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Development of a railway junction simulator for evaluation of control strategies and capacity utilization optimization

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Abstract— **This paper focuses on the development of a Python based tool for analysis and simulation of mixed rail traffic at a railway junction. The tool is helpful for evaluating various open-loop and feedback based strategies for an optimum junction utilization. The tool is implemented in Python using graph theory for finding shortest paths between various source-destination pairs. What signifies a railway *junction*, as opposed to a railway *section* is the possibility and the need to allow multiple simultaneous movements within the junction area. The tool applies network (edge and node) based approach for designing the line infrastructure of a railway junction. Source and destination are represented as nodes and every path from a source to a destination through a junction consists of a set of permissible combination of edges and nodes.**

This tool can be used for simulating scheduled passenger trains through all the allowed paths, and then selecting the best path for traversing through the junction. Further, lower priority trains are scheduled without affecting the edge/node occupancies trains of higher priorities. The best freight paths are identified and a more accurate estimate of the time required for freight trains to pass through the junction is obtained using this tool. In this way, one is able to quantify and then optimize the capacity/utilization of railway junction. In a larger scenario, the tool is useful for identifying bottlenecks in a given infrastructure. As examples, a detailed analysis of Allahabad junction and Kanpur junction of Indian Railways is presented using the tool.

I. Introduction

The increasing demand on a rail network/infrastructure calls for a detailed analysis of the movements of a train in a rail section and junction. Analysis and simulation of movements within a junction area is complex because of the simultaneity of many movements, cross-movements of trains, intricate occupancy charts of various shared resources. It is a commonly encountered phenomenon that trains (both passenger and freight trains) need to wait just short of major junctions. This is mainly because of the crossovers and track resources which provide access to various parts of the junction. The hindrance to other movements caused due to one movement is further increased due to many auxiliary movements in a junction like reversals, loco changes, loco detachments and separate exits for the train and the loco.

This paper considers the case when the infrastructure is to be used by both scheduled passenger and freight trains known as 'mixed traffic'. Such traffic is inevitable due to the sharing of infrastructure resources between passenger trains and freight trains and the significance of freight paths for the railways system (see Section II below). 'Mixed traffic' on *junctions* has been studied in [9] and [14]. The approach in [9] uses the notion of a resource to resource 'hindrance matrix' for analyzing the junction. The hindrance matrix consists of various time duration between two consecutive movements on different resources that involve safety based time-separation constraints. However, this approach is needlessly input-data intensive and does not scale up with more complex junctions.

This paper pursues an edge/node based approach for storing the infrastructural aspects of a junction and builds occupancy tables for each edge/node for the purpose of simulating a junction. Every source and destination as well as the crossovers are represented as a node. The two ends of a platform are also represented as node. In this way, a junction is represented as a network consisting of set of nodes and edges. The objectives which can be achieved using this simulator are listed below.

1) Finding good freight paths to decrease the traversal time through junction
2) Identifying the most congested platforms and crossovers: thus fish out bottlenecks
3) Accurately quantifying and comparing the effects of infrastructure changes on freight paths
4) Finding the effects of delay in scheduled trains timetable on freight paths

As examples of case studies, we use the simulator for the simulation of Allahabad junction and Kanpur junction of Indian Railways.

II. Significance of freight paths

Rail freight is a main source of income for railways and in fact, in India, rail freight also helps in subsidizing passenger fares. Rail freight helps in reducing road freight and thus reduces congestion on roads. While road freight can reach remote and interior areas, for long distances the impact of road freight is bad on both environment and economy. It is known that fuel-consumption wise, rail freight is about 3 times cheaper than road freight [11]. More number of freight path helps us to transfer more through rail freight, thus helping both cost-reduction and environment. The freight train routing problem for congested railway network with

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mixed traffic has been studied in [2]. This paper aims at finding and analyzing freight paths at a junction in addition to simulating and analyzing various resources at the junction.

III. Open-loop and feedback strategies for optimal junction capacity utilization

Key decisions involved in a junction is to decide when a certain train is allowed entry into a junction: each movement causes many conflicts to other movements and thus deciding the sequence is important for a high utilization of the junction resource. While these decisions can be precomputed, the practical implementation of a policy is affected by the small and large uncertainties prevailing in the daily schedules. There is a need for a 'feedback strategy' that uses the situation over, say, the last one hour and the trains that need to enter over the next half hour: based on this an entry/exit decision would be more robust than a precomputed 'open-loop' decision policy. We elaborate on these two types of policies below.

1) Open-loop Control: In this mode, the schedule/timetable for all the scheduled trains for that day is used to allocate the resources by simulating/running the trains as per priorities. This results in an occupancy table for each node/edge, i.e. a chart of different time durations at which the resource (node/edge) is occupied by some train. This occupancy table plays a key role in every study of complex resource sharing. This is elaborated in the following section.
2) Feedback Control: In this mode, rather than simulating the entire day's timetable apriori, only a more immediate forecast of trains and the current set of trains in the junction area are simulated to build the occupancy tables and a decision to enter a train is taken based on this information only. This is possibly sub-optimal (since only a small future window is considered) but the implementation is more robust to uncertainties in the arriving/departing train schedules. It is possible to take local decisions of prioritizing a freight train in the interest of a larger benefit elsewhere.

The simulation and analysis tool helps in evaluating policies with respect to various parameters like % capacity utilization, effect of uncertainties on punctuality.

IV. Junction model and occupancy lists

A simple junction is shown in Figure 1. Here, there are two sources S1 and S2 from which rail traffic arrives and the traffic departs to D3. For simplicity in this section, we have first considered a single path system where movement from one source to another destination has only one path available. However, there are shared resources such as node 4 and edge between node 2 and node D3. Simultaneous movements on these shared resource is not possible. To disallow these movements, we create occupancy list for very edge which contains time durations for which the resource is unavailable.

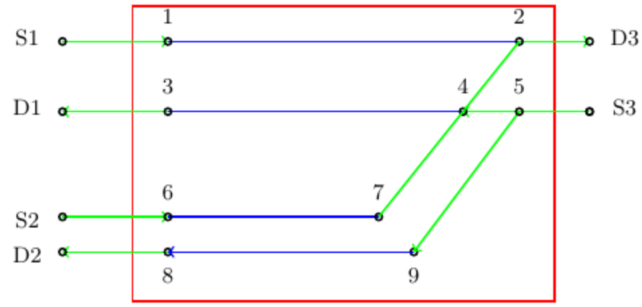

Fig. 1. A simple junction: platform edges (blue), track edges (green)

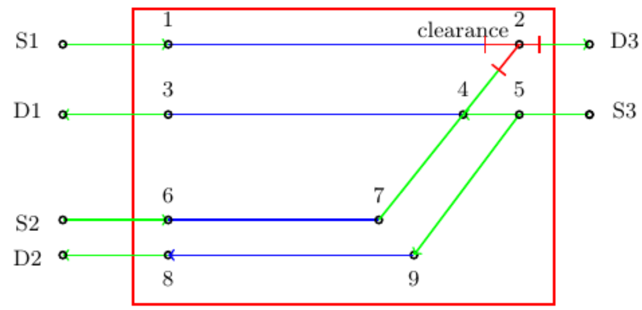

Fig. 2. Clearance shown in red at Node 2

Some nodes like node 2 can have very close movements like when one train moves from S2 to D3 and another from S1 to D3. To keep distance between both trains, we have given some clearance (in red) on both side of the nodes as shown in fig 2. Clearance is also given on every edge to give enough space between two trains.

Lesser degree nodes will have their occupancy already occupied in their adjacent edges. Nodes like node 4 have degree 4. For these nodes, their own occupancy list is required. Now, if we consider edges occupancy only for movement, simultaneous movement is possible between S2 to D3 and S3 to D1 which is not correct. So these nodes with degree greater than 3 require their own occupancy list as well.

V. Capacity of junction

The International Union of Railways (UIC) published a leaflet - the UIC 406 capacity leaflet which defines the capacity of a junction. It described railway capacity as "the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively..." [15]. Using UIC guidelines, railway capacity has been studied in [5], while station capacity has been studied in [6], [8] and [7]. This paper aims to increase passenger and freight paths at junctions thus increasing capacity of junction.

VI. Performance objectives of a scheduling policy and benefits of simulation tool

The performance of a policy of allowing/scheduling a train can be evaluated with respect to the following two main criteria:

1) Quality of service: minimizing the delay spent in traversing through a junction
2) Quantity of service (throughput): maximizing the number of train paths by optimal scheduling: either open-loop or feedback strategy

While a optimal strategy of scheduling targets the above two objectives, a simulation tool also helps in pinpointing the bottle-neck resources so that an infrastructure upgrade can target this.

VII. Input

This section elaborates on the input files that are required. These inputs are in csv format. The simulation tool processes these input files in Python to give us the required output. The set of inputs to simulate the junction are described below.

A. *Train data*

This file contains for each train:

1) source/destination
2) priority
3) maximum speed
4) arriving time
5) departing time
6) preferred platform
7) train length

B. *Node/edges at the junction*

This file contains infrastructural details of the junction.

1) edge length
2) edge type (platform, track or line)
3) clearance on both sides: this is a safety feature that prevents too-near simultaneous utilization of neighbouring edges
4) maximum permissible speed

These details are also needed for nodes that have an incidence of 4 or more edges.

VIII. Working of junction simulator

Paths consisting of set of edges and nodes are found for movement from every source to every possible destination. Every scheduled train has a source and destination. Thus all the paths are listed for the source and destination for that train. An example of path file is shown in Table I.

In Table I, E1-S1 represents an edge between node 1 and S1, P1-2 represents a platform edge between node 1 and 2 and N-4 represents a node of degree 4 in the path. The scheduled trains are send priority wise on their preferred platforms through their path. A train's arrival time is taken as the time when it is supposed to reach the platform. As platform is listed as an edge, it is checked whether the platform is free at that time. By backtracking, every edge and nodes on the path is checked for its occupancy. Even if one of the edge/node on the path is occupied, the entry time is increased by some fineness. This process is repeated till all edges/nodes are free. The same procedure is repeated for edges/nodes towards destination, till all edges/nodes in path are free. The delay in entry is taken as a cost. This method is repeated for all the possible paths through the preferred platform for that train. The path with minimum cost is selected and all the edges/nodes on that selected path is occupied for their respective time duration. This process is repeated for all the trains. The timings for which all the edges/nodes are occupied is stored in every edge's/node's occupancy list. For freight trains, multiple paths through multiple loop lines are possible. By using occupancy lists for each edge/node, best freight paths are obtained for which the cost is minimum. This simulation which uses a passenger timetable and yields freight paths is useful for scheduling freight trains from their starting point to decrease delay at junctions. The assumptions that we make for the analysis are as follows:

TABLE I
Example of paths for above junction

Source	**Desti-nation**	**Plat-form**	**Path**
S1	D3	1	E1-S1, P1-2, E2-D3
S2	D3	3	E6-S2, P6-7,E7-4,N-4, E4-2, E2-D3
S3	D1	2	E5-S3, E5-4,N-4, P4-3, E3-D1
S3	D2	4	E5-S3, E5-9, P9-8, E8-D2

1) 25 kmph average speed of passenger trains when entering/ exiting the lines other than platform lines.
2) 10 kmph average speed of passenger trains when moving on platform lines.
3) 20 minutes and 55 minutes are required for a freight train at the ALD station and GMC-Kanpur respectively for different activities like crew change.

IX. Case study: Allahabad junction and Kanpur junction

Allahabad junction is regarded as one of the most congested junction in the North Central Railway. With 19 loop lines and 10 platforms, it is a very good example for analyzing the hindrances caused due to movement of trains. The line resources at Allahabad junction are given in Table II. From Down Direction, Allahabad junction receives a three way traffic from Mughalsarai main line (through Naini), Varanasi line (through Allahabad City, Gyanpur Road) and Phapamau junction (through Prayag). The Mughalsarai Main line is double line while other two are single line i.e. any simultaneous movements can only happen at stations. From Up line, the only line is the Kanpur main line (through Subedarganj). The movements at Allahabad junction include:

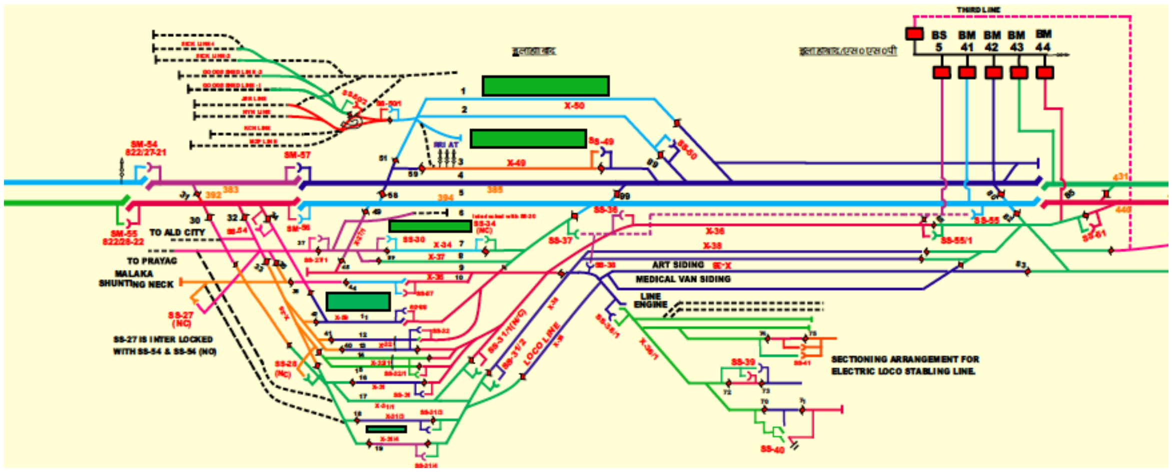

Fig. 3. Schematic layout of Allahabad junction

1) Naini-Subedarganj
2) Naini-Allahabad City
3) Naini-Prayag
4) Subedarganj-Naini
5) Allahabad City-Naini
6) Prayag-Naini

Movements 2, 3, 5 and 6 require terminal movements and the train must have a scheduled stop for 20 minutes for these activities. Apart from that, we have a bi-directional freight movement happening at Allahabad junction. So, we can say that movements at Allahabad junction are really complex and analysis on such a busy junction will give a proper insight about the wasted time due to cross-movements. The modelling of Allahabad junction has been done with total 71 nodes and 103 edges.

TABLE II
ALD STATION LINES: SEE ALSO [9]

Line num.	Purpose
1	Common line with passenger platform
2	Common line with passenger platform
3	Common line with passenger platform
4	Main up line
5	Main down line with passenger platform
6	Dock line from Naini, Allahabad City and Prayag
7	Common line with passenger platform
8	Common goods line
9	Engine line
10	Common line with passenger platform
11	Common line with passenger platform
12	Stabling line
13	Common line
14	Common line
15	Common line
16	Common line
17	Engine line
18	Common line with passenger platform
19	Common line with passenger platform

The figure 4 represents the availability, occupancy and

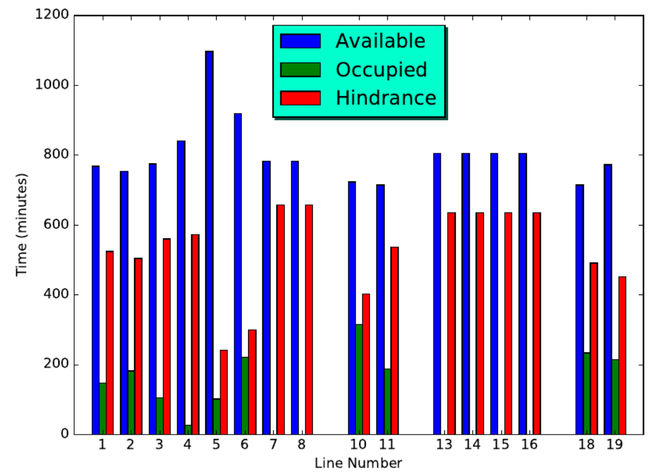

Fig. 4. Plot representing line-wise: availability, occupancy and hindrance

hindrance. The amount of 'hindrance' is to be viewed as unavailability of a resource inspite of that resource being unoccupied: this is due to other simultaneous movements happening at that time. A good junction layout is one in which hindrance values are least: this means every resource is available almost all the time when the resource is unoccupied. Clearly, the hindrance cannot be zero as cross movements are inevitable at crossovers. Also all the lines are either connected to main up line or main down line or both. The best designed junction should have all lines either available or occupied for the most amount of time. Here line 5 is the best among all these lines due to least value of hindrances (15%). Lines 13, 14, 15, 16 are not good due to very high value of hindrances. But these lines do not have platform and are used only for freight train movements. Lines 3, 7 have platform and with 42% hindrance they can hinder a lot of passenger train movements. Also, the hindrance at line 6 is low because it is a dock line from Down side.

Freight Train analysis: After scheduling all the passenger

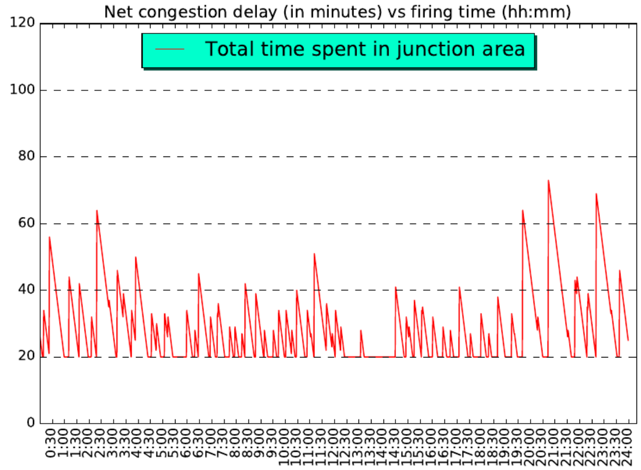

Fig. 5. Net delay at ALD with different firing time

trains, we have obtained the time for which a line is occupied/hindered/available. So now we can schedule the freight trains at every 1 minute duration and analyze how much time it takes to enter and exit the junction. The up-direction analysis of Allahabad for freight train gives the plot in fig 5.

The graph in Figure 5 reveals that freight trains arriving between 12:30 to 14:30 experience lower amounts of hindrance due to other train movements. Further, the simulation helps us recommend that halts should be less than 40 minutes: this is justifiable in junctions keeping in mind their infrastructural complexities. The simulation helps in proposing that the freight trains be backtracked and started from their source station at a time such that the freight trains experience small amounts of delay in junctions.

A. *Kanpur junction*

Kanpur Central is another busy junction on Mughalsarai-Ghaziabad section. With 11 loop lines at junction and two freight bypass, it is way more complex than Allahabad junction. It receives a two way traffic from down direction. One is the main line coming from Allahabad junction (through Chandari) and other is the line joining it to Lucknow junction. In the up direction, it has the main line movement to Ghaziabad (through Panki) and Jhansi. The Kannauj (through Kanpur Anwarganj) line has been ignored. Also, Juhi-GMC is considered as the junction where every cross movement happens for Panki trains and Jhansi trains. The main complexity is because of the direct freight bypass between Chandari and Juhi-GMC. The lines available at Kanpur is given in the below table. Also, Juhi-GMC has 15 up and 15 down lines. The analysis of Kanpur is done with the similar framework and the result obtained is given in Figure 7.
The Kanpur station layout is such that hindrances due to cross-movements are higher than for the Allahabad junction. This is because it receives more traffic than Allahabad junction. Also, it has less loop lines than the Allahabad junction. Here, hindrance is ranging between 45% to 60%. The freight bypass is of great use as Freight train rarely comes in junction area and they do not experience this much hindrance.

TABLE III
RESOURCES AT KANPUR

Line num	Purpose
Dock Line	Down dock line with passenger platform
1	Common line with passenger platform
2	Common line with passenger platform
3	Common line with passenger platform
4	Engine line
5	Common line with passenger platform
6	Common line with passenger platform
7	Common line with passenger platform
8	Common line with passenger platform
9	Common line with passenger platform
10	Common line with passenger platform
11	Common line with passenger platform
Bypass Up	Freight Bypass Up
Bypass Down	Freight Bypass Down

Freight Train Analysis: After analyzing the passenger train movements at Kanpur junction. We will schedule the freight train on line 12 which is the main up line from Chandari to Juhi-GMC. The result obtained are represented in the Figure 8.

Clearly slots like 5:30 to 8:30 and 12:30 to 18:30 are better for freight trains to pass through the Juhi-GMC area.

X. Python Version and Modules

Junction simulator has been implemented in Python 2.7. Two main modules used in the simulator are:

1) pandas: for reading input files (csv).
2) timeit: module for measuring the execution time of program.

The time required for executing of simulator depends on the complexity of infrastructure and number of trains running through junction: this is typically two minutes for the examples considered in this paper in a moderate specifications laptop.

XI. Concluding Remarks and Future Work

The use of Python based simulator to analyze the junction movement is shown in this paper. Using the simulation, we have identified better freight paths and bottlenecks in the infrastructure. This junction simulator can be combined with the works of large rail-section simulator described in works of [12] and [16] to get a combined picture of junction as well as section simulation.

Future work involves the usage of simulator for platform allocation. It can also help us understand the effect of infrastructure improvement on the throughput of a junction. Also, it can be applied to understand the effects of changing

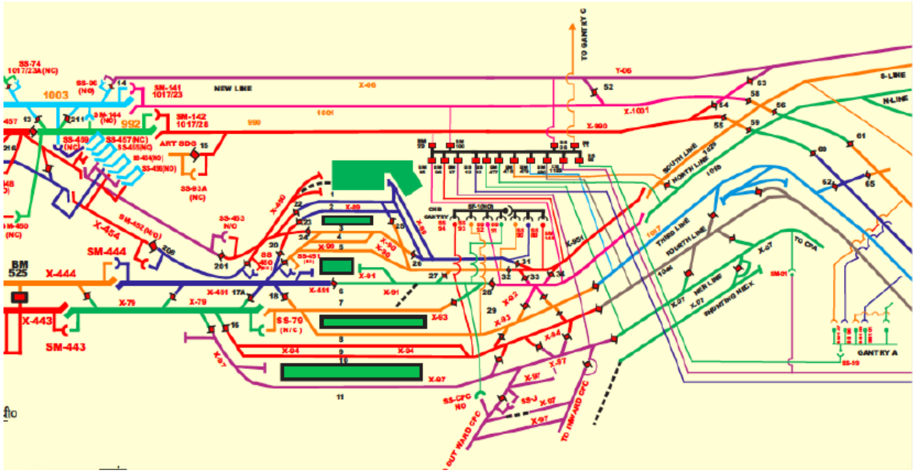

Fig. 6. Schematic layout of Kanpur junction

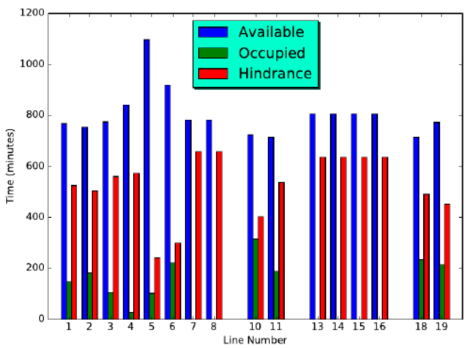

Fig. 7. Availability, occupancy and hindrance for each line at Kanpur

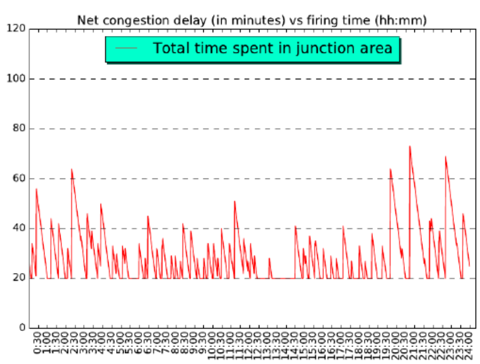

Fig. 8. Net delay at junction area with different firing time

edge parameters (max permissible speed, clearance) and delay in scheduled time table.

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