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Transport Scheme Design for Emergency Supplies Carried by High-speed Passenger Trains

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***Abstract*—Emergency supplies transportation is a key issue during the epidemic period of COVID-19. Considering the potential of high-speed passenger trains to carry time-sensitive goods, this paper studies the transport scheme design problem for emergency transportation to meet the demand in time limit. To address this problem, we develop a multi-commodity flow model based on feasible paths in a space-time network structure. And a modelling method is proposed for *k* shortest paths generation. The proposed models consider the timeliness of emergency logistics and the characteristic of railway freight transportation. A numerical example is given to test this method. Results show that the model and method are effective and efficient.**

Keywords-emergency supplies transportation; high-speed passenger trains; space-time network; multi-commodity flow; k-shortest path; time limit

I. INTRODUCTION

COVID-19 has spread rapidly around the world, causing a great loss of life and property. In the period of fighting the epidemic, transportation of emergency supplies is of the essence. Emergency logistics has the characteristic of time urgency, especially for medical devices, protective equipment, and daily necessities, the transportation of them has to be timeliness and efficient [1]. In this situation, to decide the most effective transport means and routes, and formulate an efficient transport scheme, is of great significance for ensuring the timely delivery of emergency supplies and alleviating the epidemic.

With frequent occurrences of disasters in recent years, emergency supplies transportation and scheduling have received much attention in the literature on emergency management. Wex [2] abstracted the allocation and scheduling of rescue units after natural disaster as a parallel-machine scheduling problem and developed a binary quadratic model that minimizes the sum of completion times of incidents weighted by severity level. Zhang [3] developed a multi-objective allocation-scheduling model for multiple supply points, and a hybrid algorithm based on NSGA-II and ant colony optimization was proposed for solving the problem. Considering the uncertainty of supply and demand of emergency materials, Chen [4] applied the probability distribution and triangle fuzzy number to describe uncertainty constraints, to solve the facility location and material allocation problem in an uncertain information environment. Focusing on the material delivery delay problem caused by uncertain urgency, Zhang [5] established a route planning model with the uncertainty of emergency degree, taking total delay time and total transportation time as the optimization objects.

The above studies mainly focus on natural disasters, and are based on road transportation or take helicopter transportation by considering road damage. Compared with natural disaster, public health emergency has the impact of a wider range, but the transportation facilities are less affected, so there can be more choices in means of transport of emergency supplies. In the meantime, the attendance of high-speed passenger trains is lower than usual during the epidemic period, which provides space for carrying supplies.

High-speed railway is characterized by high speed, safety, and punctuality [6-8], which has been an effective way for high-value and time-sensitive goods transport [9, 10]. The "bolt delivery" service launched by China Railway Express, for example, can provide a 10-hour delivery of goods shipped within the Beijing-Shanghai line [11]. In the period of anti-COVID-19, using high-speed passenger trains for supplies transport can not only avoid wasted capacity of empty carriages, but also save additional costs of building new logistics centers. This paper focuses on emergency supplies transportation using high-speed passenger trains, to design the transport scheme for emergency goods with time limits.

The rest of the paper is organized as follows: A problem description is made in section 2. Section 3 presents a space-time network construction and proposes a multi-commodity flow model based on *k*-shortest paths. Section 4 introduces the path generation method. A numerical example is given in section 5, and we conclude our study in section 6.

II. PROBLEM DESCRIPTION

When a public health emergency occurs, the remaining space of high-speed passenger trains can be used to carry emergency supplies. In this context, the following factors should be focused on:

- Train timetable: passenger train schedule does not change for freight demand. So a fixed train timetable is the basis of the transport scheme of supplies.
- Time window: the time limits of departure and arrival are relatively strict in emergency logistics.

This paper considers the soft time window, which means giving punishment when beyond the time limits.

- Transfer: supplies have to be transferred at station when they need to be transported by more than one train. At this time, the connection time between two trains should not be less than the minimum transfer time.
- Capacity: transportation should be performed in conformity with the capacity. Load on trains and transfer volume at stations cannot exceed the capacity.

In summary, given a series of transport demands with origin and destination (OD) stations, as well as departure and arrival time windows, the transport scheme design problem for emergency supplies in this paper is: based on the passenger train timetable, and the capacity constraints of trains and stations, to arrange transport train(s) and transfer station for each demand.

III. Problem Formulation

A. Network Construction

Construct a space-time network based on train timetable, as shown in Fig. 1, where train arcs describe the train operation plan, and transfer arcs represent feasible connections between the trains. Each arrival and departure of the train corresponds to a space-time node. Dummy source and sink nodes are also included in the network as the origin and destination of the demand, and each of them is linked to suitable starting or ending trains, respectively by starting arcs and ending arcs. The starting arcs and ending arcs have a time and cost value of zero.

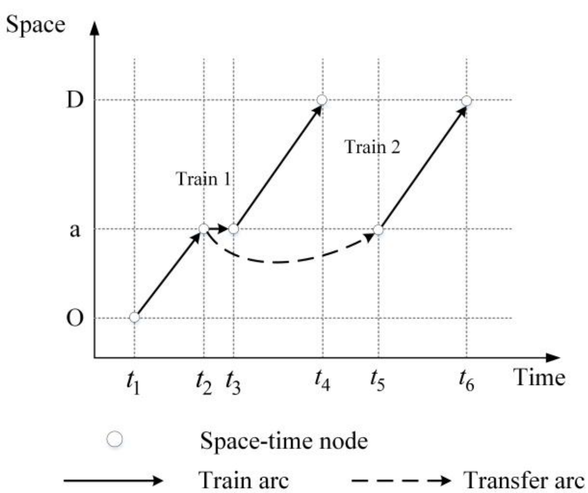

Figure 1. Schematic diagram of space-time network.

In this space-time network, a transport demand with fixed OD can be regarded as a commodity flow, and a space-time path from the source node to the sink node represents a feasible transport scheme for this flow. Thus, the transport scheme design problem can be abstracted into a multi-commodity flow problem based on feasible paths.

B. Variables Definition

$G(N, A)$: space-time network;

N : set of nodes;

A : set of arcs;

A_t : set of train arcs;

A_f : set of transfer arcs;

A_r : set of starting arcs;

A_e : set of ending arcs;

S : set of stations;

A_f^s : set of transfer arcs of station s ;

W : set of transport demands, each w represents an OD;

K_w : set of feasible paths of OD pair w ;

d_w : transport demand between OD pair w ;

l_a : load on arc a ;

u_a : capacity of arc a ;

c_a : cost of arc a , yuan;

$\lambda_{w,k}^a$: =1 if path $k \in K_w$ covers arc a ; =0 otherwise;

c_w^k : unit transportation cost on path $k \in K_w$, yuan;

q_s : transfer capacity of station s ;

$[T_{ol}^w, T_{or}^w]$: departure time window of OD pair w ;

$[T_{dl}^w, T_{dr}^w]$: arrival time window of OD pair w ;

β_o^w : unit penalty cost of violating departure time window of OD pair w , yuan/min;

β_d^w : unit penalty cost of violating arrival time window of OD pair w , yuan/min;

Δ_{ow}^k : difference between departure time window of OD pair w and departure time of path $k \in K_w$, min;

Δ_{dw}^k : difference between arrival time window of OD pair w and arrival time of path $k \in K_w$, min;

f_w^k : decision variable, volume of demand d_w transported through path $k \in K_w$;

C. Model Formulation

The multi-commodity flow model with soft time window is formulated as follow:

$$\min \sum_{w \in W} \sum_{k \in K_w} f_w^k (c_w^k + \beta_o^w \Delta_{ow}^k + \beta_d^w \Delta_{dw}^k) \tag{1}$$

$$s.t. \quad \sum_{k \in K_w} f_w^k = d_w \quad \forall w \in W \tag{2}$$

$$l_a \le u_a \quad \forall a \in A_t \tag{3}$$

$$\sum_{a \in A_f^s} l_a \le q_s \quad \forall s \in S \tag{4}$$

$$c_w^k = \sum_{a \in A} c_a \lambda_{w,k}^a \quad \forall w \in W, \ k \in K_w \tag{5}$$

$$l_a=\sum_{w\in W}\sum_{k\in K_w} f_w^k \lambda_{w,k}^a \quad \forall w\in A \tag{6}$$

$$f_w^k \ge 0 \quad \forall w\in W,\ k\in K_w \tag{7}$$

In this model, objective function (1) minimizes the total cost, including transportation cost and penalty cost; equation (2) specifies the total volume of each demand; equation (3) is train capacity constraint; equation (4) limits the transfer volume at each station; equation (7) is nonnegative constraint for decision variables.

The cost of each path and load on each arc are calculated by (5) and (6) respectively, where Δ_{ow}^k, Δ_{dw}^k, and $\lambda_{w,k}^a$ can be obtained according to the information of feasible paths.

IV. K-Shortest Paths

To solve the above multi-commodity flow model, the generation of feasible paths is a prerequisite. Based on the defined space-time network, feasible paths generation can be seen as *k*-shortest paths problem. The existing *k*-shortest path algorithms show high efficiency in theoretical calculation but care less about practical factors, so they are difficult to be applied to real problems [12]. In this paper, we consider reality constraints in railway freight transportation and propose a modelling method to obtain the *k*-shortest paths.

A. Notations

Besides the sets defined before, the notations used in this section are listed as follows:

(u_w, v_w) : source and sink node of OD pair w ;

L_w : limit on transfer times for OD pair w ;

ρ_w : direction(up=1/down=0) of OD pair w ;

(a_i, a_j) : start and end node of arc a ;

ρ_a : direction(up=1/down=0) of arc $a\in A_t$;

τ_{a_i} : start time of arc a ;

τ_{a_j} : end time of arc a ;

t_a : time length of arc a , min;

δ_{ow}^a : difference between departure time window of OD pair w and departure time of arc $a\in A_r$, min;

δ_{dw}^a : difference between arrival time window of OD pair w and arrival time of arc $a\in A_e$, min;

φ_s : minimum transfer time of station s ;

$\varepsilon_1, \varepsilon_2$: weight coefficient;

M : a large number;

x_a^k : decision variable, =1 if arc a belongs to path k ; =0 otherwise.

B. Model and Solution Method

For each OD pair w , we formulate a series of integer program to obtain feasible paths successively, where the *k*th shortest path can be obtained by the following program $[\mathrm{KSP}(w,k)]$.

$$\min z=\sum_{a\in A} t_a x_a^k+\varepsilon_1\Delta_{ow}^k+\varepsilon_2\Delta_{dw}^k \tag{8}$$

$$s.t.\ \sum_{a\in A|a_i=n} x_a^k-\sum_{a\in A|a_j=n} x_a^k=\begin{cases}1 & n=u_w\\ 0 & n\ne u_w,v_w\\ -1 & n=v_w\end{cases} \quad \forall n\in N \tag{9}$$

$$x_a^k=0 \quad \forall a\in A_t \mid \rho_a\ne\rho_w \tag{10}$$

$$\sum_{a\in A_f} x_a^k\le L_w \tag{11}$$

$$M(1-x_a^k)+(t_a-\varphi_s)\ge 0 \quad \forall s\in S,\ a\in A_f^s \tag{12}$$

$$x_a^k\in\{0,1\} \quad \forall a\in A \tag{13}$$

$$\Delta_{ow}^k=\sum_{a\in A_r|a_i=u_w}\delta_{ow}^a x_a^k \tag{14}$$

$$\delta_{ow}^a=\begin{cases}0 & \tau_{a_j}\in[T_{ol}^w,T_{or}^w]\\ \left|\tau_{a_j}-\dfrac{T_{ol}^w+T_{or}^w}{2}\right|-\dfrac{T_{or}^w-T_{ol}^w}{2} & \tau_{a_j}\notin[T_{ol}^w,T_{or}^w]\end{cases} \tag{15}$$

$$\forall a\in A_r \mid a_i=u_w$$

$$\Delta_{dw}^k=\sum_{a\in A_e|a_j=v_w}\delta_{dw}^a x_a^k \tag{16}$$

$$\delta_{dw}^a=\begin{cases}0 & \tau_{a_i}\in[T_{dl}^w,T_{dr}^w]\\ \left|\tau_{a_i}-\dfrac{T_{dl}^w+T_{dr}^w}{2}\right|-\dfrac{T_{dr}^w-T_{dl}^w}{2} & \tau_{a_i}\notin[T_{dl}^w,T_{dr}^w]\end{cases} \tag{17}$$

$$\forall a\in A_e \mid a_j=v_w$$

The optimization objective (8) is to minimize the transport time while satisfying time windows as much as possible, where Δ_{ow}^k and Δ_{dw}^k can be calculated by (14) – (17); equation (9) ensures the path is continuous; equation (10) specifies the transport direction; equation (11) limits the transfer times in a path; equation (12) ensures the transfer between two trains no less than the minimum transfer time; equation (13) specifies binary variables.

We first set $k=1$ to obtain the (generalized) shortest path, then increase k to find the second shortest path, the third shortest path, et al. When $k\ge 2$, constraint (18) is further added to the model to avoid duplication of the paths.

$$\sum_{a\in A|x_a^r=1}(1-x_a^k)\ge 1 \quad \forall r\mid 1\le r<k \tag{18}$$

Set K as the required number of feasible paths, then the stop condition of the program is a. $k=K$ or b. $[\mathrm{KSP}(w,k)]$ has no solution. According to the results, the information of feasible paths can be obtained.

V. NUMERICAL STUDY

A. Data Input

Assume a high-speed railway network including four stations, the distances (km) are shown in Fig. 2. Specify the direction from D to A as the up direction while A to D as the down direction. The train timetable is shown in Table I. Emergency supplies demands between stations are shown in Table II, where each demand has specific departure and arrival time windows.

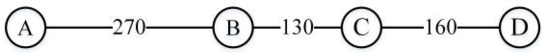

Figure 2. Sample high-speed railway network.

B. Parameter Setting

According to the train schedule showed in Table I, a space-time network consists of 116 nodes and 290 arcs can be constructed.

To calculate the cost of arcs, we set unit transportation cost as 0.023 yuan/km and unit transfer cost as 2 yuan (fixed) + 0.02 yuan/min. The capacity of each train is set as 100. For each station, the transfer capacity is set as 500 and the minimum transfer time is set as 60 minutes.

Other related parameters are set as follows: $\beta_o^w = 0.1$, $\beta_d^w = 0.2$, $L_w = 1$ for $w \in W$, $K = 3$, and $\varepsilon_1 = \varepsilon_2 = 10$.

TABLE I. TRAIN TIMETABLE IN UP AND DOWN DIRECTIONS

Train Number	**Timetable**						**Train Number**	**Timetable**					
	A	***B***	***B***	***C***	***C***	***D***		***D***	***C***	***C***	***B***	***B***	***A***
G1	8:33			10:41	10:44	11:40	G2	8:55	10:12	10:16	10:57	11:00	11:55
G3	9:35	10:52	10:55	11:35	11:38	12:26	G4	9:38	11:02	11:05			12:45
G5	10:25	11:48	11:52			13:31	G6	10:00			12:00	12:02	12:57
G7	11:05			13:14	13:18	14:19	G8	11:16	12:45	12:51			14:32
G9	11:49	13:09	13:11	13:52	13:55	14:50	G10	11:54	13:17	13:21	14:02	14:06	14:55
G11	12:12	13:29	13:31			15:12	G12	12:25			14:35	14:39	15:42
G13	12:52	14:23	14:27			16:07	G14	13:01			15:16	15:19	16:24
G15	13:02			15:25	15:28	16:29	G16	13:33	14:56	14:59			16:37
G17	13:39	15:02	15:04			16:50	G18	13:51			15:56	15:59	17:00
G19	14:03			16:15	16:19	17:12	G20	14:39	15:56	15:59	16:40	16:44	17:39
G21	14:50	16:07	16:10	16:51	16:55	18:16	G22	15:02	16:31	16:34			18:14
G23	15:13			17:20	17:24	18:19	G24	15:19			17:31	17:35	18:30

TABLE II. TRANSPORT DEMAND AND TIME WINDOW OF OD PAIRS

O	**D**	**Demand**	**Time Window**			
			Departure		***Arrival***	
A	B	150	9:30	10:30	11:00	12:00
A	C	120	8:00	9:30	10:30	12:00
A	D	90	13:00	14:00	17:00	17:20
B	A	160	15:20	15:40	16:15	16:45
B	C	210	12:00	12:40	13:00	15:00
B	D	150	10:50	13:00	13:30	14:50
C	A	100	10:15	11:15	12:00	13:00
C	B	240	15:30	16:30	16:30	17:30
C	D	200	10:30	11:50	11:40	12:40
D	A	80	8:00	10:00	11:00	13:00
D	B	230	13:00	13:40	15:10	16:40
D	C	120	14:00	15:00	15:30	17:00

C. Results and Discussion

The proposed models are coded in Python and solved by GUROBI, and the experiment is performed on a 1.8GHz Core i5 PC with 6 GB of RAM. Path generation for all OD demands takes 0.33 second in total, and the multi-commodity flow model can be solved within 0.05 second. The results are shown in Tables III.

Table III lists the first three feasible paths, including train number(s) and transfer station. For each OD, there is at least one direct train that fits the time window, so the shortest path only contains a single train. But there is a transfer in the 2nd or 3rd shortest path of some OD pairs, for example, the 3rd shortest path from A to C is to make a transfer at station B, from train G3 to G9. The number in the parenthesis shows the volume of goods transported through the corresponding path. It can be seen that over half of the demands are taken by the shortest paths, but the rest needed to be transported through the 2nd or 3rd paths due to capacity constraints. In this case, the transfer volumes of stations B and C are 20 and 80, and the transfer capacity fully meets the current demand.

Table III provides an optimized flow assignment result. On this basis, combining it with Table I, the transport scheme with train number and time schedule can be obtained.

TABLE III. FEASIBLE PATHS (REPRESENTED BY TRAINS AND TRANSFER STATION) AND CORRESPONDING VOLUME

O	D	The *k*th Shortest Path: Route (Volume)		
		k=1	***k=2***	***k=3***
A	B	G5 (50)	G3 (0)	G9 (100)
A	C	G1 (100)	G3 (0)	G3 _B_ G9 (20)
A	D	G19 (90)	G17 (0)	G15 (0)
B	A	G14 (60)	G18 (100)	G12 (0)
B	C	G9 (60)	G3 (50)	G21 (100)
B	D	G5 (100)	G3 _C_ G7 (50)	G9 (0)
C	A	G4 (100)	G2 (0)	G2 _B_ G6 (0)
C	B	G20 (70)	G10 (100)	G2 (70)
C	D	G3 (100)	G1 (100)	G7 (0)
D	A	G6 (80)	G2 (0)	G4 (0)
D	B	G14 (100)	G16 _C_ G20 (30)	G18 (100)
D	C	G20 (20)	G22 (100)	G16 (0)

VI. CONCLUSION

This paper studies the transport scheme design problem for emergency supplies carried by high-speed passenger trains. In summary, we proposed a multi-commodity flow model based on a space-time network construction for freight flow assignment and developed a 0/1 programming model to obtain *k*-shortest paths. The two models constitute a two-stage method which is tested with a numerical experiment. Using this method, we can schedule the transport plan for emergency supplies to meet the requirement of arrival and departure time limits.

This study is limited to a single line, further study will be extended to a network and the over-line transportation will be taken into account. If the calculation scale is too large, we intend to apply a heuristic algorithm as the solution method.

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