

# Transit Timetables as Multi-Layer Networks

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**Abstract**—There have been many studies on public transit networks with journey planning as an objective. Journey planning requires computation of feasible itineraries in least number of steps. Appropriate representation of transit networks allows us to study them from the perspective of transit operators and users. Optimal transit network representations help achieve both the objectives.

We present multi-layer transit network as one approach to reduce the number of steps required in the itinerary computation. We present algorithms for creation of multi-layer network representation from public transit timetables. Our proposed algorithm is capable of considering shared transit vehicles while creating the multi-layer network. We apply our algorithm on the timetable of the Indian Railways Network (IRN). We create a three-layer network consisting of space of stations, space of stops and space of changes. We also compare the network characteristics of the space of stops and the space of station networks generated from the timetable of IRN. We show that the space of stops network is a useful representation for the passengers of IRN where as the space of stations is a useful representation for the operations team of IRN.

## I. INTRODUCTION

Journey planning on public transit networks gives rise to the theoretical problem of searching for a shortest path equivalent on the physical networks with matching sets of trips available in the timetable. This is essential as commuters would like to minimize the distance they travel from their source to destination. In addition, commuters prefer to have minimum number of vehicle transfers during their journey.

Researchers of public transit networks have used graph models to represent timetables [1], [2]. Kurant et al. suggest a multi-layer approach for the study of transit networks [3]. They use a three-layer network to represent the connections formed by the train routes in the timetable [4].

In this work, we propose algorithms to create a three-layer network with only the timetable as input. We apply the proposed algorithms on the Indian Railways Network (IRN) timetable. We also consider the case of slip-trains in railways, which is an example of shared transit vehicles. We analyze the generated multi-layer network to obtain the network statistics.

The remainder of this paper is structured as follows. Section II contains a survey of the background work. Section III contains description of the dataset, mathematical notation used in the paper and the problem statement. Section IV contains details of algorithms used for the generation of multi-layer network. Section V contains the discussion of network

properties of the three layers. Section VI gives conclusions of our work.

## II. RELATED WORK

Multi-layer networks are a general form of representation for networks having multiple types of relations between nodes. Multi-layer networks have been used to represent multiple relations between participants of social networks, represent different modes of transportation systems, represent temporal networks and brain networks [5]–[7]. Kivela et al. provide a survey of multi-layer networks [7]. Barenna et al. have used hypergraphs to study the connectivity in collective transportation line networks [8].

Our approach of modeling transit networks as multi-layer networks is based on a similar approach taken by Kurant et al. [3], [4]. Kurant et al. consider the train and airline timetables of Europe to create a three-layer network. They study the network properties of the created three-layer network and also look into the implications of the three-layer representation for resilience and network load calculations. The three-layers are named as: space of stations, space of stops and space of changes. However, Kurant et al. do not consider the case of shared transit vehicles which cover multiple routes.

Researchers have analyzed the transport networks using a various graph based techniques. Sen et al. studied the small world properties of the IRN [9]. They used the physical network with links between stations if any train stops at the two stops. Sen et al. perform their analysis on the space of stops network. Ghosh et al. conducted a statistical analysis of IRN [10]. Network science based parameters of networks have been extracted to understand the network properties like degree-degree correlations [11].

In this work, we propose new algorithms for creation of multi-layer network from public timetables. We take advantage of internal structure of timetables to avoid graph processing for creation of a multi-layer network. We then analyze the network properties of the generated multi-layer networks.

## III. PROBLEM DESCRIPTION

### A. Data Description

We consider the public timetable of Indian Railways available on their website [12]. The timetable contains schedule of express and mail type of train services. The timetables of 2,018 express and mail trains are available on the website. We consider the timetables for a one week time period.

TABLE I: Sample entries of train schedules containing two slip-trains. The two examples given here illustrate two different kinds of slip-trains.

Source Station	Junction	Route No.	Destination Station
12621 MAS NDLS Express			
Chennai	N/A	1	New Delhi
12780 Goa Express			
H. Nizamuddin	Londa Junction	1	Vasco Da Gama
		2	Hubballi Junction
17603 Kacheguda - Yesvantpur Express			
Kacheguda	Guntakal Junction	1	Yesvantpur
		2	Hubballi Junction
		3	Vasco Da Gama

Indian Railways uses the practice of sharing transit vehicles; the practice is called *slip-train*. Under slip-train practice, some coaches of a given train are separated from it at a pre-determined junction. The coaches thus separated are attached to a different train which takes the coaches toward their destination. The slip-trains are identified in the train timetable by giving different route number to each slip-train.

Sample entries obtained from the IRN timetable are shown in Table I. The first train bearing 12621 as train number does not have any slip-train. The second train bearing 12780 as train number requires that a few coaches be detached from the train at the Londa Junction. The detached coaches are then attached to another train which takes them towards the Hubballi station; these coaches are identified with route number 2. Similarly, the third train bearing 17603 as the train number has two slip-trains; both the slip-trains get separated from main train at the Guntakal Junction.

## B. Definitions

Timetable of any transit network is a set of timetables of all the vehicles that are part of the transit network. In the case of Indian Railways Network (IRN), the timetable consists of a set of trains each bearing a unique train number and servicing a sequence of stations.

We start with the publicly available IRN timetable to create a three-layer network. The three layers are named as space of stops, space of stations and the space of changes. All the three layers share a common node set; the set of nodes is created by collecting the names of all the train stations available in the IRN timetable. The *state of stops* layer has an edge between two stations if the respective stations are adjacent in the timetable of any train. The *state of stations* layer has an edge between two stations if the respective stations are physically connected by a train track. The *state of changes* layer has an edge between two stations if both the stations are serviced by at least one common train. For a more detailed explanation of these terms, please refer to an earlier work by Kurant et al. [13].

TABLE II: A modified version of train schedule for the train 11063 MS Salem Express.

Station Name	Arrival Time	Departure Time	Route No.	Day
Chennai Egmore	source	23:00	1	1
Attur	03:44	03:45	1	2
Salem Junction	05:20	destination	1	2
Salem Junction	source	07:05	2	2
Omalar	07:23	07:25	2	2
Metur Dam	08:25	destination	2	2
Salem Junction	source	06:30	3	2
Erode Junction	09:00	destination	3	2

A summary of the notations used in the rest of the paper is as follows.

space of stops graph:

$$\begin{aligned}
 G_{stops} &= (V_{station}, E_{station}) & (1) \\
 V_{stops} &= \text{set of all stations from timetable} \\
 E_{stops} &= \text{set of all links formed between} \\
 &\quad \text{consecutive stops of a train}
 \end{aligned}$$

space of stations graph:

$$\begin{aligned}
 G_{station} &= (V_{station}, E_{station}) & (2) \\
 V_{station} &= \text{set of all stations from timetable} \\
 E_{station} &= \text{set of all physical links} \\
 &\quad \text{connecting adjacent stations}
 \end{aligned}$$

space of changes graph:

$$\begin{aligned}
 G_{changes} &= (V_{changes}, E_{changes}) & (3) \\
 V_{changes} &= \text{set of all stations from timetable} \\
 E_{changes} &= \text{set of all links indicating availability} \\
 &\quad \text{of a train between two stations}
 \end{aligned}$$

$T$  = IRN timetable

$t$  = Timetable of a single train

$SS$  = Stop sequence of a single train

$J$  = Set of stops at which slip-train(s) separate from the carrier train

$P$  = Stop sequence prefix for junctions

The stop sequence of a train is a sequence of ordered tuples containing (stop, route) elements implied by a given train timetable. For the train timetable given in Table II, the stop sequence (SS) is: (Chennai Egmore, 1), (Attur, 1), (Salem Junction, 1), (Salem Junction, 2), (Omalar, 2), (Metur Dam, 2), (Salem Junction, 3), (Erode Junction, 3). From SS, we can identify junction stations (J) where slip-trains separate from the carrier train. For the given station sequence, we have Salem Junction as the junction. For each of the junctions, we can identify a stop sequence prefix (P) - sequence of previous stations appearing in the space of stops. In the case of Salem Junction, the sequence of previous stations is: (Chennai Egmore, 1) and (Attur, 1).

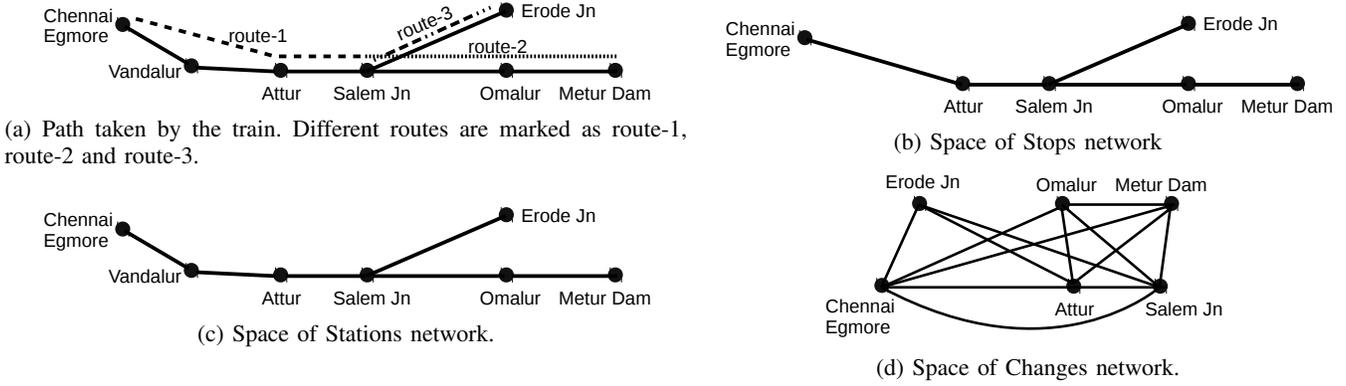


Fig. 1: Creation of three layers from one example train time table. The timetable considered is an modified version of timetable for the train 11063 MS Salem Express. A tabular representation of the timetable is shown in Table II.

The three-layers of the generated network derived from the timetable given in Table II are shown in Figure 1.

#### IV. MULTI-LAYER NETWORK

We propose a list-based technique for creating a three-layer network. Our approach takes advantage of the inherent total ordering of a train timetable. Our algorithm also incorporates the case of shared transit vehicles in the form of slip-trains.

##### A. Proposed Algorithms

First, we discuss generation of the space of stops network from the timetable (Algorithm 1). We follow it up with further discussion on the space of stations network (Algorithm 2) and the space of changes networks (Algorithm 3).

In Algorithm 1, we use the IRN timetable ( $T$ ) as input for constructing the  $G_{stops}$ . We initialize the  $G_{stops}$  to an empty graph and iterate through timetables of all the vehicles (trains) in the network. In each step of iteration, we extract the stop sequence ( $SS$ ) from a given train timetable ( $t$ ). The stop sequence is used to create stations and edges between adjacent stations that belong to the same route. At the end of its work, the algorithm creates a space of stops network.

It is common for express trains to pass through a station and not stop at it; such a scenario leads to addition of shortcut

edges in the space of stops network; there is no underlying direct physical railway track that corresponds to a shortcut edge. The space of stations network is created by pruning all the shortcut edges from the space of stops network. Algorithm 2 receives  $E_{stops}$  and checks if an edge is a real link or a shortcut. We identify an edge as a shortcut if the two stops identified by  $e_i$  are non-adjacent in at least one of the train timetables. We can utilize the stop sequence to imply the non-adjacent status of two stops identified by  $e_i$ . A single scan through a stop sequence is enough to arrive at our conclusion. This list traversal is a linear time operation and is completely scalable strategy for identifying shortcuts.

Algorithm 3 creates the space of changes network. In Algorithm 3, our goal is to connect all the stations that are serviced by a single train. In order to connect all the relevant stations, we elaborate on a given train timetable. Our analysis shows that a slip-train also travels with the carrier train till the junction where decoupling takes place. Hence, it is necessary to prefix junctions of slip-trains with their corresponding stop sequence ( $P$ ). We effectively create one stop sequence per route. All the generated stop sequences of a train timetable are stored in  $SSArray$ . We create one complete graph for

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**Algorithm 1** Algorithm for creating the space of stops network from the IRN timetable having slip-trains.

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1: procedure CREATESTOPLAYER( $T$ )
2:    $G_{stop} \leftarrow$  empty graph
3:   for all  $t \in T$  do
4:      $SS \leftarrow$  ExtractStopSeq( $t$ )
5:     for all  $s_i \in SS$  do
6:       if IsSameRoute( $s_i, s_{i+1}$ ) then
7:          $G_{stop}.AddEdge(s_i.station, s_{i+1}.station)$ 
8:       end if
9:     end for
10:  end for
11:  return  $G_{stop}$ 
12: end procedure

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**Algorithm 2** Algorithm for creating the space of stations network layer from the space of stops network layer.

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1: procedure CREATESTATIONLAYER( $E_{stop}, T$ )
2:    $E_{station} \leftarrow E_{stop}$ 
3:   for all  $e_i \in E_{station}$  do
4:     for all  $t \in T$  do
5:        $SS \leftarrow$  ExtractStopSeq( $t$ )
6:       if Distance( $e_i, SS$ ) > 1 then
7:         RemoveEdge( $e_i, E_{station}$ )
8:         break
9:       end if
10:    end for
11:  end for
12:  return  $E_{station}$ 
13: end procedure

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each stop sequence and add the generated graph to  $G_{changes}$ .

**Algorithm 3** Algorithm for creating the space of changes network from the IRN timetable having slip-trains.

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1: procedure CREATECHANGESLAYER( $T$ )
2:    $G_{changes} \leftarrow$  empty graph
3:    $P \leftarrow$  empty list
4:   for all  $t \in T$  do
5:      $SS \leftarrow$  ExtractStopSeq( $t$ )
6:      $J \leftarrow$  IdentifyJunctions( $SS$ )
7:     for all  $j \in J$  do
8:        $P.AddPathPrefix(j, SS)$ 
9:     end for
10:     $SSArray \leftarrow$  ExpandSSofSlips( $P, SS$ )
11:    for all  $ss \in SSArray$  do
12:       $G_{changes}.Add(CreateCompleteGraph(ss))$ 
13:    end for
14:  end for
15:  return  $G_{changes}$ 
16: end procedure

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## V. NETWORK ANALYSIS

We perform network analysis on the three-layer network generated using the Algorithms discussed in the previous section. A visual inspection of Figure 2 shows the difference between the space of stops network and the space of changes network. The space of stations network as distributed by Indian Railways is shown in Figure 2a; our space of stations would

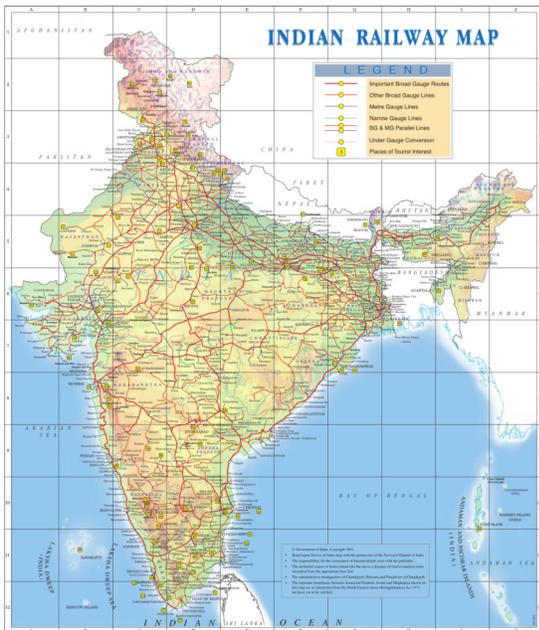
be a sub-network of the network shown in Figure 2a; we reuse Figure 2a for its level of detail on the geographic accuracy of all the train tracks; such a detail is difficult to replicate without the data of the train tracks.

Figure 2b shows the space of changes network. The stations are pinned to geographic locations and a straight line is drawn to represent an edge between two stations. The space of changes network is induced by the trains traveling on the physical track network. As expected, the diagram shows dense connectivity of the network.

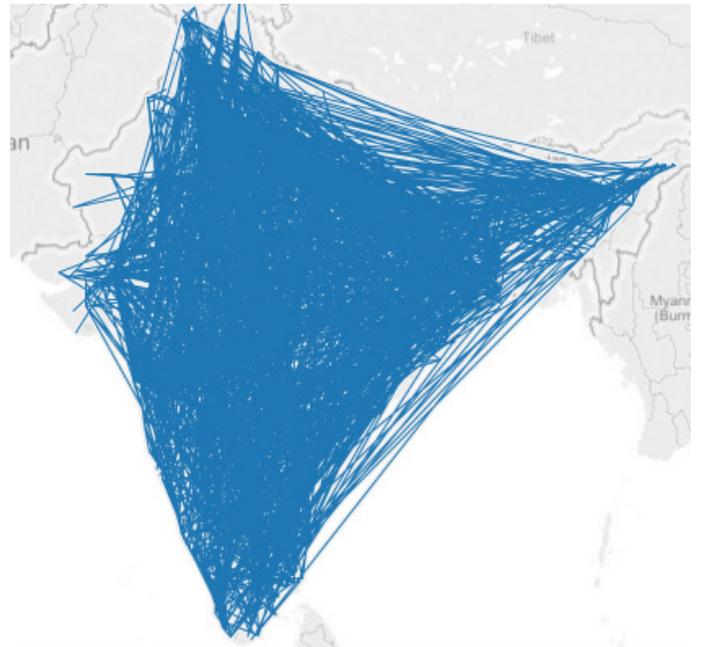
The scale of networks in different layers can be seen in Table III. As we move from the space of stations network to space of stops network, we can see the densification of the network in terms of the number of edges and the average node degree. We can also see significant reduction in the diameter - maximum shortest path length - of the network for the space of stops network vis-à-vis the space of stations network. The extent of densification can also be seen by increase in the average clustering coefficient and decrease in the average shortest path.

The node degree distributions of both space of stations and space of stops follow power-law distributions. Prior research on this topic by Sen et al. [9] and Srivastava et al. [11] attest to the power-law network nature of the IRN.

We also consider the load on the network by analyzing the weighted version of the space of stops network. Here, weight of an edge corresponds to the number of trains utilizing that edge. Edge weights can be used to estimate the load on the network. As can be seen from Figure 4, the edge weight



(a) Physical track network

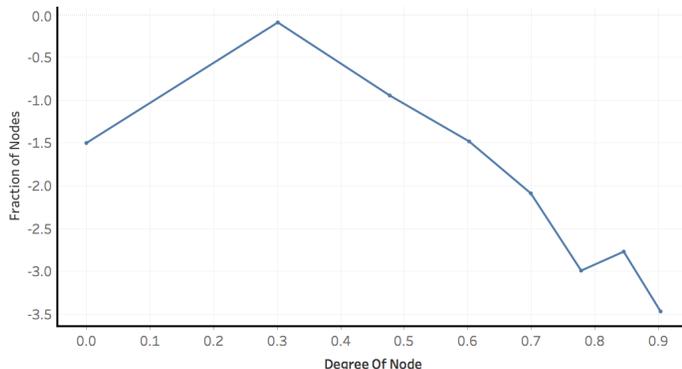


(b) Space of Changes network

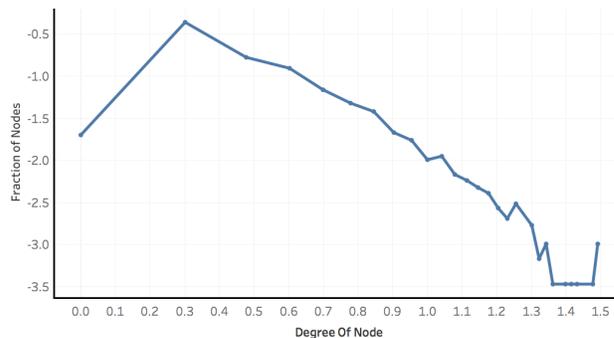
Fig. 2: Geographical layout of Indian Railways network. We compare the space of stops network released by Indian Railways with the space of changes network generated by Algorithm 3. You can see the dense network connectivity induced by the trains traversing the Indian Railways network.

TABLE III: Network characteristics of different layers created from the timetable of the Indian Railway network (IRN).

Name of Parameter	Space of Stations Network	Space of Stops Network
Number of nodes	2942	2942
Number of Edges	3217	5754
Number of Routes	2063	2063
Average Node Degree	2.18	3.91
Diameter of Network	238	43
Clustering Coefficient	0.003	0.449
Average Shortest path	70.78	10.11



(a) Space of stations network



(b) Space of stops network

Fig. 3: Node degree distributions of multi-layer networks of Indian Railways. The x-axis indicates the degree of a node and the y-axis indicates the fraction of nodes with a given degree. The plots are done on the log-log scale.

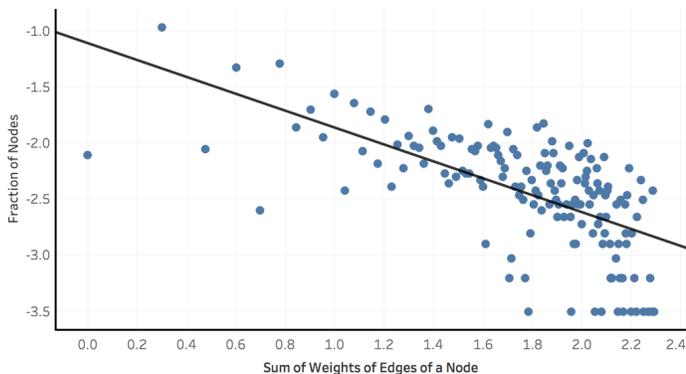
distributions of the space of stations and the space of stops networks follow power-law distributions.

## VI. CONCLUSIONS

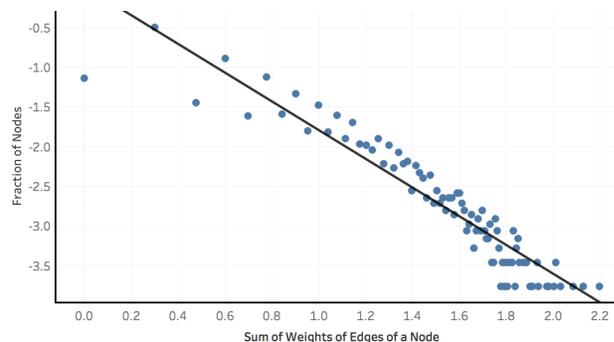
Multi-layer networks are useful in the analysis of transit networks, social networks and brain networks. In this paper we propose algorithms for creating a three-layer network representation of transit timetables which have shared vehicles (slip-trains). The three-layer network model consists of the space of stations, the space of stops and the space of changes as different layers. Using the proposed algorithms, we create a three-layer network model for the Indian Railways network

(IRN) from the publicly available IRN timetable. This has not been done in any earlier work.

We also compare the space of stops network with the space of stations network to illustrate the utility of multi-layer network representations. The average length of shortest path in the space of stops network (10.11) is much smaller the corresponding value in space of stations (70.11). Thus, space of stops network requires significantly less number of steps for computing the shortest path itinerary especially when compared with the space of stations network. From the IRN timetable dataset, we extract the network metrics of the three-layer network representation.



(a) Space of stations network



(b) Space of stops network

Fig. 4: Edge weight distributions of multi-layer networks of Indian Railways. The x-axis indicates the sum of weights of all edges of a node and the y-axis indicates the fraction of nodes with a given degree. The plots are done on the log-log scale.

This work can be extended to other modes of transport such as airlines. For instance, the problem of code sharing among airlines is similar to slip-trains. We can use the space of stops and the space of changes layers in journey planning applications. In particular, incorporating the slip-train algorithm will help in getting a complete solution to the journey planning problem. We can also use the space of changes network to estimate the ability of a transit network to service passenger traffic during disruptions in the network.

#### ACKNOWLEDGMENT

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