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Study on Optimization Model of Subway Train Operation Based on the Forecast of Passenger Flow

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Abstract: Passenger flow forecast reflects the route passenger distribution over time and inter-station. By analyzing the passenger flow prediction model of a route and dividing the all-day traffic into three sections according to time periods, the concept of passenger satisfaction and energy consumption satisfaction is proposed. The maximum operating speed meeting the objective function is found by using genetic algorithms. Then by using the train operation simulation system, the travelling location and velocity of the train on the whole line are mapped out and finally the optimized result is analyzed. The data shows that this method can not only meet passenger demand well but also perform well in energy consumption and passenger satisfaction.

Key words: Passenger flow prediction model, satisfaction, genetic algorithm

INTRODUCTION

Passenger forecasting model is a reflection of route passenger variation over time and inter-station and a reasonable passenger flow forecast model helps to carry out reasonable network planning, transportation arrangements and equipment configuration, having an important significance in daily traffic operation management. Many domestic scholars have done a lot of work on passenger traffic forecasting (Huang, 2011; Li *et al.*, 2004; Wu, 2007) but this considerable research were only focused on improving the accuracy of passenger flow forecast. As the maximum inter-station operating speed is related to passenger travel time, many scholars have done some researches on influencing factors of maximum inter-stations speed but rarely taken passenger flow into consideration (Xu, 2008) while research on subway train operation optimization usually discusses about energy and time consumption (Feng, 2001; Peng *et al.*, 2005; Mao *et al.*, 2000), rather than the traffic situation. In this paper, by studying the passenger flow forecasting model, the whole day passenger flow is divided of three time periods and referring to elevator group control strategy (Zong *et al.*, 2008; Lv, 2007) the concept of passenger satisfaction and energy consumption satisfaction is proposed. Then maximum inter-station operating speed optimizing is studied through passenger satisfaction and energy consumption satisfaction and the optimized maximum train inter-station speed is obtained and the optimization results is plugged into trains headway calculation model to obtain the impact on departure interval. The results show that the optimization results do not affect departure interval but can greatly improve the energy consumption satisfaction and passenger satisfaction of the train.

PASSENGER FLOW FORECASTING MODEL

Passenger flow forecast is the basis of passenger flow analysis and at present it is mainly adopted by the method of The Four Stage. Passenger flow forecast can be divided into hour passenger flow distribution within a day and full-day passenger flow distribution within a week according to time periods, or according to the space, divided into passenger flow distribution on various routes, upstream and downstream passenger flow distribution, section passenger flow distribution on routes and OD passenger distribution of inter-station and so on (Zhang, 2006a). The passenger flow forecasting model used in this study is based on the references (Zhang, 2006b) and passenger flow distribution is divided into working and non-working day but in this paper only passenger flow diagram of workdays is used. Figure 1 shows the passenger flow distribution of a subway line during the day and Fig. 2 shows passenger flow distribution of inter-station on a subway line.

The departure interval of a train line is as follows.

In order to facilitate the research, according to train departure intervals the all-day operation time is divided respectively into three sections: The peak period, average period and slack period (Table 1). By establishing the evaluation function, the highest speed between stations is found, which meets passenger demand of the three periods, to achieve the optimization.

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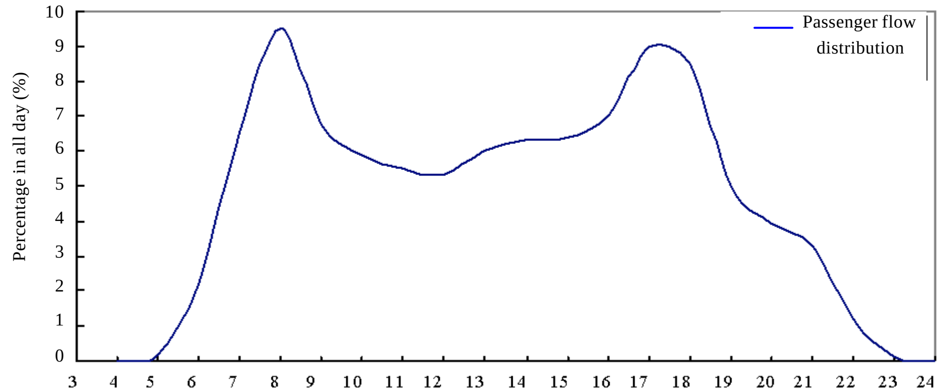

Fig. 1: Passenger flow distribution of a subway line during the day (working day)

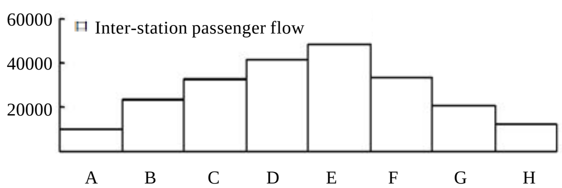

Fig. 2: Passenger flow distribution of inter-station on a subway line

Table 1: Departure interval of a train line

Run time	6:00~9:00	9:00~17:00	4:30~6:00
	17:00~20:00	20:00~22:00	22:00~24:00

OPTIMIZATION MODEL OF INTER-STATION OPERATING

Passengers congestion evaluation model: As passengers congestion degree is a psychological index of passengers, the current state of the domestic load is usually divided into four cases of AW0, AW1, AW2 and AW3. Standing area is the passenger compartment area excluding the seats and the 10mm edge in the front and weight can be calculated by 60 kg per capita. Right amount of passenger seats are set inside the passenger compartment and the rated standing number is 6 m^{-2}, if overcrowded, then 9 m^{-2}. Passenger flow in a period can be calculated by the passenger flow prediction model and then according to the distribution of traffic between stations, passenger traffic between stations can be worked out. Train parameters used in the simulation is as follows: total length of 140 m, train height of 3.8 m, width of 3 m, 48 seats in each train and at most 7 people of each seat. It can seat 336 people in state of AW1 (i.e., seats filled with people), 1, 860 people in state of AW2 (rated load), 2, 592 people in state of AW3 (overcrowding load). Congestion degree evaluation function is as follows (Fig. 3):

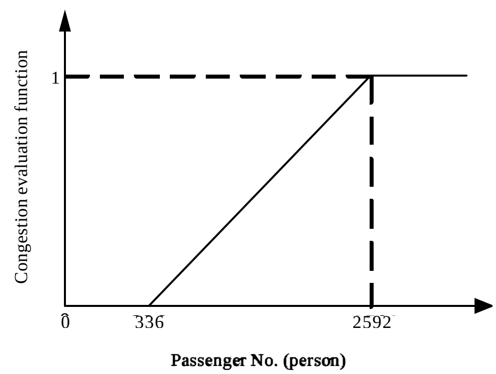

Fig. 3: Congestion evaluation function

$$f_{PC}(x) = \begin{cases} 1 & x \geq 2592 \\ 0.00044 * x - 0.1489 & 2592 > x > 336 \\ 0 & 0 < x \leq 336 \end{cases} \quad (1)$$

where, $f_{PC}(x)$ is passengers congestion evaluation; x is the number of passengers (persons).

Passenger satisfaction evaluation model: Passenger satisfaction is determined by the congestion degree. When the degree is higher, the passenger's mental irritability index increases and passengers tend to demand shorter travel time to enhance the passenger satisfaction; and when the congestion degree is lower, passengers have less demanding on riding time. Taking passenger riding time as a variate, passenger satisfaction evaluation function is established (Fig. 4):

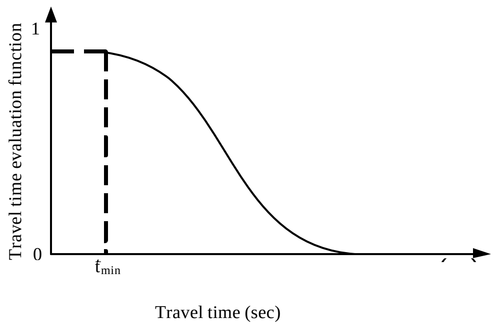

Fig. 4: Travel time evaluation function

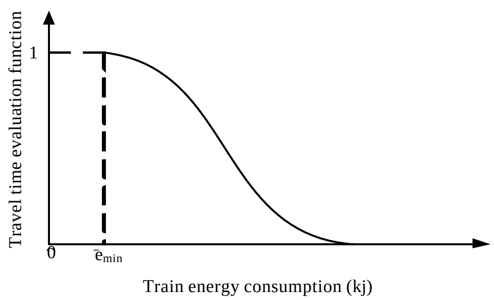

Fig. 5: Energy consumption evaluation function3

$$f_{PT}(t) = \begin{cases} 1 & t = t_{min} \\ e^{a*(t-t_{min})^2} & t > t_{min} \end{cases} \tag{2}$$

where, f_{PT} (t) is passenger satisfaction evaluation index; t is travel time between stations of the passengers; a is the coefficient of passenger satisfaction; t_{min} is the shortest running time between stations of the train.

Evaluation of train's energy consumption satisfaction: Subway train is an energy-hungry system in city, electricity accounts for a large proportion in the train's operating costs. But in the peak hour, train's energy consumption is often not the main object for consideration, instead, train's energy consumption satisfaction lies in the evaluation of energy consumption between subway stations, therefore the subway train's energy consumption satisfaction between stations is taken as a variate to build train energy consumption satisfaction evaluation function (Fig. 5):

$$f_E(e) = \begin{cases} 1 & e = e_{min} \\ e^{b*(e-e_{min})^2} & e > e_{min} \end{cases} \tag{3}$$

where, f_E (e) is the evaluation function of train energy consumption satisfaction; e is the train energy consumption between stations; b is the train Satisfaction energy coefficient; e_{min} is the minimal energy consumption of the train between stations.

Equation 2 and 3 are proposed by referring to the evaluation formula in Reference (Lv, 2007) and the a and b is obtained as following: First, maximum operating speed range between stations is set, where the setting is range of [60, 80]; then use the upper limit value (80 km h^{-1}) and lower limit value (60 km h^{-1}) of maximum operating speed as the top running speed between stations and get optimized running time (energy consumption) between stations by using the coasting control genetic algorithm between stations (Zhang, 2006a) by this time, t_1 and t_2 (e_1 and e_2 is obtained and t_1 represents running time between stations where the highest operating speed is 60, t_2 represents inter-station running time where the highest operating speed is 80 (set t_2 as t_{min} and the corresponding passenger satisfaction evaluation index is 1 and the corresponding passenger satisfaction evaluation index of t_2 is 0.001), then put them into passenger satisfaction evaluation model and the value calculation formula of a is obtained as:

$$a = \frac{\log(0.001)}{(t_1 - t_2)^2}$$

Similarly, the satisfaction evaluation index corresponding to the minimum energy consumption of inter-station is 1, the corresponding maximum index is 0.001 and the train energy consumption satisfaction coefficient:

$$b = \frac{\log(0.001)}{(e_1 - e_2)^2}$$

When optimizing train operation strategy of a certain period, the passenger flow of this period should be sought out in Fig. 1 and then the congestion degree is calculated according to the passenger flow. If the congestion degree is too high, passenger satisfaction should be the major consideration and the proportion of passenger satisfaction in operating strategy should be increased; if the congestion degree is low, train energy consumption satisfaction should be the major consideration and the proportion of consumption satisfaction in operating strategy should be increased.

Influence on the minimum departure interval acted by Maximum speed: From reference (Sun, 2007), the departure interval can be calculated as follows:

$$H = \sqrt{\frac{2(L+D)}{a_s}} + \frac{L}{v_a} + \left[\frac{1}{K} + B\right] \cdot \frac{v_a}{2d_s} + \left[1 - \frac{v_a}{v_L}\right] \cdot \frac{a_s t_{os}^{\ 2}}{2v_a} + t_{os} + t_d + t_{br} + t_{ji} + t_{om} \tag{4}$$

where, L is the train length; D is the gap from the front of the train to the top partition of station exit; v_a is the train pulling speed, a_s is () the common initial acceleration, K is the braking safety coefficient, i.e. braking efficiency of actual effect tolerance; B is interval safety coefficient, including a separate train safety margin; t_{os} is action time of the overspeed monitor; t_d is stay time at the station; t_{hr} is the response time of drivers and system; t_{i1} is maximum output time required by brake system; t_{om} is the safety operating margin. Specific coefficient refers to References (Sun, 2007).

OPTIMIZATION OF TRAIN INTER-STATION MAXIMUM OPERATING SPEED

According to objective function for the inter-stations coasting point position selection mentioned in References (He *et al*., 2011), the optimal inter-stations coasting point position is calculated and different maximum operating speeds correspond to different positions of coasting points. When the position is put in into the objective function of maximum operating speed optimization, the entire inter-station maximum operating speed can be optimized.

Objective function of genetic algorithm for coasting point selection:

$$F_{min} = W_T \cdot \left|\frac{T_g - T_D}{T_D}\right| + W_E \cdot \left|\frac{E_g - E_D}{E_D}\right| + W_S \cdot \left|\frac{S_g - S_D}{S_D}\right| \tag{5}$$

where, $W_T+W_E+W_S = 1$, W_T is the runtime weight; W_E is the train energy consumption weight; T_g is the inter-station running time optimized by genetic algorithm; T_D is the inter-station running time in the minimum operating mode; E_g is the train inter-station energy consumption optimized by genetic algorithm; E_D is the minimum inter-station train energy consumption; S_g is the train inter-station operation distance optimized by genetic algorithm and S_D is the actual distance between stations.

Objective function of genetic algorithm for Maximum speed:

$$F_{max}(t, e) = w_t * f_{PT}(t) + w_e * f_E(e) \tag{6}$$

where, $w_t+w_e = 1$; w_t is operation time weight and w_e is energy consumption weight, Blow Optimizing step:

Step 1: Calculate the value of w_t and w_e according to the passenger congestion degree; $w_t = f_{PC}$ (c), $w_e = 1-w_t$

Step 2: Find the position of optimal individuals coasting point in a population in circulation, which is decided by the genetic algorithm, then find the coasting point locations of inter-station at maximum speed and minimum speed and at last calculate the train inter-station running time at maximum speed and minimum speed

Step 3: Calculate the travel time evaluation index a and then calculate the travel time evaluation indexes of each individual in current population

Step 4: Find the position of optimal individuals coasting point in a population in circulation and then find the coasting point locations of inter-station at maximum speed and minimum speed, at last calculate the train energy consumption at maximum speed and minimum speed

Step 5: Calculate the travel time evaluation index b and then calculate the energy consumption evaluation index of each individual in current population

Step 6: Enter the genetic algorithm iterative process of maximum speed and through of the calculation of 30 generations, get the optimal maximum train operating speed of inter-station

APPLICATION EXAMPLES

Combined with the situation of a domestic subway line previously mentioned and the passenger flow prediction model, the optimal maximum operating speed of the inter-station is obtained and then it is put into train running simulation modules to get optimized operation strategy of the line by simulation. The genetic algorithm optimization conditions: the maximum velocity function population is 20, the iterations is 30 generations; coasting point function population is 20, the iterations is 20 generations; restructuring probability is 0.7, mutation probability is 0.1 and the generation gap is 0.9. The passenger congestion degree in simulation process is determined by the average hourly number of passengers and the average number of passenger of a train is determined by the maximum passenger flow in transportation time. After the simulation, based on the maximum operating speed and coasting position between stations, train operation graph of three periods is drawn. The simulation results are shown in Tab.2 and the train operation graph is shown in Fig. 6.

SIMULATION RESULTS ANALYSIS

Impact on departure interval: The minimum inter-station departure interval can be calculated by Eq. 4, shown as follows:

Table 2:Simulation result

Line information	A-B	B-C	C-D	D-E	E-F	F-G	G-H
Inter-station Distance	1287.6	1617	1021	1123	1449	1238	1768.19
Peak hour traffic	9800	23300	32450	41640	48300	33660	21060
Peak passenger congestion	0.0667	0.3637	0.5648	0.7672	0.9137	0.5718	0.3144
Inter-station highest speed in peak hours	60.9	60.5	68.36	78.6	79.1	78.4	60.2
Coasting position in peak hours	921.4	1067.5	529.3	522.4	723.9	593.2	1255.9
Off-peak hour traffic	6533	15533	21633	27760	32200	22440	14040
Off-peak passenger congestion degree	0.0425	0.3008	0.4856	0.6651	0.7953	0.5080	0.2629
inter-station Maximum speed during off-peak time	60.5	62.1	69.9	78.9	79.1	78.2	60.5
Coasting position during off-peak time	908.2	1054.2	540.6	600.0	785.7	613.1	1252.6
Slack hours traffic	3267	3383	5408	6940	8050	5610	3510
Slack hours traffic congestion	0.0187	0.0249	0.1287	0.2075	0.2203	0.1393	0.0315
Inter-station maximum speed during slack hours	60.3	61.1	61.2	60.7	60.9	60.5	60.3
Coasting position during slack hours	833.0	1191.2	653.8	684.5	980.4	826.9	969.2

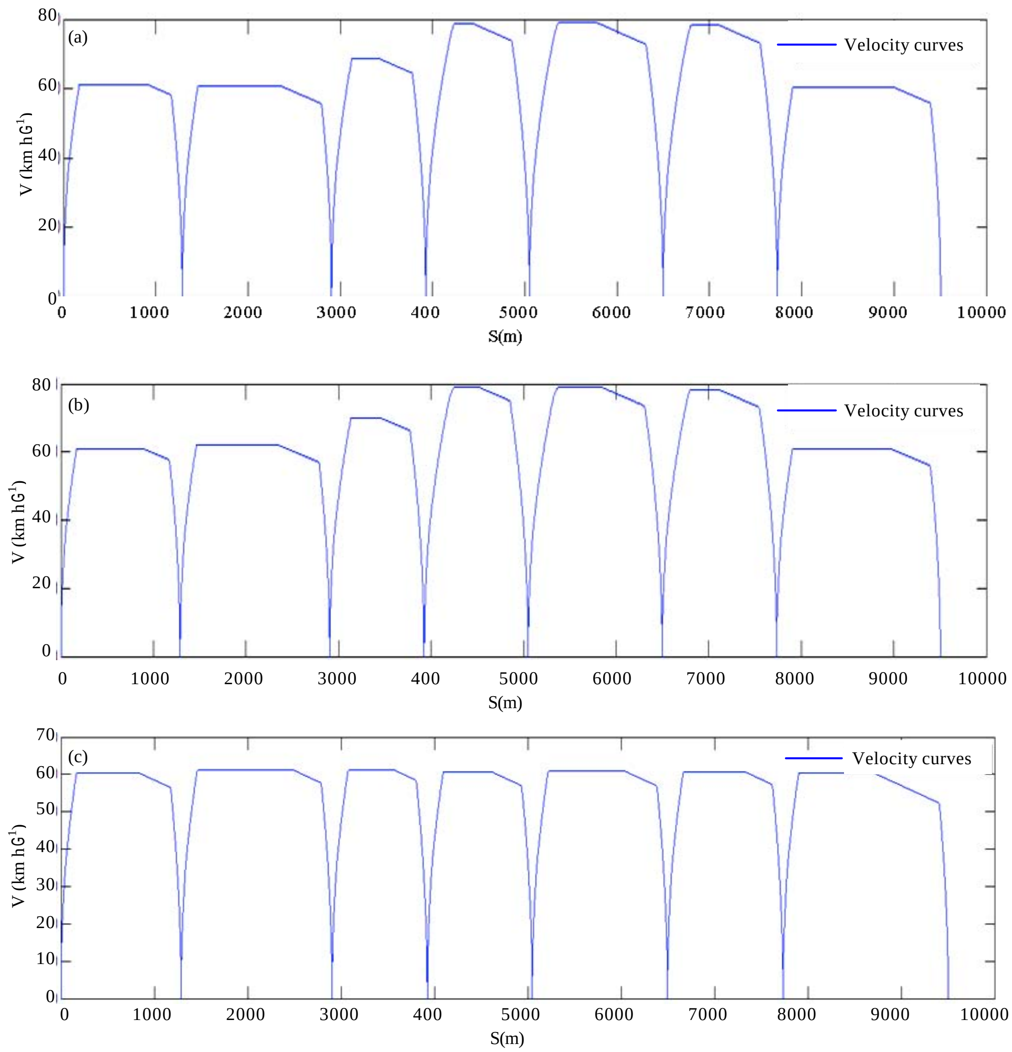

Fig. 6(a-c): Train position and velocity curves, (a) Train position and velocity curves during peak hours, (b) Train position and velocity curves during off-peak hours and (c) Train position and velocity curves during peak hours

Table 3: List of departure interval

	A-B	B-C	C-D	D-E	E-F	F-G	G-H
Maximum departure interval at 60 km h^{-1} (sec)	129.39	129.44	129.40	129.40	129.40	129.42	129.40
Maximum departure interval at 80 km h^{-1} (sec)	129.47	129.43	129.42	129.41	129.46	129.43	129.47

Table 4: Satisfaction comparison

	Average energy consumption satisfaction	Average passenger satisfaction
Peak time	0.4789	0.4632
Off-peak time	0.4504	0.4845
Slack time	0.9921	
Method in reference [13]	0.0011	0.9889

Seen from the Table 3, the difference between the maximum inter-station departure interval at 60km/h and that at 80 km h^{-1} is not obvious, so it can be considered that the optimizing of the maximum inter-station running speed in this study has no effect on departure interval and on the premise of without affecting the departure interval the proposed optimizing scheme in this study.

Impact on energy-saving and passenger satisfaction: By taking a weighted average of energy consumption satisfaction and passenger satisfaction of each inter-station of the whole line respectively, the mean value of these two indexes in each period is obtained, as shown in Table 4.

Since the congestion degree is low during slack periods, most of the passengers do not care about travel time, so the off-peak passenger satisfaction is not considered. Analysis of data shows that: inter-stations optimization strategy of operating in this study, compared to that proposed in reference (He *et al*., 2011), has improved greatly in energy consumption satisfaction, by which both of energy consumption and passenger satisfaction benefit from optimization and by reducing operating speed during slack periods, energy consumption satisfaction is improved on the premise of without considering passenger satisfaction.

CONCLUSIONS

During the congested traffic period, passenger satisfaction can be greatly increased by increasing the maximum operating speed appropriately and during the sparse traffic periods, the train energy consumption can be significantly reduced when the train is operated at a lower speed. Different inter-station operational strategies are made for different traffic situations, thus the optimal strategy of the line is obtained and it is proved that it can well meet the train operation.

Passenger flow prediction model is the basis of inter-station operating optimization and if the predictive model changes, the inter-station operating strategy should be changed accordingly. By the optimization method, passenger satisfaction and metro consumption satisfaction can be well met. As the passenger satisfaction and metro energy consumption satisfaction in this paper are just simplified models, by which the optimized inter-station operating strategy obtained is just to provide a reference for the subway operate optimization nowadays. In future studies passenger waiting time can be added to passenger satisfaction and energy consumption satisfaction can be associated with operator costs, social costs and fares of subway to make the optimization more valuable.

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