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***Highlights**

Highlights for the manuscript
"Some Insights on the Recent Spate of Accidents in Indian Railways"

* Spate of rail-accidents in India in 2010 – is excess traffic straining the system?
* We analyze traffic-flow in present IR and growth in traffic over last two decades
* High-traffic, low-headway routes concentrated in a few regions where accidents recur
* Unbalanced growth in traffic in few regions, but minimal construction of new tracks
* Flaws in scheduling of trains uncovered by simulating traffic-flow as per IR schedule

Some Insights on the Recent Spate of Accidents in Indian Railways

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Abstract

Indian Railways (IR), the largest rail passenger carrier in the world, has experienced 11 major accidents due to derailment or collision between trains in the year 2010, leading to several human casualties and large-scale disruptions in traffic. Alarmingly, 8 of these 11 accidents have occurred within a specific geographical region known as the Indo-Gangetic plain. In order to identify the general causes of such frequent accidents, and the specific factors leading to repeated accidents in a particular region, we systematically collect and analyse data of IR traffic over the last two decades. We find that there has been an unbalanced growth in IR traffic in the Indo-Gangetic plain over the last two decades, and consequently most of the high-traffic rail-routes presently lie in this region. However, construction of new tracks and train-routes has been nominal compared to the increase in traffic, leading to frequent congestion and over-utilization of existing tracks. Modeling the traffic-flow using computer simulations, we also show that if all trains were to travel in accordance with the IR schedule, the present infrastructure would be insufficient to handle the resultant traffic-flow in some of the high-traffic routes. Hence this study reflects some of the inherent problems in the scheduling of trains and evolution of IR, and also identifies several regions where traffic is likely to exceed safe limits.

Keywords:
Transportation, Indian Railway Network, trunk-routes, traffic flow, headway, train accidents

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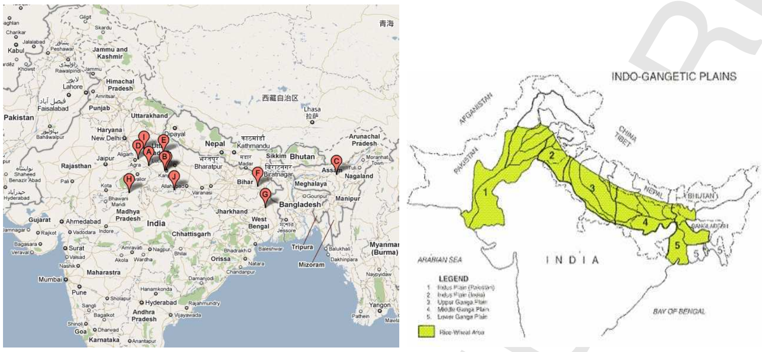
1. Introduction

The Indian Railways (IR) is the largest rail-passenger carrier in the world [1], and has long served as the backbone of the country's transport infrastructure. The rapidly growing economy of India has resulted in an exponentially increasing demand for transportation in recent years, and this has led to an enormous rise in the volume of traffic in the IR network. However, it is a commonly voiced opinion among economists that the current IR infrastructure is not capable of efficiently handling this increased volume of traffic, and this is resulting in frequent delay in running of trains and increasing cost of transportation [2, 3]. Over and above these shortcomings, there has been a spate of major rail-accidents in India in the year 2010, leading to a number of human casualties and frequent disruption of traffic over large parts of the country [4, 5]. While the causes of the accidents were various – derailment, collisions between trains, collisions of trains with other vehicles at unmanned railway-road crossings, natural calamities such as fire and even terrorist activity – 11 of the 19 major accidents in 2010 were due to derailment or collisions between trains (i.e. solely by the malfunction of some component of the railway-system), as listed in [4]. The locations of the 11 accidents involving collision / derailment of trains are shown in Fig. 1a, while their details are listed in Table A.9 in the Appendix.

The exact causes of the derailments / collisions can be widely varied - such as malfunctioning of signals or engine-drivers failing to react to signals - and hence difficult to analyse systematically. Moreover, it would require a large amount of time and official help (from the IR authorities) to know the exact details of the neighbouring circumstances of each accident. However, it is clear from the frequent derailments and collisions of trains that the IR infrastructure is under tremendous strain, which forms the basis of the repeated accidents. Further, looking carefully at the sites of the accidents (Fig. 1a) reveals an alarming pattern – as many as 8 of the 11 accidents due to derailment / collisions in 2010 have occurred within a specific geographical region which is known as the 'Indo-Gangetic plain' [6] and shown in Fig. 1b. In fact, the trend of frequent accidents in this region is continuing in the present year (2011) as well, as stated in the Appendix. The objective of our study is to investigate the causes of such frequent accidents in Indian Railways and more specifically, the factors leading to repeated accidents in a particular geographical region.

We systematically collect and analyse data of the present IR traffic as



(a) (b)

Figure 1: (a) Sites of the railway accidents in India in the year 2010 that involved derailment or collision between trains (b) The Indo-Gangetic plain (image obtained from [7])

well as the increase in IR traffic over the last two decades. Though we do not attempt to analyse the exact causes for the recent accidents, our observations identify some of the general factors that are leading to immense strain on parts of the Indian Railway system. We find that there has been an unbalanced increase in traffic in a few regions of the country, including the Indo-Gangetic plain, as a result of which most of the high-traffic routes are concentrated in these regions. On the other hand, it is an established fact that construction of new train-routes and tracks in IR has been nominal compared to the increase in traffic [3]. Hence it is quite probable that the present amounts of traffic have exceeded the safe limits considering the available resources (e.g. railway-tracks) in some of the regions. The findings in this paper also reveal serious flaws in the scheduling of trains in Indian Railways – we model the traffic-flow along specific train-routes according to the IR schedule, using computer simulations, and show that if all trains were to travel in accordance with their schedule (i.e. without any delay), then the present infrastructure would not be able to handle the resultant traffic-flow in some of the regions, especially the Indo-Gangetic plain. This situation is managed by the IR authorities by making trains wait at signals – this not only results in frequent delay in the running of trains, but also increases the possibility of collisions in the event of human errors such as failure of the driver to react to signals.

The rest of the paper is organized as follows. A brief survey of studies on transportation networks is given in Section 2 while Section 3 discusses the collection of various data on IR traffic. Section 4 details the analytical measurements on the present IR traffic, while the modeling of the traffic according to the IR schedule is discussed in Section 5. Section 6 discusses the growth of IR traffic over the last two decades. Section 7 concludes the paper by discussing the implications of our findings.

2. Related Work

Transportation networks have received considerable interest from researchers in the recent years, and different aspects of transportation networks have been studied using complex network analysis. These include the topological properties of public transport networks [8, 9, 10], their resilience to failures and attacks [11], their ability to handle congestion [12, 13, 14], the temporal evolution of transportation networks [15, 16] and so on. Among the studies on transportation networks, some have used synthetically generated network topologies (such as Erdos-Renyi or scale-free topologies) to model transportation networks [12, 14], while the others have studied specific real-world transportation networks. Examples of the later include airport networks (for instance, the airport network of China [9], airport network of India [17] and the world-wide airport network [18, 19]), urban road networks [10, 20, 21] and railway networks [22, 23, 24, 25, 26] of various countries or cities.

It is to be noted that several different models have been used in literature to study real-world transportation networks. A majority of studies, including most of the ones referred to above, adopt a network model where airports or railway stations are considered as nodes, and two nodes are linked by an edge if there exists a direct connection (flight or train) between the two nodes. Differently from these, the underground (subway) railway networks of Boston and Vienna were studied as bipartite station-train networks in [23] – several topological metrics of the networks were measured and compared with the corresponding theoretical predictions for random bipartite graphs using a generating function formalism. As opposed to these logical models of transportation networks, some of the studies have also considered the *physical topology* of railway networks, in which two nodes (stations) are connected by an edge only if there exist a physical railway-track connecting the two stations [27]. In particular, [28] proposes a technique to extract the physical topology and the network of traffic flows from the time-tables of public transportation systems. A recent study [29] has even combined the two approaches by considering railway networks as two-layered networks where the lower layer consists of the physical network of railway-tracks, while the upper layer represents the logical connections between stations that are directly connected by the same train. The topological and spatial properties of transportation networks have also motivated several attempts to propose network growth models to explain the correlations among topology, traffic-flow (which is commonly represented as edge-weights in the network) and geographical constraints in the evolution of such networks [30, 31].

In the current study, we consider the physical topology of Indian Railways network. In contrast to the studies that experiment with synthetically generated traffic-flows (such as random particle hopping [12] or the SIR model [13]), we analyse the actual traffic-flow in the Indian Railway network according to the IR schedule. However, since our objective is to study the spatial and temporal patterns of traffic-flow in the IR network (and not the topological properties of the network), the statistical metrics used in this paper vary greatly from the ones used in the papers mentioned above. To the best of our knowledge, there has not been any similar study on the Indian Railways till date. The two prior studies on the Indian Railway network – by Sen *et. al.* [25] in 2003 and recently by us [32] – have focused on the topological properties of logical models of the IR network, where stations have been considered as nodes and two nodes are linked by an edge if there is a direct train linking the two stations. However there has not been any prior statistical analysis of the traffic-flow in the physical Indian Railway network.

3. Collection of IR traffic data

The total numbers of stations and train-routes in Indian Railways are presently of the order of tens of thousands. In this study, we collected the data of IR traffic on a coarse-grained level – we consider only the 'express' train-routes and other long-distance train-routes in IR, and only those (relatively important) stations that are scheduled halts on at least one such train-route.

We crawled the data of express train-routes in the present IR from the official website of Indian Railways (`www.indianrail.gov.in`) in October 2010. The website hosts information of 2195 express train-routes and 3041 stations, along with the scheduled time of each train reaching each station on its route. We consider each train-route to be a *uni-directional* path from the source station to the destination station because the train from source station A to destination station B often runs *simultaneously* with the corresponding train from station B to station A, hence both contribute to the amount of traffic at a given point of time.

We also obtained the run-time delay of trains travelling along some of the high-traffic routes from the official IR website for knowing the running status of trains (`www.trainenquiry.com`), as detailed in Section 5.

To study the growth in IR traffic over the last two decades, we collected the data of express train-routes in the years 1991, 1997, 2000, 2005 and 2009 from the "Trains At A Glance" (TAAG) time-table published by the Indian Railways for the corresponding years [1]. However, the scheduled time of the trains reaching each station could not be obtained for the older years; hence this evolutionary data-set has only been used to analyze the growth in volume of IR traffic over the years (Section 6), and all temporal analyses use the dataset obtained from the IR websites.

Limits of the dataset: As stated above, the dataset considers only the express train-routes, leaving out suburban trains and freight trains. Suburban trains travel over relatively short distances in the vicinity of major cities, and at much lower speeds (compared to express trains); hence derailment / collisions are very rare among suburban trains – none of the accidents listed in [4] during the period 2000-2010 involved suburban trains. Hence they can safely be ignored in our study. On the other hand, freight-trains have been involved in some of the recent accidents due to derailment or collisions with express trains (see Table A.9 in the Appendix). But freight-trains in Indian Railways usually run on an 'on demand'-basis and consequently do not have any fixed schedule [33], thus making it virtually impossible to include them in the analysis.

4. Analysis of traffic in present IR

In this section, we analyse the traffic flow in the physical network of the present Indian Railway system. For this, we consider the important 'trunk-routes' in IR, which are the high-speed, high-capacity routes (e.g. with replicated tracks) connecting major stations, and are mostly used by express trains. In the IR trunk-route network, shown in the schematic map (Fig. 2), the nodes are the major stations in the country and two nodes are connected by an edge if there exists a physical trunk-route directly connecting the two corresponding stations. We partition the IR trunk-route network into a set

[1] We acknowledge the National Railway Museum, New Delhi, India for providing us with this data.

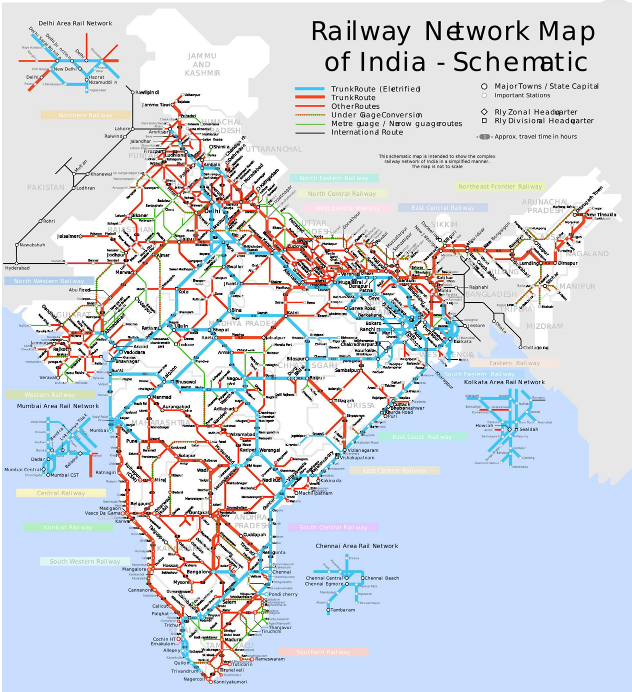


Figure 2: Schematic map of Indian Railway Network showing trunk-routes. The map can be obtained from [34].

of 52 disjoint 'trunk-segments', where each trunk-segment is the portion of a physical trunk-route between two such junction stations where multiple trunk-routes converge.

In order to study the traffic patterns in different parts of the country, we consider a set of six geographical zones - northern zone, eastern zone, western zone, southern zone, central zone and the Indo-Gangetic plain (IGP) [2]. The number of trunk-segments considered in different geographical zones, along

[2]Geographically, the Indo-Gangetic plain can be considered to comprise of parts of the northern and eastern zones. However, in view of the repeated accidents in this region, we consider it as a distinct zone in order to individually study the traffic patterns in this region.

Zone	Number of trunk-segments	Average length of trunk-segments (km)
Northern	5	306.4
Central	10	311.0
Indo-Gangetic plain (IGP)	13	247.4
Eastern	6	367.2
Western	7	319.0
Southern	11	468.0

Table 1: Statistics of trunk-segments in different geographical zones in India

with the average length of trunk-segments in each zone is given in Table 1. It is to be noted that the spatial density of junction stations where multiple trunk-routes converge varies widely in different zones – for instance, it can be seen from Fig. 2 that the density of such junction stations is much higher in the Indo-Gangetic plain than in southern India. This is reflected in the average length of trunk-segments considered, as given in Table 1. Also, in this study, we assume all trunk-routes to have a uniform capacity of handling traffic [3].

In order to recognize the significance of the statistics reported in the subsequent sections (such as per-day traffic on a trunk-segment), it is necessary to compare the observed values with a 'safe' standard or threshold. However, no universally accepted 'safe' standards are available for these metrics, possibly because the safe standard would largely depend on the technology being used in a particular railway system. Hence, we take a different approach – since there has not been any accident due to derailment or collision among trains in southern India in the last five years [4], we consider the statistics for the southern zone as a 'safe' standard for the Indian Railways.

We consider a train-route to be using a given trunk-segment only if at least two stations within that trunk-segment are scheduled halts on the train-route. Though more stringent conditions can be applied – for instance, a train-route can be considered to use a trunk-segment only if *all* stations

[3]We had approached the Department of Traffic, Indian Railways for data on the capacity of the individual trunk-segments, but we were informed that this data is not available for public use.

[4]According to [4], the last incident of derailment in southern India was in 2005, and there have been no cases of collision between trains in southern India during the period 2001–2010.

on the segment are scheduled halts on the train-route – we decided to use the above condition because express train-routes in IR have scheduled halts at only a few major stations, and do not halt at many stations within the same trunk-segment; hence using a more stringent condition would grossly under-estimate the number of express train-routes using a trunk-segment.

From the schedule of trains crawled from the IR website, we derived the traffic scenario *for each individual day of the week*, which gives the exact scheduled time of each train reaching any given station, on any given day of the week. We repeated the analyses described in the following sections individually for each day of the week, and observed that the statistics are almost similar for each day across all segments. Therefore we henceforth report statistics for a particular day (Monday) except in section 4.1 where we average the number of trains using a segment over all seven days of a week.

Finally, it can be noted that most of the metropolitan cities in India are served by multiple railway stations (e.g. the capital city Delhi is served by seven stations) and trains starting from (going to) these cities can start (end) at any of these stations. However, all trains travelling from / to a particular metropolitan city use the same trunk-routes except for a few kilometres in the immediate proximity of the city. Hence in our analysis, we represent each metropolitan city by a single node (station).

4.1. Volume of traffic in trunk-segments

In this section, we measure the average number of trains using a trunk-segment per day. It can be noted that there exist a large number of *daily* train-routes in IR which require more than 24 hours to reach the destination station. For such routes, there may be *multiple physical trains* running on the same route at a given point of time. For instance, consider a daily train-route that starts from the source station at 12:00 on each day and reaches the destination station at 17:00 on the next day. At 14:00 on any given day, there will be two trains running on this route, one having started the previous day and nearing the destination, and the other having started on the given day. We processed the datasets for IR traffic on each particular day to consider all such trains individually, since each of them contributes to the traffic in some trunk-segment.

We measured the number of trains using each trunk-segment individually for all 7 days of the week. Table 2 gives a ranked list of the 20 trunk-segments which are used by the maximum number of trains per day on average. Out of these, 12 trunk-segments are distributed over two specific geographical regions, as described below.

Rank	Trunk-segment	Average daily traffic	Geographical zone
1	Delhi-Tundla-Kanpur	104.29	IGP
2	Ahmedabad-Vadodara-Surat	86.29	western
3	Bhusaval-Manmad-Kalyan	81.29	western
4	Delhi-Mathura-Agra	80.57	IGP
5	Amritsar-Jalandhar-Ambala	79.14	northern
6	Jhansi-Bina-Bhopal	74.29	central
7	Dhanbad-Asansol-Kolkata	73.29	IGP
8	Katni-Jabalpur-Itarsi	67.71	central
9	Agra-Gwalior-Jhansi	64.71	central
10	Ambala-Panipat-Delhi	60.86	northern
11	Kanpur-Allahabad	59.43	IGP
12	Mughalsarai-Ara-Patna	59.14	IGP
13	Ujjain-Bhopal-Itarsi	56.86	central
14	Vishakhapatnam-Vijayawada	52.57	southern
15	Sonpur-Barauni-Katihar	52.14	IGP
16	Surat-Mumbai	46.86	western
17	Kolkata-Kharagpur	44.86	eastern
18	Allahabad-Mughalsarai Itarsi-Bhusaval Wardha-Kazipet-Hyderabad	41.71	IGP central southern

Table 2: Top 20 trunk-segments ranked according to average per-day number of trains using the segment. Trunk-segments are indicated by the two end-stations and intermediate stations in some cases to resolve ambiguity.

1. **Trunk-segments in the Indo-Gangetic plain:** As many as 7 out of the 20 trunk-segments handling highest per-day IR traffic are in the Indo-Gangetic plain, as indicated in Table 2. In particular, the trunk-segment having by far the highest average per-day traffic (Delhi-Tundla-Kanpur) is in the middle Indo-Gangetic plain, and of the accidents due to collision / derailment in 2010, 3 have occurred along this segment (the ones numbered 1, 2 and 4 in Table A.9).
2. **Trunk-segments in the central zone:** 5 out of the 20 trunk-segments in Table 2 are located in central India – due to their central location, these trunk-segments handle a large number of trains going from southern parts of India to the northern parts, or from western to

Rank	Zone	Avg. daily traffic considering all trunk-segments in zone
1	IGP	51.06
2	Western	48.04
3	Northern	43.11
4	Central	42.49
5	Eastern	31.26
6	Southern	30.61

Table 3: Zones ranked according to average per-day traffic, averaged over all trunk-segments in the zone

eastern parts of the country.

The rest of the trunk-segments in Table 2 are ones that link metropolitan cities to different parts of the country. For instance, the Amritsar-Jalandhar-Ambala (ranked 5) and Ambala-Panipat-Delhi (ranked 10) segments link the capital city Delhi with northern parts of India; the Ahmedabad-Vadodara-Surat (ranked 2) and Surat-Mumbai (ranked 16) trunk-segments link metropolis Mumbai with northern / north-western India while the Bhusaval-Manmad-Kalyan segment (ranked 3) links Mumbai with central India.

Table 3 gives the average per-day number of trains using the segments in a geographical zone, which is obtained by averaging the per-day traffic over all trunk-segments in the zone. The trunk-segments in the Indo-Gangetic plain handle the maximum daily traffic on average, followed by the those in the western zone.

Comparison with safe standard: As stated above, we consider the statistics for the southern zone as a 'safe standard' since no accident has occurred in southern India in the recent years. As compared to the trunk-segment in southern India that has the highest per-day traffic (the one ranked 14 in Table 2), the top-ranked segment in Table 2 handles more than twice per-day traffic, and the four segments ranked 2 to 5 handle more than 1.5 times the per-day traffic. Futher, comparing the values for the other zones with that of the southern zone (Table 3), it is evident that the trunk-segments in the Indo-Gangetic plain and the western zone are under immense strain due to high amounts of traffic.

4.2. Headway analysis of traffic in trunk-segments

In this section we perform a temporal analysis of the IR traffic in various trunk-segments by studying the distribution of traffic over time within a day. For this, we use the concept of 'headway' which is defined as the time-interval (or distance) between two consecutive vehicles travelling along the same route. Headway is measured with respect to a reference point - conceptually, a timer is started when a vehicle passes the reference point and the time elapsed until the next vehicle passes the reference point is measured. The desired (or safe) headway for a transportation system may be decided by various safety criteria, but the essential idea is to allow sufficient time to a vehicle to safely stop behind the vehicle in front of it in case the vehicle in front has to stop unexpectedly at some point.

To compute the headway for traffic on a particular trunk-segment s, we selected a station T within that segment (as the reference point) and considered the sequence of time-instants at which trains using segment s pass through station T. The average of the intervals between these time-instants gives the average headway over a day for traffic on segment s.

Table 4 shows the top 20 segments ranked in increasing order of average headway over a day (based on IR traffic on Monday, as stated earlier). Three out of the top five segments having least headway are from the Indo-Gangetic plain. Comparing the top-ranked segments in Table 4 with those in Table 2, it is evident that for several of the trunk-segments located in the Indo-Gangetic plain, as well as some of the trunk-segments located in western and central parts of India, the amount of traffic is large along with a low headway. These are the segments where the traffic is likely to exceed the safe limits considering the available infrastructure.

Further, since most of the accidents in 2010 due to collisions between trains have occurred in the early hours of the day, we also computed the average headway between midnight and 7 a.m. for the trunk-segments. The segments for which the average headway between midnight and 7 a.m. is lesser than the average headway over the entire day are marked in Table 4. It is seen that the most busy trunk-segments become even more busy during the early hours of the day. In particular, since the northern regions of India experience dense fog in the early morning hours during the winter months (which greatly reduces visibility), it can be detrimental for trains to travel with small headway in these segments in the early hours of the day. In specific, the reported cause for the three accidents on the Delhi-Tundla-Kanpur segment (which has the lowest headway between midnight and 7 a.m.) is the presence of dense fog, which disabled the engine-drivers from reacting to stop-signals [4].

Rank	Trunk-segment	Avg. headway (minutes)		Geographic
		over a day	before 7 a.m.	zone
1	Ahmedabad-Vadodara-Surat	17.93	13.96 ↓	western
2	Delhi-Tundla-Kanpur	19.06	**13.67** ↓	IGP
3	Delhi-Mathura-Agra	20.22	26.42	IGP
4	Dhanbad-Asansol-Kolkata	20.44	17.41 ↓	IGP
5	Amritsar-Jalandhar-Ambala	20.77	16.52 ↓	northern
6	Agra-Gwalior-Jhansi	22.44	19.63 ↓	central
7	Bhusaval-Manmad-Kalyan	23.04	20.39 ↓	western
8	Katni-Jabalpur-Itarsi	23.81	26.33	central
9	Jhansi-Bina-Bhopal	25.08	25.63	central
10	Ambala-Panipat-Delhi	26.47	28.20	northern
11	Mughalsarai-Ara-Patna	26.63	31.53	IGP
12	Vishakhapatnam-Vijayawada	28.27	26.33 ↓	southern
13	Kanpur-Allahabad	28.33	20.52 ↓	IGP
14	Ujjain-Bhopal-Itarsi	28.47	33.33	central
15	Wardha-Kazipet-Hyderabad	30.51	37.50	southern
16	Surat-Mumbai	31.35	27.50 ↓	western
17	Kolkata-Kharagpur	34.14	39.10	eastern
18	Itarsi-Bhusaval	35.13	37.50	central
19	Sonpur-Barauni-Katihar	37.73	58.40	IGP
20	Delhi-Moradabad	38.05	28.84 ↓	northern

Table 4: Top 20 trunk-segments in increasing order of average headway over a day (based on Monday traffic). Also shown are the average headway in the first 7 hours of the day (i.e. between midnight and 7 A.M.), segments having lesser than average headway in the first 7 hours are marked by ↓.

Comparison with safe standard: Among the trunk-segments in the southern zone (which we consider as the 'safe' standard, as stated earlier), the one having the minimum average headway is the Vishakhapatnam-Vijayawada segment (ranked 12 in Table 4). Compared to this, the two segments having the least average headway (Ahmedabad-Vadodara-Surat and Delhi-Tundla-Kanpur) handle traffic with almost half the headway during the early hours of the day. Fig. 3 shows the cumulative distribution of headways on the above three segments – it can be observed that about 50% of the headway intervals for the Ahmedabad-Vadodara-Surat and Delhi-Tundla-Kanpur segments are smaller than 10 minutes.

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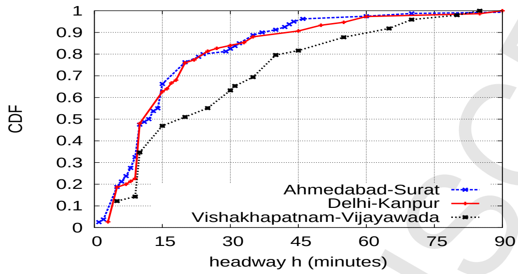

Figure 3: Cumulative distribution of headway for some select segments. The x-axis gives headway values h (in minutes) and y-axis gives the fraction of headway values that are smaller than h for a given segment.

It is to be noted that along with statistics such as the average per-day number of trains using a segment and the distribution of headway intervals, one should also observe the *temporal distribution of traffic* (within a day) in order to accurately estimate the traffic load on a segment. For instance, both the Ahmedabad-Vadodara-Surat and Delhi-Tundla-Kanpur segments have a large number of per-day trains (Table 2) and a very similar distribution of headway intervals (Fig. 3). However, a little more probing reveals that the temporal distribution of traffic on the Delhi-Tundla-Kanpur segment (the segment along which three accidents have occurred in 2010) is highly skewed as compared to the traffic on the Ahmedabad-Vadodara-Surat segment (along with there has not been any recent accident).

To illustrate this, we measured the number of trains entering a trunk-segment individually in each hour of a day (considering the IR traffic on Monday) – Fig. 4a and Fig. 4b respectively compare the Ahmedabad-Vadodara-Surat and Delhi-Tundla-Kanpur segments with the Vishakhapatnam-Vijayawada segment (the 'safe' standard) based on this measure. It is clearly seen that traffic on the Ahmedabad-Vadodara-Surat segment is about evenly distributed over the day, whereas the Delhi-Tundla-Kanpur segment is used by a much larger number of trains in the early hours of the day. Statistically, the *variance* of the distribution of number of trains entering a segment per hour is 16.3 for the Delhi-Tundla-Kanpur segment and 6.0 for the Ahmedabad-Vadodara-Surat segment (and 3.3 for the 'safe' Vishakhapatnam-Vijayawada segment). This implies that, though the distribution of headways (and average headway) are similar for these two segments, the small headway intervals are spread out uniformly over the day in case of the Ahmedabad-Vadodara-

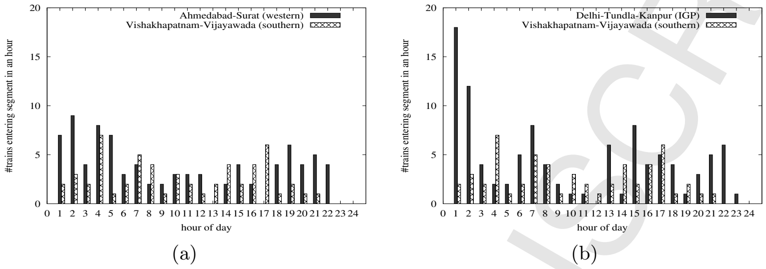

Figure 4: Distribution of number of trains entering a segment in the different hours in a day (based on Monday traffic) – (a) Ahmedabad-Vadodara-Surat segment (b) Delhi-Tundla-Kanpur segment, as compared with the Vishakhapatnam-Vijayawada segment (the 'safe' standard)

Surat segment, while they are concentrated in the some specific hours in case of the Delhi-Tundla-Kanpur segment. This leads to high levels of congestion in Delhi-Tundla-Kanpur segment during these hours, resulting in large run-time delays of trains (see statistics of delays given in Section 4.3) and higher probability of accidents.

4.3. Run-time delay of trains: Analysis of congestion

The statistics presented in the previous sections indicate the possibility of high levels of congestion in some of the trunk-segments in the IR network. A practical way to estimate the level of traffic congestion over a route is to observe the run-time delays of trains travelling along that route. The running status of an express train in Indian Railways can be obtained from the web-site `www.trainenquiry.com`, which provides daily updates of the run-time delays of each train at each station on its route. From this website, we collected the delay statistics for some selected trunk-segments – we consider that trunk-segment from each geographical region, which has the minimum average headway among all segments in the said region (see Table 4). For these segments, we collected the delay status of each train using a segment (as identified in Sec 4.1), at the two end-stations of the segment; from this data, we computed the run-time delay of a train while travelling within a particular trunk-segment. We collected the delays of all trains using the selected segments over a period of 7 days.

Fig. 5 shows the cumulative distribution of the observed delays for the six selected segments. The empirically observed delays well agree with the

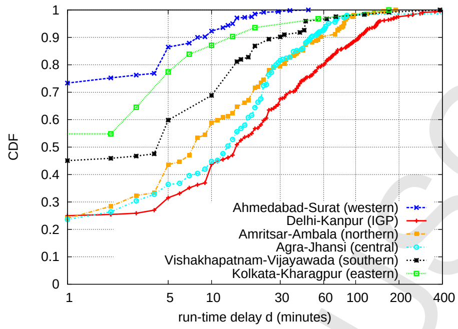

Figure 5: Cumulative distribution of run-time delays of trains on some select segments. The x-axis gives delay values d in minutes (log-scale) and y-axis gives the fraction of delays that are smaller than d for a given segment.

observations reported in the previous sections – trains travelling along the segments having high per-day number of trains and low average headway (Delhi-Kanpur, Agra-Jhansi, Amritsar-Ambala) actually have high run-time delays as compared to the segments in southern and eastern zones. For instance, 20% of the trains running on the Delhi-Kanpur segment were delayed by more than 1 hour, while only 3% of the trains on the Vishakhapatnam-Vijayawada segment (the safe standard) were delayed to that extent. The average run-time delay for trains on the Delhi-Kanpur segment is as high as 39 minutes, as compared to 14 minutes for the Vishakhapatnam-Vijayawada segment.

The above observations indicate high levels of congestion and frequent waiting of trains at signals on some of the trunk-segments, which also implies a higher probability of collisions between trains in the event of a malfunctioning signal or an engine-driver failing to react to a signal.

It can be noted from Fig. 5 that the delays for trains on the Ahmedabad-Surat segment are much lower than what can be expected from the high per-day traffic and low average headway for this segment. This can be partially explained by the fact that the traffic in this segment, though high, is uniformly distributed over the day (Fig. 4a) which reduces the possibility of congestion. Additionally, it is possible that this segment consists of higher-capacity tracks (e.g. a relatively larger number of parallel tracks) compared to some of the other segments. The lack of real-world data on the capacity of segments disables us from gaining a better understanding of this issue.

5. Simulating traffic-flow according to IR schedule

Our observations in the previous sections indicate that some of the trunk-segments in IR are having to handle large volumes of traffic with relatively short headways, leading to high levels of congestion. This motivated us to go for a more fine-grained analysis of the movement of traffic on individual trunk-segments – in this section, we extend the temporal analyses in the previous sections to a *spatio-temporal* analysis, by considering the spatial and temporal proximity of trains travelling on the same trunk-segment. Specifically, we investigate the question: *If all trains were to travel in strict accordance to their schedule, is the existing IR infrastructure capable of supporting the resultant traffic-flow?* To investigate this question, we simulate the traffic-flow over individual trunk-segments according to the IR schedule, using the concept of 'Block System' to define spatial proximity between trains.

5.1. Block System in Railways

Railways in India (and in several other countries) follow the 'Block System' [35] in which a railway track is considered as a series of 'block sections' (or simply blocks) such that when one train is occupying a block, no other train is allowed to enter that block on the same track (note that there can be one or more rail-tracks in a block, and each track can be occupied by exactly one train). At each end of a block, there are stations or signals which control the traffic entering into the block from that end. In Indian Railways, block lengths are usually of the order of 4 to 8 kilometres [35].

5.2. Simulating traffic-flow considering the block system

We simulate the flow of traffic on a trunk-segment according to the IR schedule, assuming the block system described above. In the simulation, we assume that a trunk-segment is divided into a number of fixed-length blocks, and trains are allowed to continuously proceed along the segment, according to their schedule (i.e. without being stopped by any signal). We then measure the number of instances when multiple trains would have been present in the same block if all trains would have travelled exactly according to their schedule.

For a given trunk-segment s, we know its length l_s (in kilometres) and the trains which use the segment. From the IR time-table, we note for each train T using s, the exact time of day when T enters s and the time at which it exits s. Hence we know the period of time t_s^T (measured in minutes) during which each train T is scheduled to run in segment s. We assume a

Rank	Trunk-segment	F_k		Geographic
		k=2	k=3	zone
1	Delhi-Tundla-Kanpur	0.185	0.014	IGP
2	Dhanbad-Asansol-Kolkata	0.141	0.010	IGP
3	Ahmedabad-Vadodara-Surat	0.077	0.006	western
4	Vishakhapatnam-Vijayawada	0.066	0.0	southern
5	Amritsar-Jalandhar-Ambala	0.060	0.0	northern
6	Agra-Gwalior-Jhansi	0.035	0.0	central

Table 5: Simulation of rail-traffic on selected trunk-segments assuming block length of 6 km – F_k is the fraction of time-steps when at least one block contains more than k trains (see text for details).

fixed block-length l_b (for instance $l_b = 6$ kilometres) and consider segment s as a sequence of $n_s^b = \frac{l_s}{l_b}$ number of blocks. We further assume that each train T travels at a uniform speed throughout, which implies that T requires $t_b^T = \frac{t_s^T}{n_s^b}$ time-units (minutes) to traverse each block in the segment.

The simulation of traffic on a particular trunk-segment s proceeds as follows. Each time-step in the simulation is considered to be equivalent to one minute in the real world. For each train T using segment s, T enters the segment at its scheduled time (i.e. according to the minute of day stated in the IR schedule), and sequentially traverses the blocks in the segment (i.e. T stays at each block for t_b^T time-steps before going to the next block) until it reaches the end of the trunk-segment. The simulation continues until all trains using segment s have completed their traversal of the segment. We count the fraction of time-steps (i.e. as a fraction of the total number of time-steps in the simulation for a particular segment) during which there are more than a given number (say, k) of trains in at least one block. Here k captures the notion of the number of parallel tracks in a block - a block having k parallel tracks can accommodate up to k trains simultaneously, but at least one train has to be stopped from entering the block (at a signal) if more than k trains are scheduled to be in the block at a certain point of time.

Table 5 gives the results of the simulation for traffic on some selected trunk-segments among the ones having low average headways (see Table 4). The fraction of time-steps during which at least one block is scheduled to have more than k trains is reported for $k = 2$ and 3, assuming a block length $l_b = 6$ kilometres. Experiments using block-lengths $l_b = 4$ and 8 also produced similar trends.

It is evident that if all trains were to travel strictly according to the IR schedule, then for the trunk-segments in the Indo-Gangetic plain, there would have been more than two (or three) trains in the same block much more frequently as compared to trunk-segments in other geographical zones. Though some trunk-segments in IR have intermittent triple (or more) tracks, the major portion of each trunk-route in India still has two tracks, which implies that at most two trains can be simultaneously accommodated in a block. So the existing infrastructure seems incapable of handling the traffic-flow if all trains were to travel in strict accordance with the IR schedule.

In the simulation described above, we assumed that all trains travel strictly according to their schedule irrespective of the availability of parallel tracks along their routes. In reality, when the number of trains that wish to simultaneously traverse a particular block exceeds the number of parallel tracks in the block, some of the trains are made to wait at signals, and this introduces delay in the journey of the trains. Hence, we expected the results of the simulation to agree with the empirical delay statistics of trains reported in Section 4.3. While there is qualitative agreement between the two for some of the segments – e.g. in case of the segments in the Indo-Gangetic plane – there are some discrepancies as well; for instance, the empirical delay values for the Ahmedabad-Surat segment are much lower than what is indicated by the simulation. This may be due to the differences in the traffic-handling capacity of the segments (e.g. number of parallel tracks) and the effect of freight trains which share the same tracks with the express trains; however, as stated earlier, the data regarding these are not available publicly. Incorporating these issues would enable a more realistic simulation of the traffic flow in the IR network.

6. Growth of IR over the last two decades

In the previous sections, we have identified some of the problems inherent in the present Indian Railway system, such as the volume of traffic on some of the trunk-segments exceeding that which can be supported by the existing infrastructure. In this section, we study how the IR has grown over the last two decades with respect to increase in traffic and increase in physical tracks. A look at the growth pattern of traffic ominously shows that new trains have often been preferentially added, thus further congesting the already busy trunk-segments. On the other hand, the construction of new railway-tracks and routes have been virtually negligible during this period.

Year	Number of train-routes	Number of stations
1991	750	548
1997	920	561
2000	1104	608
2005	1444	622
2009	1918	681

Table 6: Number of express train-routes and stations in different years (as obtained from the "Trains At A Glance" time-tables)

As stated in Section 3, we collected the list of express train-routes and stations on each route in the years 1991, 1997, 2000, 2005 and 2009 from the "Trains At A Glance" (TAAG) time-tables of the corresponding years. The number of train-routes and stations in the dataset for each year is summarized in Table 6.

6.1. Increase in traffic through trunk-segments

To estimate the increase in IR traffic along a given trunk-segment s over the last two decades, we measure the percentage increase in the number of train-routes using segment s in the year 2009 compared to that in 1991. Let $TR_y(s)$ be the number of train-routes using trunk-segment s in the year y (i.e. as obtained from the TAAG of year y). Then the percentage increase in traffic in s in 2009, with respect to traffic in 1991, is computed as

$$\Delta T_{1991,\,2009}(s) = \frac{TR_{2009}(s) \;-\; TR_{1991}(s)}{TR_{1991}(s)} \times 100\% \tag{1}$$

Table 7 lists the 20 trunk-segments having the highest percentage increase in total IR traffic over the last two decades; the total number of train-routes using each segment, according to the TAAG 1991 and TAAG 2009 time-tables, are also given. It is evident that some of the trunk-segments in the Indo-Gangetic plain have experienced phenomenal increase in traffic (the four top-ranked segments in Table 7 are all located in the Indo-Gangetic plain), along with some of the segments in western and central India, and it is possible that the increasing amounts of traffic have reached the safe limits considering the available resources in these regions.

The concern regarding exceeding the safe limits can be understood more clearly if one can get a feel of the amount of new tracks (i.e. resources) constructed during this period of time. We study this in the following section.

Rank	Trunk-segment	Total #trains using segment		% increase in # trains	Geographic zone
		1991	2009		
1	Lucknow-Varanasi	22	86	290.91	IGP
2	Delhi-Tundla-Kanpur	50	172	244.00	IGP
3	Sonpur-Barauni-Katihar	32	110	243.75	IGP
4	Kanpur-Allahabad	32	106	231.25	IGP
5	Ahmedabad-Vadodara-Surat	60	188	213.33	western
6	Bhusaval-Manmad-Kalyan	48	140	191.67	western
7	Katni-Jabalpur-Itarsi	38	110	189.47	central
8	Jhansi-Bina-Bhopal	60	170	183.33	central
	Wardha-Kazipet-Hyderabad	24	68		southern
10	Mughalsarai-Ara-Patna	40	112	180.00	IGP
11	Vishakhapatnam-Vijayawada	36	100	177.78	southern
12	Itarsi-Bhusaval	34	88	158.82	central
13	Vijayawada-Guntur-Chennai	46	118	156.52	southern
14	Allahabad-Mughalsarai	38	96	152.63	IGP
15	Amritsar-Jalandhar-Ambala	52	128	146.15	northern
16	Ujjain-Bhopal-Itarsi	52	120	130.77	central
17	Dhanbad-Asansol-Kolkata	56	126	125.00	IGP
18	Delhi-Mathura-Agra	62	136	119.36	IGP
19	Surat-Mumbai	36	78	116.67	western
20	Kolkata-Kharagpur	40	84	110.00	eastern

Table 7: The top 20 trunk-segments ranked according to $\Delta T_{1991,\,2009}$ (% increase in number of trains using the segment between years 1991 and 2009). The total number of trains using each segment in 1991 and 2009 (according to TAAG time-tables) are also given.

6.2. Estimating the geographical growth / spread of the IR network

In this section, we study the geographical growth or spread on the IR network in terms of construction of new railway tracks. The increase in number of train-routes and stations over the years (as noted in Table 6) may be due to (i) introduction of new train-routes and intermediate stations on *existing* physical routes, or (ii) construction of *new* physical routes (i.e. new railway tracks). Since the complete statistics of the construction of new tracks in Indian Railways is not available publicly, we estimate the increase in the number of physical routes in the period between two years y_{prev} and

Period	Nos. of new train routes	% of new routes that uses new tracks
1991 - 1997	170	41.2 %
1997 - 2000	184	38.1 %
2000 - 2005	340	5.88 %
2005 - 2009	474	10.5 %

Table 8: Increase in number of train-routes and estimated fraction of the new train-routes that used new tracks. A newly introduced train-route is assumed to use a new track if and only if the route includes at least two consecutive new stations that did not exist in the data-set for the previous year (see text for details).

y_{later} from the available data as follows.

It is obvious that increase in the number of stations in those train-routes which exist in the data-set for both years can be ignored since these stations do not reflect construction of new physical routes. Among the new train-routes that appear in the data-set for y_{later} (and do not exist in the data-set for y_{prev}), we consider a train-route to run over a newly constructed physical route (track) if and only if the route includes at least two consecutive stations that did not exist in the data-set for the year y_{prev}. Table 8 shows the increase in number of train-routes over the last two decades, and the estimated fraction of the new train-routes that used new physical routes.

It is evident that only a small fraction of the newly introduced train-routes use newly constructed physical routes (i.e. new tracks), moreover this fraction is reducing with time in general. Thus while the volume of traffic (number of train-routes) has increased rapidly, there has been relatively very little construction of new railway-tracks. The IR authorities have also admitted that "since 1950-51, route-kilometers has increased by just 18% and track-kilometers by 41% even though in the same period freight and passenger traffic had gone up by more than 12 and 11 times respectively"[5] [3].

The large increase in amounts of traffic, coupled with the nominal increase in the number of tracks / routes, reflects the strain on the IR system as a whole and more particularly in some regions such as the Indo-Gangetic

[5]Route-kilometer is the length of a route, while track-kilometer is the total length of all parallel tracks in the route. If the number of parallel tracks in a route is increased, then track-kilometer increases but not route-kilometer.

plain and parts of central and western India.

7. Concluding Discussion

We begin by summarizing the findings in the paper. Analysing the flow of traffic in the Indian Railway network, we have found that as a result of unbiased growth in IR traffic, the high-traffic and low-headway segments have dangerously got concentrated in a few regions in the country, such as the Indo-Gangetic plain and parts of western and central India. Our observations also indicate some serious flaws in the scheduling of trains in IR, such as having low headway in the early morning hours in some of the trunk-segments in northern India (where visibility is frequently impaired due to dense fog). Simulating the traffic on some of the high-traffic segments according to the IR schedule, we also, to our surprise, find that it is really difficult to maintain the schedule using the existing infrastructure (e.g. number of parallel tracks), which frequently causes delay in running of trains. Moreover, the construction of new tracks has been nominal in the last two decades, compared to the large increase in traffic along the existing tracks.

We understand that there are compulsions behind the phenomenal growth in IR traffic. In order to ensure the rapid (10%) growth of the Indian economy as well as to meet the requirements of the increasing population, the demand for transportation of passenger and freight traffic has also increased exponentially in the recent years, hence the rapid increase in IR traffic is required and justified in some way. However, the growth has not been balanced and has unduly tipped towards certain regions, which in fact is acting as a bane for those regions in the long run. A possible reason behind such bias may be political – for instance, the ministers in charge of the Indian Railways Ministry since the year 1996 have all been from the states located in the Indo-Gangetic plains (West Bengal, Bihar and Uttar Pradesh), hence a large number of new trains have been introduced every year in this region. This is primarily because introducing new trains to improve the connectivity of a region with a metropolitan city such as Delhi or Kolkata (which are located at the two extremes of the Indo-Gangetic plain) is a common and easy way of appeasing people and gaining political mileage. On the contrary, improvement of railway infrastructure is a much more time-consuming process requiring long-term planning and investment, and hence is not undertaken nearly as frequently as introducing new trains.

We anticipate that our study will be a starting point for further discourses on the trade-offs between rapid growth and safety, and will help scientists to look at the problems in transportation networks in light of overall growth of the economy. Further, the study would provide practical tools to the IR authorities in identifying the factors endangering the safety of millions of rail passengers in India.

To end on an optimistic note, we find that the Indian Railway authorities have realized the urgent need to address the problems in the system. It has been declared in 2010 that 25,000 kilometres of new railway-tracks would be constructed by 2020, which is far greater than the average rate of construction of tracks till now [36]. The IR authorities have also decided to introduce the indigenously developed "Anti-Collision Device" technology on all important routes to check recurrence of accidents due to signal malfunctioning or failure of drivers to react to signals [37, 38].

Appendix A. Railway accidents in India in 2010 and 2011

A list of major railway accidents in India since the 1980s can be found at the Wikipedia page [4]. Of the 19 major accidents in 2010, 11 involved derailment or collisions between trains, whose details are listed in Table A.9. As stated earlier, 8 of these 11 accidents – the ones numbered 1, 2, 4, 5, 6, 9, 10 and 11 in Table A.9 – have occurred in the Indo-Gangetic plain.

It is to be noted that accidents have continued to occur in the Indo-Gangetic plain in the current year (2011) – collision of an express train with trucks at a road-railway crossing as the train-driver failed to notice a stop-signal, derailment of a freight-train and derailment of an express train resulting in more than 70 casualties [4]. Further, in June 2011, a head-on collision between two express trains (which had been placed on the same track as a result of a technical snag) was narrowly averted by two alert trackmen [39].

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Sl. No.	Date	Approximate Location	Description
1	Jan 2	Etawah, Uttar Pradesh	Lichchavi Express collides with Magadh Express
2	Jan 2	Panki, Uttar Pradesh	Gorakhdham Express and Prayagraj Express collide
3	Jan 3	Nij Bogaon, Assam	Arunachal Pradesh Express derailed
4	Jan 16	Tundla, Uttar Pradesh	Kalindi Express and Shram Shakti Express collide
5	Jan 22	Sathiyaon, Uttar Pradesh	Freight train derailed
6	May 25	Naugachia, Bihar	Guwahati-Delhi Rajdhani express derailed
7	July 19	Sainthia, West Bengal	Uttarbanga Express collides with Vananchal Express
8	Sep 20	Badarwas, Madhya Pradesh	Freight train collides with Indore-Gwalior Express
9	Sep 21	Kanpur, Uttar Pradesh	Freight train derailed
10	Sep 24	Kasganj, Uttar Pradesh	Rohilakhand Express derailed
11	Oct 4	Rasoiya, Uttar Pradesh	Freight train derailed

Table A.9: Railway accidents in India in the year 2010, involving derailment or collision among trains (as listed in [4]).

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