A COMPARISON ON THE HEADWAY ESTIMATES OF KAOHSIUNG ORANGE LINE

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Abstract

The paper firstly reports the process, method, and result of a simulation study, on the estimation of minimum headway for the orange line of the Kaohsiung Mass Rapid Transit (KMRT). The headway estimate is then compared in detail with the values of minimum headway, which calculated by the formula widely described in railway traffic flow theory and railway signaling theory. The comparative result shows a big difference among these estimates. For the orange line, the operation factor (such as stop pattern and dwell time), the vehicle capability (such as acceleration and deceleration), the control system (such as moving block system), and the rail line geometric factor (such as curve and gradient) may respectively explain 66%, 14%, 13% and 7% of the difference.

INTRODUCTION

The minimum headway is an important factor for the planning, design , and operation of a rail transit line (Nigel et al., 199) . The calculations of minimum headway are discussed in many books of railway or public transportation (Vuchic, 1981; Nock, 1993) . In practice, system simulation is a widely used technique in railway planning and operation (Yoshikawa, 1992) , and it is used in this study to generate a practical minimum headway. This paper presents three estimates of the minimum headway for the orange line of Kaohsiung Mass Rapid Transit (KMRT), respectively on the basis of railway traffic flow theory, the theory of railway signaling, and the simulation study. Then, the difference among the three estimates is compared in detail, so as to find important explanatory factors. The headway-delay-capacity relationship is also discussed, for the case that the operation headway is shorter than practical minimum headway

The structure of the paper is the following. An overview of the theory of minimum headway is stated firstly in this section. Then the simulation study of the orange line is described in the second section; including the model, minimum headway estimate, and headway-delay-capacity relationship. The third section is the comparison and discussion on the important factors and stochastic effects for the headway estimates. Finally, the conclusion is made to summarize the major findings of the paper.

Railway traffic flow theory

The formula of the minimum headway in railway traffic flow theory and that in railway signaling theory are widely discussed (Vuchic, 1981; Nock, 1993) . They are briefly reviewed in the following. If a train may stop instantaneously, the separation between two successively moving trains must be larger than or equal to the braking distance of the second train. Having a steady speed ‘v’ and a minimum braking rate ‘b’, the minimum separation or braking distance is given by eqn1.

$$s = \frac{v^2}{2b} \qquad (1)$$

If the train length is ‘l’, then the minimum headway ‘H’ is written as eqn2.

$$H = \frac{s + l}{v} \qquad (2)$$

To minimize ‘H’, the optimum running speed ‘V’ is given by eqn3.

$$V = \sqrt{2bl} \qquad (3)$$

At last, take (3) into (2), the minimum headway is rewritten as eqn4.

$$H = \sqrt{\frac{2 \cdot l}{b}} \qquad (4)$$

Railway signaling theory

Fixed block signaling is the most widely used form of signaling, both for urban and inter-city railway operations. Consider a 3-aspect arrangement as shown in Figure 1, the minimum headway distance 'h_3 'is given by eqn5.

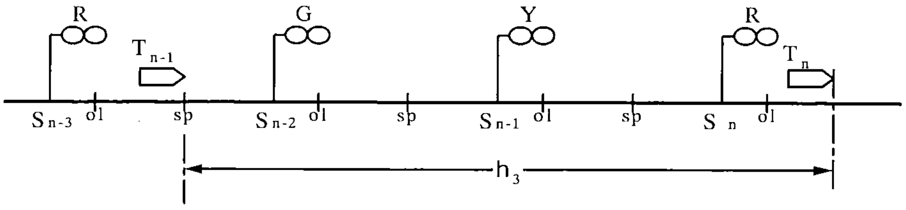
$$h_3 = 2\,d_3 + p + o + l \tag{5}$$

where 'd_3' is the block length for 3-aspects,

'p' is the sight distance,

'o' is the overlap distance beyond the signal, and

'l' is the length of train length.



ol : end of overlap.
sp : sighting point

Y : yellow
G : green
R : red

Figure 1- A 3-Aspect fixed block layout

In practice, the 3-aspect block length is the braking distance 's'. Furthermore, if the 4-aspect is incorporated as shown in Figure 2, the minimum headway distance 'h_4 ' is then written as eqn6.

$$h_4 = 3\,d_4 + p + o + l \tag{6}$$

The standard practice to the 4-aspect block length is one half of braking distance 's'. It follows that the minimum headway distance for a n-aspect arrangement is given by eqn7.

$$h_n = \frac{n-1}{n-2}s + p + o + l \tag{7}$$

In order to minimize the headway time, the optimum speed is given by eqn8.

$$V = \sqrt{2\frac{n-2}{n-1}b(p+o+l)} \tag{8}$$

Therefore, the minimum headway at the optimum speed for n-aspect can be rewritten as eqn9.

$$H = \sqrt{\frac{2(p+o+l)(n-1)}{b(n-2)}} \tag{9}$$

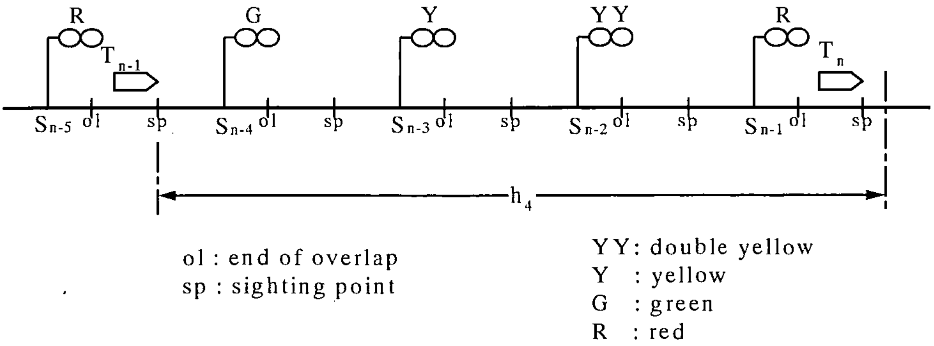


Figure 2- A 4-Aspect fixed block layout

Discussion

When 'n' is a very large number or the moving block signaling is selected, and/or if an intelligent system is chosen to decrease the value of 'p' and 'o', the limit of the headway in eqn9 approaches to the headway in eqn4. In the minimum headway eqn4, the headway is only dependent on the train length and the braking rate. It implies that a short train will result in a short headway. However, in the design and operation of a rail line, we have to consider not only the headway but also the capacity. A long train may result in a large capacity.

A lot of design and operation factors have not been considered in the formula of minimum headway mentioned above. Examples are the geometric factors of the railway line, such as curves and gradients, the mechanical characteristics of the vehicle, such as the traction and acceleration capabilities, and the practical factors in operation, such as the number of stops and the platform dwell time at a station. Therefore, the minimum headway calculated by the formula may be quite different from the operational minimum headway in practice.

A SIMULATION STUDY OF THE ORANGE LINE

The Kaohsiung Mass Rapid Transit (KMRT) is currently in the design stage. The KMRT orange line is one of the proposed projects which have been studied intensively (International Transit Consultants, 1993). The orange line is located from the east of Kaosiung to the west, its total length is 14 kilometers, and it consists of 15 stop stations. According to a demand analysis, the required minimum headway for the orange line is 200 seconds. Moreover, the orange line's basic track configurations, vehicle and traction characteristics, and types of traffic control systems have also been briefly studied. The proposed track configurations- such as the speed limit at each section of the line, the proposed vehicle characteristics- such as the train length and traction capability, and an assumed 4-aspect block signaling system are used in the simulation study to estimate the practical minimum headway of the orange line. The simulation model described in this section was developed in FORTRAN and all experiments were run on a personal computer 586.

The model

In order to find the practical minimum headway for a specific railway, a simulation model is developed. It mainly consists of two parts: a train movement simulator and a train dispatching simulator (Lee et al., 1997) . They are respectively described briefly in the following.

The heart of the simulation model is a train movement simulator. It simulates the motion of a train along a railway so as to obtain the trajectory of the train, given the input data representing the track configurations, the vehicle operating characteristics, and operation conditions. That is, the train movement simulator can generate the output which describing the running speed, running time and the traction of the train over distance.

It is well known that the speed and running time of a train can be calculated by solving the differential equations derived from Newton's law of motion (e.g. Inada et al., 1975; Andrews, 1986) . However, it is much easier and more efficient to obtain the trajectory of a train by discrete simulation techniques (e.g. Uher et al., 1987) . Assuming the acceleration of the train is a constant over a very short section, the equations of motion can be integrated to compute the speed of the train at the end of the section with a given speed at the beginning of the section. Similarly, given the train speed at the end of the section, the speed of the train at the beginning of the section can be calculated in the direction of negative time flow. An example of the forward and backward calculations is illustrated in Figure 3. In brief, the train movement simulator can simulate the functions of system units instead of simulates the operations of the units. That is, the train movement simulator is developed to plot the trajectory of a train movement in terms of velocity-distance, acceleration-distance, and so on. However, there is no consideration of the interactions among the trains on the railway network.

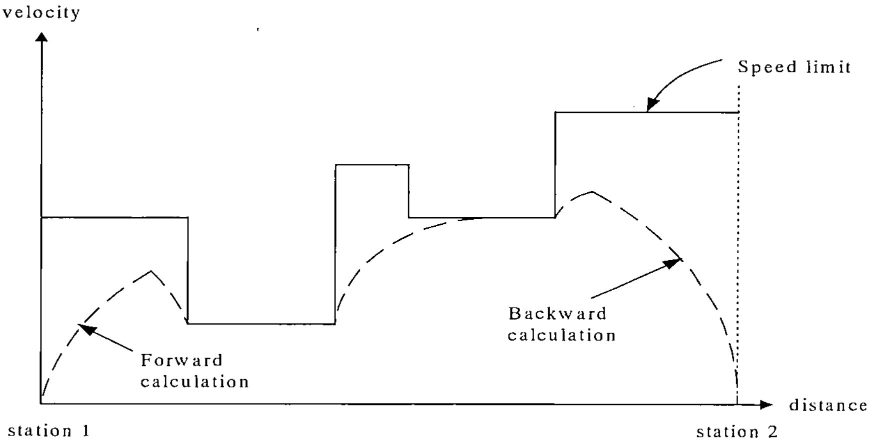


Figure 3- Trajectory calculation

The primary objective of the train dispatching simulator is to simulate the commands from the railway traffic control system to each train on the network. In general, the traffic control system consists of a fixed block signaling system and a centralized control system. According to the traffic condition at a specific simulation time interval, the train dispatching simulator updates the display of each block signal and generates commands from the dispatcher to the drivers. The result of the train dispatching simulator at that time interval will create new constrains for calculating the trajectory of train movements at and after the time interval. An example of the effect of the block signal on the calculation of the trajectory of two trains is illustrated in Figure 4. Note that the backward speed constrains due to the signals are dependent on the movement of the preceding train, and these constrains have effect on the movement of the successive train.

With the consideration of the traffic control system in the train dispatching simulator, the model can simulate the relationships of all trains on the railway network at each discrete and adjustable time interval, where the movement of each train at each time interval is calculated by the train movement simulator. In summary, the train dispatching simulator is a tool to represent the traffic control system of the railway network, and it is used to take care of the interactions among the movements of trains.

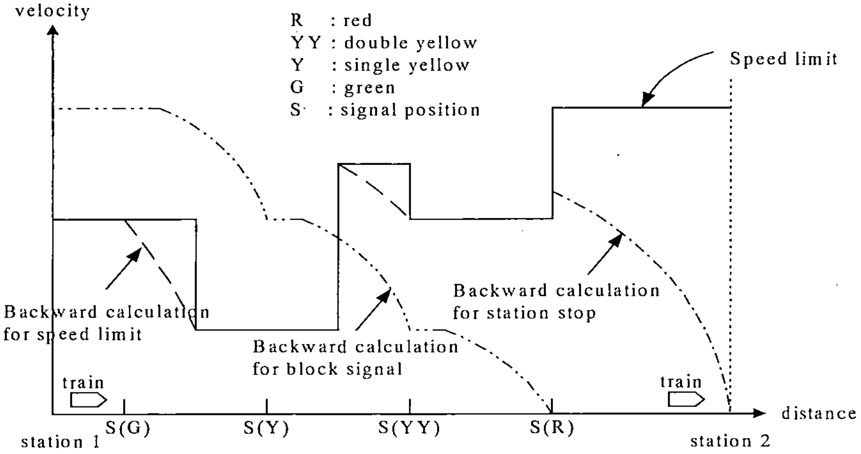


Figure 4- The effect of block signal on trajectory calculation

The practical minimum headway for the orange line

Headway is in general considered as the time between successive trains such that the speed of the following train is not restricted by the position of the preceding train. After many simulation runs, the minimum headway of the orange line is obtained as 150 seconds. As the time-space diagram shown in Figure 5, every train meets the green light at every signal position from the first station to the end terminal. If a train is permitted to meet not only green lights, the time interval between the successive trains can be shorter than the practical minimum headway. For example, the time-space diagram of 80-second headway is illustrated in Figure 6. It is clear that the interruption between successive trains happened, and the total running time for the last train is much longer than the normal running time for a train meets only green light.

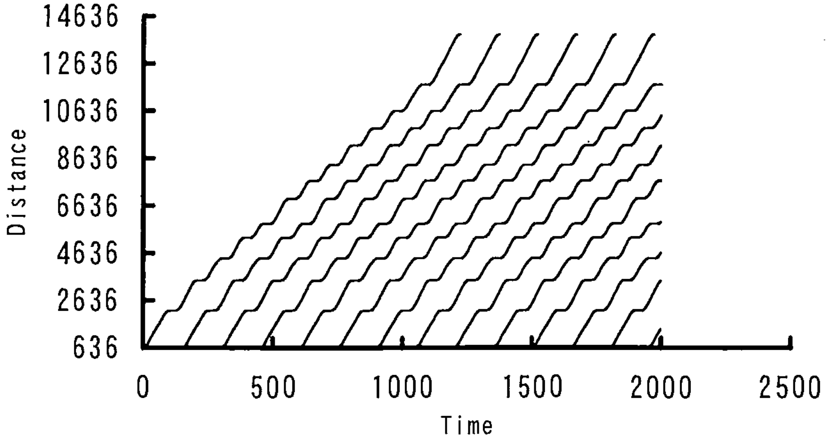


Figure 5- The time-space diagram for 150-second headway

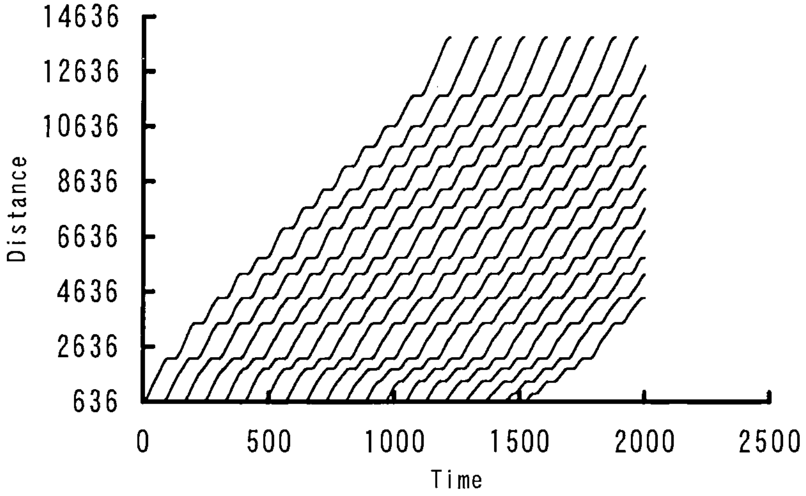


Figure 6- The time-space diagram for 80-second headway

Headway-delay-capacity relationship

Delay is defined as the difference between the actual running time and the normal running time without any interruption of signal speed restriction. There is no delay for every train if the headway is greater than or equal to 150 seconds. As the results shown in Figure 7, the average delay or the delay of the last train in the peak hour is increasing slowly, when the headway is shorter than 150 seconds but greater than 90 seconds. Therefore, the operational headway may be shorter than the practical minimum headway-150 seconds, if the safety of the system is still guaranteed and the amount of delay is acceptable. However, as also shown in Figure 7, the delay is increasing very fast when the headway is lesser than 90 seconds. The delay increase for a decrease of headway, when it is less than 90 seconds, is quite high. Therefore, with regard to the quality of service, it is not appropriate to run the train with a headway shorter than 90 seconds.

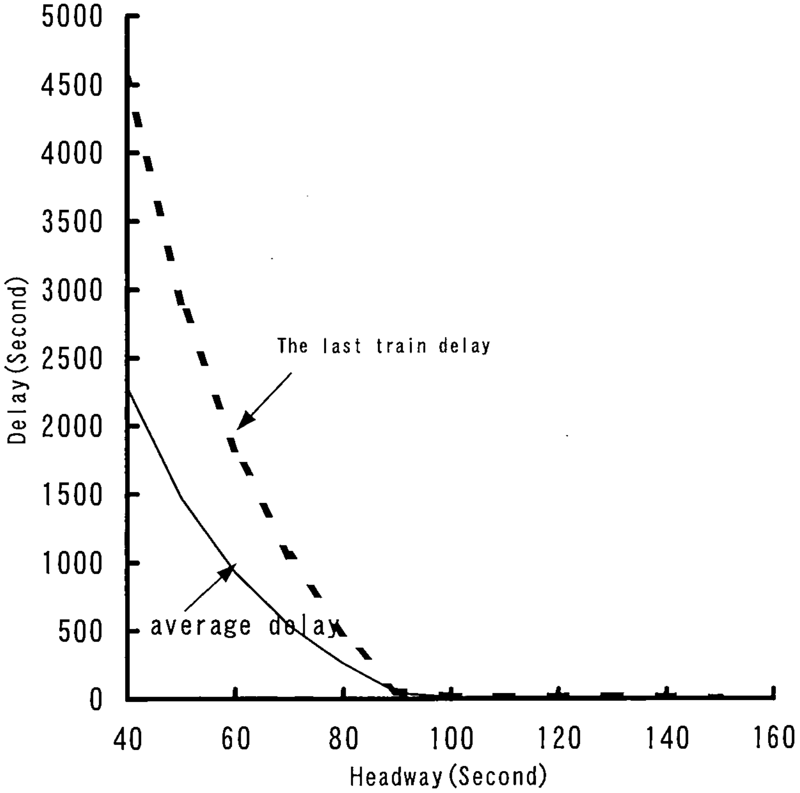


Figure 7- The relationship between delay and headway

The line capacity can be measured by the train-kilometers run in a period of interest, because the train length or passenger/train is generally fixed during peak hours. Then, as the simulation results illustrated in Figure 8, the capacity will in general increase as the headway is decreased. However, the capacity is saturated when the headway approaches to 90 seconds. The reason is that some trains at the end of the peak hour can not start to run at the first station when headway is shorter than 80 seconds. Therefore, with the consideration of delay and capacity, there is useless to operate the system at the headway lesser than 90 seconds.

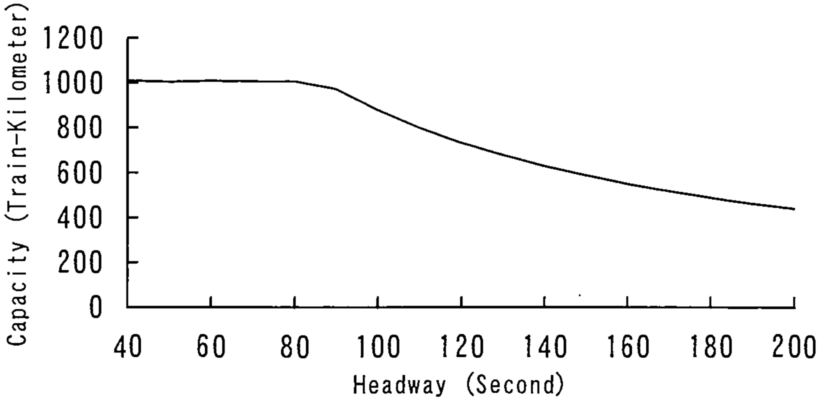


Figure 8- The relationship between capacity and headway

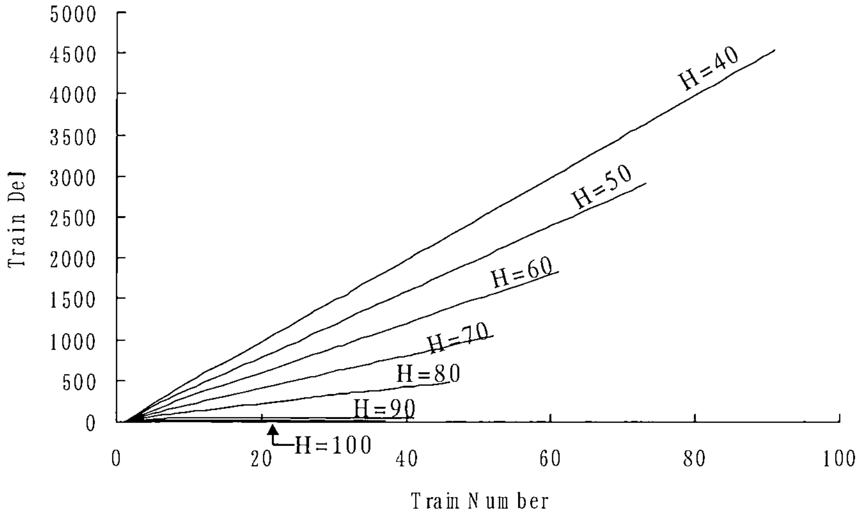


Figure 9- The relationship among delay, headway, and the number of trains

As mentioned above, a decrease in headway will usually result in an increase in train delay. Therefore, in Figure 9, the slope of a shorter headway is steeper than that of a long headway. However, for a fixed headway, the relationship of delay and the train number is almost linear. This result is quite different from the nonlinear volume-delay curve in highway transportation. The main reason is that railway signals can separate successive trains in appropriate distance. However, in highway transportation, the flow density will increase as an increase of flow volume, so as to obtain a non-linear volume-delay curve. Moreover, as shown in Figure 6, most unnecessary deceleration and stop for a late departure train happen in the first section, between station 1 and station 2; after that, the train usually follows the preceding train smoothly.

COMPARISON AND DISCUSSION

As mentioned above, the practical minimum headway for the KMRT orange line is 150 seconds. However, the minimum headway based on the railway traffic theory or eqn4 is 17 seconds, because the train length is 132 meters and the braking rate is 1 meter per second square. Moreover, the minimum headway based on the railway signaling theory or eqn9 is 35 seconds; because the block distance is 250 meters, the overlap distance is 25 meters, the train length is 132 meters, the braking rate is 1 meter per second square, and a 4-aspect block signal is considered. It is clear that the difference among the three estimates of the minimum headway is quite big. Therefore, we have to use the textbook formula of the minimum headway very carefully in practice. Furthermore, it is useful to obtain the simulation results of practical estimates of the minimum headway, and the relationship between headway and delay if the headway is shorter than the practical minimum headway.

Important factors for the difference between the estimates

In order to understand the effect of the assumptions used in developing the theoretical formula of the minimum headway, several simulation experiments has been done. First, assume that there is no speed limit, then, the minimum headway is obtained as 140 seconds. That is, the curves and gradients on the orange line have only 10-second effect on the practical minimum headway. Secondly, assume that there is no speed limit and there is no platform dwell time at each station; then, the minimum headway is obtained as 100 seconds. It seems that the 25-second dwell time at each station is an important factor for the decrease of headway. Therefore, it is essential to keep the dwell time as short as possible in practical operation, so that the headway can be short. Thirdly, assume that there is no speed limit, no dwell time at each station, and no stop along the whole line; then, the minimum headway is obtained as 55 seconds. The 45-second difference represents the effect of acceleration and deceleration of the train for its midway stops. Hence, the effect of train stops is also quite obvious. This result may also indicate the capability of the French ARAMIS system. In ARAMIS, a vehicle can separate and/or connect to the train automatically when it is close to a station. Thus, the train just go through the bypath of a midway station, but a vehicle will separate from the train and stop to the midway station, and another vehicle will start from the station and connect to the train.

For the KMRT orange line, the practical minimum headway is 150 seconds and the minimum headway based on railway signaling theory is 35 seconds. Many practical factors have effect on the 115-second difference. The maximum deduction of headway due to the geometric factors of railway line is about 10 seconds. The maximum deduction of headway due to the dwell time of 13 intermediate stops is 40 seconds. The maximum deduction of headway due to the 13 stops at intermediate stations is 45 seconds. Therefore, the effect of acceleration at the original station and the deceleration at the destination station is about 20 seconds. Finally, the 18-second difference between the 35-second headway based on railway signaling theory and the 17-second headway based on the railway traffic flow theory may represent the maximum possible improvement for intelligent traffic control system on the minimum headway. In summary, the difference between the practical minimum headway (150-second) and the minimum headway of railway traffic flow theory (17-second) is 133 seconds. During the big difference, (1) the geometric factor, such as curve and gradient, has an effect of 7%, that is 10/133; (2) the operation factor, such as stop pattern and dwell time, has an effect of 66%, that is (40+45)/133; (3) the vehicle capacity, such as acceleration and deceleration, has an effect of 14%, that is 20/133; and (4) the control system, such as moving block system, has an effect of 13%, that is 18/133.

The stochastic effect of platform dwell time

The running time of a train on a modern urban rail transit system is very accurate because of its advanced automation equipment. But the platform dwell time is in general not a constant because it is partly affected by the uncertainty of passenger volume, boarding time, etc.. In order to investigate its stochastic effect, the platform dwell time was tested in some simulation experiments as a stochastic variable ‘w’. Because the orange line has no operation data to estimate the function of ‘w’. It is simply defined as eqn10:

$$w = 25(1 \pm r) \qquad (10)$$

where 25 is the standard dwell time, and

r is a random number uniformly between 0 and 5%, 10%, or 20%.

As shown in Table 1, the mean of the last train delay of the peak hour with stochastic dwell time is in general longer than that with 25 seconds dwell time. The difference illustrated in Table 1 is not big if the confidence interval includes 0 (Law, 1991) . However, for the cases listed in the table, the difference is significantly different from 0 only if headway equals to 80 seconds.

Moreover, because the platform dwell time is in general longer than the standard 25 seconds during the peak hour, ‘w’ is redefined as eqn11:

$$w = 25(1 + r) \qquad (11)$$

As also shown in Table 1, the mean of the train delay with the stochastic dwell time of eqn11 is in general longer than that with the stochastic dwell time of eqn10 and that with 25 seconds dwell time. Furthermore, the difference between the train delay with the stochastic dwell time of eqn11 and the train delay with 25 seconds dwell time is significant different from 0, no matter what value of headway is tested. Therefore, the stochastic effect of platform dwell time is also an important factor to find the operational headway if the eqn11 is considered.

Table 1- The stochastic effect of platform dwell time on train delay

The last train delay (second)	Headway =150	Headway =120	Headway =80
25-second dwell time	0 second	13 seconds	487 seconds
25(1±5%)	0+0.87 (-0.4,2.2)	13+1.46 (-0.3,3.2)	487+5.71 (1.3,10.1)
25(1±10%)	0+0.72 (-1.7,3.1)	13+3.06 (-1.3,7.4)	487+10.8 (3.0,17.3)
25(1±20%)	0+0.95 (-3.8,5.7)	13+4.97 (-5.0,8.9)	487+21.66 (9.5,12.2)
25(1+5%)	0+4.54 (3.8,5.3)	13+5.06 (3.7,6.5)	487+22.80 (19.2,26.4)
25(1+10%)	0+8.45 (6.9,10.0)	13+9.22 (6.6,11.9)	487+41.22 (36.7,47.1)
25(1+20%)	0+17.15 (14.1,20.2)	13+17.10 (12.3,21.9)	487+82.36 (72.0,92.4)

0+0.87 represents 0+the mean of the difference; o is the last train delay at H=150.
The sample size = 10; (Confidence Interval) .

CONCLUSION

The paper firstly reports three estimates of the minimum headway for KMRT orange line, respectively on the basis of railway traffic flow theory, railway signaling theory, and a simulation study. Because the three estimates are quite different, it is important to choose the appropriate approach to calculate the minimum headway in a practical study. However, the differences can be well explained in accordance with the assumptions used in the development of the formula.

The second major finding of the paper is the following. In brief, the geometric factor, such as curve and gradient, has an effect of 7%; the operation factor, such as stop pattern and dwell time, has an effect of 66%; the vehicle capacity, such as acceleration and deceleration, has an effect of 14%; and the control system, such as moving block system, has an effect of 13%. It is evident that the operation efficiency is centrally important for the capacity utilization of orange line. However, further researches, for different cases or stochastic factors, have to be done, in order to generate general concluding remarks for the effect of each factor on the minimum headway.

Thirdly, the paper has shown the relationship between headway and delay for the orange line. The operational headway can be shorter than the practical minimum headway, if the interruption between successive trains is permitted and the delay of the train is acceptable. For the orange line, the delay of the last train in the peak hour is just a little higher than one minute, when the operational headway is about two third of the practical minimum headway. Therefore, a short headway, between 150 seconds and 90 seconds for the orange line, can be chosen to deal with very crowded traffic condition in a short period. However, the delay of train will increase very fast if the headway is shorter than 90 seconds.

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