Simulation and analysis of mixed traffic on railway sections

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***Abstract*—This paper focuses on the development of a tool for simulation of traffic of freight trains at rail sections carrying mixed traffic. This tool can be used for simulating mixed traffic (typically trains of different speeds and composed of passenger and freight type) across a major section. The major purpose of the tool is to estimate the time halt for freight trains on a section if a passenger timetable is fixed. This analysis can be further used to accurately model the whole route and hence will help us in scheduling the freight trains to maximize the throughput. An analysis of a rail section of Indian Railways that handles significant traffic is presented using the tool.**

Keywords: railway planning, freight train capacity, simulation, mixed traffic, throughput, capacity utilization

I. Introduction

A rail transportation network involves large expenditure in its infrastructure, even before it can start offering effective service. Modeling rail networks involves considerable modeling difficulty and complexity.

Infrastructural changes do not always yield the expected results in performance - throughput, punctuality and effective capacity for handling different types of traffic are three of the measures that rail managers could be interested in. This motivates simulation as a methodology for analysis. Simulation of railway networks is challenging because accurate modeling often involves minute details of the network being modeled and of the traffic that is handled on the network.

In this paper we describe the working of a rail traffic simulator that has been developed at IIT Bombay over a number of years. The results of the different experiments that have been performed on one of the most congested sections of Indian Railways are indicated.

II. Background

A. Railway simulation

In recent years, there are software products and computer simulation decision support for rail operations. These are used at different levels of planning and operation in rail systems. The Control Office Application and the Satsang timetabling tool provide some amount of simulation support on Indian Railways, but formal use of these is limited, as of now. An earlier system, the LRDSS (Long Range Decision Support System) at the Railway Board had simulation as part of its set of tools.

1) Synchronous simulation: In a synchronous simulation, all train movements are simulated simultaneously [2]. This is time-based computation of paths of all trains that are in the system of interest. The system clock controls the sequence of activities that are relevant. This is close to the actual control situation. In congested periods, and especially in the case of disruptions and unavailability of some resources for some time, there is a logical possibility of deadlocked movements, which has to be algorithmically handled with some care. Synchronous simulation would have some elements of look ahead and attempt to give workable, short-term (e.g. one hour) feasible solutions quickly.

2) Asynchronous simulation: This is a simulation of prioritized and planned movements of several trains, perhaps over a long time interval (a day or even more), so as to understand the impact of traffic on a given infrastructure, if movements happen as per plan. These normally proceed one train at a time, over the time horizon of interest, and guarantee a feasible path (if one exists) for a train, before taking up another train. Reservations are made ahead of time, depending on priority. These simulations avoid deadlock situations because of the constructive method of creating schedules, which ensures feasibility at every step.

The IIT Bombay simulator is an asynchronous one, designed for timetabling and capacity estimation studies, and not for real time control of trains.

III. Working of the IITB railway mixed traffic simulator

In this section we describe the working of the simulator. The inputs to the simulator are the infrastructural details of the section that is being simulated. Both fixed and moving infrastructural details of the section have to be input. The fixed infrastructure involves stations, loops, blocks, maintenance block, gradient, type of signalling and permanent speed restrictions. The moving/mobile infrastructure involves passenger trains, their running characteristics and their timetable. After constructing a complete test case with all the above inputs, various kinds of analysis as below can be performed using the simulator:

1) with respect to a fixed infrastructure:

- comparison of parameters before & after infrastructural changes,
- quantification of loop occupancy and provide suggestions for upgrades,

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- suggestion of maintenance block timings,
- identification bottleneck sections.

2) with respect to passenger trains:

- construction of passenger timetables,
- comparison of timetable allowances vis-a-vis simulated timings,
- identification of new conflict free passenger train paths,
- identification of planned overtakes and its impact.

3) with respect to freight trains:

- suggestion firing times for effective freight paths,
- estimation throughput of desired types of freight trains,
- analysis of planned freight paths,
- estimation of Hours-On-Run (HOR),
- number of overtakes of freight trains.

The following subsections define the working logic of important features of the simulator.

A. Priority based scheduling

Given the operating regime on Indian Railways, the first step in simulating any section is to schedule the passenger trains in the section. The passenger trains characteristics such as acceleration, deceleration & maximum speed and its timetable were taken as input to the model. The simulator follows asynchronous simulation i.e. priority based scheduling, thus we allocate a priority to each train. Based on the priority value, the simulator schedules higher priority trains before lower priority trains. Once a train is scheduled, its occupancy tables of blocks and loops are updated accordingly. Before scheduling the next train, simulator estimates a path for the next train. A conflict is defined as a situation in which two trains tend to occupy the same resource in a same time interval. If such conflict occurs for a resource (block or loop) while estimating a path for the next train, then the path of the next train is backtracked to the resource where there is no conflict. The next train gets delayed in such a manner that conflicts are resolved. In a similar manner, all passenger trains will be scheduled in a conflict free manner by the simulator.

This type of *priority based scheduling* (Asynchronous simulation) will generally have lesser time complexity to resolve conflicts or deadlocks than that of Synchronous simulation. However, we note that our speed calculations are detailed and depend on signal aspects seen by each train (which indicate the locations of trains ahead of it). This allows a lot of different options in despatching decisions, and trade-offs between throughput and hours-on-run (or average traversal time). This is still a matter of ongoing research.

B. Capacity analysis

One of the purposes of the simulator is to give an estimate of the carrying capacity of a rail section. A simple notion of capacity is the number of standardised freight trains that can be run in one day in the section without conflicts.

$$\text{Raw Capacity} = \frac{1440 \times 70\%}{T \text{ in critical block}} \tag{1}$$

In the above equation, 1440 is the number of minutes in a day, and 'T in critical block' refers to the maximum across all block sections of the time (in minutes) spent by any freight train. A factor of 70% accounts for the loss of capacity due to the presence of maintenance blocks and other factors.

Of course, such a notion of capacity is *not* appropriate for sections where the traffic is mixed, i.e. trains are of both freight and passenger type. Further, the passenger trains are often of different priorities. In such situations, passenger trains are timetabled and have higher priority and a question of interest is the number of additional freight trains that can be carried effectively. For estimating this mixed capacity we introduce Algorithm 1. Here, starting times of the freight trains are

Result: Capacity of the section is C_{mixed}
C_{raw} = Raw Capacity of the section;
C_{mixed} = Raw Capacity of the section;
Simulate C_{mixed} number of trains with random firing times;
X_{free} = Free running time of C_{raw} number of trains;
X_{mixed} = Running time of C_{mixed} number of trains;
while *1.9*$X_{\text{free}} \geqslant X_{\text{mixed}}$ *or* $X_{\text{mixed}} \geqslant$ *2.1*X_{free} **do**
  if $X_{\text{mixed}} \leqslant$*1.9*$X_{\text{free}}$ **then**
    C_{mixed} = $1.5C_{\text{mixed}}$;
  end
  if $X_{\text{mixed}} \geqslant$*2.1*$X_{\text{free}}$ **then**
    C_{mixed} = $0.5C_{\text{mixed}}$;
  end
  Simulate C_{mixed} number of trains;
  X_{mixed} = Running time of C_{mixed} number of trains;
end

Algorithm 1: Calculation of Mixed Capacity [1]

selected randomly, reflecting the random arrivals of trains at a particular point in a large network. Depending on the initially selected random starting time, the trains may or may not find a free path. Thus our estimate of mixed capacity is a randomized one. We try to reduce the randomization error using equation (2).

$$C_{\text{actual}} = \frac{\sum_{i=1}^{n} C^{i}_{\text{mixed}}}{n} \tag{2}$$

We also note the importance of assigning fixed halts in important junctions for freight trains. Given that the simulator is designed for sectional performance, this allows us to model the running of freight trains more realistically and also helps us in validating the computation of good freight paths, which is done on some freight intensive divisions of Indian Railways.

In our simulator we also have the possibility of analyzing the changes in capacity on changing the type of signaling on different sections - absolute or intermediate.

IV. Detailed Example

In this section we describe the analysis on a specific section of Indian Railways, including an overview of the infrastructure

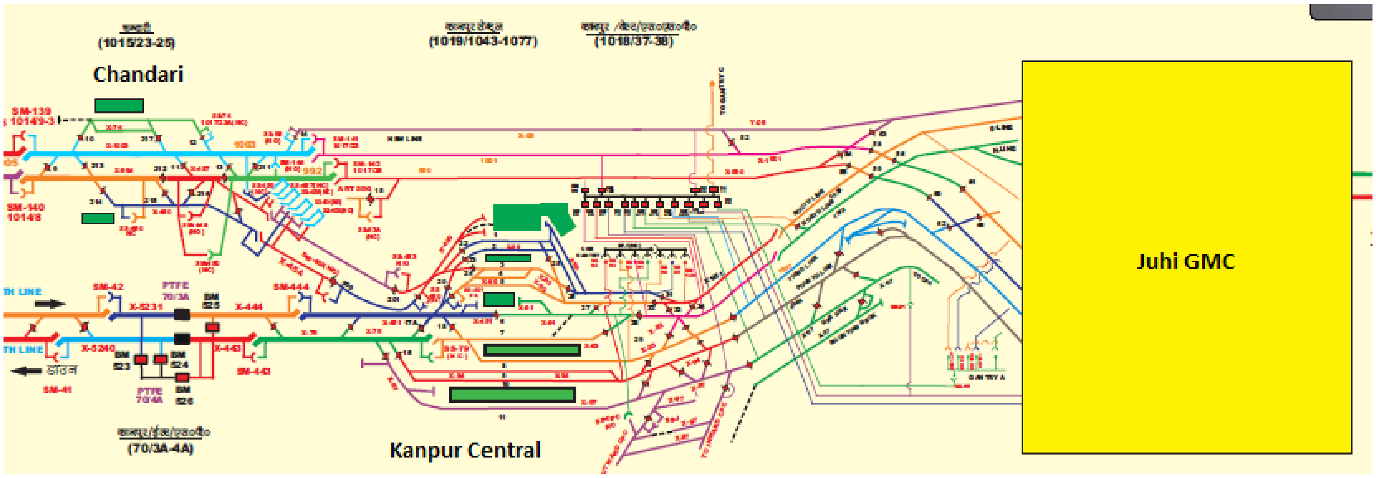

Fig. 1. Kanpur station detailed schematic layout

on the section.

Allahabad division

The Allahabad Division is one of three railway divisions of the North Central Zone of Indian Railways. The bulk of the division consists of a 760 km long mainline stretch with 106 stations under its jurisdiction. The jurisdiction of the division starts just after Mughalsarai and ends a little before Ghaziabad. This large section on Indian Railways is analyzed in four subsections:

- Mughalsarai (MGS) -Allahabad (ALD)
- Allahabad (ALD) -K anpur (CNB)
- Kanpur (CNB) - Tundla (TDL)
- Tundla (TDL) - Ghaziabad (GZB)

together with the infrastructure at each of the major junctions ALD, CNB and TDL. Apart from these mainline sections there are some branch lines in Allahabad division, which are not considered in this analysis. The geographical location of the division has resulted in heavy traffic comprising both passenger and freight trains. The details of the section under consideration are as follows.

Infrastructure	Number
Stations	106
Loops	476
Blocks	900

TABLE I: Infrastructural details of ALD Division [5]

Although branch lines are not considered, the trains that move into the section from these branch lines are considered and their impact is taken into account. We now note some complexities that arise in modeling this section. While the details are specific to this section, such modeling difficulties typically arise while modeling any section.

Kanpur Junction Area Modeling: Kanpur Central is among the busiest railway stations in India and Kanpur area has among the largest interlocking system infrastructures in the world. From Figure 1, we see that Kanpur is structurally very complex, and modeling it a challenging task.

The major complexity arises because of a freight bypass line between Chandari and Juhi-GMC parallel to the Kanpur Central station. In order to remove congestion in the Kanpur Central Station, freight trains (and a few passenger trains not stopping at Kanpur) take this line. This line has been modeled in the simulator as shown in Figure 2. The modeling procedure

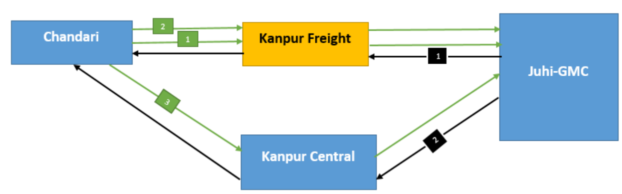

Fig. 2. Kanpur station simplified model for simulation [5]

is explained below:

- A dummy station “Kanpur-Freight” is created
- The lines joining Chandari and Kanpur-Freight station are given higher priority than those joining Chandari and Kanpur-Central
- Freight trains will enter Kanpur-Central only if both loops at Kanpur Freight station are occupied, this can be avoided by providing adequate headway between freight trains
- Passenger trains stopping at Kanpur will however use their designated platform loops at Kanpur Central Station in accordance with their timetable

In a similar manner, other infrastructural complexities and data formatting issues were resolved during modelling of the operations on Allahabad division. After incorporating many of these, a complete model for end to end traffic handling has been done using the simulator.

V. Traffic performance analysis

With the creation of a model for the entire Allahabad division, various kinds of analyses can be performed. We discuss a few of them.

A. Analysis of passenger timetable

As per Section III-A, all passenger trains of this section will be simulated in a conflict free manner. After timetable generation, a comparison can be made between our simulated timetable and the timetable currently in force. With this comparison, the allowances that are present in the operating timetable can be analyzed and the quality of the passenger train timetable can be evaluated using the simulator.

B. Effects of infrastructure addition

The simulator can give an estimate of the increase in capacity that might happen due to certain infrastructural additions. In order to test this, we consider the stations near Allahabad, another major junction in the division. The stations that we consider are Naini and Chheoki. Naini presently has only a single resource (i.e. mainline loop) in the up direction. However due to trains waiting to enter Allahabad and also additional traffic joining at Naini, trains wait at Chheoki for longer periods of time than is desirable. Therefore we consider adding an up loop at Naini and present two scenarios before and after the addition.

Loops	Waiting Time at Chheoki (Before)	Waiting Time at Naini (Before)	Waiting Time at Chheoki (After)	Waiting Time at Naini (After)
Up Mainline	04:17:07	06:05:00	04:00:16	04:07:00
Up Loopline	09:07:14	-	05:17:30	11:18:00
Common Line 1	10:06:31	-	07:26:45	-
Common Line 2	07:32:08	-	03:22:40	-
Total	**31:03:00**	**06:05:00**	**20:07:00**	**15:25:00**

TABLE II: Changes after infrastructure modification

The waiting times mentioned in Table II accounts for both passenger trains in the section and 50 freight trains which were simulated at predetermined timings. In both before and after situations, the same set of trains were simulated for comparison. Therefore from Table II, we conclude that with an addition of a new loop at Naini, congestion at the previous station i.e. Chheoki, has reduced and the combined halting time at the two stations (Chheoki and Naini) has also reduced. The waiting of trains at looplines of Chheoki has reduced, and the consequent delays due to entering looplines at Chheoki. However, there is an increase in total waiting time at Naini station because of the addition of the up-loop there. Freight trains halt at Naini when they cannot access an appropriate resource at Allahabad junction. The backtracking due to this congestion effect at Chheoki is reduced. In fact, since quite a few passenger and freight trains leave the section at Chheoki, the effect is likely to be even more significant in practice (this aspect has not been simulated and analysed in full detail here).

C. Analysis of scheduled freight paths

We schedule freight trains at firing times suggested by the Operations Department and the simulator allows us to validate them. This also allows us to explore better free good paths with changed firing times.

D. Change in signalling regime

We now present the capability of the simulator to estimate the change in capacity due to change in signaling regimes. The Allahabad-Kanpur section is considered for this analysis. This section follows absolute block system of working as of 2016. Between any two stations of this section and a few specific intermediate block huts, only one signaling block is present. We present the infrastructural details of this section:

- **Stations**: A total of 36 stations were considered including ALD, CNB and GMC
- **Loops**: 172 loops (up + down + common) were considered as per data
- **Blocks**: 88 blocks (up:49 & down:39) were considered as per actual data
- **Corridor block**: of 2 hours were considered from 13:05 to 15:05 as per actual working
- **Passenger Trains**: 39 up direction passenger trains were considered

To compare the impact of absolute and automatic block system, additional blocks were introduced in the up direction of the section. Additional automatic signals were introduced so that block sections of approximately equal lengths between two stations are created. The number of blocks introduced depends on length of the block section between 2 stations. With the introduction of new blocks in the ALD-CNB absolute block system, new section which is labelled as"ALD-CNB Automatic block system - has been created. In the ALD-CNB Automatic block section, a total of 141 up blocks were considered as compared to 49 blocks of the same section with an absolute block system. With this modification, up passenger trains were simulated and the comparison is recorded in the following table:

We note that the average time for travel is reduced slightly on introduction of "Automatic Block Signaling". The average speed has also increased in this case. We now present the effect of introducing automatic block signaling on the movement of freight trains.

From Table IV, we conclude that introducing automatic signaling improves the performance of the section both in terms of average speed of trains and average traversal time. We also note that if we increase the number of freight trains

Passenger train max speed	Freight train max speed	Raw capacity	Mixed capacity
160 kmph	45	112	57
160 kmph	60	123	70
130 kmph	45	112	60
130 kmph	60	123	77

TABLE V: Comparison of mixed capacity [4]

Parameters	ALD-CNB Absolute-block system	ALD-CNB Automatic-block system
Number of signal colours	3	4
Number of up passenger trains	39	39
Number of up blocks	49	141
Average time (hh:mm:ss)	02:20:38	02:17:52
Distance (km)	191	191
Average speed (km/hr)	81.49	83.12

TABLE III: Comparison of running of passenger trains in Absolute and Automatic block system

Signaling type	Number of freight trains	Average traversal time	Average speed
Absolute	60	04:33:18	41.98
Absolute	40	04:14:43	45.12
Automatic	60	03:59:32	47.95
Automatic	40	03:57:27	48.35

TABLE IV: Comparison of running of freight trains in Absolute and Automatic block system

in the system with a fixed number of passenger trains, the improvement of the performance of the section is considerably higher than with lower number of trains in the section. This is intuitive as Automatic block signaling will allow trains to move out of stations even if there is a train two blocks ahead in contrast to Absolute Block Signaling. Therefore congestion is reduced in the former, thereby leading to a better performance.

E. Introduction of new type of trains

In this section we analyze the effect on both raw and mixed capacity of a section when we introduce new type of trains. In this experiment we consider the following four categories of trains in a section.

- Passenger trains of maximum speed 160 kmph
- Passenger trains of maximum speed 130 kmph
- Freight trains of maximum speed 60 kmph
- Freight trains of maximum speed 60 kmph

We now present the mixed capacity for the 4 possible combinations of passenger and freight trains.

From Table V, we see that the mixed capacity reduces as we increase the speed differential of the trains in the system. This implies that if we keep the freight train speed fixed, the carrying capacity actually *reduces* if we introduce passenger trains of higher speed. Conversely, if we increase freight train speeds we can actually achieve an increase in capacity with the same number of passenger trains.

VI. Conclusion

This short paper presents an overview of traffic analysis of rail sections handling mixed traffic, which is quite common in congested sections on Indian Railways. This type of working environment at this level of traffic intensity vis-a-vis resources is somewhat unique to Indian Railways. Pending major infrastructure upgrades which are quite expensive, there is a need to handle this mixed traffic in an efficient and cost effective way. This paper outlines the type of decision support and analysis that is possible using a suitably designed mathematical and computational tool. The main challenge is to describe physical resources and train operations with sufficient detail, while keeping the computational model tractable.

The major task that still remains is to model junction and terminal movements in adequate detail and incorporate them into sectional analysis. This is currently being attempted.

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