Development and Evaluation of Different Models for Urban Rail Capacity during Peak and Off-peak Hours: A Case Study of Jaipur Metro in India

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Abstract
The objective of this paper to develop the conceptual model for managing the carrying capacity of urban railway during peak and off-peak hours For this firstly focus on the influencing factors and interactive relations of the rail carrying capacity of a low and high speed mode rail. In this paper six different models developed for an urban rail by the ratio of tracking low and high speed trains. Taking Jaipur metro rail corridor-1 in India as a case study The proposed model proved to be valid for utilizing urban rail capacity by low and high speed train concept. This paper contributes the previous related researcher's history by modifying the concepts and methods are applied to improve the carrying capacity. As the train types increase in a network than more interference increases and less capacity occurred in a network In this paper, a model for estimation of the capacity of a network is presented. The model is helpful for railway planners for capacity planning of a network.

Keywords: Cycle time, Minimum time interval of departure, Overtaking, Frequency of a train, Waiting time at the intermediate stations, Number of stopping, Low and high speed train, Line carrying capacity

1. Introduction

Metro systems are better than other modes because they provide higher carrying capacity, quicker, smoother and occupy less space, safer journey, are Eco-friendly and energy-efficient. With increasing population and big expansion plans coming up for the Pink City, the travel demand is expected to grow sharply. With the growing economy and insufficient public transport services, the passengers shall move to private modes, which are already shows from the high vehicle rights trend in the region. This would not only worsen the overcrowding on streets but also increase the pollution. Hence, it was measured necessary to plan and provide a Metro Rail in Jaipur. Hence, total length of two corridors with a 35.666 km has been identified. The corridor-2 (North-South) line starts from Sitapura to Ambabari with a total length of 23.099 km. MRTS (Mass Rapid Transit Systems) manage huge passengers. The corridor-1 (East - West) line start from Manasarovar to Badi Chaupar, the length of the corridor-1 is 12.067 km, in which 2.789 km is under ground and 9.278 km is elevated, together with switch over ramp. Total eleven stations have been planned along this corridor out in which 8 are elevated and 3 are underground stations. These data are taken from open sources.

Many researchers have presented methodologies of the operation of mixed trains. Chen et al. gave the model for factors influencing the MRT carrying capacity and developed efficient algorithm to find a better solution[18]. Wang et al. have suggested the fuzzy markov chain theory for measuring rail carrying capacity [19]. The aim of this paper is to determine factors influencing the rail carrying capacity under the peak and off peak hours by measuring the number of low and high speed trains, number of overtaking with locations.

2. Literature review

Xiaoming Xu et. al studied for balanced train time table with optimum velocity for single line. This model is used for non constant train velocity[13]. Sameni, Melody Khadem, and Arash Moradi gave three categories of capability assessment methods as analytical, optimization and simulation [9]. Ranolds et. al developed a statistical method to model the traversal times in a variable-speed model [8]. By Zhang, Xin, and Lei Nie. An iterative approximation method is proposed to reduce the computational time [16]. Chen, Angyang, et. al. to provide more transport services, it is necessary to add more and more trains to a section to increase the capacity [2]. Yang Yuxiang, et. al. eleven suggested delay events are classified, and a detailed analysis of the delay distribution for each classification is presented [15]. Researchers Yan, Fei, Nikola Besinovic and Rob MP Goverde aim to find an efficient, regular and robust timetable that utilizes infrastructure capacity as much as possible [14]. Pouryousef, Hamed, Pasi Lautala, and David Watkins state that their model can provide conflict free and compact timetables from the initial schedule and operate on single or multiple track corridors with directional or bi directional operations [6]. According to Tang, Jia, et. al. The high speed rail service design will help passengers engage in various activities and improve their travel experience [10]. According to Pouryousef, hamed, pasi lautala, and thomas white, capacity methods are usually divided into analytical and simulation methods but their paper also introduces a combined “simulation and analytical” category [7]. The method of calculating capacity in single track railway lines is different from that of double or more tracks [1]. Pengling Wang et. al. many different things are considered including locomotive utilization, yard capacity, crew availability, track structure, and traffic levels, which all play a role and combine to determine rail efficiency [5]. Peng Sheng Yu et.al. developed heuristic algorithm and worked on train scheduling with parallel tracks [4]. T. Van Doelevoet et. al. provided the maximum allowable delay to measure the optimal result and developed a framework for optimizing train scheduling [11]. The multi objective train scheduling model given by Xiang Li et. al. [12] to focus on reducing fuel consumption cost. According to author Mittal, Manoj, and Anand Kishore Chaturvedi, analytical models are useful at the planning stage and can evaluate the railway capacity of the entire network of railway with use of existing resources [17].

3. Factors affecting the railway carrying capacity

3.1 MRT carrying capacity

Maximum frequency of a train [20] during peak hours passes through a line in per hour including various types of train with restrictions. The maximum interval of train tracking time and turning back time has considered when measuring the rail carrying capacity [23]. The rail carrying capacity can be evaluated by [21,22]:

$$\text{Maximum frequency of train } (N_{max}) = 3600/I \quad (1)$$

(Per hour per direction)

$$I = \text{maximum}\{I_{running}, I_{returning}\} \quad (2)$$

Where, I is minimum time interval of two departed trains (in seconds)

Based on specific characteristics of MRT rail under the peak and off peak hours, this paper modifies the methodology and develops six models for efficient utilization of rail carrying capacity for urban lines.

$$N_{max} = 3600/R \quad (3)$$

R = trains release in t duration (in seconds) / number of mix trains in t duration

$$R = T/(p+q) \quad (4)$$

$$\text{So,} \quad N_{max} = (p+q)*(3600/T) \quad (5)$$

Where, N is maximum carrying capacity of a line for mix (low-high) mode trains, p is no of slow trains and q is the no. of fast trains within a cycle time (T). As shown in eq. (3) the rail carrying capacity of a line for mix mode increases as the departing time is reduced and number of trains is increased.

3.2 Effect of mix train mode on MRT rail carrying capacity

This paper presents the combined effect of number and proportion of low and high speed trains and total number of overtaking with position under peak and off peak hours. It is assumed that the departure time difference between two trains is the same in our study and the ratio of number of low and high trains within a release time period (in second) is equal to q:p. Some researchers did not implement stops at any intermediate stations when the high speed train was overtaking in their study [25] which is impractical and would result in a large demand reduction. This paper does not consider this situation. Three cases are considered in this paper when no overtaking occurs, overtaking occurs once and twice. For this purpose six models have been developed to manage the line carrying capacity of mix trains during peak and non peak hours. When two equally slow trains are operated there is no overtaking so rail carrying capacity is based on minimum time gap between two trains as per eq. (1). In this paper it is assumed that stoppage time of fast train will be less than that of slow train and stoppage of fast train will be equal to that of slow train for efficient utilization of resources and for maximize carrying capacity in pick hours. Overtaking will be done only in intermediate stations. In this regards the operating mix of fast and slow trains are given below in 6 models.

3.2.1 Model 1 (No overtaking and high train operated between two low trains)

Fast train is the high speed train. In this model one high speed (p) trains are operated between two slow (q) trains and no overtaking as shown in figure 1. The time gap of two mix trains at destination must not be greater than the minimum time gap of departure. The cycle time (T) of model 1 is evaluated by:

$T = 2.I + n.Z_{stop}$ (6) According to eq. (5)

(p:q=1:1),

$Nmax = 2*[3600/ (2.I + n.Z_{stop})]$ (7)

Where n is the slow train stopping frequency and Z_{stop} is the waiting time of a train at one station with including accelerating and retardation time.

Fig. 1 One fast trains operated between two slow trains and no overtaking

3.2.2 Model 2 (Overtaking occurrence once by the fast trains)

As shown in figure 2, total 11 stations is available and overtaking occurrence at stations L7 between the terminal stations L 1 to L 11. Cycle time calculated by:

$T = 2.I + n.Z_{stop}$ (8)

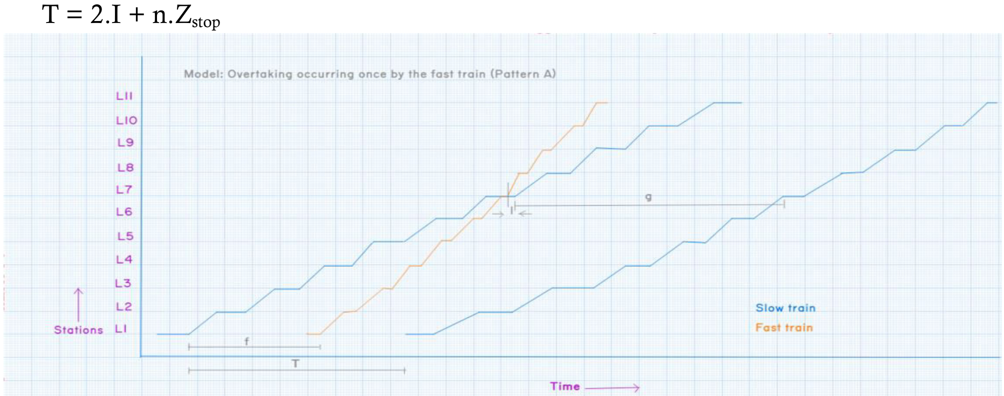

Fig. 2 Over taking occurrence once by the fast trains

3.2.3 Model 3 (Overtaking occurrence once by the fast train and one additional slow train run between the pair of slow and fast train).

As shown in figure 3, overtaking is occurrence once. The cycle time capacity of mix train can be calculated by:

$$T = 3.I + n.Zstop \quad (9)$$

$$Nmax = 3*[3600/ (3.I + n.Zstop)] \quad (10)$$

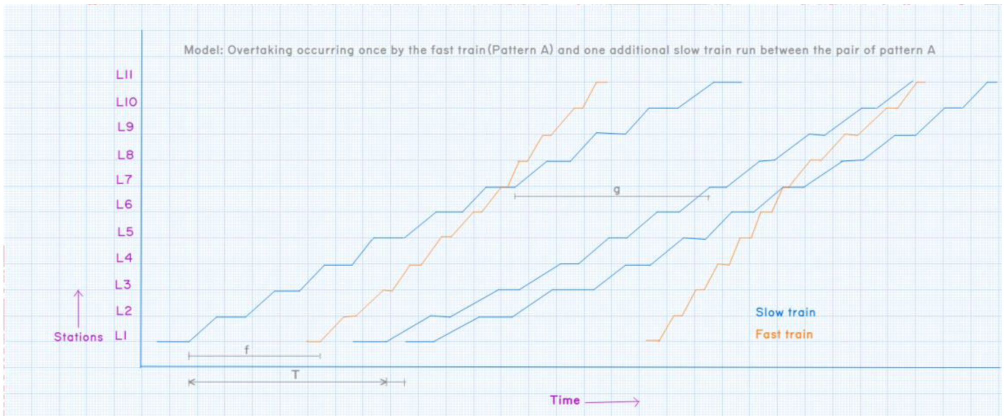

Fig. 3 Overtaking occurrence once by the fast train and one additional slow train run between the pair of slow and fast train

3.2.4. Model 4 (overtaking of two slow trains by fast trains and repeat this pattern)

Overtaking is occurrence as shown in figure 4,where W is waiting time of slow train when fast train is overtaking at particular station.Cycle time and carrying capacity of this model can be calculated by:

$$T = W + 3.I + n.\ Z_{stop} \quad (11)$$

$$Nmax = 3*[3600/ (W + 3.I + n.Z_{stop})] \quad (12)$$

Fig. 4 Overtaking of two slow trains by fast trains and repeat this pattern

3.2.5 Model 5 (Two fast train overtaking the slow train once and repeat pattern)

Overtaking pattern is shown in figure 5.Overtaking can be occurred at station L 6 and at station L 8. For safer conditions longer operation time should be taken either L 1 to L 6 section or L 8 to L 11 section. Cycle time of this model is given below:

$T = W + 3.I + n.Z_{stop}$ (13)

Fig. 5 Two fast train overtaking the slow train once and repeat pattern

3.2.6 Model 6 (Two fast train overtaking the slow train once and repeat this pattern)

Overtaking occurrence as shown in figure 6 Cycle time can be calculated by:

$T = W + Im + 3.I + g + h$ (14)

$Im = \max \{L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1011}\} / V_{AVG}$ (15)

Where, Im is the maximum operation time of all sections (in second), f is departure time gap between 2nd fast and slow train during overtaking, g is departure time gap between 2nd and 3rd slow train during overtaking and h is departure time gap between 3rd and next slow train during overtaking.

Fig. 6 Two fast train overtaking the slow train once and repeat this pattern

3.3 Effect of overtaking on MRT rail carrying capacity

As per model 3 and 4, overtaking twice can increase the MRT rail carrying capacity and the fraction of low and high speed train is 2:1. As the number of overtaking increases the cycle time will decreases. When the number of overtaking is three or more, the waiting time of slow trains will increase, thereby reducing the quality of passenger service [26, 27]. This paper does not consider the effect of three or more overtaking on rail carrying capacity.

4. Case study

4.1 Introduction

Jaipur metro routes are divided into two corridors i.e. corridor-1 and corridor-2.Corridor-1 is East –West corridor and Corridor-2 is North-South corridor. This paper focused on corridor-1. Corridor-1 starts from Manasarovar and ends at Badi Chaupar. Route map is given below. Total length of this route is 12.067KM and it consists of 11 metro stations (8 Elevated and 3 Underground). Maximum speed of metro is 80 Km/h. Low speed trains take 25 minutes and high speed train takes 15 minutes from origin to destination. Six marshaling tracks considered in this study. The Minimum time gap between two departing train is 10 minutes and the stoppage time for slow and fast train is 50 seconds and 30 seconds in each station including acceleration and deceleration time respectively. A train with four carriage are operated and carry total 644 passengers comfortably on the corridor-2. The total number of passengers can be estimated by:

$E_p = (C * A * 60) / D$ (16)

Where,

E_p = Estimated total number of passengers

C = Carry no. of passengers

A = overloading factor

D = Minimum departure time between two trains

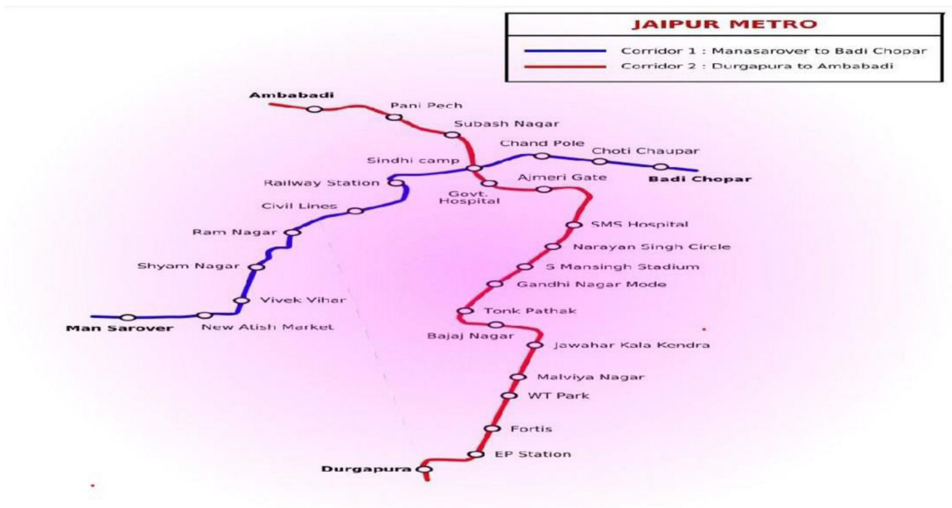

Fig. 7 Route map of corridor-1 of Jaipur Metro (India) from open sources

Estimated number of passenger (E_p) = (644 X 150% X 60)/10

= 5796 Passengers

4.2 As per proposed model MRT rail carrying capacity

The passenger carrying capacity of Corridor-1 can be measured based on the proposed model. Proposed six models have three basic cases i.e. ratio p:q is 1:1, 1:2 and 2:1 respectively.

(1) When p:q = 1:1 and mix trains run during the combined period,

$Nmax = (p+q)*(3600/ T)$,

$Nmax = 2*[3600 / (2.I + n. Z_{stop})]$,

Nmax = 2 X [3600 / 2 X 600 + 10 X 50]

= 4.24

(2) When p:q = 1:2 and mix trains run during the combined period,

$Nmax = 3*[3600/ (W + 3.I + n .Z_{stop})]$

= 3 X [3600/(90+3 X 600 + 10 X 30

= 4.52

(3) When p:q = 2:1 and mix trains run during the combined period,

$Nmax = 3*[3600/ (W + 3.I + n .Z_{stop})]$

= 3 X [3600 / (60+3 X 600+ 10 X 30)] = 5

Hence scientifically observed the variation of carrying capacity with respect to the running mix (high and low) trains is given in table 1. Figure 9 shows that with an equal number of high and low trains, the carrying capacity will be minimum and the carrying capacity will increase when the ratio of the number of high and low trains increases and vice verse [28, 29]. The determination of the proportion of high and low trains depends on the actual demand during peak and off peak hours of the day. Carriage designed for the capacity of 340 passengers and 20% passengers can be overloaded during peak hours.

Table 1. Ratio of mix (high and low) train flow with carrying capacity

The proportion of mix (high and low) train flow combinations (p:q)	4:1	3:1	2:1	1:1	1:2	1:3	1:4
Carrying capacity (N_{max})	7.89	6.49	5	4.2	4.5	5.8	7

Table 2. Passenger flow during peak and off peak hours of Jaipur Metro Corridor-1

Station Name	Peak hours (total no. of passengers)	Average Peak hours (passenger/h)	Off-peak hours (total no. of passengers)	Average off-peak hours (passenger/h)
Mansarovar	16564	4141	31200	2600
New Aatish Market	7332	1833	14412	1201
Vivek Vihar	8436	2109	15672	1306
Shyam Nagar	6272	1568	12516	1043
Ram Nagar	5320	1330	9768	814
Civil Lines	5612	1403	10416	868
Railway Station	8772	2193	12780	1065
Sindhi Camp	5416	1354	8316	693
Chand Pole	8156	2039	13764	1147
Choti Chaupar	8216	2054	12384	1032
Badi Chaupar	7616	1904	11484	957

5. Implementation of proposed model

The proposed concept and methods can be applied in real way by measuring the actual number of trains required to carry passengers during peak and off-peak hours of the day. These numbers can be compared to the maximum carrying capacity to determine the ratio of the number of high and low trains, as shown in table 1. Peak hours of the day are 6:30-8:30 and 16:30-18:30.Sixteen hours train run during peak and off-peak hours of the day.Required number of trains with respect of the actual demand is determined by:

$$N_T = N_P / (N_R \times \Upsilon \times N_M) \quad (17)$$

Where,

N_T Number of trains required for actual demand

N_P Total number of passenger in particular period

N_R Allowed capacity of a carriage

Υ = overloading coefficient

N_M = Marshaling tracks

According to table 2, the total number of passengers during the peak hours is 20024 and off peak-hours is 11769, required no of trains calculated by:

During peak hours,

$N_T = 20024 / (340 X 1.2 X 6) = 7.85$

During off-peak hours,

$N_T = 11769 / (340x6)$

$= 5.77$

Hence, the numbers of trains calculated in peak hours are 7.85 and off-peak hours are 5.77. It is observed that on comparing the table 1, the ratio of number of high and low speed trains in peak hours is 4:1 and the ratio of number of high and low trains in off-peak hours is 1:3. This paper provides guidance for both planning and operational phase.

6. Conclusion

This paper studied Corridor-1 of Jaipur Metro Rail in India and established the actual relationship between carrying capacity and required number of trains in peak and off-peak hours of the day. The urban rail carrying capacity and rail demand were calculated by the six models proposed and even the ratio of high and low number of trains was calculated and proved in this study. If the number of overtaking exceeds two, the quality of service may deteriorate. With high and low trains crossing many different metro lines, optimizing carrying capacity are a challenging task.

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