Simulator for Railway Line Capacity Planning

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Abstract

The demand for more and varied types of services on Indian Railways (IR) has to be met through better use of existing resources and judicious augmentation wherever necessary. To provide help in planning and assessing investments in line or section capacity, a simulator has been designed which uses priority based scheduling of trains along with the operating constraints of block occupancies and platform availability. The operating logic of railway movement and the engineering detail in train running has been captured to allow for realistic analysis. The major outcomes of the simulation are (i) section capacity, quantified as the number of trains that can be handled with accepatble traversal time, on the section, and (ii) resource utilization profiles. The simulator also permits analysis of various operating parameters such as signalling regimes, signal spacings, train speeds etc.

1 Introduction

Indian Railways (IR) is one of the largest railway networks in the world with a total rail length of 60,000 km. The operating rules and diverse geographical conditions make it a challenging problem to use its resources efficiently. An important operating resource is that of track or line or section capacity. This accounts for a large part of the investments in any railway system. The Indian railways face a challenging task of dealing with resource limitation in resource support, and increasing demand on services. This basically means that possible demand for more varied service constraints will have to be met through better use of existing resources and judicious augmentation wherever necessary. In this context, good operational control practice assume importance, in the short run for meeting todays demands and in the medium run for identifying areas of improving the network carrying capacity.

A simulator has been developed at I.I.T Bombay for IRISET (Indian Railways Institute of Signal Engineering and Telecommunications) to model the operational behaviour of trains in sections of Indian Railways in sufficient detail. The simulator is useful as a Decision Support tool for commercial use, as well as a reliable computational mechanism for testing design hypotheses

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in an academic environment. The simulator has been designed primarily to analyze section capacity in a given rail network. The tool can be used to suggest changes to time-tables, and to analyze the effect of adding scheduled trains in a section, additional investment at a local level (such as additional loop lines and platforms) and the effect of signal failure and train delays.

The simulator includes the following utilities:

- Train plots on a distance vs time graph, with details of individual trains and resource usage as hidden displays.
- Velocity curve of trains as a graphical display
- The signal aspects seen by a train during its traversal.

The simulation algorithm uses priority based scheduling of trains along with the operating constraints of block occupancies and platform availability. The operating logic of railway movement and the engineering detail in train running has been captured to allow for realistic analysis. Train velocities that depend on signal aspect (that in turn depends on the status of several trains ahead of the signal) is modelled in detail.

1.1 Line Capacity, Capacity Management and Capacity Enhancement

Traditionally, the line capacity on a section of the railway network is defined as the maximum number of (standardised) trains that can be handled in a time frame (a day). This notion has been slightly refined over the years to reflect the need for a service based measure, both internally and to external customers. IR now also defines the section/line capacity as the number of trains that can be run with a certain consistency over a portion of railroad with a permissible transit time [12].

Capacity management can refer at various levels to infrastructure planning, timetable preparation and even the management of day-to-day movement of trains. Apart from building new lines, the railways would typically line to invest in existing sections which are utilized to a large extent (by freight traffic) or sometimes links that are viewed as critical and effecting the network reliability, apart from other concerns of passenger demands.

Capacity enhancement in IR is very complex. This involves decision making at various levels. For example, large-scale investment decisions for network upgradation are made at an aggregate level of overall network, and decisions such as selecting the signal regime and selecting the section for up gradation is done at a divisional level. At local levels, several decisions need to be made to improve section capacity [11] such as providing halt stations or intermediate block huts, providing twin or multiple single line working over small sections,increasing number of loops at stations, providing for accession of loops from different directions etc.

1.2 Simulation as a Methodology

As a means to plan and assess capacity investments, simulation of traffic on railway sections is one of the techniques that has been used. Simulation models can be effective in estimating the section capacity and to analyze the effect of various factors.

A few simulators for simulating the behaviour of single and multiple trains on a section are already in use on Indian Railways and elsewhere. These include the RAILS simulator as part of the LRDSS project at the Railway Board, the ITrain and MTrain simulators developed at RDSO and the RailPlan simulation software currently in use at the Mumbai Rail Vikas Corporation and other bodies. A detailed technical comparison of these existing tools is not made here, but each has been designed for certain specific needs and conditions.

2 Literature Review

The technical and academic literature in the area has a reasonably large selection of approaches and applications. A complete classification is not attempted here. There are methods based on mathematical programming models, simulation and AI search techniques for characterizing the constraints of operation of several trains on shared resources. These and the more recent constraint based techniques all have some common characteristics. These refer to the linear and sequential representation of some constraints, typically track segments and more complex representation of constraints at stations or crossovers. It is seen that there is some commonality of approaches.

Carey and Lockwood [3] developed a model algorithm and strategies for the scheduling of train in European railway context. They have mathematically modelled the problem and developed heuristics to solve the problem in a reasonable amount of time. They focus on trains of different speeds on a rail track dedicated to traffic in one direction. There are constraints on the acceptable delay at intermediate station, and additional costs and penalties are to be minimized. This formuation results in a large 0-1 integer programming problem. A heuristic suggested in the paper is to path the trains one at a time according to the priority associated with the train. This method reduces the number of 0-1 integer variables, but the computing time associated with each optimization sub-problem is high.

Carey [1] extended the above model to more general railway networks. Here constraints like choice of lines, station platforms etc. are also considered. He models a more complex and general railway network, considering multiple one-way tracks in each direction between stations, complex intersections when entering and exiting stations, and where trains have a choice of platform. In another paper, Carey M. [2] extends the train pathing model from a one-way to a two-way track.

Higgins et al. [5] developed an online model for scheduling of trains on a single-line track. They considered the minimum and maximum velocities of each train on each block. Thus the minimum and the maximum traversal time from each block can be calculated and incorporated into the constraints. The objective function considers the cost of the delay of each train at each destination multiplied by appropriate penalty for each train and also the operating cost of the train. Decision variables are arrival and departure times and which trains traverse the section first. The relusting IP is solved by branch and bound methods using a lower bound estimate of remaining overtake delays.

Taylor [13] developed an expert system for route selection in transport networks. He discusses the application of knowledge-based systems technology to the production of an expert system for route selection in transport networks.

Peterson and Taylor [9] presented a problem of scheduling of trains and a line blockage at high traffic intensities, using simulation and optimization techniques. The algebraic structure of the problem permits an arbitrary number of different trains with different priorities to be dispatched over any line configuration. They discuss the effect of line blockage at high traffic intensities and conditions so that this does not occur.

Harker and Jovanovic [4] describe the SCAN system that they have developed for railway simulation. The SCAN system takes the train routes blocking and yard policies and maintenance operations as input. The maintenance operations are treated as a special train in this model. The SCAN system starts with a given train schedule and evaluates its feasibility. If not feasible, it suggests some changes through interactive or automatic procedures to modify the schedule till it is feasible. For checking the feasibility of a schedule there is a meet-pass plan that can be viewed as a mixed integer-programming problem without an explicit objective function. Most of the constraints in the objective function are the same as discussed above.

Raghuram and Rao [10] describe the implementation of an interactive software system that determines the line capacity of a section for freight trains. The DSS allows user to input various section parameters and input data related to passenger train schedules stations and track details. The constraints are that only one train can occupy a block at a time, the trains priorities should be respected while doing resource allocation etc. The model uses a priority based scheduling strategy.

3 The Line Capacity Simulator

The present simulator has been developed for IRISET (Indian Railways Institute of Signal Engineering and Telecommunications) to address some specific needs as below. These encompass the decision making, software and analytical perspectives on the use of the tool.

1. A simulator is needed that is capable of modelling the operational behaviour of trains in sections of Indian Railways in sufficient detail, an ideal train scheduling simulator should capture train operating rules (implicitly and explicitly stated) on a given railway network taking into account the gradients, curvatures and speed limits, the interaction of trains with the signaling system, train timetables, delays, routing and regulation logic, tractive efforts and braking characteristics of the trains.
2. The decision parameters to do with a variety of capacity investments can be studied.
3. The decision parameters of signalling improvements (e.g. introduction of automatic signalling, multiple-aspect signalling and signal spacing) should be modelled in a transparent way that the user can specify with ease.
4. Reliability features such as signal failures, late running of trains, introduction of speed restrictions and provisions of maintainence blocks should be possible to model. The impact of these has to be estimated.
5. The simulator should be compact, easy to install, use and maintain.
6. The software should work in the same manner on different operating systems/software platforms.
7. The simulator should be easily extendable and for this it needs to be object-oriented.

8. The simulator should provide a reliable computational mechanism for testing design hypotheses, such as the optimum placement of signals, loops and other facilities.
9. It should be possible to validate the performance of the simulator in standard operating scenarios which can be theoretically analyzed.
10. The simulator should also serve as a tool for evaluating different scheduling rules.

3.1 Inputs to the Simulator

The following inputs are required by the basic simulator.

a) Station: - Station code, starting and ending kilometre co-ordinates from a reference.
b) Blocks and loops: - A block is a section of track controlled by a signal. A block can accommodate one train (at most) at a time. In our simulator, station blocks are also referred to as "loops"(short for loop lines). Station blocks can be of three types: (i) Main line, (ii) Directional loops (Up or Down), and (iii) Common loops. Blocks and loops have co-ordinates and linkages with other blocks in each direction, which are specified.
d) Freight train characteristics: - Train characteristics, viz. acceleration, deceleration, maximum velocity of train and the start time are given.
e) Passenger train schedule: - Passenger trains run to a timetable. The timetable consists of (announced) arrival and departure times at stations. If a passenger train runs to schedule, its timetable poses occupancy constraints on blocks (according to its priority). But if is delayed, it is considered akin to a freight train (i.e. with some running characteristics of acceleration, maximum speed, deceleration, etc.), with the additional constraint of its timetable. The constraints are of two types: (i) departure from a station cannot be before its scheduled time and/or (ii) the duration of halt at a station should be respected.
f) Gradient information: - Rising or falling gradients in a section affect the speed characteristics of a train. The section is subdivided into portions where the gradient is specified.
g) Gradient effect information: - Each train type has acceleration, deceleration and speed characteristics depending on the tractive power of the locomotive and the trailing load and other characteristics of the rolling stock.
h) Signal aspect: - The simulator provides for absolute block working (with manual setting of signals) or automatic 3 or 4 aspect signalling.

3.2 Outputs of the Simulator

The simulator has been developed with several graphical and tabular displays and intermediate outcomes. These help in

(a) Providing detailed insight on the precise behaviour of the system in complex scenarios.
(b) Allowing the developers of the software to validate and debug the software.
(c) Allowing users to fine tune the parameters and specifications of the system.

The utilities include

- Single and multiple train plots on a distance vs time graph, with details of individual trains as hidden displays The simulator provides a graphical display of position of train at various time units (minutes) on a graph (distance on Y-axis and time on X-axis). This is similar to planning documents (master charts) and control documents (control charts) used by the railways. There are hidden display tables with details of individual train movements and resource occupancies.

- A graphical display gives the velocity profile of the last scheduled train on the Y-axis (see Figure 2).
- At the signal (block) locations, the signal aspects seen by the last scheduled train are also displayed on the Y-axis (see Figure 2).

4 Train Pathing Algorithm

Consider a train movement (say for train k) over a section in which the movement of trains with higher priority have already been planned. Finding a consistent path for the new train will then be planned as per the following operational conditions:

- The occupancy of train k in various track segments cannot conflict with reservations made for those segments by higher priority trains. This would typically impose a collection of earliest departure and latest departure type constraints at the beginning of each block. Raghuram and Rao [10] have defined and used the notion of prohibited intervals to model this.
- The velocity of train k will follow its acceleration, maximum speed and deceleration characteristics. All of these are affected by the gradient characteristics of a section.
- The halting of a train is because of a scheduled halt at a station (for passenger trains running to schedule) or for allowing trains of higher priority to pass (for freight trains or delayed passenger trains).
- The signalling regime and the signal aspect seen by a train determines the location of a temporary halt of a train and thereby the location where deceleration should begin.
- If train k has to enter a loop line at a station, the velocity of the train has to respect the loop entry velocity condition.
- Any speed restrictions at various locations have to be respected.

4.1 Overall Algorithm

The overall train scheduling algorithm is described in [8], [7], and other technical reports. The basic logic is that of priority based scheduling of trains without violating the operating constraints. This assumes that the controller (the simulator) has an unlimited look into the future as to all the timetabled and expected trains in the system and is able to reserve resources in order to maintain prioritized use of all resources. This is an idealized assumption, but is a fair approximation to actual section use and provides an unambiguous benchmark for capacity evaluation.

The algorithm can be summarized as follows.

Step 1. During the time horizon of the simulation, all the trains (both scheduled and unscheduled) are sorted according to priority in ascending order. Typically a passenger train has a higher priority than a freight train. If two trains have the same priority then they are sorted in ascending order of their departure times from their starting stations.

Step 2. The next unscheduled train in the sorted list is selected and scheduled. The process is continued until the list becomes empty.

Determining the path of a single train follows the principle of departing from a station at the first available time subject to finding a feasible path on the entire section. This can involve some backtracking steps if infeasibility is detected (due to clashes with already scheduled trains) at succeeding stations.

5 Analysis and Indicative Results

The simulator was primarily designed to estimate the section capacity of a given long distance track segment on the railway network, under mixed traffic conditions. The main performance measure related to capacity is the average traversal time of a freight train that arrives at some time point in the system. If this can be reasonably expected to be some factor of the minimum time required by that train to traverse the section, the section capacity utilization is considered acceptable. Following the LRDSS norm [12], a factor of 2 was chosen as the threshold level of acceptable traversal times, on average.

After the validation of all aspects of running of trains, the simulator was tried on test sections, with close to real life conditions. Initially, this was done on the Secunderabad-Kazipet section of South Central Railway, to compare the simulation results with the analysis of the railways. One of the important motivations of the study was to see if the automatic signalling option on a section yields significant benefits.

A sample study related to capacity calculation is as shown in Fig (1).

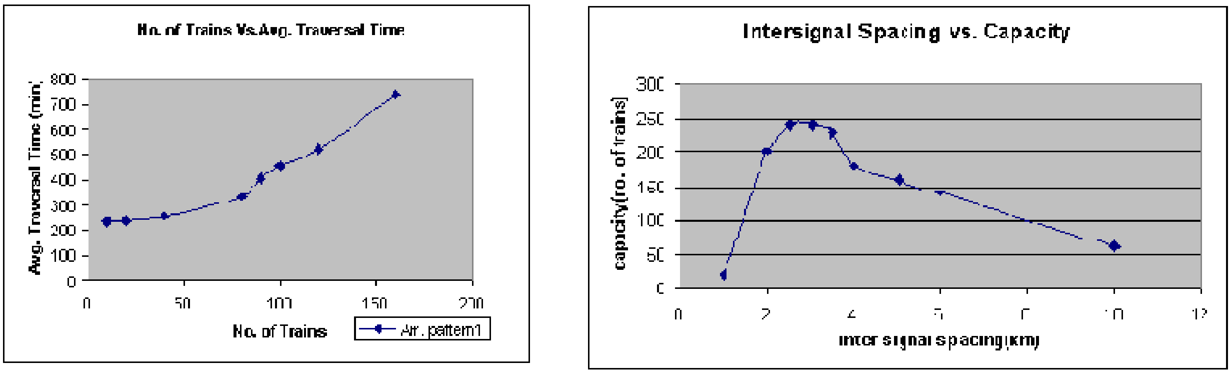

Figure 1: (Left)No. of Trains vs Average Traversal Time and (Right)Signal Spacing vs Capacity

It is seen that the average traversal time initially is small, and close to the bare minimum running time, as most of the trains find good running paths. As the congestion increases, the trains encounter more and more waiting times and the traversal time shoots up, on average. When it increases to more than twice the running time without waiting, the section is declared as saturated.

The results of these simulation studies were encouraging enough to allow us to propose and experiment with some hypotheses to do with the design of facilities on railway sections [7]. Two important observations in that study are as follows. First, there is an optimum inter-signal spacing for a given section, from the point of view of maximizing the capacity. A high inter-signal spacing causes long time gaps between trains and does not allow for enough track utilization. Low values reduce the average speed of trains and ultimately affect the number of trains that can traverse the section at a fast enough average speed. The studies indicate a clear optimum signal spacing for a given section, as illustrated in Fig (1).

Secondly, loop utilization is a complex function of the track geometry and the traffic pattern, but a good rule of thumb is that loops at stations just after small traversal time sections and just before long traversal time sections are utilized heavily, see Fig (2). This has important implications for design of facilities at stations. For more details, see [7].

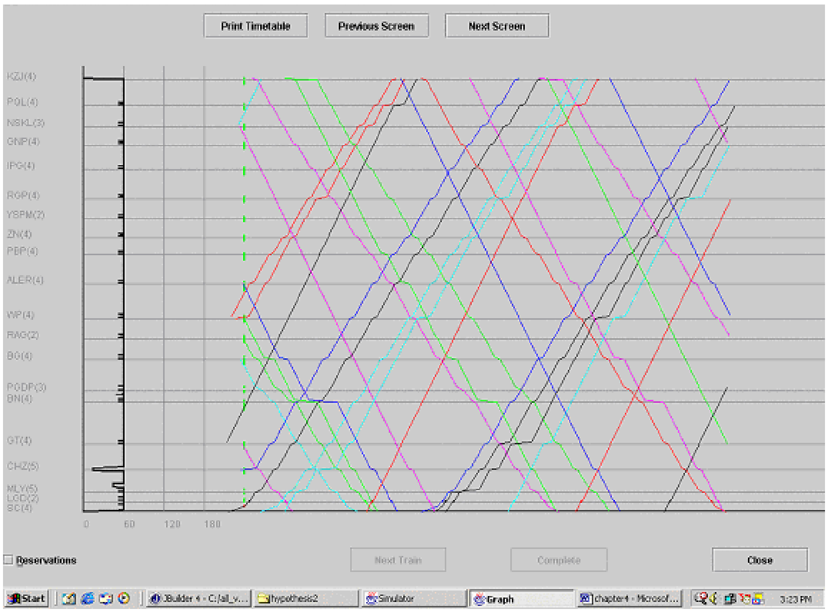

Figure 2: Snapshot displaying trains waiting at stations RGP, WP, GT for UP direction traffic

Subsequently, experiments are being carried out in various environments, viz. , suburban traffic section on Mumbai divison of Central Railway and mixed traffic conditions on different sections of Mumbai division of Western Railway. The former study is directed at spacing signals for achieving a desired headway (frequency of service) and the latter study is to enable preparation of temporary timetables in the presence of major maintenance works and the ensuing speed restrictions on train movement.

The simulator has also been designed to include two elements of probabilistic behaviour that real life systems possess. One is the randomness in traversal times of trains, for various operational and commercial reasons and the other is the possible failure of automatic signalling equipment. Both of these have been considered, although systematic parametric analysis of these effects is yet to be done.

The simulator is designed to model and analyze movements of a standardized variety. This is relevant for a large class of main line traffic on segments of the rail network between large junction stations or terminals. Further analysis needs to be done to analyze terminal movements (see [14]) and network-wide capacity for handling traffic, where multiple routes are possible. Other areas of development of the simulator include the consideration of scheduling rules to manage traffic in different conditions, the various dimensions of probabilistic analysis of performance and using the simulation as part of actual control of traffic (rather than as an off line planning and timetabling tool).

6 Conclusion

A simulator for traffic on general sections of the rail network was designed at IIT Bombay for Indian Railways Institute of Signal Engineering and Telecommunications. The simulator provides a transparent, usable and versatile tool for representing stations, track segments and train movements on general main line sections of railways. The simulator is useful for both practical decision support as well as for theoretical analysis.

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