Research on Optimization Model and Algorithm of Initial Schedule of Intercity Passenger Trains based on Fuzzy Sets

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***Abstract*—The initial schedule of passenger trains is the base of train working diagram . Taking the maximization of passenger satisfaction as the objective function and considering some constraint conditions such as the coordinate utilization of arrival and departure tracks and train-set joining time, etc, a mathematics model for optimizing the initial schedule of intercity passenger trains is constructed based on fuzzy sets. Furthermore, a heuristic genetic algorithm is designed to solve the model and the example is proposed to prove the effectiveness of the model and algorithm.**

***Index Terms*—initial schedule; fuzzy sets; passenger trains; genetic algorithm**

I. INTRODUCTION

The initial schedule of passenger trains is the skeleton of passenger train working diagram. Rational determination of the initial schedule of passenger trains, namely rational determination of passenger train's departure time and arrival time, is the important measures for attracting passengers, and improving service quality of passenger trains, more, how to determine it rationally is deserve attention in compiling train running schedule.

There have been many scholars have discussed how to run scheme of passenger trains from different perspectives. Fu Zhuo[1] presented a new optimal algorithm for the problem with the combination of qualitative analysis. Sun Yan[2] gave a mathematics model and induced a three sub –programs from the main promgram. Ma Jiangjun[3] bases on mode of organization of the middle-speed train running on the high- speed railway network and studies the calculation methods of the scopes of the originating time and the terminating time of the changing-line middle- speed t rain which runs on the existing railway line. Liu Aijiang[4] proposed a new paired train model based on genetic algorithm on single-track lines. Chen Tuansheng[5]taking the maximum degree of passenger travel convenience as t he objective f unction and considering some constraint conditions such as t he carrying capacity of arrival and departure tracks and passenger trains must departure and arrive in rational time intervals , an objective programming model for optimizing the departure and arrival time interval s of passenger trains is constructed. Chen Lingling[6] used the congruence theory to investigate the time interrelation for two passenger trains from up and down direction in a big station to shorten the change and ride time of passengers in a transfer station. Shi Feng[7]Taking the minimum degree of passenger's travel costs as the objective function, a bi-level programming model was designed for optimizing the departure time distribution of passenger trains was constructed and an optimal algorithm based on the simulated annealing algorithm.

Literature mentioned above have carried on the beneficial exploration to the initial schedule of passenger trains, but existing mathematics models are designed mainly considering how to facilitate passenger, while passenger convenience and passenger station's capacity are not considered comprehensively. More, reasonable travel time for passenger changes is a time range, existing deterministic mathematics models can't measure reasonably. In view of this, based on fuzzy set theory, comprehensively considering some constraint conditions such as passenger station's capacity and train-set joining time, etc, a mathematics model for optimizing the initial schedule of intercity passenger trains is constructed. With the paper[10],we established the model and give a simple example. In this paper, we further discussed the genetic algorithm in detail and give the more actual example with the problem. Based on the paper[10], there have been a integral discussed the initial schedule of intercity passenger trains .

II. BASIC CONCEPTS AND CONCLUSIONS

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Definition1[8]: let U be a universe, A is a subset of. For any $x \in U$,function $\mu_A : U \to [0,1]$,then A is called fuzzy set. $\mu_A(x)$ is called membership function, which expresses the degree of x belong to A

Definition2: Fuzzy expectation of passenger trains' time (arrival time): passenger's expectation departure time range (arrival time) is $[F^1, F^4]$, the level of service satisfaction is lower if time is outside the range, specially, if trains' departure time (arrival time) is in $[F^2, F^3]$,the degree of passenger satisfaction is highest. Suppose x is the time for passenger departure (arrival), membership function of satisfaction of passenger' fuzzy expectation time (arrival time) is defined as follows:

$$\mu(x) = \begin{cases} \dfrac{x-F^1}{F^2-F^1}, & if \quad F^1 \le x \le F^2 \\ 1, & if \quad F^2 \le x \le F^3 \\ \dfrac{x-F^4}{F^3-F_i^4}, & if \quad F^3 \le x \le F^4 \\ 0, & else \end{cases}.$$

III. Mathematics Model for Optimizing the Initial Schedule of Intercity Passenger Trains Based on Fuzzy Sets

A. Problem description and parammeters setting

Suppose there are m stations between city A and city B, $S = \{ s_j \mid j = 1, \ldots, m \}$ is station set, s_1 , s_m is respectively the station of A , B .In passenger train running plan, there are n pairs of passenger trains running between city A and city B , so , there are n trains running from A to B and n trains running from B to A. Suppose train 1,…, train n are running from B to A, train n+1,…, train 2n are running from A to B.

$t^s_{is_j}$ ——the departure time of train i at station s_j;

$t^z_{is_j}$ ——the arrival time of train i at station s_j.

$i = 1, \ldots, 2n$, $j = 1, \ldots, m$;

So, the problem translate that

if $i = 1, \ldots, n,$ the value of $t^s_{is_1}$ and $t^z_{is_m}$ must be solved;

if $i = n+1, \ldots, 2n$, the value of $t^s_{is_1}$ and $t^z_{is_m}$ must be solved.

B. The establishment of objective function

All passenger have desired departure time and arrival time, this time is a range, so, desired time can be considered as trapezoidal fuzzy number.If train can departure and arrive at the time in the range of expected time, it can be obtained that passenger are satisfied.

$\sum_{i=1}^{n} \mu(t^s_{is_1}) + \sum_{i=n+1}^{2n} \mu(t^s_{is_m})$ is the departure time satisfaction, $\sum_{i=1}^{n} \mu(t^z_{is_m}) + \sum_{i=n+1}^{2n} \mu(t^z_{is_1})$ is the arrival time satisfaction. Suppose λ is weight, the objective function is described as follows:

max

$$\lambda \left(\sum_{i=1}^{n} \mu(t^s_{is_1}) + \sum_{i=n+1}^{2n} \mu(t^s_{is_m}) \right) + (1-\lambda) \left(\sum_{i=1}^{n} \mu(t^z_{is_m}) + \sum_{i=n+1}^{2n} \mu(t^z_{is_1}) \right)$$

Passenger expected departure time and arrival time of train i can be described as the trapezoidal fuzzy numbers $(F_i^1, F_i^2, F_i^3, F_i^4)$, while,

$$F_i^1 < F_i^2 \le F_i^3 < F_i^4 .$$

C. The establishment of constraint conditions

(1) Constraint condition of minimum secure time interval

The time interval of any two passenger trains' departure (arrival) time is not less than the minimum safety time interval.

$$\left| t^s_{is_j} - t^s_{ks_j} \right| \ge I_{\text{departure}},$$
$$i \ne k, i, k = nx+1, nx+2, \ldots, nx+n , \quad x = 0,1 , \quad j = 1, 2, \ldots, m$$

$$\left| t^z_{is_j} - t^z_{ks_j} \right| \ge I_{\text{arrival}} ,$$
$$i \ne k, i, k = nx+1, nx+2, \ldots, nx+n , \quad x = 0,1 , \quad j = 1, 2, \ldots, m$$

(2) Constraint condition of arrival and departure tracks

At any time and at any station, the number of arrival and departure tracks occupied by trains is not more than the number of station tracks. For station s_j, at time t, the number of tracks occupied by trains is $\sum_{i=1}^{2n} \left[w(t^z_{is_j}, t) - w(t^s_{is_j}, t) \right]$,suppose the number of available tracks of station s_j is Ns_j ,while

$$\sum_{i=1}^{2n} \left[w(t^z_{is_j}, t) - w(t^s_{is_j}, t) \right] \le Ns_j ,$$
$$j = 1, 2, \ldots, m$$

While $w(x,t) = \begin{cases} 1, & x \le t \\ 0, & x > t \end{cases}$

(3) Constraint condition of stopping time at station of passenger trains

Suppose in passenger train running plan, minimum stopping time at station s_j of train i is T_{is_j}, then

$$t^s_{is_j} - t^z_{is_j} \ge T^s_{is_j},$$
$$i = 1,\dots,2n,\ j = 1,\dots,m$$

(4) Constraint condition of train running time

$$t^z_{is_j} - t^s_{is_{j-1}} \ge \xi_{j-1j},$$
$$i = 1,\dots,n,\ j = 2,\dots,m;$$
$$t^z_{is_{j-1}} - t^s_{is_j} \ge \xi_{ij}.$$
$$i = n+1,\dots,2n,\ j = 2,\dots,m;$$

(5) Constraint condition of balance function

In the paper, we use the balance function[2] to show the departure time and the arrival time of trains.

$$\psi \le B(X) \le \gamma$$

We can also from the paper[2] that if $\gamma \le 1$,we think the time of trains is equilibrium .

(6) Constraint condition of train-set joining time

Considering train-set using in planning initial schedule of passenger trains and rationally arranging train joining time can reduce the number of using train-set.

$$\sum_{k=1}^{n} \min\left\{t^s_{is_m} - t^z_{ks_m} \,\middle|\, t^s_{is_m} - t^z_{ks_m} \ge t_{\text{joining}}, i = 1+n,\dots,2n\right\} +$$
$$\sum_{k=n+1}^{2n} \min\left\{t^s_{is_1} - t^z_{ks_1} \,\middle|\, t^s_{is_1} - t^z_{ks_1} \ge t_{\text{joining}}, i = 1,\dots,n\right\} \le \beta T_{\text{joining}}$$

While, t_{joining} is the minimum train-set connecting time, T_{joining} is a fixed value of train-set connecting time, the value can be given or can be adjusted by considering total joining time of existing scheme.

$\beta \in R^+$, the value of β can be determined according to the actual situation.

D. Optimization model of initial schedule of intercity

$$\max\ \lambda\left(\sum_{i=1}^{n}\mu(t^s_{is_1}) + \sum_{i=n+1}^{2n}\mu(t^s_{is_m})\right) +$$
$$(1-\lambda)\left(\sum_{i=1}^{n}\mu(t^z_{is_m}) + \sum_{i=n+1}^{2n}\mu(t^z_{is_1})\right)$$

s.t.

$$\left|t^s_{is_j} - t^s_{ks_j}\right| \ge I_{\text{departure}} \quad (1)$$
$$\left|t^z_{is_j} - t^z_{ks_j}\right| \ge I_{\text{arrival}} \quad (2)$$
$$t^z_{is_j} - t^s_{is_{j-1}} \ge \xi_{j-1j} \quad (3)$$
$$t^z_{is_{j-1}} - t^s_{is_j} \ge \xi_{ij}, \quad (4)$$
$$t^s_{is_j} - t^z_{is_j} \ge T^s_{is_j} \quad (5)$$
$$t^z_{is_m} = t^s_{is_1} + \sum_{u=1}^{m-1}\xi_{u(u+1)} + \sum_{j=1}^{m-1}T_{is_j} \quad (6)$$
$$t^z_{is_1} = t^s_{is_m} + \sum_{u=2}^{m}\xi_{u(u-1)} + \sum_{j=2}^{m}T_{is_j} \quad (7)$$
$$\sum_{i=1}^{2n}\left[w(t^z_{is_j}, t) - w(t^s_{is_j}, t)\right] \le Ns_j \quad (8)$$
$$\alpha \le B(X) \le \gamma \quad (9)$$
$$\sum_{k=1}^{n} \min\left\{t^s_{is_m} - t^z_{ks_m} \,\middle|\, t^s_{is_m} - t^z_{ks_m} \ge t_{\text{joining}}, i = 1+n,\dots,2n\right\} +$$
$$\sum_{k=n+1}^{2n} \min\left\{t^s_{is_1} - t^z_{ks_1} \,\middle|\, t^s_{is_1} - t^z_{ks_1} \ge t_{\text{joining}}, i = 1,\dots,n\right\}$$
$$\le \beta T_{\text{joining}} \quad (10).$$

VI. GENETIC ALGORITHM FOR INITIAL SCHEDULE OF INTERCITY PASSENGER TRAINS BASED ON FUZZY SETS

(1) Chromosome structure

$$X = \overbrace{x^s_{11}, x^z_{12}, x^s_{12}, x^z_{13}, \dots, x^s_{1m-1}, x^z_{1m}}; \overbrace{x^s_{21}, x^z_{22}, x^s_{22}, x^z_{23}, \dots, x^s_{2m-1}, x^z_{2m}};$$
$$\dots \overbrace{x^s_{n1}, x^z_{n2}, x^s_{n2}, x^z_{n3}, \dots, x^s_{nm-1}, x^z_{nm}};$$
$$\overbrace{x^s_{(n+1)m}, x^z_{(n+1)(m-1)}, x^s_{(n+1)(m-1)}, x^z_{(n+1)(m-2)}, \dots, x^s_{(n+1)2}, x^z_{(n+1)1}},$$
$$\dots \overbrace{x^s_{(2n)m}, x^z_{(2n)(m-1)}, x^s_{(2n)(m-1)}, x^z_{(2n)(m-2)}, \dots, x^s_{(2n)2}, x^z_{(2n)1}}$$

Where, x^s_{ik} —The departure time of train i at station k . x^z_{ik} — The arrival time of train i at station k .Chromosome X is the set of $2n$ rains' departure time and arrival time at each station.

(2)Initial population

In order to increase convergence rate, the initial population generated by the following two methods:

1) If plan initial schedule of the trains which are already running, existing initial schedule can be used as an initial solution. In order to facilitate passenger and not to disrupt existing schedule too seriously, other initial solutions can be controlled within a certain range.

2) If plan initial schedule of the trains which don't have existing initial schedule, initial solutions can be selected randomly in the range of passengers' desired departure time and arrival time. The train's departure time and arrival time at each station can be generated according to formula 6 and formula 7.

3)Selection operator

Fitness function

$$f_i = \lambda\left(\sum_{i=1}^{n}\mu(t_{is_1}^{s}) + \sum_{i=n+1}^{2n}\mu(t_{is_m}^{s})\right) +$$

$$(1-\lambda)\left(\sum_{i=1}^{n}\mu(t_{is_m}^{z}) + \sum_{i=n+1}^{2n}\mu(t_{is_1}^{z})\right)$$

Selection operator can be determined by the method of roulette.

(4) Crossover operator

Flat crossover is adopted: parent can be selected by the probability $p_c = \varphi$, two Y_1, Y_2 offspring can be generated by parent X_1, X_2 crossing, while, $X_1 = (x_1^1, x_2^1, ..., x_n^1)$, $X_2 = (x_1^2, x_2^2, ..., x_n^2)$, $Y_i = (y_1, y_2, ..., y_n),\ i = 1,2$, and y_i is the number generated randomly and uniformly in the range of interval (x_i^1, x_i^2) .

(5) Mutation operator

For randomly selected chromosome mutation, mutation rate is $p_m = \eta$, combined with actual problem, mutation operation is interpreted as follows:

Mutation operator is determined according to the inverse membership function of train departure time, the gene locus which represents train departure time in chromosome can be varied according to the following rules, other gene locus can be changed by the corresponding change.

Suppose t_i is the original time of train departure, if the chromosome is varied, time of train departure is $t_{ichange}$, then

$$t_{ichange} = \mu^{-1}(1-\mu(t_i)) =$$

$$\begin{cases} t_i + F_i^3 - F_i^2, & if\ \ \mu(t_i)=1 and t_i \le \frac{F_i^2+F_i^3}{2} \\ t_i - F_i^3 + F_i^2, & if\ \ \mu(t_i)=1 and t_i > \frac{F_i^2+F_i^3}{2} \\ (1-\mu(t_i))(F_i^3 - F_i^4) + F_i^4, & if\ \ 0<\mu(t_i)<1 and t_i < F_i^2 \\ (1-\mu(t_i))(F_i^2 - F_i^1) + F_i^1, & if\ \ 0<\mu(t_i)<1 and t_i > F_i^3 \\ \frac{F_i^2+F_i^3}{2}, & if\ \ \mu(t_i)=0 \end{cases}$$

(6) Heuristic strategy

In order to find the global optimal solution more quickly, the following strategy is adopted

1) Elite strategy

A certain proportion of high-fitness chromosomes which is selected from parent population in each generation can join into the next generation directly, so, the operation of crossover and mutation can be adjusted.

2) Conflict strategy

In the process of chromosome, if the chromosome does not meet the constraints, adjust the train schedule with low satisfaction priority (membership degree of train's departure time is low), furthermore, chromosome mustn't be adjusted more than one time. If the train schedule already adjusted one time is not feasible, chromosome should be regenerated.

3) Stopping rule

Based on the actual problem, if algorithm can meet one of the following rules, algorithm stop:

a. fitness value of chromosome is $2n$,that is, all trains schedule has reached the maximum satisfaction.

b. the number of iterations is $M_{\max}$.

V. Example

To show the model and algorithm is a effective method, we take the high-speed intecity railway of Chengdu-Du Jiangyan for example. We only considerer the Chengdu and Du Jiangyan as the departure and arrival station easily .There are 5 stations between city Chengdu and Du Jiangyan, that station Chengdu, Xipu, Hongguang town, Du Jiangyan, Pixian west and Qing Chengshan. We note A,B,C,D,E,F show the stations respectively. there are15 trains running from city Chengdu to city Qing Chengshan, and also there are 15 trains running from city Qing Chengshan to city Chengdu. In the paper, we only discussed the trains which running from city Chengdu to city Qing Chengshan.

By the survival and the fact of passengers psychology, the fuzzy expectation time (departure time)of trains D6101, D6105, D6107, D6109, D6111, D6113 are defined as follows:

$$\mu(x) = \begin{cases} x-7, & if\ \ 7 \le x \le 8 \\ 1, & if\ \ 8 \le x \le 10 \\ 11-x, & if\ \ 10 \le x \le 11 \\ 0, & else \end{cases}$$

And the fuzzy expectation time (arrival time)of trains D6101, D6105, D6107, D6109, D6111, D6113 are defined as follows:

$$\mu(x) = \begin{cases} x-7, & if\ \ 7 \le x \le 8 \\ 1, & if\ \ 8 \le x \le 11 \\ 12-x, & if\ \ 11 \le x \le 12 \\ 0, & else \end{cases}$$

By the survival and the fact of passengers psychology, the fuzzy expectation time (departure time)of trains, D6119, D6121, D6123, D6125, D6127, D6129, D6183, D6185 are defined as follows:

$$\mu(x) = \begin{cases} x-13, & if\ \ 13 \le x \le 14 \\ 1, & if\ \ 14 \le x \le 16 \\ 17-x, & if\ \ 16 \le x \le 17 \\ 0, & else \end{cases}$$

And the fuzzy expectation time (arrival time)of trains, , D6119, D6121, D6123, D6125, D6127, D6129, D6183, D6185 are defined as follows:

$$\mu(x)=\begin{cases} x-13, & if \quad 13\le x\le 14 \\ 1, & if \quad 14\le x\le 17 \\ 18-x, & if \quad 17\le x\le 18 \\ 0, & else \end{cases}$$

The distance between two stations and the number of departure and arrival tracks which are listed in table Ⅰ translate to the distance relationship which are listed in table Ⅱ for necessary.

TABLE Ⅰ.

THE DISTANCE BETWEEN TWO STATIONS

Distance (km)	A	B	C	D	E	F
A	0	15	18	27	57	65
B	15	0	3	12	42	50
C	18	3	0	9	39	47
D	27	12	9	0	30	38
E	57	42	39	30	0	8
F	65	50	47	38	8	0
Number of departure and arrival tracks	5	3	3	3	8	3

TABLE Ⅱ.

RUNNING TIME BETWEEN TWO STATIONS

Running time (minute)	A	B	C	D	E	F
A	0	11	15	21	34	40
B	11	0	4	10	23	29
C	15	4	0	6	19	25
D	21	10	6	0	13	19
E	34	23	19	13	0	6
F	40	29	25	19	6	0

TABLE Ⅲ.

TRAINS' STOPPING TIME (INCLUDING ADDITIONAL START AND STOP TIME) AT EACH STATION

minute	B	C	D	E
D6101	2	2	0	2
D6103	2	0	2	2
D6105	2	2	2	2
D6107	2	2	2	3
D6109	2	2	0	3
D6111	0	0	0	3
D6113	2	2	2	2
D6119	0	0	0	3
D6121	0	0	2	2
D6123	4	0	0	2
D6125	2	2	2	2
D6127	2	2	2	3
D6129	0	0	2	2
D6183	0	0	2	3
D6185	0	0	0	0

TABLE Ⅳ.

THE RESULT OF ALL THE TRAINS

	D6101	D6103	D6105	D6107	D6109
Departure time	7.21	7.50	8.30	9.10	9.45
Arrival time	8.10	8.34	9.18	9.59	10.40
$\mu(x)$	0.368	0.6	1	1	1
	D6111	D6113	D6119	D6121	D6123
Departure time	10.33	11.00	14.51	15.24	15.40
Arrival time	11.10	12.47	15.30	16.04	16.22
$\mu(x)$	0.444	0	1	1	1
	D6125	D6127	D6129	D6183	D6185
Departure time	16.50	17.15	18.44	17.25	18.21
Arrival time	17.49	18.04	19.24	18.08	18.52
$\mu(x)$	0.28	0	0	0	0

The trains' stopping time (including additional start and stop time) at each station are listed in table Ⅲ.

At last, minimum safety interval is 3 minute, and the effectiveness of optimization algorithm of initial schedule of passenger trains proposed in the paper is demonstrated by the examples by programming in Matlab7.0. While $\alpha=0.9$, $\beta=1.2$, $N=30$, $p_c=0.8$ $p_m=0.1$, $\gamma=1$, $M_{\max}=400$, $\lambda=0.8$, $t_{joining}=25$, $I_{departure}=I_{arrival}=3$, $T_{joining}=1000$, the result is listed in Table Ⅳ.

From the table Ⅳ, it is infer that the results can be drawn that objective function value is 7.692, which increase 2.13 to the current time schedule. the lowest satisfaction degree of five trains is 0, because of both the expectation time and the equilibrium requirement. the 40% trains schedules have reached the maximum satisfaction. The example obtains good results by the algorithm.

Secondly, in order to analyze the effect of important factors and parameters on the solutions, the other following experiments were done[10].

(1) The effect of number of departure and arrival tracks on the solutions(table V)

From the table, it is infer that when the number of departure and arrival tracks is increasing, objective function value is increasing, however, if the number of departure and arrival tracks reaches a certain quantities, value of objective function can't be changed.

TABLE V

f	7.81	8.37	8.59	8.59	8.59	8.59	8.59
Number of departure and arrival tracks	5 1 1 2 2 2 5	5 2 2 2 2 2 5	5 3 3 2 2 2 5	5 3 3 3 3 3 5	5 4 4 3 4 3 5	5 4 4 4 4 3 5	5 4 4 4 4 4 5

(2) The effect of value λ on the solutions (table VI)

TABLE VI

f	10	8.59	8.26	8.13	9.22
λ	1	0.8	0.5	0.2	0

The table shows that if $\lambda = 1$, that is only considering satisfaction of trains' departure time without considering the arrival time, the result reaches the maximum satisfaction ; if $\lambda = 0$, that is only considering satisfaction of trains' arrival time without considering departure time, the results doesn't reach the maximum satisfaction. The solution is the result is realistic, because in the process of solving, the schedules of departure trains with low satisfaction are adjusted priority when the solutions are not feasible.

(3) The effect of value β on the solutions (table Ⅶ)

TABLE Ⅶ

f	6.53	8.06	8.59	8.59	8.59	8.59	8.59
β	0.5	0.8	1	1.2	2	5	8

The table shows that when value β is increasing, objective function value is increasing, however, if value β reaches a certain value, value of objective function can't be changed. This is also consistent with the model and algorithm, because value β is weight coefficient of train-set joining time, if value β is too big, the corresponding constraint will not work, the objective function value can't be changed any more..

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