Rationalized timetabling using a simulation tool: a paradigm shift in Indian Railways

Anoop K. P.[a,*], Madhukumar Reddy A.[d], Mandeep Singh Bhatia[d], Amit Kumar Jain[e], R. Gopalakrishnan[e], Merajus Salekin[e], Samay Pritam Singh[b], R. V. Satwik[b], Sudarshan Pulapadi[b], Chandrashekhar Bobade[b], I. Sidhartha Kumar[b], Shivasubramanian G.[c], Kumar Appaiah[b], Narayan Rangaraj[a], and Madhu N. Belur[b].

[a]*Industrial Engineering and Operations Research, Indian Institute of Technology Bombay, Mumbai, India, 400076.*
[b]*Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India, 400076.*
[c]*Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai, India, 400076.*
[d]*Railway Board, Rail Bhavan, New Delhi, India, 110001.*
[e]*Centre for Railway Information Systems, Chanakyapuri, New Delhi, India, 110021.*

*Corresponding author email: kpanoop05@gmail.com

Abstract: During the year 2020, Indian Railways undertook an extensive timetabling exercise for its entire network. The timetable for its six principal routes known as the Golden Quadrilateral plus Diagonals (GQD) was generated using a rail-traffic simulation tool. The simulation tool and the methodology had to be customized to handle the complex technical requirements of the GQD network, which spans more than 9,000 kilometers. Challenges related to using and integrating data into the simulator also had to be addressed. This was the first time that a simulation software tool of this kind was used for timetabling in Indian Railways and hence there were uncertainties regarding the timely delivery, which gave rise to additional challenges to the overall effort. This paper focuses on these challenges and the managerial and human aspects of this massive timetabling exercise. It also explains how this project leverages the benefits of combining top-down and bottom-up approaches in timetabling and how it sets a new paradigm for network-wide timetabling in Indian Railways.

Keywords: Railway timetabling, Simulation, Indian Railways, rationalized timetabling

Background

Indian Railways (IR) has one of the largest railway networks in the world, with a total route length of 67,956 kilometers (126,366 track kilometers) and operates 13,169 passenger trains and 8,479 freight trains daily (Indian Railways yearbook 2019-20). The whole network is divided into 16 main-line zones and 71 divisions.

Every year, Indian Railways creates a timetable for each zone accompanied by a conference to coordinate across zones. Most of the changes in these yearly timetables are incremental, making small changes in start times, or introducing new trains one at a time. The main items of coordination between various zones (especially relevant for trains that operate across multiple zones) are as follows:

- Ensure feasible paths (the plots denoting the movement of a train on a distance-time chart) for all trains
- Avoid conflict of train paths with the planned maintenance blocks (the regular time slots reserved for undertaking the maintenance of the railway infrastructure)
- Decide on the ownership of the railway rakes (railway rakes are owned and maintained by various railway divisions) and rolling stock planning (planning the movement and maintenance of locomotives, railway coaches, and wagons)

Every decade or so, an effort is made to re-compute the timings by taking advantage of technological advances in rolling stock, track, signaling, and traction. The Rationalized Timetabling (RTT) project in 2020 was such an exercise. While previous timetabling exercises had been largely manual, RTT was executed with the aid of a software-based scheduling tool.

A railway timetable must be consistent with the rolling stock plan (linking of coaches) and terminal management (e.g., occupancy of platforms and maintenance facilities). However, crew schedules are usually planned later. The main challenge in preparing a railway timetable is establishing an agreement between the planners at various levels of the hierarchy, starting from the railway board at the top, down to the various railway zones, and finally to the railway divisions under each zone. Since the objectives of the timetabling exercise are set at the top level and the actual execution happens at a lower (divisional) level, apprehensions can easily arise among timetable stakeholders. These apprehensions need to be overcome by proper coordination and ensuring the participation of all the planning levels. All the planners should be able to get a network-level view of the system, while still being able to design a local-level timetable. This approach is also essential to ensure the adoption of the new scheduling tool across the organization.

The six principal routes of Indian Railways connecting the major cities of New Delhi, Mumbai, Chennai, and Kolkata is known as the Golden Quadrilateral + Diagonals (GQD). The GQD routes, which covers 15% of the network and spans 9,100 kilometers, carries 52% of the total passenger traffic and 58% of the total freight traffic on the IR network. The possibility of using operations research-based methods and software to create timetables for the six GQD routes was explored. The work was taken up jointly by the Railway Board, Centre for Railway Information Systems (CRIS), Indian Institute of Technology Bombay (IITB), and all the Zonal Railways. This effort resulted in the core timetable of the GQD that was implemented in October 2021.

The level of details incorporated during timetabling determines its quality. For instance, using the granularity of inter-station runtime in seconds instead of minutes reduces the average runtime between Mumbai and New Delhi by 45 minutes. Similarly, accurately capturing speed restrictions, train running characteristics, and incorporating allowances in detail produces a better result.

The RTT exercise aims to generate a new passenger timetable for all six GQD routes with the following characteristics:

- Faster run times: taking advantage of the modern rolling stock available

- Rationalized halt pattern: new trains have been added on each route over the years and hence the halts for each train are to be rationalized depending on the train profile and the overall traffic profile on the route
- Changes in the arrival and departure times of services
- Sufficient and uninterrupted time windows for maintenance activities
- Wide-duration freight time windows (paths) well-spaced during the day for efficient freight operations: a freight path is a valuable and scarce resource on a congested rail network operating both passenger and freight traffic
- Compaction of the schedule for trains with similar speeds

The total time of the RTT project (from its inception to implementation) was around one and-a-half years, while the collaboration with IIT Bombay, including the data-reformatting at the input and output sides, was about six months. In June 2019, IR undertook an internal exercise to recompute train paths on the New Delhi-Mumbai route. Following the exercise, IR approached IIT Bombay to validate these revised train paths. This step marked the beginning of the RTT project. Later, a joint effort was undertaken by IR and IIT Bombay to generate passenger train timetables on all six of the GQD routes of IR. The joint effort generated four timetables, each better than that of the previous iteration. The IR then fine-tuned the final version of the timetable and implemented it in October 2021.

Problem details

A railway timetable determines a path for all the scheduled trains on a time-space network. A railway timetable involves the following decisions:

- Start time of train services
- Inter-station running times respecting speed restrictions
- Allowance (slack) times to be incorporated: to absorb any minor delays in the running of the train and control the propagation of delays across the network to ensure more

robustness and punctuality

- Planned overtakes: to ensure the precedence of trains, low-priority trains are held back, and high-priority trains are allowed to overtake the former at pre-planned locations.

In the case of long-distance passenger train services, timetabling is more connected with rolling stock planning and provisioning for time windows for (a) maintenance of track and (b) freight operations.

Railway scheduling and timetabling problems have been studied widely over the years. Optimization-based models and methods are commonly applied to solve such problems (Caprara et al. 2007; Higgins et al. 1996; Xu et al. 2019). However, most of these models and solution approaches are limited to single or double track railway systems or smaller railway sections. A detailed review of models and methods for railway timetabling, dispatching, platforming, and routing problems can be found in Lusby et al. (2011).

Railway scheduling on a mixed traffic rail network is more challenging due to the sharing of resources between various passenger and freight services. Liu and Dessouky (2017) considered joint routing and scheduling of passenger and freight trains to minimize the sum of travel times for freight trains and total tardiness for passenger trains. Borndörfer et al. (2016) calculated feasible routes for each freight train in a congested railway network, and Godwin et al. (2007) proposed a heuristic for routing and scheduling freight trains in a passenger rail network. The present work considers a mixed traffic rail network with a highly heterogeneous fleet of trains, making the scheduling task more challenging.

Railway timetabling at a national level requires a high degree of coordination and effort from various stakeholders, and has many managerial and technical challenges. A large-scale, national-level timetabling exercise undertaken by Netherlands Railways is reported in Kroon et al. (2006). The paper reports that a new timetable was generated for about 5,500 daily trains by solving a sequence of planning problems using various operations research techniques.

However, the paper does not elaborate on such an extensive exercise's managerial and human aspects. The present article focuses on various challenges encountered while undertaking a network-wide timetabling exercise using a newly developed simulation-based scheduling tool. A schematic diagram of the six GQD routes is provided in Figure 1. We number these routes as follows (with railway station codes given in parentheses):

- Route 1, R1: New Delhi (NDLS) - Mumbai (MMCT)
- Route 2, R2: New Delhi (NDLS) - Chennai (MAS)
- Route 3, R3: Kolkata (HWH) - Chennai (MAS)
- Route 4, R4: Kolkata (HWH) - Mumbai (CSMT)
- Route 5, R5: Chennai (MAS) - Mumbai (CSMT)
- Route 6, R6: New Delhi (NDLS) - Kolkata (HWH)

Figure 1 GQD routes of Indian Railways under consideration (Source: Google Maps)

In Figure 1, common rail sections on multiple routes are darkened and the list of these sections is given in Table 1. Five out of the six routes have such common sections and the timetabling on the routes which share these common sections (resources) was to be done simultaneously.

Table 1 Common rail sections on various GQD routes

Section	Routes sharing this section
New Delhi (NDLS) - Mathura (MTJ)	R1 and R2
Sevagram (SEGM) - Nagpur (NGP)	R2 and R4
Kharagpur Junction (KGP) – Howrah (HWH)	R3 and R4
MGR Chennai Central (MAS) – Vijayawada (BZA)	R2 and R3
Mumbai CST (CSTM) – Kalyan (KYN)	R4 and R5

The RTT exercise combines the benefits of a top-down approach with a bottom-up approach to railway timetabling. The strong bottom-up culture of detailed timetabling at the divisional and zonal levels was already supported by standardized IT infrastructure and some planning tools at the corporate level through the CRIS. Active planning at the corporate level was mainly through an annual coordination conference. The current exercise enhanced the top-down initiatives in the following ways:

- Uniform standards for allowance (slack) time provided in different sections based on field trials and data from across Indian Railways were discussed and agreed upon at the corporate level. These standards could be moderated judiciously where local conditions warranted. The earlier procedure of setting allowance times varied from one railway division to another and overall, too much slack time was incorporated in the timetable.
- Based on rolling stock characteristics, consistent values for acceleration and deceleration were used for their timetables.
- The timetable was defined to the granularity of seconds rather than minutes (although some zonal railways operating high-density traffic and suburban sections already used

½ and ¼ minutes in the timetable).

- Divisions, where trains originate, were asked to propose the start times of long-distance trains, considering the travel demand, terminal constraints, and rolling stock planning at their end. However, once these train schedules were propagated across the entire network, some key bottleneck sections in the heart of the network had difficulty planning maintenance blocks and freight corridors. Corporate direction was then given to propose alternate start times keeping these crucial mid-sections in mind. The simulation tool helped in evaluating these alternate start times quickly and systematically. The timetable planners at the zonal and divisional levels were able to visualize the effects of these alternate start times themselves using the tool, which was not possible in the traditional method.

Another essential objective of the RTT exercise was to achieve “compaction” in the passenger train timetable; this means a compact use of the line and station resources on the rail network. Compaction is achieved by several measures including but not limited to the following.

1. Operating trains with a controlled headway to make use of all available time windows.
2. Reducing the variability in train speeds, and sequencing trains of like speed in a group, so that overtakes of slower trains or enforced slow running of potentially faster trains do not occur.
3. Speeding up of trains by taking advantage of the local improvements over time in infrastructure like rolling stock, track, signaling, and traction. The timetable is recalibrated to utilize these improvements.
4. Canceling or truncating trains that are not viable by analyzing the changes in demand and occupancy patterns.
5. Reduction of the number of halts and halt duration in response to changes in the demand and occupancy patterns.

The simulation tool achieves the first item in the list automatically and allows effective numerical evaluation of the second item. The tool is also tailored to incorporate all the parameters in the third item in the list efficiently. Items 4 and 5 in the list are achieved by a demand analysis and service planning, which is a separate and important exercise.

Procedure

The timetable for the six GQD routes was generated by a step-by-step procedure using the semi-automated simulation-based scheduling tool built at IITB. The simulator was built over the years incrementally and was scaled up from a section simulator to a network-wide simulator during the RTT exercise. The simulator incorporates mixed rail traffic, undertakes detailed simulation for train-by-train velocity profile generation, and provides the user with traversal details for multiple trains over some period. In addition, pre-and post-processing procedures are incorporated for accepting inputs, report generation, and output analysis. The pre-processing and post-processing were required since the data in Indian Railways' central database (hosted by CRIS) has its predefined formats, and the tool output needed for Zonal Railways' usage also has required formats and consistency checks.

The simulator uses a travel-advance, greedy heuristic with asynchronous train movement, and high-priority trains are scheduled from first to last stations, followed by low-priority trains. The occupancy information of high-priority trains is respected, and the tool generates a feasible, conflict-free timetable. Speeds of trains are as per the occupancy of block sections ahead of the train. If a train cannot move ahead from a station, it will wait at an appropriate loop line and if no loop line is available, the algorithm backtracks to the previous station, and, if necessary, to the beginning of the section, where it is assumed that there are a sufficiently large number of loop lines. All trains move as per their acceleration value (from rest or from any other speed) until they reach the maximum permissible speed and decelerate as per their deceleration value (until they reach zero or any other speed dictated by speed restrictions). The tool incorporates the following sectional infrastructure and train characteristics.

Sectional infrastructure:

- All stations on a route with distances from the zero-mileposts.
- Block sections between stations and the maximum permissible speed.
- Loop lines at stations and individual loop-level speed restrictions.
- Maximum permissible speed and permanent speed restrictions on all track sections.
- Safety and signaling arrangements (for headway between trains).

Train characteristics:

- Maximum speed of the train.
- Acceleration/deceleration values.
- Origin-destination details of the train.
- Priority of various trains (to enforce precedence).

The sequence of tasks undertaken to generate the passenger train timetable on the GQD routes is as follows:

- Preparation of infrastructure data:
    - Collecting and retrieving data related to the six GQD routes
    - Cleaning up the data: Matching the existing and required formats, removing data inconsistencies, imparting uniformity in parameters wherever required.
    - Changing the time units to seconds and recalculation of train starting, running, and arrival times and updating the data in the existing software.
- Preparation of train running data:
    - Finalizing the starting times of various trains on different routes: after discussion and approval of the Railway Board and Zonal and Divisional Railways.

    - Finalizing allowance schemes: traffic allowance (allowance time to absorb minor operational delays in train running, and the knock-on effects of such delays on other train movements) and engineering allowance (allowance time to accommodate delays due to temporary speed restrictions on a track due to inspection and maintenance activities) are announced, systematically tabulated, and included in the CRIS database.
    - Adding the maintenance windows on various sections: implementation of a uniform policy for deciding maintenance blocks after ratification at the zonal and divisional levels.
- Input the data and run the simulator to generate a draft timetable:
    - Trains are scheduled one by one as per priority. Among trains with the same priority, scheduling is done in the order of starting times.
    - A lower priority train should not delay a higher priority train and this is achieved by reserving the block occupancy of the higher priority train first.
    - Scheduled trains move as per their velocity characteristics following the timetable at every station in the section. Scheduled trains can arrive early at a station but cannot depart earlier than the scheduled departure time.
    - Unscheduled trains (e. g. freight trains) have a firing time when they enter the section and try to find the earliest departure time ensuring a valid path through to the end of the section.
- Generate distance-time charts and velocity profiles for the simulated trains.
- Obtain feedback on the draft timetable from the zonal and divisional railways, finalize the changes required and run the simulator with updated input and generate the next improved version of the timetable.

Challenges overcome during the exercise

Many challenges related to simulation-based tool interfacing, data handling, and those of a managerial nature were encountered and overcome during the RTT exercise. These challenges included the following:

- **Inconsistencies in data format**: Data from a central database was inconsistent with the data Zonal and Divisional Railways had in their database. The data inconsistency was observed in parameters like distances, maximum-permissible speed, permanent speed restrictions, and maintenance blocks. The tool needed a centralized way of data handling with uniform formatting and milestones. Overall, data interfacing required close interaction with individual zones for the preparation of the timetable and the correction of infrastructure-related data.
- **Change management**: The two major technical and data-handling partners in the RTT exercise were CRIS and IITB, which had two different approaches and beliefs. But a potential for the integration of these two independent efforts was identified to make use of the complementary skills. However, the integration posed challenges due to the changes required in the existing CRIS database. CRIS integrates other railway level systems like zonal level operations, rolling-stock-planning information systems, and procurement and maintenance systems. Hence the simulation tool's inputs and outputs had to be compatible with CRIS's inputs and outputs. The zonal and divisional railway teams had some concerns while integrating their data with the central CRIS database. These teams were responsible for meeting the key performance indicators related to punctuality that had been decided at the corporate level. Until the RTT exercise, the various parameters like permanent speed restrictions and their impact on running times were assessed locally at the zonal and divisional levels.
- **Change of the base time unit to seconds (from minutes):** This shift could not be

purely from the viewpoint of tool usage since many other railway information systems have traditionally been built at a minute-level accuracy (except for a few zonal railway systems where half-minute and quarter-minute accuracy was the norm). Shifting to seconds required systemic changes in other software also. This shift was possible due to the Covid-induced "incentive" to change.

- **Maintaining timelines for the activity**: Since the tool was being used for the first time for actual timetabling, there was an apprehension about the delivery within the given timelines. The zonal railways had to invest in a parallel effort as a failsafe measure. This parallel effort was reasonable from a top-administrator viewpoint, but the hands-on employees viewed this parallel effort as a duplication of their tasks and were sometimes apprehensive about the new approach. Winning the confidence of railway timetabling experts required that the tool output be available in the same format (SATSaNG) as that of the timetable preparation software used by Indian Railways. The timetabling experts valued easy interpretation of the results, and the outputs were generated over multiple iterations. The railway personnel were trained so that they could tweak the tool themselves.
- **Future role of hands-on employees**: The hands-on employees were uncertain about their future role in a largely automated timetabling effort. The need for retraining to use the simulation tool for future timetabling needs resulted in an apprehension among such employees.
- **Integrating suburban timetabling**: While generating a timetable for the GQD routes, the scope was limited to these GQD routes and non-GQD routes were timetabled separately. A pertinent question was to what extent the suburban timetables for the Chennai, Mumbai, and Kolkata areas were to be integrated. This question of scope needed to be negotiated with the suburban timetabling teams. The issue was resolved

as follows. The suburban areas of Chennai, Mumbai and Kolkata are in the terminal areas of the GQD network. For the part of the suburban rail network that is shared with the GQD network, the arrival and departure slots of long-distance GQD trains were fixed by the concerned zonal and divisional railway. Further, overtaking of suburban services by GQD trains was avoided during peak hours. During non-peak hours, suburban services were timetabled separately by the divisional planners, keeping the proposed GQD timetable in mind.

- **Top-down approach for deciding train timings**: In the earlier mode of timetabling, zonal level timetabling personnel had some flexibility in deciding allowance times and thereby tried to achieve corporate goals of punctuality in train running. In the current exercise, more detailed norms of allowance times per 100 km of train running were used, by default, and this led to some apprehensions about the performance of the proposed timetable. To resolve this issue, some discussions and adjustments were required with the Railway Board, regarding some exceptional cases, for example, in junction areas and suburban sections. The simulation tool enabled a quick evaluation of the effects of various train timings across zones and divisions over multiple iterations. The timetable planners at the zonal and divisional levels were able to visualize these effects themselves using the tool. This capability of the tool made the coordination between various zones and divisions easier, and the Railway Board played an active role in resolving any conflicts. (The screenshots of the visualization tool developed as part of the RTT project are given in Figures 2 and 3. Figure 2 is a screenshot of the train running statistics provided by the visualization tool. The user can quickly see the fastest and slowest trains on a particular route and their average traversal speeds. Box plots for train traversal times and distance-time charts for trains can also be obtained using the tool as shown in Figure 3 and Figure 4 respectively.)

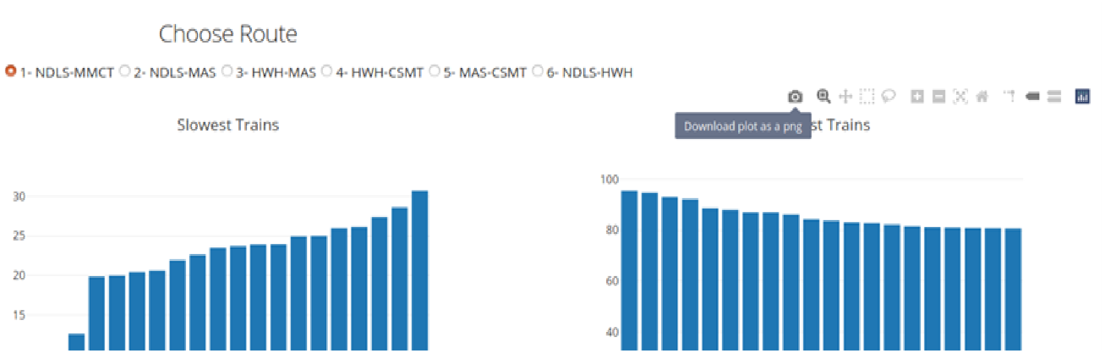

Figure 2 Screenshot of train running statistics generated by the visualization tool

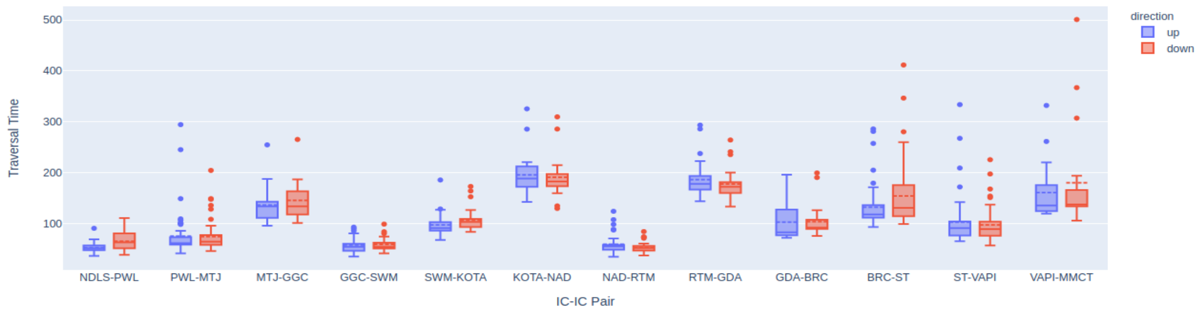

Figure 3 Box plots generated by the visualization tool

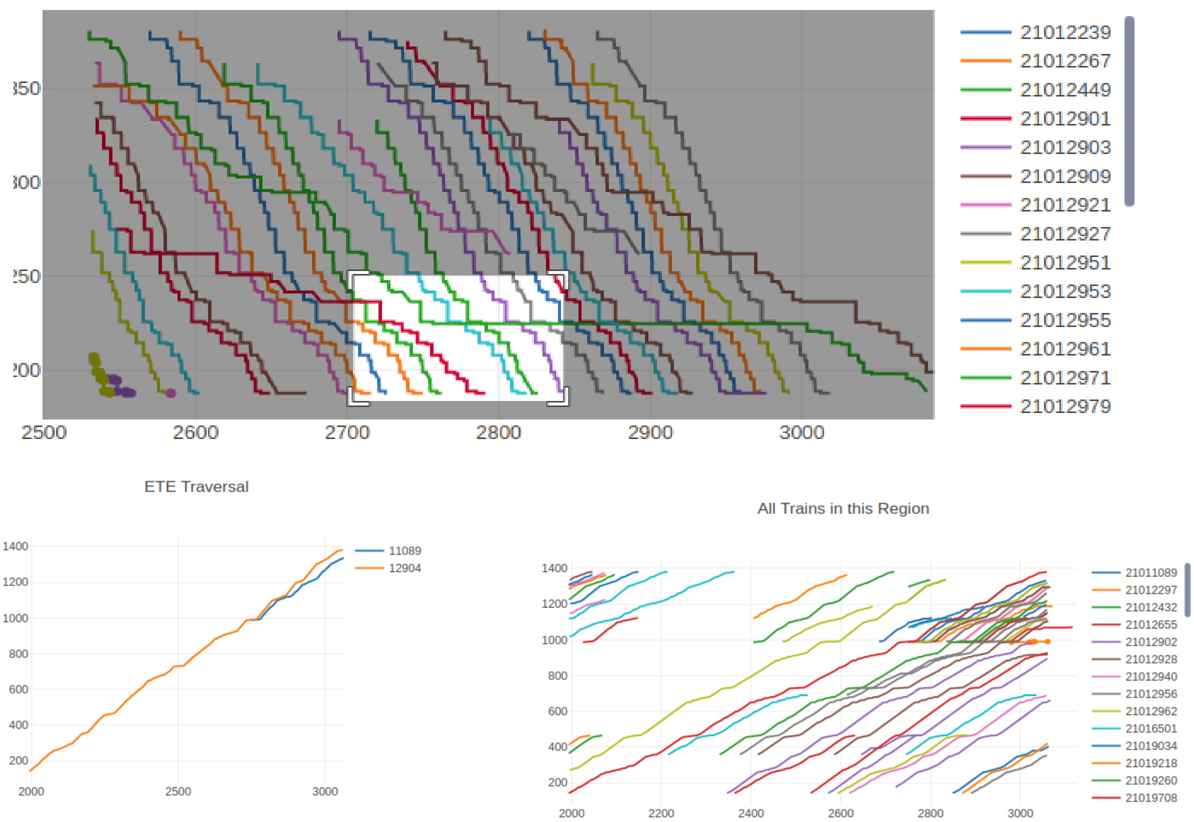

Figure 4 Distance-time charts generated by the visualization tool

Implementation and benefits

The timetable for the six GQD (and non-GQD) routes was prepared and implemented by October 2021 after modifications to incorporate non-GQD trains and the rest of the non-daily trains of the GQD network. The timetable was scaled up from the then-existing sparse COVID-Special timetable in phases. The timetable was further re-adjusted for short-distance train schedules. The following accomplishments were achieved on the GQD network because of the RTT exercise:

- A de novo timetable that caters to the present-day demand taking advantage of the advancements in rolling stock, track infrastructure, signaling, and traction.
- Compaction of the timetable, thus freeing up resources for other uses.
- Wider, uninterrupted freight corridors on all six GQD routes.
- Transition of the GQD timetabling process to software: it now allows the generation of a newer timetable for the GQD routes within 45 minutes (1600 daily train paths, i.e., simulation of 8000 trains across five days to check for any potential conflicts).
- Timetabling software that allows priority-wise scheduling and resource allocation and a comparison with the existing timetable and freight paths wherever possible.
- Setting maintenance blocks on all sections in a conflict-free manner.
- Uniform policy formulated and applied for setting traffic and engineering allowances, permanent speed restrictions, maximum permissible speed, and acceleration and deceleration values of trains.

Improvements in passenger train timetable:

The average increase in speed over all the passenger trains in the six GQD routes (after post-processing by the timetable controllers) was reported to be 6.12%. The improvement can be partly attributed to the removal of stoppages with poor customer demand and the elimination of various unscheduled halts for overtakes. As a result, the total time on the run has been reduced by 3.67% and the time saved on account of acceleration/deceleration gain is 0.80%. The compaction of the timetable achieved during the exercise is quantified using the following two parameters:

1. Minimum homogeneous time headway, h_k, achieved on a route k
2. Best achievable freight, maintenance time corridor, g_k, on a route k

To understand how h_k and g_k are defined, let t_{ijk} represent the time between the i^{th} and $(i+1)^{th}$ trains through block (section of a railway track governed by a signal) j on route k. These values are represented on the distance-time chart of train movements shown in Figure 5.

Then, the route-wise parameters h_k and g_k for each route k, are defined as follows:

$$h_k = \underset{\forall\ j\ in\ k}{Max}\left(\underset{\forall\ i\ through\ j}{Min}(t_{ijk})\right) \quad (1)$$

$$g_k = \underset{\forall\ j\ in\ k}{Min}\left(\underset{\forall\ i\ through\ j}{Max}(t_{ijk})\right) \quad (2)$$

The lower the value of h_k, the closer (in the time dimension) the running of consecutive passenger trains, and the better the compaction achieved. The higher the value of g_k, the wider the time window (in the time dimension) between consecutive passenger trains that are distantly planned from each other. Thus, minimizing h_k and maximizing g_k results in shorter time gaps between passenger trains and adequately longer time windows for maintenance planning and freight operations. Therefore, unnecessary overtakes and unscheduled halts for freight trains can be minimized.

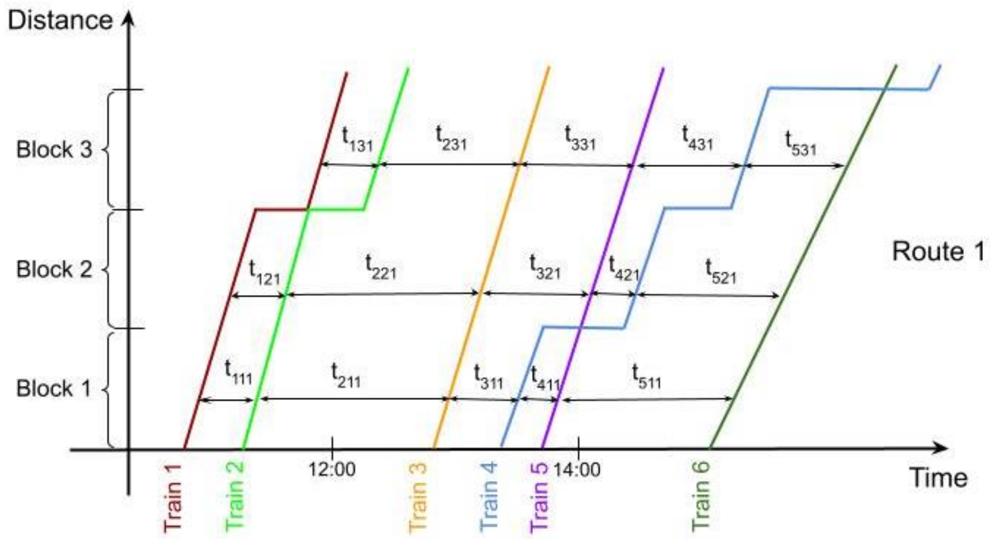

Figure 5 Distance-time chart of train movements

The average values of h_k and g_k over the six GQD routes achieved during the current timetabling exercise are 24 minutes and 196 minutes, respectively. Thus, shorter time gaps between passenger trains and adequately longer time windows for maintenance planning and freight operations are achieved. The following section illustrates the importance of interaction-free time windows for freight operations on a network with mixed rail traffic.

Figure 6 represents an interaction-free distance-time chart for a network with mixed rail traffic wherein freight trains are scheduled during the time gaps between passenger trains.

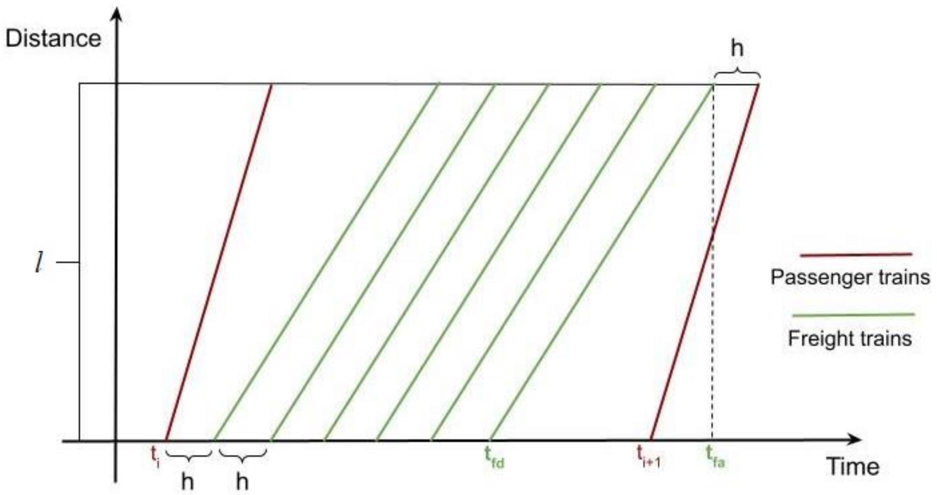

Figure 6 Interaction-free distance-time chart for a mixed traffic rail network

Consider the following notations:

- l : length of the section
- h : minimum headway between any two trains
- t_i : departure time of the i^{th} passenger train from the start of the section
- t_{i+1} : departure time of the $(i+1)^{th}$ passenger train from the start of the section
- t_{fd} : departure time of the last freight train between the i^{th} and the $(i+1)^{th}$ passenger trains from the start of the section
- t_{fa} : arrival time of the last freight train between the i^{th} and the i+1th passenger train at the end of the section
- v_p : uniform velocity of the passenger trains in the section
- v_f : uniform velocity of the freight trains in the section

To ensure an interaction-free operation of passenger and freight trains on a section, the following conditions must be satisfied.

$$t_{fa} \leq \left[\left(t_{i+1} + \frac{l}{v_p} \right) - h \right] \tag{3}$$

$$t_{fd} \leq \left(t_{fa} - \frac{l}{v_f} \right) \tag{4}$$

Hence, the maximum number of freight trains that can be scheduled in a section without interaction with passenger trains is equal to $\frac{(t_{fd} - t_i)}{h}$ (5)

We consider two example scenarios on the rail section New Delhi – Mathura (the common section on routes R1 and R2), to illustrate the importance of longer time windows between passenger trains to increase freight train throughput. To put the examples in context, a freight path is a valuable resource, as a freight train on Indian Railways would typically carry 3000 -

4500 tons of bulk commodity (depending on the commodity) or 90 Twenty-foot Equivalent Unit (TEU) containers, implying considerable revenue potential for the railways, and value for customers. Every additional freight path on a congested part of the network is a valuable resource and is often the bottleneck for carrying more freight traffic on the network.

Scenario 1: Freight window of 3 hours

Let: { l = 120 km; h = 10 mins; t_i = 720 mins; t_{i+1} = 900 mins; v_p = 2 km/min (120 kmph); v_f = 1 km/min (60 kmph)}

Then, as per Equations 3 and 4, for an interaction-free operation, the maximum value of t_{fa} is equal to 950 mins and the maximum value of t_{fd} is equal to 830 mins. Hence, the maximum number of freight trains that can be scheduled is 11.

Scenario 2: Freight window of 1.5 hours

Let: { t_{i+1} = 810 mins with other values as in the first scenario}

Then, the maximum value of t_{fa} is equal to 860 mins and the maximum value of t_{fd} is equal to 740 mins. Hence, the maximum number of freight trains that can be scheduled is two.

These examples illustrate that, during an interaction-free operation, two freight windows of 1.5 hours each can have a combined throughput of only four trains compared to 11 trains that can be scheduled in a single longer freight window of three hours. However, in practice, an interaction-free operation is not always possible and as a result, freight trains encounter unscheduled halts for overtakes by higher priority passenger trains. We simulate the freight operation on a test section with the same parameter values as given above but allowing for overtakes whenever required.

We find that 11 freight trains can be scheduled without interaction with passenger trains on the test section during a three-hour (180 min) window with a total average traversal speed of 55.8 kmph. Even though the maximum running speed of freight trains is set to 60 kmph, acceleration/deceleration characteristics and speed restrictions on various block sections limit the total average speed to 55.8 kmph. The following scenarios are tried in succession.

- Scenario A: One passenger train is introduced in the middle of the time window (at 90 mins) and the total average traversal speed of 11 freight trains reduces to 54 kmph.
- Scenario B: Two passenger trains are introduced at 60 and 120 mins respectively and the total average traversal speed reduces to 52.63 kmph.
- Scenario C: Five passenger trains are introduced one-by-one every 30 mins (30, 60, 90, 120, and 150 mins respectively) and the total average traversal speed reduces to 48.58 kmph.

The results of these scenarios show how delay propagation affects the performance of the whole set of freight trains, causing a drop in their traversal speeds. The effect of delay propagation is especially significant when trains are bunched up with minimum headway between them. One way to retain the average traversal speed at a particular level is to compromise on the throughput and reduce the number of freight trains being run during the time window. If we limit the drop in total average speed to 5% of what is achieved without interaction with passenger trains, the following results are obtained.

- In Scenario A, the throughput of 11 freight trains can be maintained (but speed drops by 3.2%).
- In Scenario B, the throughput reduces to nine freight trains.
- In Scenario C, the throughput reduces to two freight trains (with a speed drop of 6.3%).

These results underscore the benefits of long uninterrupted time windows for freight train operations.

Improvements in freight path statistics

The objective of the freight path generation exercise was to generate an average of 16 good quality sectional paths and four end-to-end paths in each of the six GQD routes. The target traversal speed was 45 kmph. This target was comfortably achieved for all six routes, since 17-20 sectional paths and four end-to-end paths were generated with average traversal speeds ranging from 45 to 51 kmph. Furthermore, the simulator provides the option of carrying out a what-if analysis for other likely or hypothetical scenarios. Using this capability, freight paths were generated by removing low-priority stopping passenger trains from the network and with improved acceleration/deceleration values for trains. Results indicated a clear improvement in the number of sectional freight paths generated and the overall speed of paths. (An average of 1.5 additional sectional paths were generated on the six GQD routes. The traversal speeds increased by an average of 2.2 kmph and 3.95 kmph for sectional and end-to-end paths, respectively). This result indicates that there can be a trade-off made between low-priority passenger trains and high demand freight trains, when required.

Furthermore, a comparison was carried out between the freight paths generated by the simulation-based tool and the paths charted by Central Railway (CR) on one of the congested sections (Igatpuri (IGP) - Nandgaon (NGN) - Bhusaval (BSL)) on Route 4 of the GQD. The paths generated by the simulation tool outperformed the paths charted by CR in terms of number of paths and average traversal speed in three out of the four sections.

Conclusion

The RTT project established a new paradigm for timetabling in Indian Railways by replacing the traditional method with an integrated network-wide effort using a simulation-based scheduling tool. The approach systematizes the timetabling exercise and enhances the process's transparency and visibility by making the proposal and its effects available across all levels of the organization. The simulation-tool based approach enabled the rapid generation of multiple, improved versions of the timetable. The approach also exploited the benefits of combining top-down and bottom-up approaches in railway timetabling. As a result, the proposed timetable could improve the running times of trains, achieve compaction, and create wider and uninterrupted freight corridors, a requirement to cater to the increasing demand for rail freight movement in India. Also, the tool enabled the transition of the railway timetabling process to utilize software while establishing a uniform policy for setting various parameters like traffic and engineering allowances, permanent speed restrictions, maximum permissible speeds, and acceleration/deceleration values of trains. This project also supports the case for extending the scope of the proposed approach to cover the entire network of Indian Railways in future timetabling efforts.

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