Speed differential impact on bottleneck section: an analysis with a case study on Indian Railways section

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Abstract. In rail-network infrastructure that caters to a "mixed-rail traffic", i.e. the trains are heterogeneous in the sense of speed capabilities, acceleration or deceleration capabilities, and importantly, priorities, it is an important question about whether a difference in the speeds of the trains is harmful or beneficial. This question is relevant with respect to the overall throughput, the quality of service for the high-priority and fast trains, and the quality of service to the low-priority (and often low-speed) trains. This paper analyzes this question and focusses this study for a specific (relatively) bottle-neck section of the Indian Railways Network. We also quantify the extent to which the speed differential causes a decrease in the quality of service, and beyond what speed differential, the quality of service, in fact, improves for both: the higher priority trains and the lower priority trains. Given that real-data for a bottle-neck section were used in the simulation study, the observations and concluding remarks have relevance to various rail networks when deciding amongst the various options with the objective of increasing the overall throughput for a bottle-neck section.

Keywords: Speed Differential, Bottleneck section, Mixed-rail traffic, Throughput, Quality of Service, Indian Railways

1 Introduction

Freight trains have a lower priority on rail networks with mixed traffic and ensuring feasible paths (the plots denoting the movement of a train on a distance-time chart) for freight trains on congested sections is a challenge [1]. Passenger trains generally operate at a higher speed compared to freight trains and this results in a speed differential between both types of trains. This speed differential can also be detrimental to the overall freight train throughput and traversal speeds in a section since slower low priority freight trains have to give way for faster high priority passenger trains that cross/catch up with them. In this work, we consider the case of Indian Railways (IR), one of the largest railway networks in the world. Indian Railways operate both passenger and freight trains on most of its routes.

Freight capacity on rail sections where there is significant passenger train movement has been a major bottleneck in the revenue earning potential of Indian Railways [2]. In the Indian context, the Dedicated Freight Corridors will address this issue, but only on the routes that they are aligned. For the next many years, there will continue to be sections where mixed traffic has to be handled effectively. It has long been held that the speed differential between passenger and freight train movements has a big impact on the capacity (examples of high throughput are there on both pure passenger traffic sections such as suburban sections and some freight only sections).

The impact of increased speed of freight trains (in particular, the impact of speed differential) on system performance is worth exploring. This is to be evaluated on congested/bottleneck sections of the network, where the impact is likely to be the most. The Bilaspur (BSP) - Jharsuguda (JSG) - Rourkela (ROU) section of Indian Railways has been identified as one such section. There can be many other ways of improving throughput, including re-timetabling of passenger trains, improving signal headways, loop line access speeds, and optimized use of multiple line sections.

This study aims to quantify the impact of increase/decrease in the speed of freight trains (in particular, the impact of speed differential) with respect to passenger train speeds on system performance. A simulation based analysis using the numerical rail traffic simulator developed at IIT Bombay is used for the study [3]. With some care, the conclusions from this study should continue to hold on sections where there is significant mixed traffic.

The portion of the route to/from Bilaspur/Rourkela falls partly in South Eastern Railway (SER) and partly in South East Central Railway (SECR) zones of Indian Railways. This portion is heavily utilized by freight and passenger trains and any improvement in the throughput for this part can help the two zones in particular and several routes that use that portion. While freight trains go at typically very low average speeds (around 20 kmph), the high-priority and long-distance passenger trains go at speeds higher than 100 kmph. Given the difference in the priorities and also their acceleration/speed abilities, one potential concern is whether the throughput can be improved (and if yes, the extent of improvement) if the speed differential is varied. By "throughput" here we mean the number of trains in unit-time (say one day) that can utilize the bottle-neck section, but with path-quality that is of at least a certain pre-specified "quality": and quality of a path refers to the average speed of the train. Better quality means higher speed, and vice-versa. Further, while throughput increase is reasonably an important objective, a related concern is whether the increase of speed-differential has same or opposite effects on the high-priority trains and the low-priority trains. We summarize this in the following problem formulation.

1.1 Problem formulation

Consider a bottle-neck section in which trains with two or more speed-capabilities and priorities are to utilize this section. Suppose the higher speed train (of say speed S_H) also has higher scheduling priority, and the lower speed train (of say speed S_L) also has lower priority. If the speed S_H is increased, then the speed differential increases too, and this increase of speed differential has what all consequences (and to what extent) on:

- throughput, i.e. the number of trains that can utilize the bottle-neck section with at least a certain pre-specified path-quality,
- the average speed of the high-speed trains (usually also high-priority trains serving passengers: also called "coaching trains"),

- the average speed of the lower-priority trains (usually the slower freight trains).

Thus, by requiring the train-paths to have at least a certain path-quality, we are seeking that the throughput increase ought not come at the cost of an unacceptable decrease in the average speeds of the slowest train. The paper is organized as follows: the second section presents a review of the literature on freight capacity analysis on rail corridors in the presence of passenger trains. The third section describes the simulation based method used in the study. The computation study and the results are presented in the fourth section. The fifth section concludes the work with the recommendations made based on the findings.

2 Literature Review

The article by Sogin et al. [4] evaluates the effects of higher speed passenger trains in single track freight networks considering the case of North American freight railroads. They simulate the simultaneous operation of passenger and freight trains by varying the mix of trains and their speeds. Introduction of additional passenger trains is found to introduce more delay in the system compared to additional freight trains. It is found that with higher speed differential between train types, freight trains encounter more delay at passenger train speeds up to 90 mph. Beyond this point, the marginal effect of speed is found to decrease. The study is limited to a single track section and route characteristics like curvature are not considered. The paper by Shih et al. [5] presents a capacity evaluation process to analyze the performance of rail lines serving three train types: passenger, intermodal and bulk freight trains. The study uses train delay data obtained from Rail Traffic Controller (RTC) simulation of a hypothetical rail line. A polynomial regression model is developed based on this delay data and is later transformed into a line capacity model. The case study presented in the paper demonstrates that reducing speed heterogeneity/differential among trains can enhance capacity and reduce the incremental impact of additional passenger trains on the slowest-speed freight train types. Another article by Dingler et al. [6] analyzes the impact of train type heterogeneity on single-track railway capacity. Train dispatching simulation software is used to analyze the effect of various combinations of freight and passenger trains on a hypothetical, signalized, single-track line. It was found that homogeneous speeds lead to fewer delays on all traffic but may not have much effect if trains are already traveling at less than maximum speed because of congestion, heterogeneity, or both. The article by Dingler et al. [7] also reports that traffic volume, heterogeneity of trains and delay are closely related and congested sections with high volume of traffic experience the largest delays due to heterogeneity. All the reported works consider a hypothetical rail section with a single line and the route characteristics are not incorporated in detail during the study. The real system is more complex due to the cascading effect of one event/entity on others and this can be captured only through a more realistic representation of the actual operation of the system. The findings from a practical case analysis can also provide surprising results and insights compared to ideal/hypothetical test scenarios. Since the existing works have not studied this problem on a real network at a practical scale, we try to address this gap. Our work uses a mixed-traffic rail simulator developed at IIT Bombay which has been used extensively for generating the timetable on the six major routes of Indian Railways in 2020 [3,8]. We consider a congested rail section (Bilaspur - Rourkela) with two lines on a real (Indian Railway) network and the train and route characteristics are also incorporated during the simulation of train movement to gather more practical insights. Other work that reports about the use of this mixed rail traffic simulator developed at IIT Bombay can be found in [9].

3 Experiment Method

3.1 Numerical Rail Traffic Simulator

The speed differential impact analysis has been conducted using a numerical rail traffic simulator developed at IIT Bombay over many years [3]. The simulator is a Java based tool, which has detailed inputs regarding the rail section of interest (station locations, loop line configuration at stations, directionality of block sections and loop lines, permanent speed restrictions and max permissible speeds) and of the trains that are intended to be run on the section (lengths, priorities, timings - in case of scheduled passenger trains, max speeds, and acceleration/deceleration characteristics). The basic simulation is done by reserving occupancies related to passenger train movement, as per a master chart (planned movement of trains consistent with the Working Time Table) and also control chart data (chart based on the actual running of trains). Subsequently, freight trains are introduced at appropriate times, and their traversal times are computed based on the simulated conditions. Simulations are iterated with different speeds for both freight and passenger trains in order to study the effect of speed differential. The numerical outcome of the rail simulator has been verified to be sufficiently accurate for this purpose, using standard train running data for single and multiple train scenarios.

3.2 Theoretical Impact Analysis

For the theoretical impact study of speed differential, freight trains and passenger trains are simulated for different speeds for an ideal case i.e. no halt pattern for passenger trains, traversal at max permissible speed and no permanent speed restrictions. The effect of a bunch of higher priority passenger trains (of different speeds) on the average speed of a bunch of six freight trains is studied. Infrastructure for the theoretical impact analysis consists of a test section of 200 km with 20 intermediate stations with block sections of 10 kms between each station. The running of two platoons of passenger trains and six freight trains in between them is simulated with a constant headway of 12 min. The max speeds of freight trains and the passenger trains are varied keeping all other train and route parameters constant.

4 Computational study and Results

4.1 Experiment setting and assumptions

- Through freight paths are generated on the 306 km BSP-ROU section (both directions), respecting passenger train occupancies.
- No time is reserved for maintenance blocks (time for undertaking maintenance activities on the rail section); All the freight windows (time gaps available between passenger trains to operate freight trains) are utilized for scheduling freight trains and 50 freight paths are generated in each direction.
- Movement of trains is considered on two lines only and Permanent Speed Restrictions (PSRs) on the section are verified with the Working Time Table (WTT).
- Two sets of passenger train occupancy data are considered for the study: (i) Control Chart data and (ii) Master Chart data.
- Freight train parameters used are: acceleration = 0.07 m/s^2, deceleration = 0.15 m/s^2.
- Headway between freight paths: 10 to 15 minutes.
- Maximum effective speeds for freight trains are calculated by accounting for the Engineering Allowance (allowance time to accommodate delays because of temporary speed restrictions on a track because of inspection and maintenance activities). Maximum effective speeds calculated for different freight train types are: 56.6 (for 60 kmph max speed); 69.77 kmph (for 75 kmph max speed); 90.91 kmph (for 100 kmph max speed).
- Block working time (additional time when a section is not accessible after the passage of a train) of 5 minutes is imposed on the simulated trains to account for headway between the trains.
- Passenger train occupancy increased by 5 min on both sides of the actual path (for control chart data) to account for headway between the trains.

4.2 Summary of the results

The simulation experiments are carried out for various combinations of passenger and freight train speeds. A summary of the simulation results is provided in Table 1.

Table 1. Summary of the impact of speed differential on average speeds of 50 freight paths (All values in percentage. Baseline for comparison - 60 kmph max speed of freight trains)

Scenario	Effect of passenger train speed variation (freight: 60 kmph)		Speed variation (freight): 60 to 75 kmph		Speed variation (freight): 60 to 100 kmph		Speed variation (freight): 60 to 45 kmph (slowing down)	
	Up	Down	Up	Down	Up	Down	Up	Down
Passenger train data - Control chart			9.74	5.37	12.50	8.91	-7.99	-9.85

Passenger train data - Master chart			10.61	15.84	11.35	25.61	-18.50	-21.72
Passenger trains - 130 kmph (increased)	25.13	4.19	18.30	22.46	25.37	41.49	-27.87	-21.39
Passenger trains - 160 kmph (increased)	24.50	5.05	27.37	21	42.54	48.25	-22.24	-19.78
Passenger trains - 100 kmph (reduced)	-7.25	2.51	-0.61	10.62	2.69	15.87	-15.14	-20.63

Except the 2.51% increase in average freight speed observed for the last scenario with 100 kmph passenger trains, all the remaining percentage variation (positive or negative) in average freight speed can be explained by noting the following two contrasting effects: 1. an increase in max-allowed freight speeds causing an increase in average freight path quality, and 2. a decrease in the speed differential with respect to passenger trains causing a detrimental effect on the average freight path quality, due to freight trains being lower priority. However, the increase of 2.51% could be due to other factors not easily explainable by the various typical causes. This particular increase is perhaps due to extraordinarily helpful freight-windows/freight-paths that get created at exactly the (reduced) 100 kmph max-speeds of passenger trains: this could be extremely specific to the timetable and the freight-windows and inter-station distances: and thus an outlier, and without a plausible explanation. In order to be certain that this speed (of 100 kmph) is indeed an outlier, we propose to perform more simulation experiments: this is a potential future direction.

A sample distance vs time chart representing all the train paths generated for the BSP-ROU section is given in Fig. 1. Red lines represent the passenger train paths and green lines represent the freight paths.

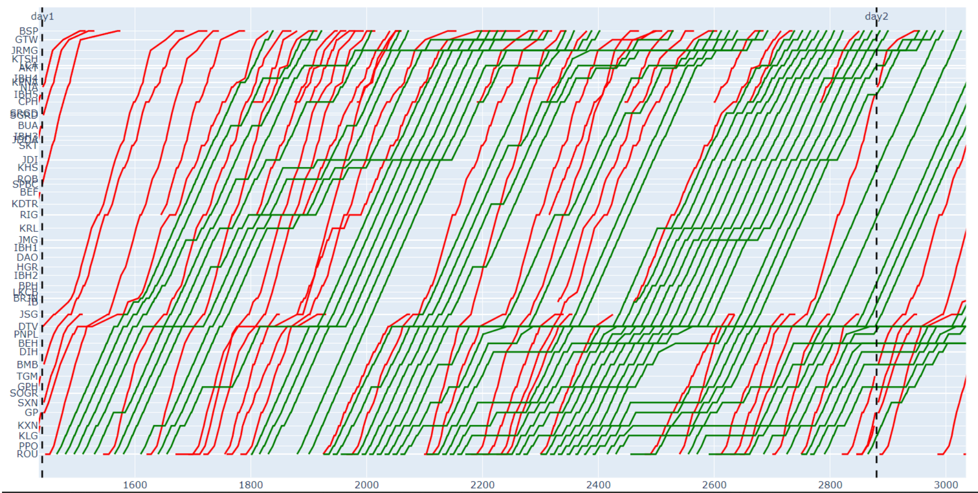

Fig. 1. Sample distance vs time chart: freight paths (green) generated respecting passenger train occupancies (ROU-BSP, max speeds of freight trains: 60 kmph): fully used all freight windows in a day

Ideal test scenarios

Eight test scenarios are generated by maintaining the freight train max speed at 45 kmph and increasing the passenger train max speed from 45 kmph (i.e. no speed differential) to: 60, 75, 90, 110, 120, 130, and 160 kmph. Simulation experiments are carried out on the ideal/theoretical test infrastructure explained in Section 3.2. For each ideal test scenario, the average speeds of the freight trains is plotted against the speed differential with respect to passenger trains and is provided in Fig. 2.

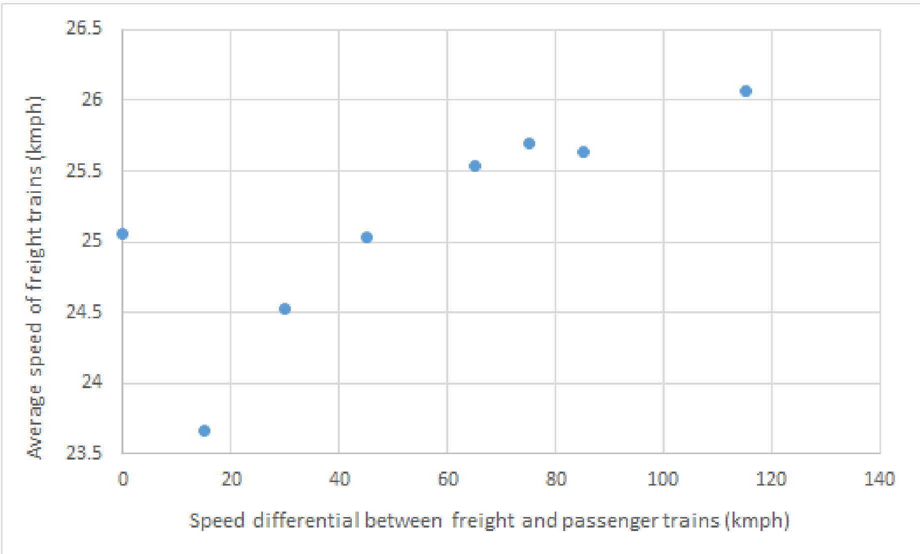

Fig. 2. Effect of the speed differential between freight and passenger trains on the average speed of the freight trains (with freight train max speed as 45 kmph).

The damage to the average speed of freight trains (compared to when there is no speed differential) is found to decrease when the speed differential increases. In fact, eventually the "damage" becomes "improvement" (for sufficiently large speed differential). This is because the freight trains have to wait for a lower amount of time for blocks to get cleared (when the passenger train leaves faster). For a passenger train that is only slightly faster than a freight train, the deterioration would be significant, and this deterioration decreases only beyond a certain speed difference.

5 Conclusions and Recommendations

Below is a list of concluding remarks and also recommendations based on the case-study and the ideal-infrastructure experiments. Though many of the finer aspects of the conclusions would depend on the exact infrastructure and the specific timetable (of passenger trains), the items below are broad and convey the typical inter-relations between speed-differential and throughput.

- In congested portions of the network like BSP-ROU, it is best to eliminate all the overtakes mutually amongst passenger trains that get caused solely due to their different priorities. The “minimize overtakes amongst passenger trains” is a policy only for the bottle-neck section, and only mutually amongst passenger trains. This is similar to how long-distance trains and suburban trains do not overtake each other once they enter the Mumbai Metropolitan Region: this increases overall throughput.The following points are noteworthy.
  - ★ Overtake of one passenger train (train A) by another passenger train (train B) *at a scheduled halt of train A* is harmless and can be planned.
  - ★ The policy of no overtaking (solely due to different priorities) could potentially cause slowing down a 130 kmph train to 110 kmph: however, this is a mere increase of at most 25 minutes of traversal time to the 130 kmph train in the BSP-ROU portion.
  - ★ While this delay is 17% of the time for the BSP-ROU portion, the delay as a percent of the overall traversal time would typically be much lower.
- Beyond a “threshold number of freight trains per day, per direction” (say 50 freight trains), pushing/scheduling slightly more than 50 freight trains per direction can cause:
  - ★ significant deterioration in the path quality of the 51st freight path
  - ★ significant loss of schedule robustness on the BSP/ROU portion (due to absence of buffer time)
  - ★ and thus the deterioration of throughput/path-quality for all trains: both passenger and freight.

  A graph representing freight train traversal durations versus freight path (sorted quality-wise) is plotted for the BSP-ROU section and is provided in Fig. 3. A significant increase in traversal time is observed when the number of freight paths generated in a day goes beyond 45.
- Speed differential does have a deteriorating effect (up to a threshold) and thus an increase of freight trains’ maximum speeds can mitigate this deteriorating effect.
- Reducing the existing max speeds of the passenger trains could deteriorate the freight paths as the speed differential between them reduces.
- Increasing the current max speed of the passenger trains could improve the freight paths due to a larger speed differential between them: this increase is subject to the extent that safety and track quality permits.
- Reducing the max speed of the freight trains from 60 kmph to 45 kmph (expectedly) deteriorates their average speeds by around 20% (average value) and this has to be evaluated vis-a-vis the benefit from any extra loading possible due to lower max speeds.

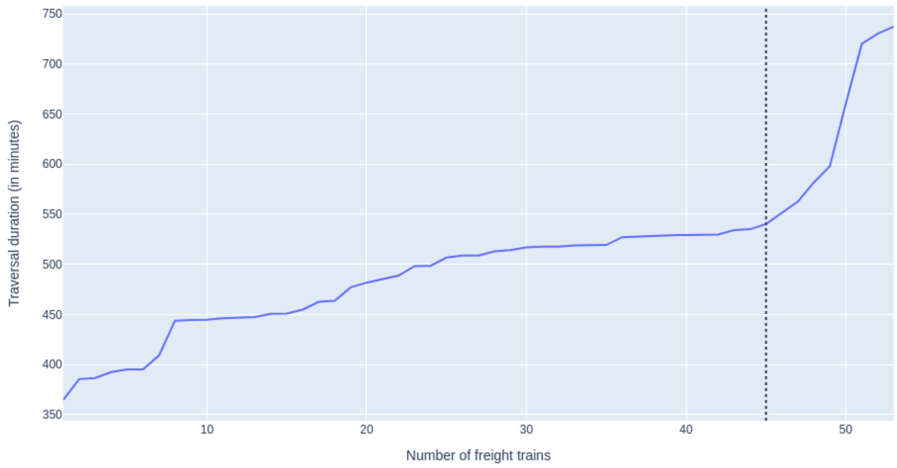

Fig. 3. ROU-BSP freight train traversal durations versus freight path (sorted quality-wise): based on passenger train occupancies obtained from Master-chart with 60 kmph Max. Freight Speed. Speeds (best - 50.35 kmph, knee (dotted line, 45th train) - 33.98 kmph, worst - 23.96 kmph)

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