A Microscopic Simulation Method to Calculate the Capacity of Railway Station

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Abstract. This paper introduces a microscopic simulation based method to analyze and calculate carrying capacity of railway stations. Due to the random disturbance of train operations in station area, an analytical stochastic model of train delay and operation time is proposed, which considers the stochastic variations of train operations and resources occupations. In addition, we implement a computer-aided tool to analyze and evaluate the carrying capacity of railway stations. Finally, taking Beijing South railway station as a real world example, we use the method to calculate the capacity of this station.

Introduction

Facing continuous growth of traffic demand and needed train services, most railway managers are extending the infrastructure tracks and improving the signalling systems to create additional transport capacity. Capacity analysis is to determine the maximum number of trains that could be able to operate on a given railway infrastructure, during a specific time interval, given the operational conditions (Abril, 2005) [1]. The most relevant methods can be classified in three main categories: analytical methods, optimization methods and simulation methods.

Analytical methods are designed to model the railway environment by means of algebraic expressions mathematical formulae. Burdett and Kozan (2006) [2] developed several approaches to calculate absolute capacity for railway lines and networks. Yang and Wang (2011) [3] evaluated the capacity of railway stations by Bayesian interval. Malavasi G, Molková T, et al (2014) [4] represented the beginning of an extensive research, aiming to analyse several and different analytical methods, also in comparison with other methodologies (e.g. simulation models), with the purpose of comparing and possibly integrating them in a unique new approach to evaluate the use of stations in a synthetic mode.

Optimization methods have been widely used in solving the railway capacity problems. Caprara et al. (2000) [5] presented some different models that are based on a graph theoretical representation of the problem. Ahuja et al. (2006) [6] provided an Optimization-Based decision support system for train scheduling, which revealed benefits and losses accumulated through insignificant changes in the entire rail network. Yuan and Ingo A. Hansen (2007) [7] optimized capacity utilization of stations by estimating knock-on train delays. The model can determine the maximal frequency of trains passing the critical level crossing with a given maximum knock-on delay at a certain confidence level.

Simulation methods provide a model, which is as close as possible to reality, to imitate dynamic behavior of a real-world process. We give a short description of some main simulation tools. Microscopic simulation tools, such as RailSys (Radtke and Hauptmann, 2004) [8] and OpenTrack (Nash and Huerlimann, 2004) [9] can be used to model the propagation of train delays in large railway networks, but require extensive work to model the infrastructure topology, signalling and timetables. SIMONE (In Control Enterprise Dynamics) is a simulation model for railway networks. It can support: determination of the robustness of a timetable, trace and quantification of bottlenecks in a network, and analysis of cause and effect relations when delays emerge.

More information about these systems and other simulation environments can be found in Barber et al. (2007) [10].

In this paper we consider the random disturbances of knock-on delays and operation time. We introduce a microscopic simulation based method to analyze the carrying capacity of railway stations. We have developed a software platform to perform the analyzing process automatically.

The paper is structured as follows. Section 2 shows the outline of the method. In Section 3, we introduce the switch grouping method. Section 4 presents the capacity analyzing method in detail. Section 5 provides a case study of Beijing South railway station. Finally, comes with the conclusion.

Outline of the method

Railway station capacity is tightly related with infrastructure of railway station, to analyze the capacity by computer program, the first step is modelling the infrastructure of railway station. Then divide all switches into different groups. The principles and methods will be introduced in detail in section 3. Due to complexity of railway system, there are always random disturbances during the daily operation, the theoretic capacity is only the reference capacity, usually cannot be reached. To analyze the realistic capacity of a railway station, we need consider random disturbances. Put many simulation results together, we can analyze the practicality capacity of the railway stations.

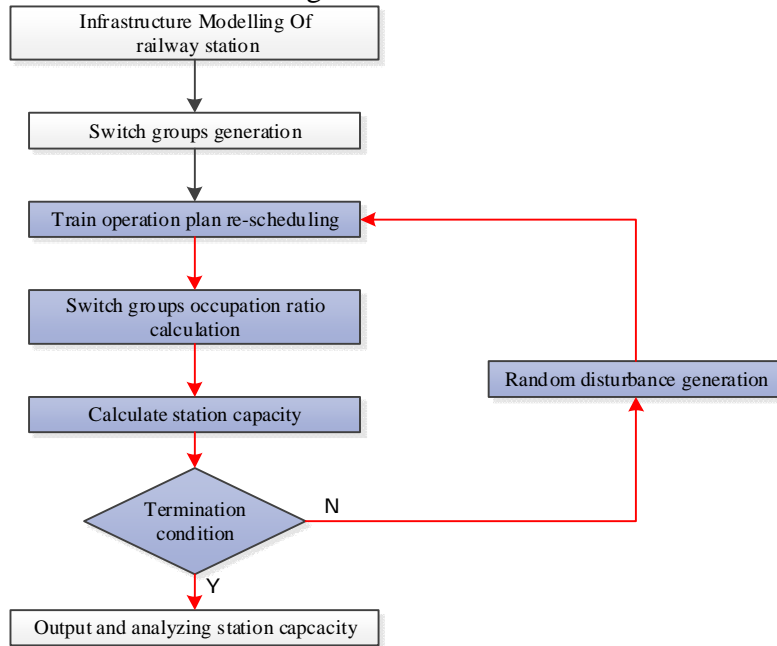The outline of the method is shown as Figure 1.

Figure 1：The outline of the method

Automatic switch grouping method

When a conflict occurs, one resource must be occupied by two operations at the same time. That means when a switch is occupied by an operation route, some other operations also apply using the same switch at the same time.
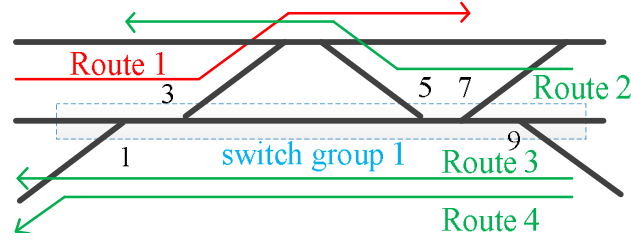
Figure 2：The example of switch groups

If some switches are occupied by a train operation or shunting operation, the other switches in this switch group are not available. We put these unavailable switches and the occupied switches together into a group. This group is called "*switch group*". The occupation time or exploitation rate of all switches which are in the same switch group is the same.

For example, in Figure 2, if a train is occupying Route 1, switch 1 and switch 3 are occupied by the train. Meanwhile, the switch 5, 7, 9 are not available. Because Route 1 and any route which contains the switch 5 or 7 or 9 will be conflicting routes, such as Route 2, 3, 4. As the same reason, any one of switch 1, 3, 5, 7, 9 is occupied, the others are unavailable. Thus, the time or utilization of the switch 1, 3, 5, 7, 9 are the same. We consider switch 1, 3, 5, 7, 9 is in one "switch group". If two switches are on two parallel routes respectively, the two switches shouldn't be in the same switch group. If not, they should be in the same switch group.

The microscopic simulation based method

The exploitation rate method is a traditional method to calculate carrying capacity of railway stations. But the calculation results usually can't truly reflect the capacity. Based on the traditional method of utilization and probability theory, we provide an analyzing method based on random probability. Train delays and operation time variation of route is considered in this section. The corresponding probability distribution is derived from large empirical data, and the disturbances is simulated by computer and put into the model.

The calculation method of exploitation rate

The basic idea of this method is to compute exploitation rate of each switch group in station based on current operation plan. Choose the most heavily used switch group, according to the existing number of trains and exploitation rate of switch, we can get the maximum number of trains during the whole service time span.

The formulation of exploitation rate method is as follow.

$$K = \frac{\sum_{i=1}^{n} t_i}{T} \tag{1}$$

$$N = \frac{n}{K} \tag{2}$$

The variables used in exploitation rate method are defined as follows:

T ：The total operation time. Usually its value is 86400 seconds (24 hours).

t_i ：The time of train i occupying the critical switch group

K ：Exploitation rate of the critical switch group

n ：The existing number of trains in each direction of a station

N ：Carrying capacity of throat for one direction of a station

According to exploitation rate method, first, we need to compute the exploitation rate of each switch based on equation (1). Finally, according to equation (2), we can obtain carrying capacity of throat in railway station.

The arrival time and departure time distribution of trains

It's hard for all trains to arrive at the station on time. The arrival time of a train may fluctuate near the scheduled time. We adapt the Erlang distribution to model the arrival time distribution of a train (Yuan and Hansen, 2007) [7].

The probability density function of the Erlang distribution is as follows:

$$f(x;k,l) = \frac{l^k x^{k-1} e^{-lx}}{(k-1)!} \ (\forall x, l \geq 0) \tag{3}$$

The parameter k is called the shape parameter, and the parameter l is called the rate parameter.

The cumulative distribution function of the Erlang distribution is as follows:

$$F(x;k,l) = 1 - \sum_{n=0}^{k-1} \frac{1}{n!} e^{-lx} (lx)^n \ (\forall x, l \geq 0) \tag{4}$$

For example, when $k = 2, l = 0.5$, the probability density function and cumulative distribution function are as follows: Figure 3(a) shows the distribution probability density curve and Figure 3(b) shows the cumulative Erlang probability distribution curve.
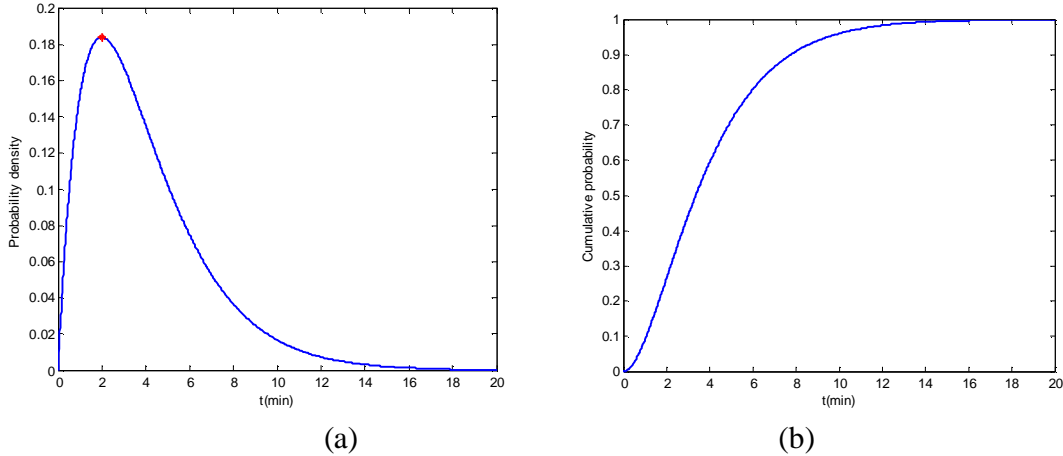

(a)   (b)

Figure 3: The Erlang distribution curve of arrival time

The extreme point is (2, 0.1839). When $t = 2$, it means the train arrives on time. When $t < 2$, it means the train arrives early. When $t > 2$, it means the train arrives late. The train arriving disturbances will be generated according to this function.

In a similar way, we use the Erlang distribution to model departure time distribution of a train. But the parameters are different. According to data analyzing results, we choose Erlang distribution with parameters of $k = 2, l = 2$. The cumulative distribution function is shown in figure 4.
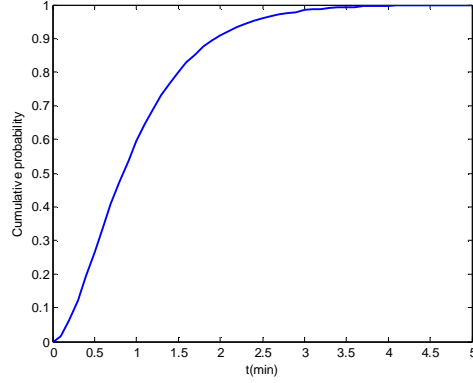
Figure 4: The Erlang distribution curve of departure time

A train is not allowed to depart earlier than the scheduled departure time. So when $t=0$, it means the train departures on time. $P(t<1.5)=0.80$, $P(t<2)=0.90$, $P(t>3)=0.0005$. It means train departure disturbances range from 0 to 3 minutes.

The operation time distribution of trains

There is certain time standard for every train operation. However, in actual situation, the operation time may fluctuate. We use the normal distribution to model the operation time distribution of a train.

The probability density of the normal distribution is:

$$f(x\mid m,s)=\frac{1}{\sqrt{2ps}}e^{-\frac{(x-m)^2}{2s^2}} \quad (\forall x\geq 0, s>0) \tag{5}$$

Here, m is the mean or expectation of the distribution. In this paper it means the time standard of a certain operation. The parameter s is its standard deviation. Here it means the size of the operation time fluctuation. To each operation, there is a provision that the actual operation time can't less than 80% of the standard time. For example, if the standard operation time is 5 minutes. According to the provision the occupation time can't less than 4 minutes.

Case study

We have developed a software platform to calculate carrying capacity of railway stations with the proposed simulation method. In this section we take Beijing South railway station as an example to calculate carrying capacity.

The Beijing South Railway Station is one of the largest integrated transport terminals in China. There are receiving-departure yard, depot and temp yard in the station. The station is connected to four adjacent railway stations, a large depot, and has four yards: a regular-speed train yard, a high-speed train yard, an inter-city train yard and a temporary storage yard for inter-city trains. The station connects five directions, Liu Village, Beijing South turn, Depot, Lang fang and Yi Zhuang.

(1) According to the existing data of Beijing South railway station, the system automatically calculates the theoretic carrying capacity of Beijing South railway station throat without considering the random disturbances. Table 1 shows the calculation results without disturbances.

Table 1: The theoretic capacity without disturbances (unit: trains/day)

Direction	Arrival capacity	Departure capacity
Liu Village	351	339
Beijing South turn	215	224
Depot	151	103
Lang fang	332	332
Yi Zhuang	560	560
Sum	1609	1558

(2) In this subsection we consider the random disturbances of train delay. When the probability of delay is from 0.7 to 0.95 and the delay time is from 60s to 210s, the first cell means 95% train will arrive at station within 60 seconds delay. We simulate 36 pair input parameters, and calculate the occupation rate to get total departure and arrival capacity (in Table 2) of Beijing South railway station.

Table 2: Capacity with train delay disturbances (departure/arrival, unit: trains/day)

Probability \ Delay Time	60s	90s	120s	150s	180s	210s
0.70	1598/1608	1571/1538	1391/1429	1387/1361	12481269	1264/1247
0.75	1628/1642	1518/1515	1454/1461	1357/1362	1293/1325	1208/1217
0.80	1634/1657	1533/1542	1510/1516	1410/1454	1349/1373	1269/1281
0.85	1579/1586	1545/1539	1413/1419	1332/1332	1286/1290	1196/1214
0.90	1677/1661	1587/1599	1548/1544	1525/1482	1469/1458	1367/1395
0.95	1655/1681	1625/1638	1609/1597	1491/1516	1509/1507	1420/1435

(3) In this section we consider random factor of operation time fluctuation. Calculation results are as follows. The first cell means 95% operations can be performed within 60 seconds. We simulate 36 pair input parameters, and calculate the occupation rate to get total departure and arrival capacity (in Table 3).

Table 3: Capacity with operation time disturbances (departure/arrival, unit: trains/day)

Probability \ Delay time	60s	90s	120s	150s	180s	210s
0.70	1399/1388	1332/1364	1252/1213	1179/1204	1108/1086	1082/1098
0.75	1429/1414	1321/1322	1273/1265	1179/1173	1156/1123	1055/1045
0.80	1438/1414	1340/1330	1314/1307	12681223	1188/1163	1117/1104
0.85	1381/1373	1336/1340	1223/1216	1167/1165	1129/1124	1056/1037
0.90	1445/1459	1392/1379	1346/1348	1287/1329	1270/1279	1217/1188
0.95	1460/1433	1420/1406	1385/1396	1315/1289	1309/1310	1250/1234

Comparing the calculation results of different methods, we can get the following conclusions.

(1) The capacity with random disturbances is less than theoretic capacity. It is closer to the real ability of the station.

(2) Less train delay disturbances can improve railway station capacity. What's more, the greater the probability is, the greater the ability is. If 95% trains can arrive at station within 60 seconds, the total capacity is 1681. When 70% trains can arrive at station within 210 seconds, the total capacity is to 1247, and nearly 25.8% capacity decreases, as Table 5 shows.

(3) Less operation time disturbances also can improve railway station capacity.

Conclusions

This paper provides a microscopic simulation method and a stochastic model for evaluating capacity of railway stations. The calculation results show that this computer aided tool can be used for general railway station capacity analyzing and is also beneficial to guiding design or expansion of

station. The models and method presented in this paper have been developed as application software which is running in several big railway stations in China.

In further research, we will focus on: (1) Improving model and method of microscopic simulation based method. (2) The capacity we computed is about the carrying capacity of a railway station, and neglects other capacities such as line capacity, network capacity. How to integrate all these capacities and evaluate the railway network capacity is a more useful further research.

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