \omega_{\gamma}(t)\xi^{(a)}_{\gamma}(t) \]

\( \omega \): It refers to the coefficient for intangible cost transformed by lag between the expected time;
\[ f_1 = \begin{cases} \frac{t_u - T\gamma^{(a)}_u(t)}{T\gamma^{(a)}_u(t)} & \text{is difference function between departure time and expected departure time for } \gamma \text{ passengers } q^{(a)}_\gamma(t) \text{ in } \omega \text{ of OD during } t \text{ period;} \\ \frac{T\gamma^{(a)}_u(t) - t_u}{T\gamma^{(a)}_u(t)} & \text{is difference function between arrival time and expected arrival time for } \gamma \text{ passengers } q^{(a)}_\gamma(t) \text{ in } \omega \text{ of OD during } t \text{ period;} \end{cases} \]

The target function of the model indicates that the generalized impedance for multi-consumption leveled passengers’ traveling in the complex train space-time service network is in minimum level.

\[
\min \sum_{t=0}^{T} \sum_{n\in P} \sum_{\gamma} \lambda^{(a)}\gamma^{(a)}(n, q^{(a)}_\gamma(t)) (1)
\]

Constraint condition:
1. It reflects the transfer times constraint in this service level:
\[ \mu(S^{(a)}_\gamma(t)) - 1 \leq H^{(a)}_\gamma(t) \] (2)
2. It reflects the transfer time constraint in this service level:
\[ T^{(a)}_{k,\gamma} \leq T^{(a)}_\gamma(t) \] (3)
3. It reflects the time window constraint for passengers’ service demands:
\[ t_u \leq T\gamma^{(a)}_u(t) \leq t_b \] (4)
\[ t_u \leq T\gamma^{(a)}_u(t) \leq t_b \] (5)

4. ALGORITHM
The problem of the route search for passengers’ reasonable travel route in the condition of space-time service network of train is a typical NP-problem, the satisfied solution to which can not be obtained with traditional methods. Due to different demands of travelers on transfer times, transfer time, therefore, in the stage of micro-planning, the collection search or collection generation of passengers' reasonable travel route, which takes the passengers’ demands of service window with constraints into consideration is more suitable to the actual act of choice of travelers.

The search for algorithm of space-time service travel route of passengers includes generated sub-algorithm of K-short-circuit of search algorithm of service time window of travel with multi-constraints. Service time window of travelers’ travel refers to the range of expectation of travel on service time in the progress of choosing space-time service node and transfer, and choosing another departure service node. Therefore, choosing an appropriate service time window for passengers is an essential component of route search of passengers based on complex network of space-time service of train.

4.1 The Basic Symbolic Definition
\[ DR^b(n) \]: Refers to the collection of departure time sequence of train operation plan \( R^b \) on physical station node, shows the connection between each physical station node \( n \) and departure time.
\[ \mu : \text{Stands for the subsequent physical station node of physical station node } n \ (\mu \in S(n)) ; \]
\[ d_{\mu} : \text{Stands for time series of physical networked arc } (n, \mu) , \text{ and the departure time of train } j \text{ leaving a certain physical station node } n , \text{ that is the initial time of space-time service arc} ; \]
\[ p : \text{Stands for former physical station node of physical station node } n \ (p \in P(n)) ; \]
\[ AR^b(n) \]: Stands for the sequence collection of arrival time of operation plan \( R^b \) of train on physical station, showing the connection between each physical station node \( n \) and arrival time of train. Among them, there is \( AR^b(n) = \{a_{\mu}, a_{\nu}, ..., a_m\} \) \( p \in P(n) \):
\[ a_{\mu} : \text{Stands for time series of physical network arc, or the time of train } m \text{ arriving at physical station node, and is also called as the terminal time of service in the space-time arc chosen by passengers} ; \]
\[ Y_{\gamma}(p,n) : \text{Refers to the travel time from physical station node } p \text{ to node } n , \text{ that is time consumed in the arc of space-time service by passengers}; \]
\( H_J (p,n,\mu) \): Refers to the dwell time on node \( n \) spent by the train which sets out on node \( p \), passes through node \( n \) and reaches at node \( \mu \) (\( p,n,\mu \in \mathbb{N} \));

\( DL(p,n,\mu) \): Stands for the time spent on physical node \( n \) by passenger.

\[ d_{ip} \]
\[ d_{\mu} \]
\[ DL(p,n,\mu) \]
\[ Y_J (p,n) \]

**Figure 2.** The relationship of physical node and space-time service node

On the physical station node \( n \) finding out the time window of passenger travel as \( \left[ \left[ d_{1,\mu},d_{\mu,p} \right] \right]_{\mu \in \mathbb{N}} \).

Through analysis of space-time network and correlation of relative elements of service time window of passenger, this paper proposes to adopt advanced Dijkstra algorithm to solve the set of alternate route of passenger trip with constraints on service time window and transfer.

This algorithm adds space-time service node \( i \) containing time vector group in space-time service network. Moreover, the \( k \) short-route from initial node of passengers’ travel to subsequent node in network may be composed of the former node from \( 1 \) short-route to \( k \) short-route. Therefore, the vector group of node label is \( \text{node}_i = \{ \text{label} [k], \text{cost} [k], \text{pre} [k], \text{rout} [k], T[k] \} \).

In order to reduce search scope, the order of search node in network regards physical node as primary and search for space-time service node on this physical node based on the physical node.

Among them:

- \( \text{label} [k] \): Refers to temporary label, and the value is zero or one. Zero shows the \( k \) short-route label on this node is a temporary label. One show it is a permanent label;
- \( \text{cost} [k] \): Refers to temporary label, that is the length of the \( k \) -short space-time service route from initial space-time service node of travel to space-time service node \( i \);
- \( \text{pre} [k] \): Refers to former space-time service node of the \( k \) -short space-time service route from initial node to space-time service node \( i \) in order back to find the route after algorithm;
- \( \text{rout} [k] \): Refers to the \( k \) -short space-time service route from initial node to space-time service node \( i \) coming from \( k \) -short-circuit route of the previous vertex;
- \( T[k] \): Refers to current time label of the \( k \) -short space-time service route on service node \( i \);
- \( SL, TL \): Refers to the collection of space-time service node of permanent and temporary label;

### 4.2 Algorithm Steps

Based on given complex space-time service network of trains, first search the reasonable travel-route aggregation of multilevel passengers restrained by time windows between origin-destinations (OD), and complex space-time service network of trains was dynamically updated.

**Step1**: Initialization;

**Step1.1**: Marking the starting point of space-time service \( \text{node}_s \) as

\[ \text{label} [k] = 1, \text{cost} [k] = 0, \text{pre} [k] = \phi, \text{rout} [k] = 0, T[k] = t \]

**Step2**: Putting starting point of space-time service of passengers \( \text{node}_s \) into the collection of permanent label node \( SL \), and the collection of not marked space-time service is called as \( TL \);

**Step2.1**: Choosing a minimum of \( \text{cost} [k] \) as \( i \) from the collection of temporary label node called as \( TL \). Node \( i \) is chosen as the point of route of space-time service of \( k \), and is added into the collection of permanent label node named as \( SL \), and then eliminating node \( i \) from the collection of temporary label node;
Step3: Calculating the current time to arrive node $i$, as $T[k]$, and starting to set it;

Step4: Verifying the feasibility of transfer from space-time service node $i$ to all adjoining space-time service node. It compares all the constraint set of passenger transfer from space-time service node $i$ to all the adjoining space-time service nodes $j$. If the transfer failed, we continue to come to next space-time service node, or turn to Step5;

Step5: Improving $\text{cost}[k]$ label on the adjoining space-time service node of space-time service node $i$. It is necessary to check the entire adjoining node $j$ corresponding to label $\text{cost}_j[k]$ of $i$, and set up the label, $c_{ij}$ refers to generalized cost of space-time service arc from space-time service node $i$ to $j$, that is $\text{cost}_j[k] = \min[\text{cost}_j[k], \text{cost}_i[k] + c_{ij}]$;

Step6: Modifying space-time service node $i$ and time label $T[k]$ of the entire connected space-time service node. We can use time window of service to search for sub-algorithm, and the best matching time window connecting with space-time service node $j$. If we failed to find out, then we continue to find next node; if we succeeded, we should calculate the time of node $j$ and set the label, $t_{ij}$ stands for the time spent from node $i$ to node $j$, then there is $T_j[k] = \min[T_i[k], T_j[k] + t_{ij}]$;

Step7: Looking for the collection of service node of permanent label, that is $SL$, and estimating whether it satisfies condition of the equation \( \text{node}_j = \text{node}_j', j \in SL, j' \in TL \). If it satisfies the equation, then there is the same node in $SL$; if it does not satisfy the equation, then put $C_k$ into $TL$.

Figure 3. The network of high-speed railway
Step 8: If the label $[k]$ of all service node is one, previous $k$-short circuit from initial node to final node exists, and the algorithm is finished, then turning to Step 9. Otherwise, turning to Step 2 and continuing;

Step 9: From final service node to initial node back to find route of space-time service of former $k$-short circuit.

5. CASE ANALYSIS

Case analysis according to the predicted passenger flow and open high-speed rail network in 2017 has been conducted. The network nodes and distance of high-speed railway are as Figure 3. It is predicted that the passenger flow volume is 3091816 people/day, involving 15338 passenger OD. It obtains passengers density of each line section through physical network passengers flow distribution, with a total of 24 traffic OD more than 10000 people per day. Passenger Travel routes in Space-Time Service Network are shown as table 1.

<table>
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<th>passenger train</th>
<th>arrival time</th>
<th>passenger train</th>
<th>departure time</th>
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6. CONCLUSIONS

This article proposes to use passenger travel time window search algorithm and improved Dijkstra algorithm combination to carry out the passenger route searching in space-time service network. It has effectively solved passenger travel route searching problems in uncertain environment under multi-constraints, and overcomes the difficulty for the shortest route to solve this problem of space-time service network in traditional static environment. Finally, it verifies the convergence of algorithm in Space-Time Service Network of Railway Transport.
Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities (Beijing Jiaotong University) under Grant (2015RC089-C) and the Joint Funds of the National Natural Science Foundation of China (NO.U1434207).

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