ANALYZE THE IMPACT OF DIFFERENT PARAMETERS AND THEIR INTERACTIONS EFFECT ON RAILROAD CAPACITY UTILIZATION

Ph.D. Thesis

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DECLARATION

I, **Neeraj Saini**, declare that this thesis titled, "**Analyze the impact of different parameters and their interactions effect on Railroad capacity utilization**" and the work presented in it, are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself, jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Date:

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CERTIFICATE

This is to certify that the thesis entitled **“ANALYZE THE IMPACT OF DIFFERENT PARAMETERS AND THEIR INTERACTIONS EFFECT ON RAILROAD CAPACITY UTILIZATION”** being submitted by **Neeraj Saini (2013RME9526)** is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

Place: Jaipur
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ABSTRACT

Capacity is the concerned and crucial issue in the railroad industry. By the analysis of railway capacity, it is identified whether the network is saturated or there exists leftover capacity that can be utilized to bear additional traffic volume. Due to the high demand for trains and limited infrastructure, it becomes more critical to utilize efficiently the railroad capacity. This thesis reviews the extensive research work on capacity and categories according to significance. This research presents a prominent model for railway capacity problem. To show the applicability and validity of the model, it is applied to a part of a network of Indian Railways.

As the primary requirement of railways is to meet the increasing demand by expanding the capacity with the least cost. A key factor that influences the network capacity is the speed of train types. Low-speed trains create the interference in the network and hence reduced the capacity. The effect of incremental speed change of train types on capacity is analyzed.

An incremental infrastructure improvement technique is presented and numerically investigated in this research work. To make new infrastructure is extremely costly and time-consuming so, it is suggested to expand the network in parts. First, choose the bottleneck section, improve it and then select another bottleneck section.

In summary, the model presented in the thesis is useful and important for railway planners to perform decision-making activities.

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ABBRIBIATIONS

IR	Indian Railways
ATC	Air Traffic control
UIC	International union of railways
CUI	Capacity utilization index
DOF	Degree of freedom
AREMA	The American Railway Engineering and Maintenance of Way Association
IM	Infrastructure manager
AAR	Association of American Railroads
PPM	Public performance measure
ERTMS	European Railway Traffic Management System
UNIFE	Association of the European Rail Industry
RCET	Railway Capacity Evaluation Tool
SCAN	Strategic Capacity Analysis for Network
OPL	Optimization programming language

TERMINOLOGY USED

- **Corridor**- All main and alternative routes between source and target.
- **Route**- Consecutive lines and nodes as a whole, between a defined source and destination.
- **Line**- A link to two large nodes and usually the sum of more than one line section.
- **Nodes**- Points of the network where at least two lines converge.
- **Stations**- Points of a network where overtaking, crossing or direction reversals are possible.
- **Junctions**- The point of a network in which at least two lines converge and neither overtaking or crossing nor direction reversals are possible.
- **Rolling stock**- Type of vehicles moves on a railway track.
- **Line sections**- The part of a line, in which the number of trains, the infrastructure, and signaling conditions does not change fundamentally.
- **Block sections**- Section, which determines the minimum headway along the entire line section.
- **Dwell time**- Time elapsed in boarding and alighting at the station.
- **Buffer time**- Extra time inserted between train paths in addition to the minimum interval between trains to reduce the transfer of delays from one train to the next.
- **Knock-on-delay**- The delays intended by one train to others.
- **Passenger kilometer (pkm) -** A kilometer traveled by a passenger. Used as a unit of measure of passenger transport.
- **Tonne kilometer (tkm) -** Unit of measure of freight transport. Which represents the transport of one tonne of goods over a distance of one kilometer.
- **Track kilometers**- The length of all running tracks and tracks including tracks in sidings, yards, and crossings.
- **Tractive effort-** Load-hauling capability of a locomotive expressed regarding the tractive force exerted by the locomotive at the wheel.
- **Density-** The volume of traffic moving between any two points on the Railway expressed regarding passenger kilometers or net tonne-kilometres per route kilometer/running track kilometer or train kilometers per running track kilometer.

- **Headway -** Headway is a measurement of the distance or time between vehicles in a transit system. The minimum headway is the shortest such distance or time achievable by a system without a reduction in the speed of vehicles.

CHAPTER 1

INTRODUCTION

1.1 Background

Transportation facilitates the movement of individuals and goods from one place to another. Modern civilization is extremely dependent on transportation to sustain its way of life. It is the essential part of business activities in conveying raw material to industry and to distribute the finished goods to market. The basic modes of transportation are land, marine, and air. Land transport is divided into Road transport and rail transport. On Road transport, we use buses, trucks, cars and in Rail transport trains are used to carry goods as well as passengers. In air transport, aeroplanes and helicopters are used. In marine transport, ships and steamers are used to convey passengers and goods. Table 1 shows the comparison matrix of different modes of transport.

Table 1.1: Comparison of different modes of transport

Mode of transport → **Criteria** ↓	**ROAD**	**RAIL**	**MARINE**	**AIR**
Guideways	Roads	Rails	Water	Air
DOF for movement on guideways	2	1	2	3
Relative speed	Moderate	Moderate	Slow	Very high
Reliability	Good	Good	Limited	Very high
Cost per tonne/Km	Medium	Low	Very low	High
Flexibility	High	Low	Low	Medium
Capacity	Low	Moderate	Very high	Very low
Control policy	Traffic lights	Signalling	Automatic identification system	Air traffic control (ATC)
Bottlenecks	Junctions	Junctions/ stations	Ports	Airports

Different modes of transport have the varying degree of speed, reliability, flexibility and cost criteria. Physical characteristics of certain goods, customer requirement, and socio-economic factors are considered in selecting a specific mode of transport.

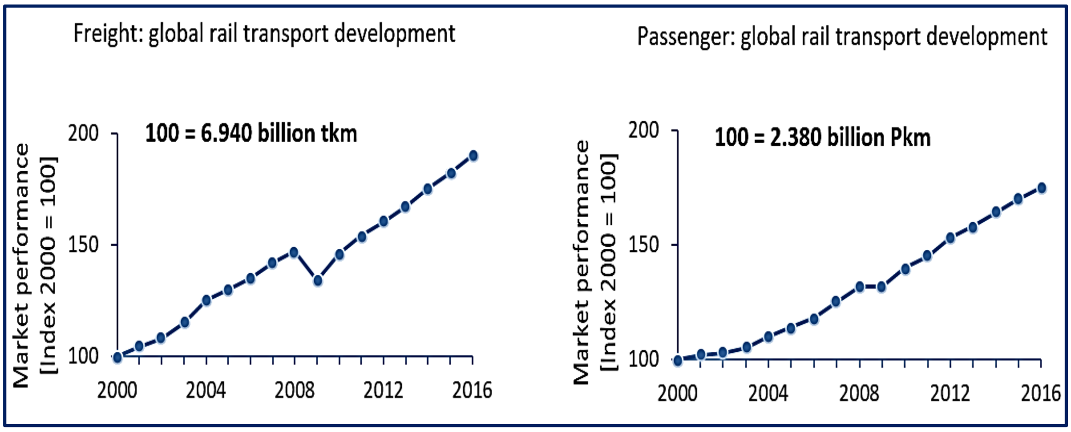
Rail transportation is the safe public transportation mode compared to other modes of transportation. Railway transportation has an important role in the transportation system of a country because the growth of trade, industry, and commerce of a country highly depends on the development of railways. The advantages and disadvantages of rail transportation are summarized in Table 2.

Table 1.2. Advantages and disadvantages of rail transportation

	Items	Description
Advantages	Energy efficient	More energy efficient due to the low friction between steel wheels and rail lines, energy efficiency is more than four times than road transportation.
	Environmental considerations	Less emission of harmful gases, superior fuel efficiency
	Better organised	Better organized sector than other modes of transportation, Has fixed routes and schedules, services are more uniform and certain
	High speed over long distances	High speed than any other form of transport, except airways
	Suitable for heavy and bulky loads	It is economical and quicker for long distances heavy freight transport
	Economical mode of transport	More economical than other modes of transport, if traffic is increasing average cost of transport decreases

	Safety	Safest in all modes of transport, fewer chances of accidents and breakdowns, also protect from the exposure of sun, rain, and snow.
	Larger capacity	Railways has extremely large capacity, can also be increased easily by adding more wagons
	Employment opportunities	Provide the highest employment for both skilled and unskilled persons
Disadvantages	Huge capital investment	Huge investment in infrastructure, rolling stock, maintenance and in overhead expenses, if traffic is not sufficient than wastage of vast resources.
	Less flexibility	Inflexible mode of transport, routes, and schedule are fixed and cannot be altered according to individual requirement.
	Not door-to-door services	Services are bounded by particular tracks. Intermediate loading and unloading increases the cost of transportation and wastage of time
	Booking formalities	Takes much time and labor in booking formalities compared to road transportation
	Limited services in rural areas	Due to the huge investment, rail transport services cannot start in uneconomical rural areas.

Railways have always played a distinctive role to accomplish transportation needs of people and simultaneously serving as a critical infrastructure facilitator for carriage of goods. Due to globalization and fast progression in the economy, an extensive growth is observed in rail transportation sector worldwide as shown in Figure 1.



Source: SCI Verkehr report

Figure 1.1: Global rail transport development in freight and passenger sector respectively

A huge demand for railways is one side of aspect but on the other side limited infrastructure is a constraint to meet the demand (Cambridge Systematics, 2007). Numerous railroads over the world are facing the same challenges as Indian Railways. The main challenges for Indian Railways are described as follows:

1. The main challenge in front of IR is to meet the demand of customers in both passengers and freight. Aside from the quantum of investment, quality of service is additionally an issue. Safety and security of passengers, cleanliness of coaches and terminals, and the capacity of tracks and ease of tickets booking are some issues that need earnest consideration.
2. Due to the deficient investment, network expansion and technical modification have not occurred at requisite pace promoting to loss of the share in national cargo and traveler activity. It is evident that for serving as a lifeline of the nation, IR needs to become operationally and fiscally stable.
3. Indian Railways is endeavoring to upgrade its piece of the pie and service quality to provide a better experience of traveling than other modes of travel. This can be accomplished by removing capacity bottlenecks which oblige growth, the efficiency of operations and improve the productivity of assets.
4. Safety is also a concerned challenge for Indian Railways. The unmanned level crossing is a major source of accidents that need urgent attention. However, the safety records of IR are well compared with the European countries.

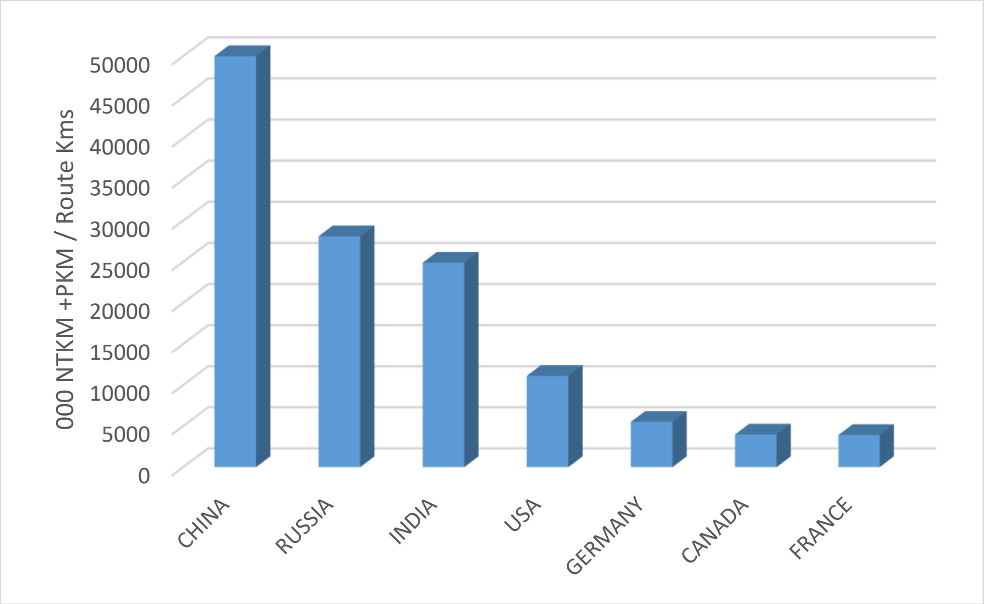
Statistical data of Indian railways, as presented in Table 1, show that from 2001 to 2016, there is enormous growth in passenger Kilometres by 150.11% and in Tonne Kilometres by 107.79%. However, in this duration Railway infrastructure has increased by just 5.80%.

Table 1.3: Growth in Passenger traffic, Freight traffic, and infrastructure in Indian Railways.

Item	**Passenger Kilometers (Millions)**		**Net Tonne Kilometers (Millions)**		**Track kilometers**	
Year	2001	2016	2001	2016	2001	2016
Value	457,022	1,143,039	315,516	655,605	63,028	66,687
% Growth	150.11%		107.79%		5.80%	

Source: IR statistical publication 2015-16

The limited infrastructure is producing large-scale congestion of the system so the quality of service is affecting that impacts customer satisfaction. As per UIC standards, the traffic density on Indian Railways is quite high as shown in graph 1. The growth of infrastructure is not commensurate with the demand.



Source: UIC statistic

Figure 1.2: Traffic density

It is clear from the above discussion that there is urgent need to increase the railroad capacity. Railroad capacity can be enhanced either by making new infrastructure or by using the available capacity excellently. As the investment in infrastructure development to enrich capacity is extremely costly and time-consuming, so it needs to focus on capacity enhancement techniques through improved operations. The goal of the capacity analysis is to best use the potentially available capacity to maximize the number of trains subject to constraints levied by heterogeneity in traffic, the average speed of trains, etc.

1.2 Aim of the thesis

Capacity is the concerned and crucial issue in the railroad industry. Various quantitative models used to measure railroad capacity and to solve associated issues like scheduling, routing, and sidings. Most studies on capacity highly depend on diversity in railways operations and indigenous factors of a country.

This thesis focuses on the understanding the concept of capacity, analyze the impact various factors on capacity utilization and examine the proposed techniques for improving railroad capacity.

1.3 Research Methodology

This research show the way how to manage the increasingly traffic of diverse mix of train types in limited capacity networks. In particular, different strategies are demonstrated to increase the capacity of existing lines. Following research questions are addressed:

1. How to develop a model to measure capacity utilization in mix traffic pattern with the help of basic data that is typically available to railway planners?

2. What will be the key characteristics of the developed model concerning computational complexity and sensitivity to the model parameters?

3. Explore how multiple operational and infrastructural alternatives affect rail line and network capacity.

To elaborate the concept of capacity and scope of research a systematic approach is needed, which is defined step-by-step by research stages as shown in Figure 3. These stages are in the sequential way in which problem flows in the manner of scope definition which can sustain the research potential. Further, a detailed exhaustive literature review is carried out based on the past researches that motivate towards structuring the problem formulation, input data, and development of a mathematical model for railroad capacity followed by results in CPLEX.

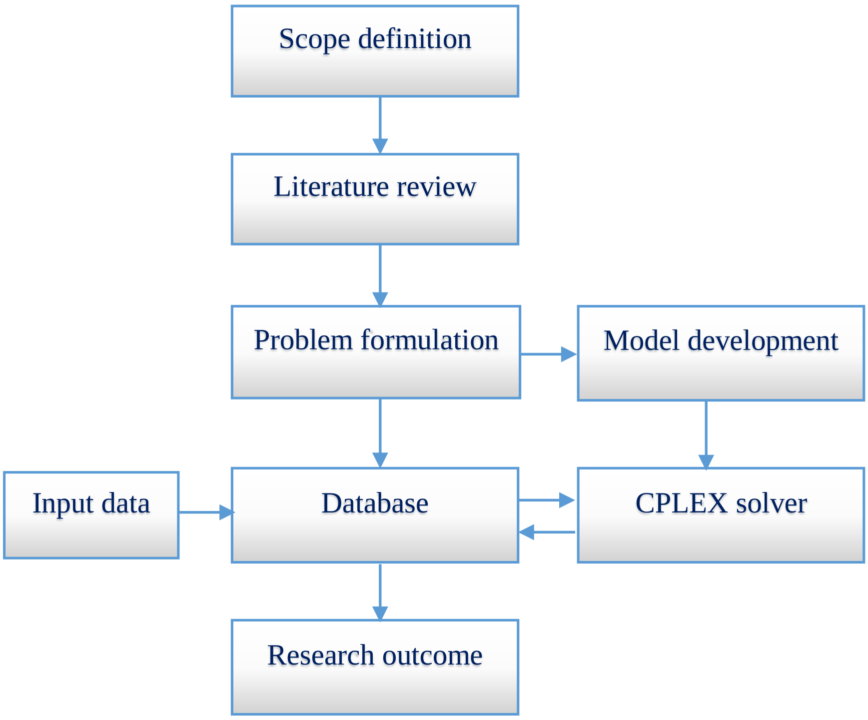


Figure 1.3: Research stages

1.4 Structure of thesis

This thesis is designed as a series of chapters. Chapter 1 and 2 gives the overview of capacity through related literature review. Model for capacity determination is described in chapter 3. A case study on the part of a network of Indian Railways is presented in chapter 4. Future research work is mentioned in chapter 5.

Chapter 1

This chapter introduces the railroad capacity and defines the scope of the study. Different challenges for Indian Railways are summarised and based on these challenges need of study is identified. Research methodology followed by research questions and research stages are also presented.

Chapter 2

Different railroad concepts, definitions, and factors that affect railroad capacity utilization are discussed in this chapter. An extensive literature review of capacity models is presented in this section. Simulation software with their important features is also compared. Based on literature review, research gap is identified, and specific objectives of research are set.

Chapter 3

This chapter is dedicated to modeling details. Mathematical and computational models for determination of railroad capacity are described here.

Chapter 4

In this chapter, a case study is performed on the network of Indian Railways. Database for a part of the network is prepared. The impact of train speeds, dwell times, and infrastructure expansion strategies are accessed in the chapter.

Chapter 5

This chapter provides the summary of 2-4 chapters. Future research topics are also proposed based on this research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Capacity: Concept and Definitions

The concept of capacity seems simple in the instance of theoretical capacity that is calculated in idealized conditions like, speed is same for all trains, traffic is homogeneous and one directional. Under these circumstances, the capacity is the number of hours of train operation divided by the time headway. Theoretical capacity is the hypothetical limit that cannot be attained in practice. Practical capacity is a more sensible measurement of the capacity that is the number of trains moves through a track with an acceptable amount of delay, the level of service, and reliability. A study by Kraft (1982) shows that Practical capacity of a railroad section cannot be reached to its maximum limit (theoretical capacity) due to constraints in infrastructure, traffic as well as in operations. It is observed about 60-70% of theoretical capacity at desired reliability level as shown in figure 2.

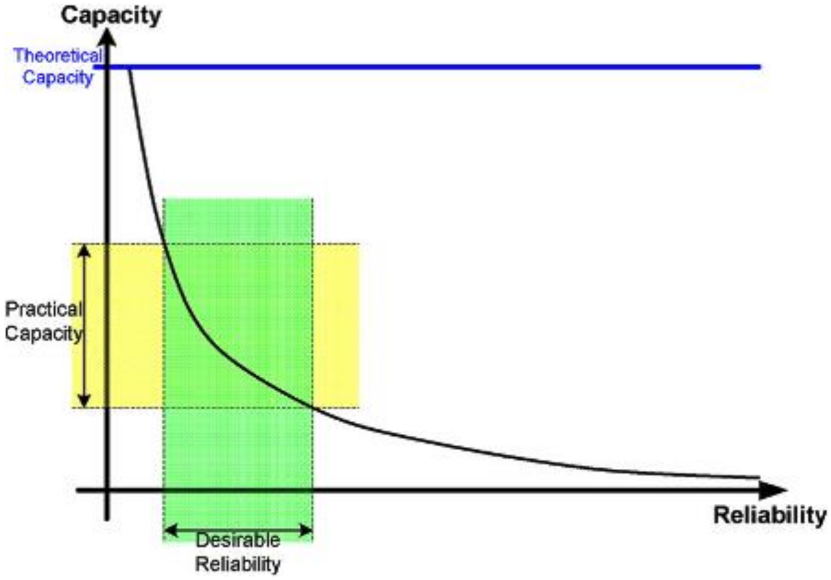


Figure 2.1: Capacity v/s Reliability plot for railroad

The types of capacity defined by utilization are as follows (Kruger 1999, Abril et al. 2007):

Used capacity: it shows the actual traffic volume occurring over the network. It is lower than the practical capacity.

Unused Capacity: it is the difference between the practical capacity and used capacity.

Usable capacity: if the available capacity is used to accommodate new trains than it is called usable capacity.

Lost capacity: if the available capacity is not used to accommodate new trains than it is called lost capacity.

The American Railway Engineering and Maintenance of Way Association (AREMA) (1998) presents a simplified approach for estimating practical line capacity for freight operation. According to AREMA, practical line capacity (C_p) is calculated by multiplying theoretical capacity (C_t) and dispatching efficiency (E) for a line segment ($C_p = C_t \times E$). Dispatching efficiency depends on many factors like type of signal and traffic, class of line and, terrain.

According to Krueger (1999), Capacity is a measure of the ability to move the traffic over a defined rail line with a given set of resources under a specific service plan. The service plan depends on the average speed of trains, on-time performance, track maintenance time, reliability in service, and train handling power of the rail section.

Transportation Research Board (2003) in the transit capacity manual for the United States defines the capacity as the maximum number of trains operate on a section of track in a certain period, typically one hour. A more prominent and practical definition of capacity was given by the international union of Railways (UIC) in 2004. According to UIC code-406R:

“The capacity of any railway infrastructure is:

- the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the IM's own assumptions;
- in nodes, individual lines or part of the network;
- with market-oriented quality.

UIC comment that capacity cannot be defined in a generally applicable delineation because it depends on the concerns and expectations that can be varying among the customers, infrastructure planners, timetable planners and railroad operators. According to UIC, the capacity depends on the four major factors; average speed of trains, the number of trains, stability in operation, and heterogeneity in traffic as shown in figure 3.

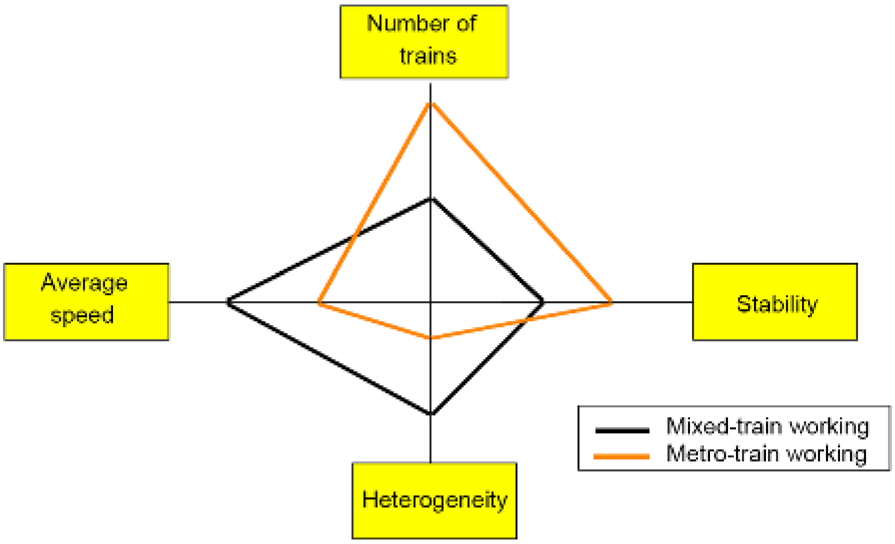


Figure 2.2: Capacity balance (Source: UIC Code-406R)

The capacity balance shows that in a mixed traffic line due to higher heterogeneity level, stability in operation is less compared to the dedicated metro line. Due to the increased headway requirement, the total number of trains can be operated on the mixed corridor are less than the metro corridor while mixed corridor might be operating at higher average speed.

Barter (2008) defined capacity as the number of trains that can be incorporated into a timetable that is conflict-free, commercially attractive, meeting regulatory requirements, and can be operated in the face of anticipated levels of primary delay while compliance with performance targets. He incorporated primary delays in the definition that may be the results of mechanical failures, malfunctioning infrastructure, adverse weather conditions, excessive boarding times of passengers, accidents at road-railroad crossings and so on (Carey & Kwiecinski 1999, Vromans et al. 2006).

2.2 Metrics to measure capacity level

It is always concerned that what is a suitable measure of determining capacity level? According to requirements and situations metrics to measure capacity may be from which throughput, the level of service, asset utilization or profit generation. Each metric has explicit applicability and weaknesses, and analyzing trends using single metric fails to capture the complexity of rail performance (Weatherford et al. 2008). Table 2 shows the different metrics with measurable units for railroad capacity.

Throughput is a measure of how many passengers and how much material can be transported over a definite period. The most common unit of throughput is the number of trains; it is easy to understand and directly measure the maximum capacity of the line. Another unit is Cars per unit time that is favorable to measure terminal capacity. Tonnage-Km and Passenger-Km are useful metrics to compare the traffic load between different line sections (Dingler et al., 2010).

Table 2.1: Different metrics for railroad capacity

Metric	**Units**
Throughput	Trains, Cars, Tonnage-Km, Passenger-Km
Level of Service	Terminal Dwell, Average Velocity, Delay
Asset Utilization	Average Velocity
Profit generation	Revenue

The level of service is a measure of the reliability of operations and timeliness of transportation. Excessive long travel time and unreliable deliveries are undesirable for both shippers and passengers. AAR (2010) defines the terminal dwell as the average time a car resides at a specified terminal location. Terminal dwell and average velocity both are used together to access the travel time of traffic and, high variability in these factors leads to low level of service (Laurits R. Christensen Associates, Inc. 2008). The delay is also a popular and significant unit of the level of service because it directly measures the variability in travel times.

Infrastructure, rolling stock, locomotives, and personnel are the critical asset for a railroad industry. They are expensive to procure and maintain, so there is need to use them efficiently and economically. Average velocity is chosen as a primary metric for system-wide asset utilization. For a specified traffic level, an increase in average velocity tends to shorter cycle time thus using the assets more efficiently. Hamburger (2006) estimated that increase in average velocity by one mile per hour make available additional 250 locomotives, 180 trains, 5000 cars and employees to move extra traffic.

Khadem Samani (2011a) gives profit-generating capacity as a new metric to calculate the profitability of infrastructure assets. This metric is based on ‘value’ which is used to define the relationship between performance requirement of customers (like service level) and resources (like labor, material, price, and time). Revenue regarding currency is chosen as a unit of capacity metric which only justifies the financial goals of a railroad.

2.3 Factors affecting railroad capacity

As capacity is a multidisciplinary area, there are a number of factors that affect it. Most recently Khadem (2012), landex (2008) analyzed and, categorized these factors in different groups that are; timetable, signaling, infrastructure, rolling stock, nodal capacity constraints and others. The overview of these factors is presented by cause and effect diagram in figure 3. Here, the delay is chosen as a measure of capacity whether it may be other from the list of metrics but it seems to be convenient to understand the impact of various factors on the capacity.

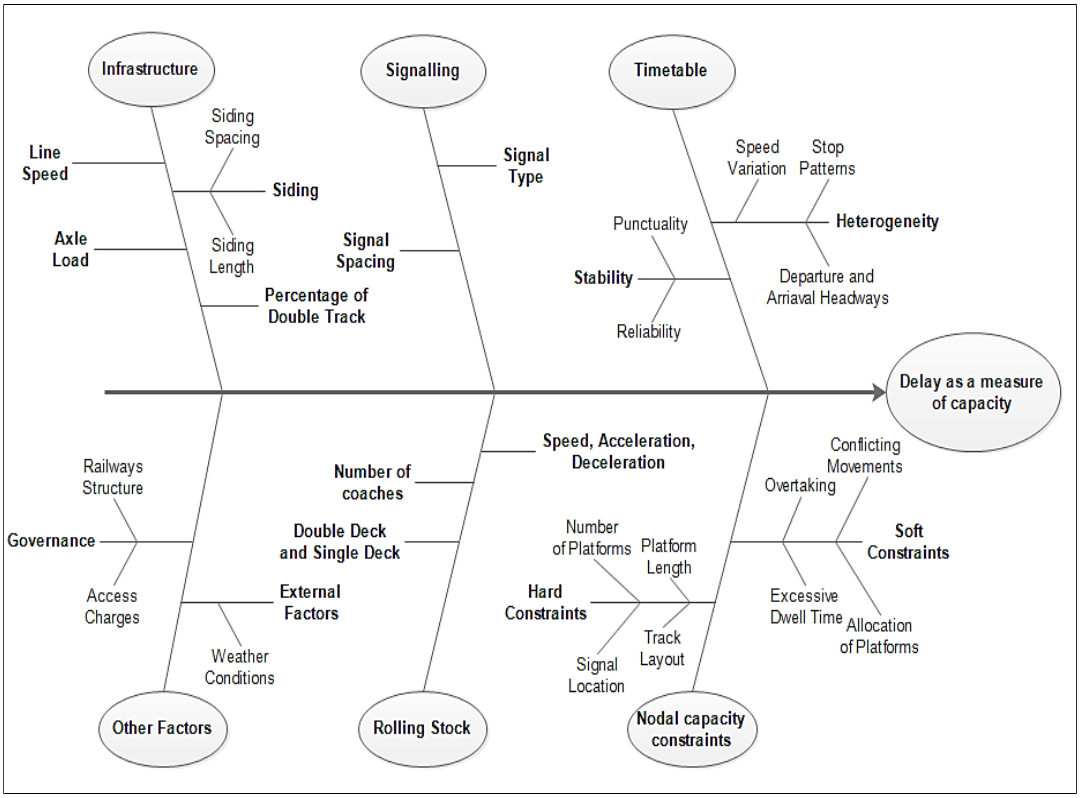


Figure 2.3: Factors affecting capacity

Timetable

A timetable is a tool for coordinating the trains that make possible to use the infrastructure effectively. It ensures the predictability of trains and provides information of train concerns (Pachl, 2008). Heterogeneity in traffic severely affects the capacity utilization due to irregularities in traffic flow (e.g., variation in speed, the difference in headways) and complex timetable planning. Dingler (2009) studied the effect of heterogeneity on delays and confirmed that heterogeneous traffic stimulated the delays adversely than homogeneous traffic. Punctuality and reliability are the essential factors for timetable stability and also the essence of public performance measure (PPM) of United Kingdom.

Signalling

Railway traffic on track is maintained using signaling system that regulates the trains in a safe manner by maintaining the safe distance between them (Bonnett, 2005). Advancement in signaling systems is reducing the safe distance between trains or decreasing the headways and improving the capacity utilization to a great extent. The European Railway Traffic Management System (ERTMS) is capable of maintaining safe braking distance at higher operation speed thus make increase the capacity utilization (UNIFE, 2009).

Infrastructure

The key infrastructure parameters that affect the capacity utilization are; siding, line speed, axle load and percentage of double track. Siding is the location that is used in railroad network for the overtaking or crossing purpose so, the length of siding should be enough to accommodate the passing train. Siding spacing, the distance between sidings, also have a great impact on railway capacity if it is not planned in uniform and effective way. The operational speed of the railway depends on line speed and rolling speed. If the line does not permit the high speed, then it will affect the overall operational speed and hence will affect the capacity utilization adversely. For the heavier freight, the line should be designed to bear maximum axle load. Double track significantly increases the capacity due to separate lines for each direction so, no crossing issue arises. A study by Kittelson and Associates (2003) shows that the double track usually has four times capacity than a single track.

Nodal capacity constraints

Stations and junctions are the points in the network from where the traffic originates merges and terminates. These points serve as a bottleneck for smooth flow of trains in a network. Various constraints that affect the nodal capacity of the network can be divided into soft and hard constraints. Soft constraints are related to operational restrictions that propagate the delays in operation, and these are - excessive dwell time of trains at a station, overtaking and conflicting issues of trains at the platform, allocations of platforms for the approaching trains. Hard constraints are infrastructure related factors like a number of the platform, length of the platform, crossing layout and, signal location.

A number of platforms and the length of platforms should be sufficient to accommodate necessary train services otherwise it will increase waiting time. The crossing layout provides the flexibility of changing tracks for trains and avoids the conflicting movements at level crossings. Well-planned crossing layout and properly selected signal location reduce the delay and increase the capacity utilization effectively.

Rolling stock

More loading capacity and diminishing travel time of the rolling stock significantly increase the capacity utilization. More loading capacity is possible with double deck and more number of coaches. The travel time can be reduced considerably, if the operational speed of the rolling stock is higher, and it has quick acceleration and deceleration. Speed, acceleration, and deceleration depending on the tractive effort of the locomotive and technical specification of rolling stock.

Other factors

Severe weather conditions (like fallen leaves, flood and, snow) are uncontrollable to human beings that affect the railway operations and have a negative impact on capacity utilization. These circumstances also increase the cost of operation and also increases the accidents. According to estimation in Great Britain, the annual cost of severe weather conditions to railway industry is about £50 million. (Network Rail, 2010a)

The structure of railways is different in diverse parts of the world, so capacity utilization naturally varies worldwide.

2.4 Models to estimate railroad capacity utilization

There are several approaches to determine the rail line capacity. Each approach has its pros and cons because these are modeled for a particular application and are developed in different infrastructural and operational conditions. Specific parameters and constraints chosen in these models are also separate them from each other. Some models exactly emulate railway operations and give precise results, however; they are complex in practice but are helpful in taking operational and business decisions. Some models provide approximate answers quickly that can guide for the planning stage of the project (Assad 1980). In the literature, the methods to calculate railways capacity are categorized into four sections as analytical, parametric, optimization and simulation models (Krugner, 1999; Abril, 2008; Sogin, 2013).

2.4.1 Analytical models

Analytical models are simple in practice and give the initial and quick estimate of line capacity. These models are useful in the planning phase and can evaluate the complete network of railways. Poole (1962) developed a simple mathematical formula to measure the maximum capacity of single track line (capacity = speed/distance between sidings ×24). Mirko Cicak and Dragomir Mandic (1995) calculated the capacity utilization of Yugoslav Railways regarding oscillation coefficient. Petersen and Taylor (1982), Martland (1982), Kraft (1988), Malaspina and Reitani (1995) shows the accountable work in determining railways capacity with different models. Analytical methods comprise two most renowned CUI and UIC-406 method.

2.4.1.1 CUI Method

In this method, Capacity Utilization Index (CUI) is used to determine capacity level. Gibson et al. (2002) define the CUI as the ratio of operating time after squeezing the timetable (B) to the actual operating time of the timetable (A). The timetable is squeezed according to the minimum headway allowed between the trains as shown by thick lines in figure 1.

The CUI method is more popular in British operating context as it is based on *Timetable Planning Rules* (also known as *Rules of Plans*) which were produced by Network Rail (owner and operator of British Rail). Faber Maunsell (2007) used the CUI method for estimating the effect of the extra train on tariff charges.

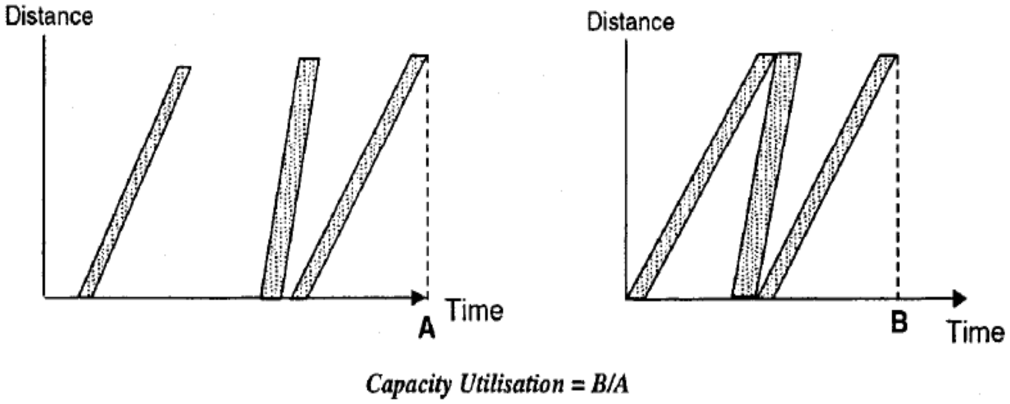


Figure 2.4: Definition of capacity utilization index (Gibson et al.)

2.4.1.2 UIC-406 Method

In 2004, for the capacity calculation, a method was proposed by International Union of Railways, which enables the infrastructure managers to carry out the capacity calculations from the standpoint of universally accepted definition and criteria.

The proposed methodology in this leaflet was based on existing timetable compression process within a line section. The timetable graph is compressed to keep up the minimum headway time as shown in figure 4. Buffer times and maintenance times have also added that favor to stability in operation.

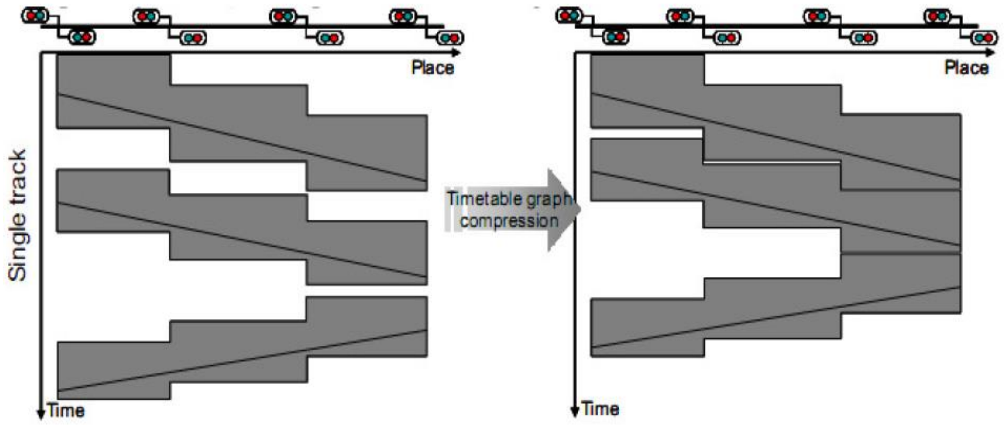


Figure 2.5: Timetable compression according to UIC-406.

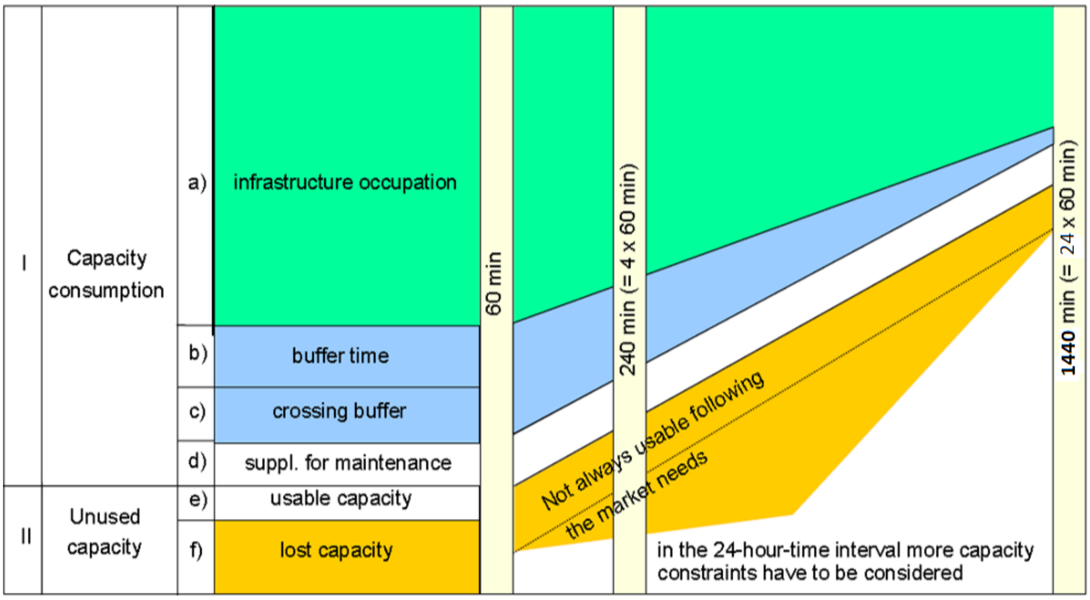


Figure 2.6: Capacity consumption

Capacity consumption is determined as follows:

Total consumption time (in Minutes) = (Infrastructure occupation time) + (Buffer time) + (Buffer time for crossing on single lines) + (Supplements for maintenance)

$$\text{Capacity consumption } (\%) = \frac{\text{Total consumption time}}{\text{Chosen time window}} \times 100$$

Then it is compared with standard values of Table 3 to know whether the infrastructure is congested, or there is leftover capacity exist.

Table 2.2: Recommended values for capacity utilization according to UIC-406

Type of line	**Peak hour**	**Daily period**	**Comment**
Dedicated suburban passenger traffic	85%	70%	The possibility to cancel some services allows for high levels of capacity utilization.
Dedicated high-speed line	75%	60%	
Mixed-traffic lines	75%	60%	Can be higher when number of trains is low (smaller than 5 per hour) with strong heterogeneity

Höllmüller and Klahn (2005), Landex (2006), Lindner (2011) extended the applicability of this holistic approach respectively in Australian railways, Denmark railways, and North American Railways network.

CUI and UIC-406 methods are similar in approach as both are based on Timetable Compression but have the difference in the level of details. UIC-406 is more detailed because it is applied at signal block levels while CUI is applied for route sections that do not consider individual block sections. The drawback of CUI approach is that it can be used only at the macro level. Therefore, it gives a broad estimation of capacity, and there is no provision to access the nodal (e.g., station) capacity. However, Armstrong et al. (2009) tried to remove the drawbacks of CUI method by extending the applicability of CUI approach from network links to nodes. He showed the procedure to handle many complex capacity assessment problems.

2.4.2 Parametric models

In parametric models infrastructure, operational and traffic parameters are used to develop a model and to analyze the capacity of railway's network. The parametric models are best suitable for strategic capacity planning as they are dynamic and capable of determining the capacity of subdivisions of railroad network. Prokopy and Rubin (1975) developed a multivariate regression model to analyze the effect of various operational parameters on train delays. Krugner (1999) also followed the Prokopy and Rubin and explored the Railroad capacity with the help of different parameters. He divided the parameters in three categories as plant parameters (length of subdivision, meet-pass point spacing, signal spacing, percentage of double track), operation parameters (track outages, temporary slow orders, train stop time, maximum trip time threshold) and traffic parameters (traffic peaking factor, priority probability, speed ratio, average minimum run time). The delay was chosen as a capacity measure. The model was capable of determining line section capacity and was also useful in sensitivity analysis of different parameters.

Lai and Barkan (2009) followed the Krueger's work (1999) and developed a parametric model. The model is an integral part of Railway Capacity Evaluation Tool (RCET), which is used to evaluate an investment in capacity expansion strategies. The tool consists of three modules as sown in Figure 6.

- Alternative generator (enumerates the possible expansion options)
- Investment section model (determine the suitable parts of network for improvement)
- Impact analysis model (gives the trade-off between investment and costs of delay)

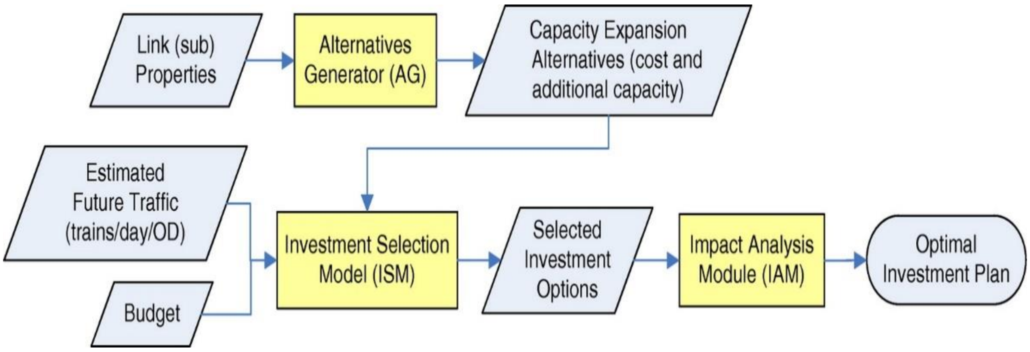


Figure 2.7: Railway Capacity Evaluation Tool (RCET)

Mitra et al. (2010) developed a computer algorithm and user-friendly interface to measure the sectional capacity of railways network. He used five parameters in the user interface that are average speed, speed uniformity, the distance between sidings, length of line section and, block section length. Lai and Huang (2014) developed the models based on regression analysis and neural networks to estimate train delay and line capacity.

Parametric models are seen to bridge the gap between analytical and simulation models as they use more data than analytical models to give more accurate results, but exhaustive simulation work is diminished so provide solutions quickly. However, parametric models are not popular as others because they provide an only single estimate to judge the performance. White (2006) illustrates that in most of the parametric models, the delay is chosen as performance measure that is insignificant in all situations. These models cannot also provide the comprehensive analysis of individual train as possible in case of simulation models.

2.4.3 Optimization models

Optimization methods are extensively used to find the strategic solutions to specific problems of capacity like Train scheduling, routing, platform allocation, and siding. These methods search the optimal solutions generally in the form of saturated timetable subject to constraints levied by heterogeneity, stopping patterns and so on.

In a paper, Asad (1980) reviewed the capacity calculation techniques before the 1980s. Jovanovic and Harker (1991) solved a mixed integer linear programming model by using branch-and-bound method for feasible schedule. The economic impact of Timetable scheduling was studied by Harker and Hong (1994), who introduced a computable model of an internal market for track resources. Cai and Goh (1994), Carey and Lockwood (1995), Higgins et al. (1996) illustrate heuristic driven approaches to obtain capacity and associated objectives.

Schobel (2001), Mattson (2004) Yuan and Hansen (2007) developed fast algorithms for rescheduling and managing delays. Oliveira and Smith (2000) model the problem as a job shop scheduling problem. They consider the trains as jobs that are to be accommodating on Railway paths. Burkolter (2005), Jia et al. (2009), Milinkovic et al. (2011) used the Petri Net to measure the node capacity.

2.4.4 Simulation models

In simulation models, solutions are generated by imitation of real-world process or system over the time. Due to the dynamic behavior of the model they are used for realistic and accurate analysis of Railroad capacity problems. These models are used as combinational approaches with other methods or in the form of complete simulation packages. In combinational models, results are obtained by analytical or optimization methods and then refined by simulation process. These models are also used as a tool for validation of optimization results. Petersen (1974) combined the dynamic programming and branch-and-bound in a simulation context. Welch and Gussow (1986) combined simulation and heuristics to evaluate the relative effect of the many factors that influence line capacity.

Kass (1991) developed a simulation model SCAN (Strategic Capacity Analysis for Network) for Rail network analysis. Jovanovic and Harker (1991), Cofessore et al. (2009), Armstrong et al. (2011) combined the simulation with optimization to access used capacity.

Simulation packages are helpful in academic as well as in rail industry to an extensive analysis of rail operations. Abril (2008), Barber (2007), Kontaxi and Ricci (2011), Khadem sameni (2012) presented a broad survey of railway simulation packages.

Popular software for railways operations

Popular software with their vital features is summarized in Table 4. This table also gives the comparison among them by following characteristics tools of software:

Simulation: The tool provides the function to generate simulation models of railways network and graphically display real-time train operations.

Infrastructure Manager: The tool helps to model the existing infrastructure and simultaneously shows the possible infrastructure variants.

Station Manager: The tool supports the planners in solving routing problem of trains at a railway station.

Timetable Optimization: The tool helps in scheduling the train movements and generates a timetable by optimization algorithms.

Timetable Manager: The tool has the functionality of editing train timetables data in graphic or tabulates way.

Investment evaluation: This tool helps to analyze the investment in project

Capacity Analysis: The tool is used to assess railway capacity.

Table 2.3: Comparison of popular software for Railways operations

Software	Producing company/ Country	Simulation	Infrastructure Manager	Station Manager	Timetable optimization	Timetable Manager	Investment evaluation	Capacity analysis			
								Theoretical capacity	Practical capacity	Used capacity	Available capacity
AFAIG	EPFL + SBB/ Switzerland	x	√	√	x	x	x	?	x	x	x
CAPRES	EPFL + SMA and partner/ Switzerland	x	√	√	√	x	?	√	x	x	√
CMS	AEA Technology Rail/ UK	√	√	√	√	√	?	√	x	x	√
DEMIURGE	SNCF/ France	x	√	√	√	x	?	√	√	√	√
FASTA	EPFL + SBB/ Switzerland	√	√	x	x	√	?	?	x	x	x
FAST TRACK II	MultiModal Applied Systems + Rail Sciences of Atlanta/	√	√	√	√	√	?	?	?	x	x
IRCIM	I. A. P. - Institute for Process Automation/ Slovenia	√	√	x	√	x	x	√	√	√	√
MOM	ADIF/ Spain	x	√	?	√	√	?	√	√	√	√
MULTIRAIL	MultiModal Applied Systems/ USA	√	√	√	√	√	?	?	?	?	?

Software	Producing company/ Country	Simulation	Infrastructure Manager	Station Manager	Timetable optimization	Timetable Manager	Investment evaluation	Capacity analysis			
								Theoretical capacity	Practical capacity	Used capacity	Available capacity
OPENTIME TABLES	EPFL + SBB/ Switzerland	x	x	x	x	√	?	√	x	x	x
OPEN TRACK	Institute for Transportation planning and systems/ Switzerland	√	√	x	√	√	?	?	?	?	?
PETER	Delft University/ Netherland	x	√	x	x	√	?	x	x	x	x
RAILCAP	Stratec/ Belgium	√	√	x	x	x	?	√	√	√	√
RAILSYS	Rmcon/ Germany	√	√	√	x	√	?	√	√	√	√
ROMAN	Siemens AG/ Europe	√	√	x	x	√	?	x	x	x	x
RTC	Berkeley Simulation Software/ USA	√	√	?	?	√	√	?	?	?	?
SIMONE	Railned/ Netherland	√	√	?	√	x	?	?	?	?	?
TPS	HaCon/ Germany	√	√	x	x	√	?	x	x	x	x

2.5 Research trend in Railways Capacity Analysis

This section contains the recent research trend on different capacity assessment and improvement approaches.

2.5.1 Capacity analysis through bottleneck analysis approach

In the bottleneck analysis approach, the overall capacity of the complex network is determined by the capacities of its sections. First, the capacity of different sections is determined to identify the potential bottleneck sections in the network and then least capacitated section indicate the overall capacity of the network (Schwanhäußer, 1994).

In 2001, Heidergott and De Vries outlined the application of (max, +) algebra for train networks. De Kort (2003) used this technique for determining the capacity of infer-elements such as bridges and tunnels. He followed the Wakob's saturation theory (1985) with a different performance major that is the proportion of trains arriving in time at a station. This measure is more accurate than previous measure total waiting times of trains reaching to a station, which was used by Wakob. This approach was dealt with stochastic fluctuations and service demand uncertainties and was also claimed to determine station capacity.

Burdett and Kozan (2006) analyzed the traffic carrying capacity by extending the bottleneck analysis approach by including different regimes. These include a mix of trains travel to both of direction, the variable length of trains, intended dwell time of trains, intermediate signals and crossing loops in networks. Lorenzo Mussone (2013) followed the work of De Kort and, Burdett and Kozan and proposed a new approach with a potential to explore the whole circulation system systematically and also make it possible to analyze all bottlenecks with capacity constraints. He solved the model with a simplex method that makes this approach more attractive.

2.5.2 Capacity analysis through multi-commodity flow model

Do Chung et al. (2011), Berglund and Kwon (2013) find the different applications of discrete-time multi-commodity flow model in transportation. Şahin et al. (2010) demonstrated the problem as Binary Multi-commodity network design model with the help of route arcs and node-arc. The route arc represents the occupancy of the line segment between two nodes by a train in a discrete time unit, and node-arc is for stopping time for a node. The constraints used for problem limit the concurrent occupation of track for one train and occupation of the station for user-defined train. Masoud Yaghini et al.

(2014) formulate the multi-commodity problem in two steps. In the first step, possible train paths are generated based on train types and infrastructure. In a second step, the problem is modeled as discrete-time multi-commodity network design problem and solve by local branching heuristic algorithm.

2.5.3 Capacity analysis through infrastructure improvement

Some studies also have been done to increase line capacity through infrastructure improvements, for instance, Petersen et al. (1987) given the simulated solution for the preeminent location of longer sidings to accommodate the passenger trains with freight train lines. Sam Paul Singh Pawar (2011) determined the length of longer sidings by analytical models to enhance the capacity of single track line. These studies have limited applicability because these are based on some particular type of alternatives and not cover all possible situations of general scenarios. Lindfeldt (2013) discussed the comparatively more general case in which a successive and stepwise process is suggested to upgrade to a double line. This analytical strategy can be helpful in cost-benefit analyzes to value upgrade measures of the different parts of the railway line. However, these strategic results are also difficult to be generalized because he analyzed the case of a line section with specific existing characteristics. In another study, Lindfeldt compared the partial double track with a single track with sidings and found that partial double track provides more timetable flexibility and improve more capacity. Sogin et al. (2013) focused on how the capacity is affected in the transition process from a single line to double. He found out the simulation results for each intermediate phase of infrastructure changes for different traffic levels to determine the amount of double track needed to mitigate the effect of increased traffic on rail corridor. Shih et al. (2013) also performed a similar type of work with the sparse sidings and determined the best strategy to concentrate passing siding projects towards the middle of a sparse single-track corridor. These results are valid when the amount of second track is in the range of 9.5 to 19 percent.

Martin Kendra et al. (2012) suggested changing infrastructure and operation parameters of railway line brings an increased level of track capacity. He derived formulae based on fundamental physical laws to calculate the maximum capacity and maximum capacity of transported wagon units per track section. The calculations were based on the minimum radius of curvature changes, and work was limited to freight trains.

2.5.4 Capacity analysis through UIC-406

Dl Robert Prinz (2005) used the UIC-406 method to calculate the capacity consumption on Australian railways lines and experienced it effectively. He concluded that the method has over other because it is based on hard facts like infrastructure, existing timetable and little influenced by other factors, e.g. priorities, the current level of quality, and so on.

Landex (2006, 2008) expounded the UIC-406 method in different ways in Denmark. He explained how to choose the correct length of line section and how to calculate the capacity consumption for two or more tracks. He suggested not dividing the railway line into line sections at the overtaking because it leads to more capacity utilization, and trains order remain same during compression graphs at both ends of line section to avoid additional overtaking. Landex (2009) extended the UIC-406 application to evaluate the railway networks with single track operation.

Lindner (2010, 2011) found problems with applying the UIC-406 method to assess the capacity of the station because code concentrates only on the line sections and not give the procedure to find station capacity. The code also not dictates how to choose the correct length of line sections in case of longer sections of single track with many sidings that are very common on North American railroads. Lindner suggested using virtual traffic diagram method than the original timetable to get the more realistic results. He also advised the UIC to demonstrate the procedure for capacity calculation in the mixed traffic pattern. Landex (2011) showed with examples that how can find the node capacity (e.g., station).

Jiamin Zhang, Baoming Han, Lei Nie (2011) developed a framework for calculation and assessment of Chinese High-Speed Railways (CHSR). This framework was based on UIC-406 code but uses the plan of operation instead of existing timetable to calculate the capacity of line section or station.

2.5.5 Capacity analysis through DEA

Khadem Sameni (2012) analyzed the efficiency in railway capacity utilization by Data Envelopment Analysis (DEA). DEA is a helpful tool for evaluating the performance where inputs and outcomes are in a complex relationship. He chose the inputs by economic and engineering information, and the output was obtained regarding qualitative (delay minutes) and quantitative (passenger-Km) data to judge the value of provided services by Great Britain Railways.

All the work on capacity cannot be explained in details, so recent and noticeable work is summarized in Table 2.4.

Table 2.4: Recent and noticeable work on railroad capacity

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
Dl Robert Prinz (2005)	UIC-406; Simulation	Capacity analysis	• Analyzed capacity consumption for main lines of Railway network	Followed UIC406 method and calculations are done by simulation tool named SIMU	Australian Railway Network
Abril et al. (2006)	Simulation	Capacity utilization	• Review of capacity analysis methods • Analyze network capacity utilization and timetable robustness	Developed a system termed as MOM system examined the capacity	Railway network in Spain
Burdett and Kozan (2006)	Optimization	Absolute capacity	• Determined absolute capacity for railway lines and networks with uni and or bi-directional traffic	Mathematical model developed, solved by GAMS algorithm and got locally optimal solutions	171.59 kilometers long track of Australian Railways
Cambridge Systematics (2007)	Theoretical study	Capacity expansion through infrastructure improvements	• Identified service level for primary corridors in the US Railways • Anticipated future demands for freight Railroad in the US	Data analysis technique	United States

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
Harrod (2007)	Optimization; IP	Improving capacity utilization	• Investigate the capacity limits and service quality on congested networks	With the help of FileMaker database created, model the problem and interpreted the results by Ampl program	United States
Cofessore et al. (2009)	Simulation	Maximize commercial capacity of Railways	• Access the practical capacity of the whole line and line section	Developed an algorithm to minimize the departure times of trains using compression method then simulated in ARENA to validate the results	Italian rail line Verona-Brennero
Lindfeldt Olov (2010)	Simulation	Analyzing and improving capacity utilization	• Analyze the impact of infrastructure improvements timetable variants on capacity utilization	Through Railsys software prepared the model of infrastructure and rolling stock. Enter the timetable, and primary delays are calculated	Swedish railway
Murali et al. (2010)	Simulation	Managing capacity	• establish relationships with travel time delay, train mix, operating parameters, and the network topology	Use a simulation model to collect travel time data and then regression model is fitted to the data to develop the delay model.	Los Angeles Railway Network

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
			• Estimate delay and capacity of a network		
Pudney et al. (2010)	Theoretical study	Corridor capacity analysis	• Develop methods for assessing and ranking the impact of projects designed to improve the capacity of a rail network	Data analysis	Australia
Roberts et al.(2010)	Optimization	Improving the capacity utilization	• Develop a matrix tool for capacity independencies • Gives a model for choosing capacity enhancement measures	A relationship matrix is developed and solved to estimate sensitivity of parameters	UK
Mitra et al. (2010)	Parametric	Capacity estimation	• Developed a computer algorithm to measure railroad section capacity • Identify bottlenecks and measure system capacity of a railroad network	for capacity estimation, multivariate regression analysis is performed to develop a continuous relation between the discrete parameters	North Dakota
Kontaxi and Ricci (2010)	Simulation	Measuring and analyzing capacity	• Survey of capacity measuring methodologies since the 1950s	Different parameters are inserted in simulation software RailCAT	Railway network in Italy

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
			• Developed an integrated online capacity calculating tool RailCAT		
Milinkovic et al. (2011)	Simulation	Improving capacity utilization	• Estimating primary delays for each train	Fuzzy Petri Net (FPN) and Adaptive Network Fuzzy Inference System (ANFIS) used to estimate delays	Belgrade railway node
Armstrong et al. (2011)	Analytical; CUI	Node capacity analysis	• Extending the application of CUI method to measure capacity utilization of junction and station nodes	Compression graphs	Pirbright Junction, London, Southampton Airport Station
Zhang J. et al. (2011)	Theoretical	Analysis and improving capacity utilization	• Gives a framework to plan future capacity of high-speed railways through simulation	Based on developed framework	Chinese high-speed railways
Khadem Sameni (2012)	Simulation	Measuring, analyzing and improving capacity	• Improving and controlling capacity utilization by applying variation reduction and FMEA analysis	DEA model is developed, solved by PIM DEA-V3.0 software and results are validate by Tobit regression model; by a mathematical expression, revenue is calculated	120 busiest train stations in the UK; 262 miles long North American single track line

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
Martin Kendra et al. (2012)	Parametric	Track capacity analysis	• Minimized the travel time and increased the track capacity and volume of goods by changing basic infrastructure and operation parameters	Parameters are calculated by fundamental physical laws and occupation time is calculated	15-kilometer long line section in Western Europe
Sogin et al. (2013)	Simulation	Capacity analysis of rail corridors	• Studied the effects of higher passenger train speed son capacity in various infrastructure configurations	Using RTC software and regression analysis	245 mile long North American rail corridor
L. Mussone (2013)	Analytical	Capacity of a railway system	• Timetable free approach to determine line capacity • Analyzing priorities between trains and possible delays	Translate the non-linear problem into linear by removing constraints and solved by simplex method	32 kilometers Swiss transport network
Alex Landex et al. (2013)	UIC-406; Optimization	Station capacity analysis	• Analyses the capacity of stations by the use of track complexity and robustness of operation • Analyses the infrastructure complexity in the switch zone(s).	For station capacity, UIC-406 methodology used; Probabilistic modeling based complexity index methods for infrastructure complexity and robustness of timetable	Skanderborg station, Denmark

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
Dingler et al. (2014)	Simulation	Heterogeneity versus capacity analysis	• Derive correlation between volume, Heterogeneity, and delay • Analyze the impact of heterogeneity on speed, acceleration, braking and priority decisions	The delay is chosen as a primary metric; Multiple operational and infrastructure scenarios were simulated by RTC to calculate various effectiveness methods of reducing delays.	Single track line of 262 miles long with 10-mile siding spacing; Northern America
Shih et al. (2014)	Simulation	Capacity expansion	• Give a model to choose the best infrastructure expansion strategy	efficiency and reliability analyses were used to evaluate the performance of alternatives according to RTC simulation data	240-kilometer long single-track line in North America
Lai and Huang (2014)	Parametric	Estimating and improving rail capacity	• Model to Predict capacity for both single and double Identify critical factors of rail capacity	Modeling the problem with associated parameters, simulate the results by RTC those are validated by neural networks and regression analysis	260 miles long mainline rail network, North America
Masod Yaghini (2014)	Optimization; IP	Impacts of different train types on railway line capacity	• Calculate the capacity of the railway line and a line section	Discrete-Time-Multi-commodity network design model generates the compressed	Single track line of 332 kilometers long with 21

Author(s)	Model Description	Main Theme	Major contributions	Solution mechanism	Study performed on
				timetable based on UIC-406, solved by local branching heuristic algorithm	stations of Iran Railways
Hamed Pouryousef et al. (2015)	Simulation	Examine the trade-off between level of service and capacity utilization	• Find a relationship between Level of service parameters and capacity utilization	The output of RTC was used as input to RailSys	28 scenarios were developed in RTC
Lars Wittrup Jensen (2015)	Optimization	Estimate the capacity of Railway Network	• Estimate how many trains can be added to the mix solution until the capacity threshold	Model the problem and solved by greedy heuristic to schedule the trains; dichotomic search algorithm is used for capacity threshold by adding more trains	161 kilometers long double track of Danish Railways
Francisco A. Ortega Riejos (2016)	Optimization	Optimize the capacity of Railway network	• Analyze the capacity of the main corridor and radial lines	Developed an algorithm for scheduling a railway line	High-speed line Madrid–Seville.

2.6 Research gap identification

Based on literature review, it has been observed that,

- A less number of approaches are observed to measure Network capacity of mix corridor network in heterogeneous traffic.
- Impact of various parameters on railroad capacity in mix corridor network with heterogeneous traffic is not sufficiently analyzed.

- No noticeable study has been carried out to manage the capacity of networks through improved operations in the context of India.
- Incremental infrastructure expansion process is not sufficiently analyzed.

2.7 Research objectives

The following objectives are set based on the research gap;

a) **Measure capacity utilization-** Develop an optimization approach based on basic infrastructural and operational data to measure capacity utilization of mix corridor network in heterogeneous traffic.

b) **Analyze the impact of different parameters on capacity-** Analyze the impact of different parameters on railroad capacity. Also, enhance the capacity by considering operational and infrastructural parameters.

2.8 Summary

This chapter explores the concept of railways capacity and examine the vital research work on capacity concisely. This chapter defines the capacity and parameters that affect it. It is found that a globally accepted definition of capacity is still a challenge to researchers and to examine the impact of all the parameters is a vital task. To choose a metric for performance measurement is also controversial in many situations.

Different capacity models are also reviewed. Analytical models are found best for the new planning of lines, where the only rough estimate is sufficient for a new project. Optimization tools are found to solve a specific problem and gives the optimal solution to the problem. Simulation tools are best suited for the operational phase of a project where inappropriate results may lead to increasing the project cost adversely. Popular software packages with their key features are also addressed in table 3. Parametric tools also found good for planning and operational phase but give the less exact solutions than simulation tools.

The last part of the chapter summarizes the noticeable researches on railways capacity through table 4. Based on the literature specific objectives for research are set.

CHAPTER 3

MODEL FORMULATION FOR RAILROAD CAPACITY ANALYSIS

3.1 Introduction

The literature review presented in chapter 2 indicated that a capacity analysis of railroads demands a model, which can provide the optimal and advantageous movement of trains on railway networks. For capacity determination, different techniques and models are also discussed in chapter 2. In this chapter, the proposed model for railroad capacity determination is first described then a computational model of the proposed mathematical model is developed.

3.2 Assumptions of proposed model

The following assumptions are considered for the capacity model development;

- Headway distance is not considered.
- Track structure is considered same for the whole line
- Buffer time is not considered
- All the trains have same dispatching priorities.

3.3 Mathematical model

This thesis focuses on railroad capacity analysis through optimization model. The prerequisite of optimization model is the following basic infrastructure and train type attributes.

- List of corridors which forms the railway network
- Line sections present in each corridor
- Length of all the line sections
- Number of train types
- Average speed of train types
- Number of tracks present in each line section
- Sectional running times of train types
- Sectional occupation times of train types
- Intended period of study
- Dwelling time of train types on corridors

- Proportion of train types on corridors
- Directional distribution of train types on corridors

The variables and parameters of the model are defined in Nomenclature.

Nomenclature

C	capacity of network
i	Train type index. The set of trains is I = {1, 2...}.
T	Intended period of study
n_1, n_2	Location index
Φ	The set of input/output (IO) points
Δ_{i,n_1,n_2}	Total dwelling time of train type *i* on corridor
p_i	Proportion of train type *i* on corridor
D_i	Directional distribution of train type *i* on corridor
t^s_{i,n_1,n_2}	Sectional running time of train *i* between n_1, n_2
t_{i,n_1,n_2}	Sectional occupation time of train i between n_1, n_2
P_c	Proportion traffic on corridors

The objective function of the model is a maximizing function that gives the maximum network capacity, over a specified period T. Number of trains for both forward and backward direction are considered in the model.

$$MAX, C = \sum_{\forall n_1,n_2 \in N} \sum_{\forall i \in I} (X_{i,n_1,n_2} + X_{i,n_2,n_1}) \qquad (3.1)$$

In the equation (3.1) X_{i,n_1,n_2} ,X_{i,n_2,n_1}defines the number of number of train types *i* traversing in forward and backward direction respectively on the corridor.

Constraint 1:

The constraint (3.2) defines the proportional distribution of train types across corridor.

$$X_{i,n_1,n_2} + X_{i,n_2,n_1} = p_i \sum_{\forall j} \left(X_{i,n_1,n_2} + X_{i,n_2,n_1} \right) \qquad (3.2)$$

$$\forall i, j \in I, \forall n_1, n_2 \in N$$

Constraint 2:

The constraint (3.3) defines the directional distribution of train types across corridor c.

$$X_{i,n_1,\, n_2} = D_i \left(X'_{i,n_1,\, n_2} \right) + (1 - D_i) \left(X'_{i,n_2,\, n_1} \right) \qquad (3.3)$$

$$\forall i \in I, \forall n_1, n_2 \in N$$

Constraint 3:

Sectional occupation time is the sum of sectional running time and dwell time. Sectional occupation time is restricted by the constraint (3.4) which ensure that the Sectional occupation time must be less than the intended period.

$$t^s_{i,n_1,n_2} + \Delta_{i,n_1,n_2} = t_{i,n_1,n_2}$$

$$t^s_{i,n_2,n_1} + \Delta_{i,n_2,n_1} = t_{i,n_2,n_1}$$

$$\sum_{\forall i} (t_{i,n_1,n_2} + t_{i,n_2,n_1}) \leq T \qquad (3.4)$$

$$\forall i \in I, \forall n_1, n_2 \in N$$

Constraint 4:

Constraint (3.5) enforced the proportional traffic to corresponding corridors. This regulates the competition between corridors with common sections.

$$\sum_{\forall i} \left(X_{i,n_1,n_2} + X_{i,n_2,n_1} \right) = P_c \sum_{\forall n_1,n_2 \in N} \sum_{\forall i \in I} (X'_{i,n_1,n_2} + X'_{i,n_2,n_1}) \qquad (3.5)$$

$$\forall c \in C, \forall n_1, n_2 \in N$$

Constraint 5:

Constraint (3.6) satisfied the condition of Positivity.

$$X_{i,n_1,n_2}, X_{i,n_2,n_1} \geq 0 \qquad (3.6)$$

The complete mathematical formulation is described as follows:

$\boldsymbol{Objective\ function}$:

$$MAX, C = \textstyle\sum_{\forall n_1,n_2 \in N} \sum_{\forall i \in I} (X_{i,n_1,n_2} + X_{i,n_2,n_1})$$

$\boldsymbol{subject\ to}$:

$$X_{i,n_1,n_2} + X_{i,n_2,n_1} = p_i \textstyle\sum_{\forall j} (X_{i,n_1,n_2} + X_{i,n_2,n_1})$$

$$X_{i,n_1,n_2} = D_i \left(X'_{i,n_1,n_2} \right) + (1 - D_i) \left(X'_{i,n_2,n_1} \right)$$

$$\textstyle\sum_{\forall i} (t_{i,n_1,n_2} + t_{i,n_2,n_1}) \leq T$$

$$\textstyle\sum_{\forall i} \left(X_{i,n_1,n_2} + X_{i,n_2,n_1} \right) = P_c \sum_{\forall n_1,n_2 \in N} \sum_{\forall i \in I} (X'_{i,n_1,n_2} + X'_{i,n_2,n_1})$$

$$X_{i,n_1,n_2}, X_{i,n_2,n_1} \geq 0$$

3.4 Implementing the mathematical model in commercial software

The mathematical model for determination of railroad capacity is described in section 3.3. As the number of variables is increased computational complexity is also increased so for the solution of the model it becomes necessary to convert the model into computational form. Graphical view of the computational model is shown in Figure 3.1. The following tools are required to convert the mathematical model into computational form.

- **A console window to write the program**- An optimization programming language (OPL) interface is used to script the model that is recognized by the IBM ILOG CPLEX. Different file types are used for solving an optimization problem with OPL:
  - Model file (used to write the program)
  - Input data file (worked as a data source for model)
  - Command file (used to run configuration)

  Usually, a model file has an extension .mod; an input data file has an extension .dat.

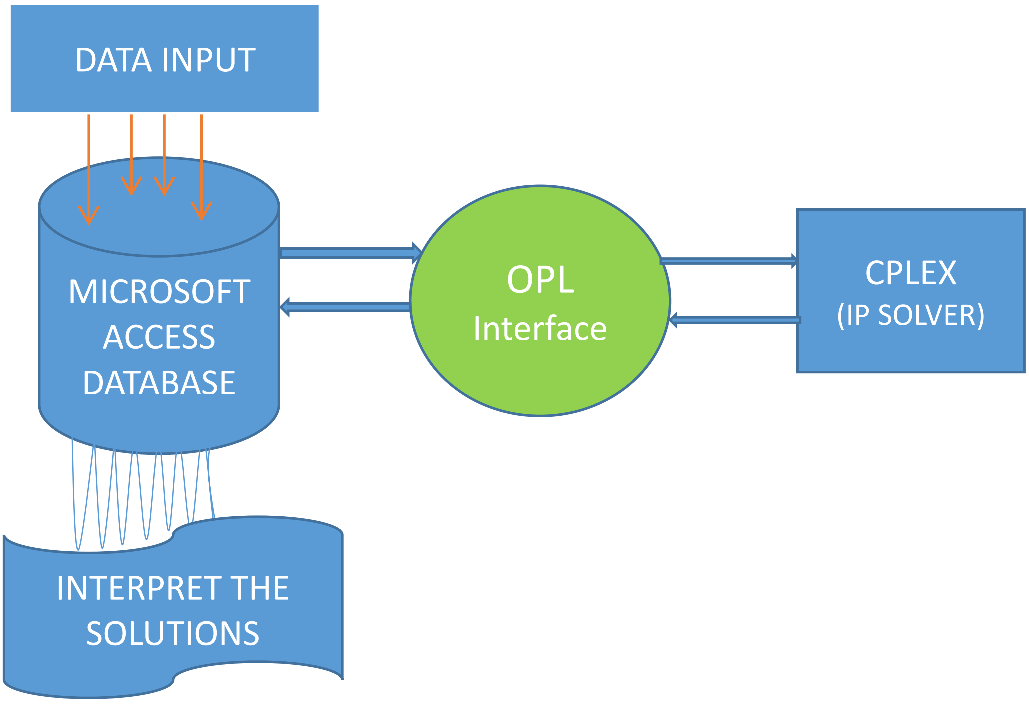


Figure 3.1: Graphical view of computational model of capacity

- **An IP solver-** The model is implemented in OPL to ensure recognition of the network structure by CPLEX12.

- **A database system-** A custom database written in Microsoft Access database facilitates editing of data sets, submits data to OPL in the proper format, and interprets the solutions returned.

3.5 Computational model

The complete formulation of a computational model for capacity calculation is presented in APPENDIX III. The following notations are used in the modeling of the computational model. These notations are different from the notations used in the mathematical model.

Constants

T	Time frame of the study
nbTrain	Number of train types
nbSec	Total number of sections
nbL	Total number of location
nbCor	Number of corridors in network
nbIO	Number of Input Output points in network

Ranges

Train = 1 .. nbTrain	Range of train types
Sec = 1 .. nbSec	Range of sections present in network
Cor = 1 .. nbC	Range of corridors in network

Sets

SECT	Set of sections
TRAIN	Set of train types

Parameters

SPEED [Train]	Speed of train types
LOS [Sec]	Length of line sections
CORS_SECT [Cor]	Corresponding sections present in each corridor
SRT [Sec] [Train]	Sectional running time
SOT [Sec] [Train]	Sectional occupation time
DD [Cor] [Train]	Directional distribution of train types on corridors
PD [Cor] [Train]	Proportional distribution of train types on corridors

PF [Cor]	Percentage flow of trains on each corridor
MAX_TRK [Sec]	Maximum number of tracks that can be added in a section
TRK [Sec]	Number of tracks present in a section
DT [Sec] [Train]	Dwell times

Decision Variables

CAPACITY	Capacity of network
NC_f [Cor] [Train]	The number of trains utilizing each corridor – in forward direction
NC_r [Cor] [Train]	The number of trains utilising each corridor – in backward direction
NS _f [Sec] [Train]	The number of trains utilising each section
NS _r [Sec] [Train]	The number of trains utilising each section
NC [Cor]	The number of trains running on each corridor
Used [Sec] [Train]	Time used by train types on each section
Used Total [Sec]	Time occupied on each section

3.6 Conclusion

In this chapter mathematical and computational models for determination of railroad, capacity are described. The model described here can be extended according to various scenarios. The model is implemented in commercial software CPLEX that provide the quick and exact solutions.

CHAPTER 4

APPLYING THE PROPOSED MODEL TO A SEGMENT OF INDIAN RAILWAYS

4.1 A case study

A real-life case study is selected to show the capability of the model. This thesis considers the simplified version on of Indian Railway network. A part of a network of 1315 Km length is selected for the study. The time frame of the study is chosen Figure

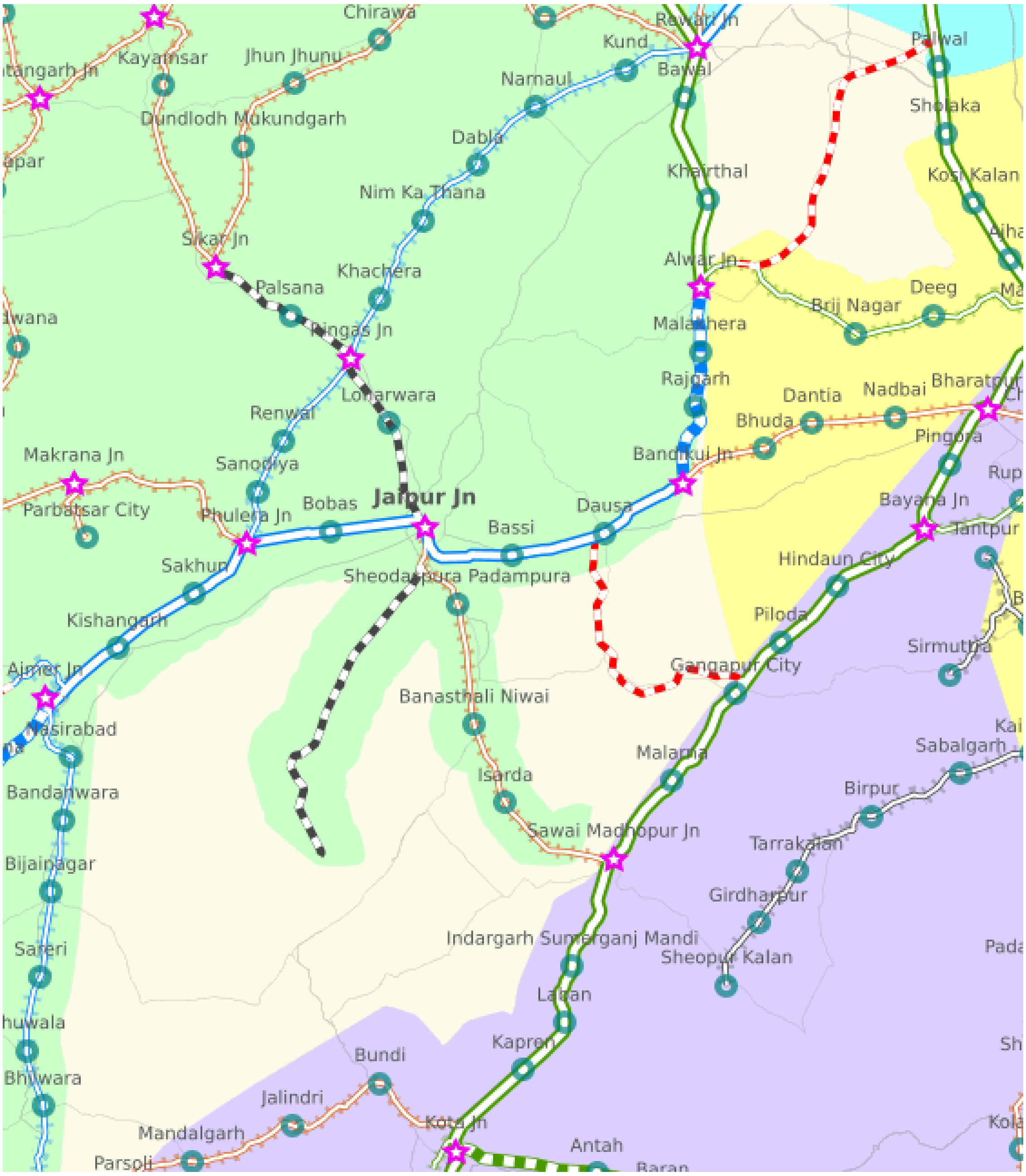


Figure 4.1: Network diagram

4.1 is the visual representation of main corridors and lines where passengers and freight are transported over the single and double tracks. The network is extracted from an official map of Indian Railways.

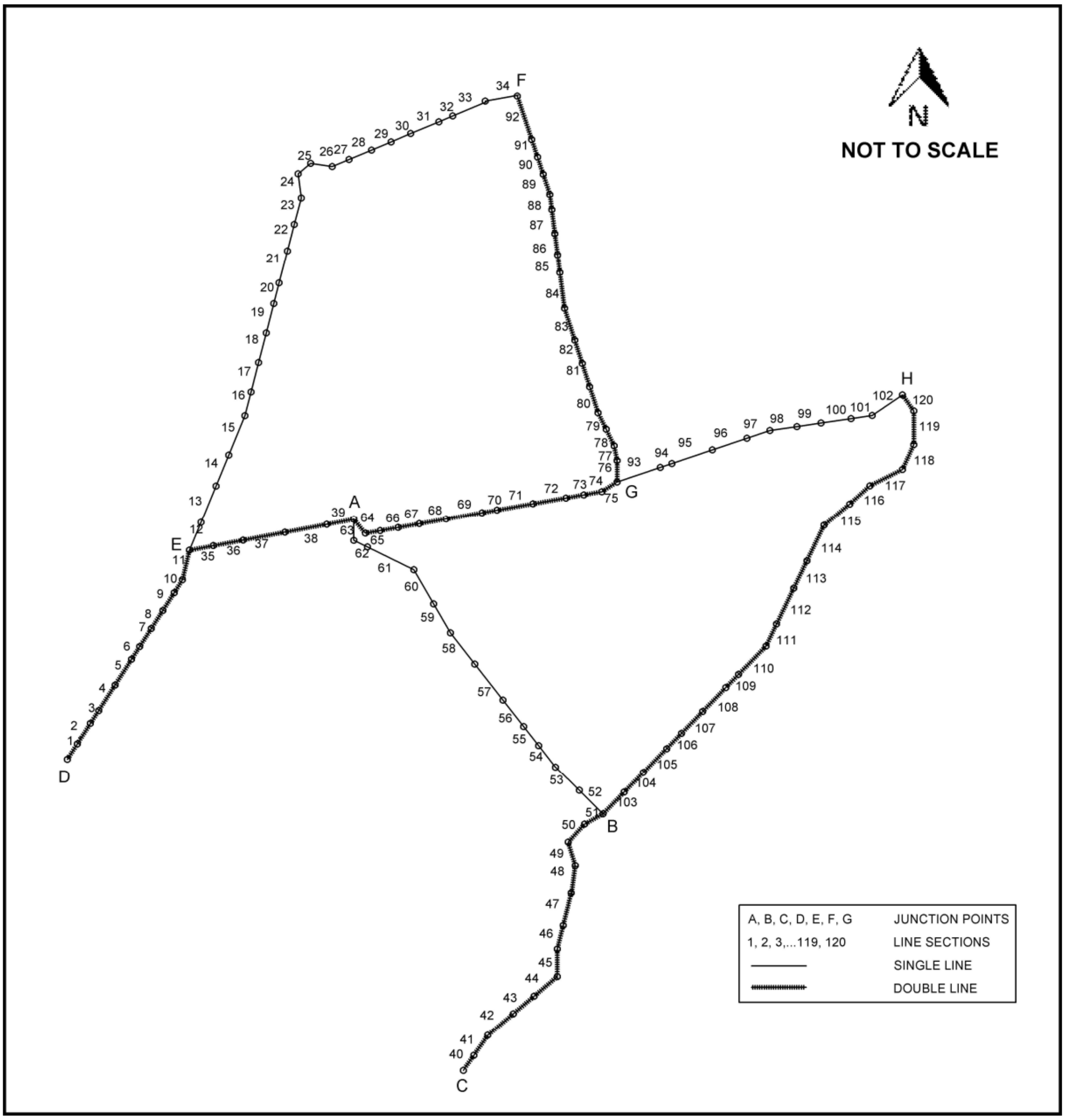


Figure 4.2: Schematic network diagram

Figure 4.2 shows the schematic diagram of the railway network. This diagram is not to scale, but it is close to the real network. It consists both single and double tracks of 120 line sections with seven junction points. The network has six operational corridors namely, (D-E-F), (D-E-A), (C-B-A), (A-G-F), (A-G-H) and, (C-B-H) out of all possible corridors. In this network, five points (D, F, A, H, C) are input-output nodes from where services are started or terminated. Six train types are running on the defined corridors with the average velocities as given in Table 4.1.

Table 4.1: Average speed of train types of Indian Railways

S. No.	**Type of trains**	**Average speed (in KMPH)**
1	Freight trains	25
2	Passenger	45
3	Mail express	55
4	Superfast Holiday special Garibrath	65
5	Shatabdi Janshatabdi Duranto	75
6	Rajdhani	85

Source: open government data

Sample network data for D-E-F corridor is shown in Table 4.2. The complete network data is presented in APPENDIX I. Sections present in each corridor are shown in Table 4.3.

Table 4.2: Sample network data

D-E-F CORRIDOR				
SECTION NO.	FROM	TO	SECTION LENGTH (in KM)	LINE
1	AJMER(AII)	MADAR JN(MDJN)	6	2
2	MADAR JN(MDJN)	LADPURA(LR)	8	2
3	LADPURA(LR)	GEGAL AKHRI(GEK)	5	2
4	GEGAL AKHRI(GEK)	KISHANGARH(KSG)	10	2
5	KISHANGARH(KSG)	TILONIYA(TL)	10	2
6	TILONIYA(TL)	GAHLOTA(GLTA)	5	2
7	GAHLOTA(GLTA)	SAHELI(SALI)	7	2
8	SAHELI(SALI)	SAKHUN(SK)	7	2
9	SAKHUN(SK)	DANTRA(DTRA)	7	2
10	DANTRA(DTRA)	NARAINA(NRI)	5	2
11	NARAINA(NRI)	PHULERA JN(FL)	10	2
12	PHULERA JN(FL)	KHANDEL(KNDL)	10	1

D-E-F CORRIDOR				
SECTION NO.	FROM	TO	SECTION LENGTH (in KM)	LINE
13	KHANDEL(KNDL)	BHESLANA(BILA)	13	1
14	BHESLANA(BILA)	RENWAL(RNW)	11	1
15	RENWAL(RNW)	BADHAL(BDHL)	14	1
16	BADHAL(BDHL)	KISHANMANPURA(KMNP)	8	1
17	KISHANMANPURA(KMNP)	RINGAS JN(RGS)	10	1
18	RINGAS JN(RGS)	SHRI MADHOPUR(SMPR)	10	1
19	SHRI MADHOPUR(SMPR)	KHACHERA(KHRA)	10	1
20	KHACHERA(KHRA)	KANWAT(KAWT)	7	1
21	KANWAT(KAWT)	BHAGEGA(BAGA)	11	1
22	BHAGEGA(BAGA)	NIM KA THANA(NMK)	9	1
23	NIM KA THANA(NMK)	MANDOLA(MADA)	9	1
24	MANDOLA(MADA)	JHILO(JLLO)	8	1
25	JHILO(JLLO)	DABLA(DBLA)	8	1
26	DABLA(DBLA)	NIZAMPUR(NIP)	11	1
27	NIZAMPUR(NIP)	AMARPUR JORASI(APJ)	6	1
28	AMARPUR JORASI(APJ)	NARNAUL(NNL)	8	1
29	NARNAUL(NNL)	MIRZAPUR BACHHAUD(MBV)	7	1
30	MIRZAPUR BACHHAUD(MBV)	ATELI(AEL)	7	1
31	ATELI(AEL)	KATHUWAS(KTWS)	10	1
32	KATHUWAS(KTWS)	KUND(KUND)	5	1
33	KUND(KUND)	KHORI(KORI)	12	1
34	KHORI(KORI)	REWARI(RE)	11	1
		Total length of corridor D-E-F	**295 KMS**	

Table 4.3: Sections present in each corridor

Corridor	Sections present in each corridor
D-E-F	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34
D-E-A	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 35, 36, 37, 38, 39
C-B-A	40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63
A-G-F	64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92
A-G-H	64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102
C-B-H	40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120

The proportional distribution shows the train types running in which proportion on each corridor in both the forward and backward direction. Data for proportional distribution is presented in Table 4.4. The directional distribution shows that on the particular corridor in which proportion train types are traveling in the forward direction. Directional distribution data is shown in Table 4.5. The rest of modal file data is shown in table 4.6.

Table 4.4: Proportional distribution on corridors (in both directions)

Proportional distributions %							
Corridor	TRAIN TYPE						Total
	1	2	3	4	5	6	
D-E-F	0.40	0.40	0.00	0.20	0.00	0.00	1.00
D-E-A	0.40	0.02	0.30	0.24	0.02	0.02	1.00
C-B-A	0.40	0.07	0.13	0.40	0.00	0.00	1.00
A-G-F	0.40	0.08	0.35	0.16	0.04	0.00	1.00
A-G-H	0.39	0.00	0.29	0.26	0.06	0.00	1.00
C-B-H	0.43	0.05	0.14	0.22	0.06	0.10	1.00

Table 4.5: Directional distribution on corridors (in forward direction)

Directional distributions % (i→j)						
Corridor	TRAIN TYPE					
	1	2	3	4	5	6
D-E-F	0.50	0.50	0.00	0.33	0.00	0.00
D-E-A	0.50	0.50	0.52	0.53	0.50	0.50
C-B-A	0.50	0.50	0.50	0.50	0.00	0.00
A-G-F	0.50	0.50	0.50	0.50	0.50	0.50
A-G-H	0.50	0.00	0.67	0.50	0.50	0.00
C-B-H	0.50	0.50	0.33	0.45	0.33	0.60

Table 4.6: Data for capacity model

Constant	
T	= 24 hours or 1440 minutes
nbTrain	= 6
nbSec	= 120
nbCor	= 6
nbIO	= 5
Parameters	
SPEED [Train]	= [25, 45, 55, 65, 75, 85] KMPH
LOS [Sec]	= See APPENDIX I
CORS_SECT[Cor]	= See Table 4.3
PD [Cor] [Train]	= See Table 4.4
DD [Cor] [Train]	= See Table 4.5
PF [Cor]	= [0.06 0.32 0.11 0.19 0.12 0.20]
MAX_TRK [Sec]	= 1,2..
TRK [Sec]	= See APPENDIX I
DT [Sec] [Train]	= See APPENDIX II

4.2 Different cases

Different cases are considered for the study according to Table 4.7.

Table 4.7: Different cases for study

Case 1	Base case capacity	Dwell times are not considered, Percentage flow of train types is not considered
Case 2	Effect of proportional distribution on Railroad capacity	Dwell times are not considered, Percentage flow of train types is considered
Case 3	Effect of incremental speed change on Railroad capacity	Dwell times are not considered, Percentage flow of train types is considered
Case 4	Effect of dwell times on Railroad capacity	Dwell times are considered, Percentage flow of train types is considered
Case 5	Effect of infrastructure expansion on Railroad capacity	Dwell times are not considered, Percentage flow of train types is considered

4.2.1 Case 1: Base case capacity

In this case, dwell times are not considered, and Percentage flow of train types on corridors is not considered. Trains are free to flow on corridors. It gives the maximum capacity of the network.

```
CAPACITY   = 444.58
NC =   [49.039  131.4  54.147  60.693  62.323  86.985]
NC_f = [[9.8079 9.8079 0 3.2366 0 0]
          [26.279 1.314 20.498 16.714 1.314 1.314]
          [10.829 1.8951 3.5195 10.829 0 0]
          [12.139 2.4277 8.8005 4.552 1.2139 1.2139]
          [12.153 0 12.109 8.102 1.8697 0]
          [18.702 2.1746 4.0187 8.6115 1.7223 5.2191]]
```

NC_r = [[9.8079 9.8079 0 6.5713 0 0]
[26.279 1.314 18.921 14.822 1.314 1.314]
[10.829 1.8951 3.5195 10.829 0 0]
[12.139 2.4277 8.8005 4.552 1.2139 1.2139]
[12.153 0 5.9643 8.102 1.8697 0]
[18.702 2.1746 8.1592 10.525 3.4968 3.4794]]

The results show the network capacity and the distribution of train types on each corridor. The maximum number of trains could run the network are 444.58 in this scenario.

4.2.2 Case 2: Effect of proportional distribution on Railroad capacity

In this case, dwell times are not considered, and Percentage flow of train types on corridors is considered according to following values. Table 4.8 compares the corridor and network capacity in case 1 and case 2.

PF [Cor] = [0.06 0.32 0.11 0.19 0.12 0.20]

Table 4.8: Comparison of case 1 and case 2 corridor capacity

Corridor	Case 1 capacity	Case 2 capacity
D-E-F	49.04	23.73
D-E-A	131.40	126.58
C-B-A	54.15	43.51
A-G-F	60.69	75.16
A-G-H	62.32	47.47
C-B-H	86.99	79.12
Network Capacity	444.58	395.57

The results show that while considering the Percentage flow of train types, there is a reduction in network capacity by 11.03%.

4.2.3 Case 3: Effect of incremental speed change on Railroad capacity

In this case, the effect of train speed change is investigated. This is a straightforward technique to increase the capacity that does not require any investment in infrastructure and topology of the network remains same.

In this case, dwell times are not considered, and Percentage flow of train types on corridors is considered according to following values.

PF [Cor] = [0.06 0.32 0.11 0.19 0.12 0.20]

In this case, six train types of different speeds are considered. Now the speed of each train type is increased by 9 KMPH (1 KMPH in each step). The speed of train type cannot be increased by 10 KMPH as it becomes equivalent to the speed of another train type. Then two train types have the same speed. The results of 9 incremental changes are tabulated in Table 4.9. The last column of Table 4.9 shows the capacity when the speed of all train types increases simultaneously.

Table 4.9: Effect of incremental speed change on Railroad capacity

Incremental speed	TRAIN TYPES						
	1	2	3	4	5	6	ALL
0	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]
1	24.302 129.61 44.554 76.956 48.604 81.006 [405.032]	23.756 126.7 43.553 75.227 47.512 79.186 [395.932]	23.82 127.04 43.671 75.431 47.641 79.401 [397.006]	23.775 126.8 43.588 75.288 47.551 79.251 [396.255]	23.742 126.62 43.527 75.183 47.484 79.14 [395.7]	23.737 126.6 43.519 75.169 47.475 79.125 [395.624]	24.469 130.5 44.861 77.487 48.939 81.565 [407.824]
2	24.852 132.55	23.777 126.81	23.904 127.49	23.815 127.01	23.749 126.66	23.74 126.62	25.199 134.39

Incre-mental speed	TRAIN TYPES						
	1	2	3	4	5	6	ALL
	45.562	43.59	43.824	43.661	43.541	43.524	46.198
	78.699	75.293	75.696	75.414	75.207	75.178	79.797
	49.704	47.553	47.808	47.63	47.499	47.481	50.398
	82.841	79.255	79.68	79.384	79.165	79.135	83.997
	[414.203]	[396.277]	[398.398]	[396.918]	[395.824]	[395.674]	[419.983]
3	25.386	23.796	23.985	23.854	23.757	23.743	25.923
	135.39	126.91	127.92	127.22	126.7	126.63	138.26
	46.541	43.627	43.973	43.732	43.554	43.529	47.526
	80.389	75.356	75.953	75.537	75.229	75.187	82.091
	50.772	47.593	47.97	47.708	47.513	47.487	51.847
	84.62	79.322	79.95	79.513	79.189	79.144	86.411
	[423.099]	[396.608]	[399.751]	[397.564]	[395.945]	[395.722]	[432.057]
4	25.904	23.816	24.064	23.892	23.764	23.746	26.643
	138.15	127.02	128.34	127.42	126.74	126.65	142.1
	47.49	43.662	44.117	43.801	43.567	43.535	48.846
	82.029	75.416	76.203	75.657	75.252	75.196	84.37
	51.808	47.631	48.128	47.783	47.527	47.492	53.286
	86.346	79.385	80.213	79.639	79.212	79.154	88.81
	[431.732]	[396.926]	[401.067]	[398.194]	[396.062]	[395.77]	[444.052]
5	26.407	23.834	24.141	23.928	23.771	23.749	27.358
	140.84	127.11	128.75	127.62	126.78	126.66	145.91
	48.412	43.695	44.258	43.869	43.579	43.54	50.157
	83.621	75.474	76.446	75.773	75.274	75.205	86.635
	52.814	47.668	48.282	47.857	47.541	47.498	54.717
	88.023	79.446	80.47	79.761	79.235	79.163	91.194
	[440.113]	[397.232]	[402.348]	[398.807]	[396.177]	[395.816]	[455.972]

Incremental speed	TRAIN TYPES						
	1	2	3	4	5	6	ALL
6	26.895 143.44 49.308 85.168 53.79 89.651 [448.253]	23.852 127.21 43.728 75.53 47.703 79.505 [397.526]	24.216 129.15 44.395 76.683 48.431 80.719 [403.594]	23.964 127.81 43.935 75.887 47.929 79.881 [399.405]	23.777 126.81 43.592 75.295 47.555 79.258 [396.289]	23.752 126.68 43.545 75.214 47.503 79.172 [395.862]	28.069 149.7 51.461 88.887 56.139 93.565 [467.824]
7	27.37 145.97 50.178 86.671 54.74 91.233 [456.163]	23.869 127.3 43.759 75.584 47.737 79.562 [397.809]	24.288 129.54 44.529 76.913 48.577 80.962 [404.808]	23.999 128 43.999 75.998 47.999 79.998 [399.988]	23.784 126.85 43.604 75.316 47.568 79.28 [396.399]	23.754 126.69 43.55 75.222 47.509 79.181 [395.906]	28.777 153.48 52.757 91.126 57.553 95.922 [479.611]
8	27.831 148.43 51.024 88.132 55.662 92.771 [463.853]	23.885 127.39 43.789 75.636 47.77 79.616 [398.082]	24.359 129.92 44.659 77.138 48.719 81.198 [405.99]	24.033 128.18 44.061 76.106 48.067 80.111 [400.557]	23.79 126.88 43.616 75.336 47.581 79.301 [396.505]	23.757 126.7 43.554 75.23 47.514 79.19 [395.95]	29.48 157.23 54.047 93.354 58.961 98.268 [491.338]
9	28.28 150.83 51.846 89.553 56.56 94.266 [471.33]	23.901 127.47 43.818 75.686 47.801 79.669 [398.345]	24.429 130.29 44.786 77.357 48.857 81.428 [407.142]	24.067 128.36 44.122 76.211 48.133 80.222 [401.112]	23.797 126.92 43.627 75.356 47.593 79.322 [396.61]	23.76 126.72 43.559 75.239 47.519 79.198 [395.992]	30.18 160.96 55.331 95.571 60.361 100.6 [503.008]

The effect on capacity by the incremental change in speed is shown in Figure 5. When the speed of all train types is increased by 9KMPH than the capacity of the network is increased by 27.16%. The results also show that capacity of network is affected by slow speed trains (i.e., Train type 1)

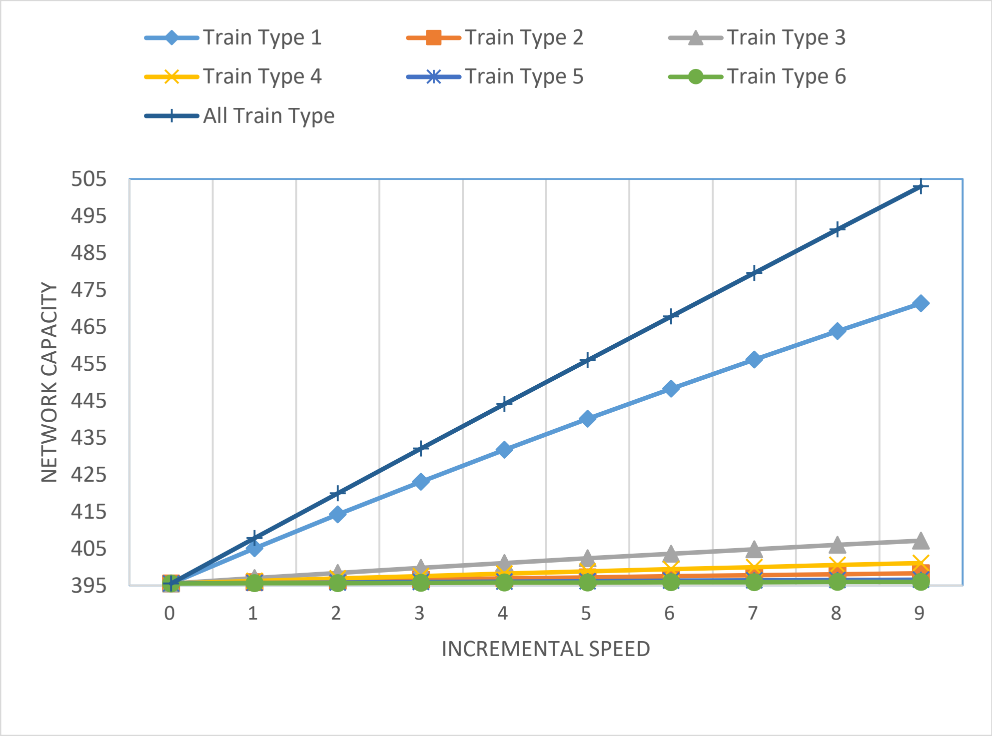


Figure 4.3: Incremental speed v/s Network capacity plot

4.2.4 Case 4: Effect of dwell times on Railroad capacity

It is common in railway operations for trains to provide the pre-planned dwell times at the intermediate junctions/stations to boarding and alighting of passengers, and loading and unloading of freight. Due to the dwell times, railroad capacity reduces considerably because when the train is not moving, then it does not utilize the capacity efficiently.

In this case train type 1 (Freight trains) are not considered due to unavailability of dwell time data. For other train, types sample dwell time data is shown in Table 4.12. Complete dwell time data is given in APPENDIX II. Percentage flow of train types on corridors is also considered. Table 4.10 and Table 4.11 show the proportional and directional of train types respectively.

Number of train types = 5

Speed of train types = [45, 55, 65, 75, 85]

Table 4.10: Proportional distribution on corridors in case 4

Proportional distributions						
	TRAIN TYPE					Total
Corridor	1	2	3	4	5	
D-E-F	0.67	0.00	0.33	0.00	0.00	1.00
D-E-A	0.04	0.50	0.38	0.04	0.04	1.00
C-B-A	0.11	0.22	0.67	0.00	0.00	1.00
A-G-F	0.13	0.53	0.27	0.07	0.00	1.00
A-G-H	0.00	0.47	0.42	0.11	0.00	1.00
C-B-H	0.07	0.30	0.36	0.10	0.17	1.00

Table 4.11: Directional distribution on corridors in case 4

Directional distributions % (i→j)					
	TRAIN TYPE				
Corridor	1	2	3	4	5
D-E-F	0.50	0.00	0.33	0.00	0.00
D-E-A	0.50	0.52	0.53	0.50	0.50
C-B-A	0.50	0.50	0.50	0.00	0.00
A-G-F	0.50	0.50	0.50	0.50	0.50
A-G-H	0.00	0.67	0.50	0.50	0.00
C-B-H	0.50	0.33	0.45	0.33	0.60

Table 4.12: Sample dwell time data

Location	Dwell Times (in Minutes)				
	Train Types				
	1	2	3	4	5
1	1	0	0	0	0
2	1	0	0	0	0
3	1	0	0	0	0
4	1	2	2	2	0
.					
.					

.					
118	1	0	0	0	0
119	1	0	0	0	0
120	0	0	0	0	0

Capacity without considering dwell times-

CAPACITY = 601.14

NC_f = [[12.083 0 3.9279 0 0]
[3.8473 50.015 38.742 3.8473 3.8473]
[3.9675 7.9351 24.166 0 0]
[7.4241 30.268 15.419 3.9976 0]
[0 22.716 15.149 3.9675 0]
[3.9976 11.307 18.503 3.7692 11.65]];

NC_r = [[12.083 0 7.9748 0 0]
[3.8473 46.168 34.356 3.8473 3.8473]
[3.9675 7.9351 24.166 0 0]
[7.4241 30.268 15.419 3.9976 0]
[0 11.188 15.149 3.9675 0]
[3.9976 22.958 22.615 7.6525 7.7668]

NC = [36.069 192.37 72.137 114.22 72.137 114.22]

Capacity with considering dwell time-

CAPACITY = 491.28

NC_f = [[9.8747 0 3.21 0 0]
[3.1442 40.874 31.662 3.1442 3.1442]
[3.2424 6.4848 19.749 0 0]
[6.0673 24.736 12.601 3.267 0]
[0 18.564 12.38 3.2424 0]
[3.267 9.2409 15.121 3.0803 9.5209]];

NC_r = [[9.8747 0 6.5173 0 0]
[3.1442 37.73 28.077 3.1442 3.1442]
[3.2424 6.4848 19.749 0 0]
[6.0673 24.736 12.601 3.267 0]

[0 9.1436 12.38 3.2424 0]

[3.267 18.762 18.482 6.2539 6.3473]

NC = [29.477 157.21 58.953 93.342 58.953 93.342]

Percentage reduction in network capacity due to dwell time,

$$= \frac{(\text{capacity without dwell time} - \text{capacity with dwell time})}{\text{capacity without dwell time}} \times 100$$

$$= \frac{(601.142 - 491.276)}{601.142} \times 100$$

= 18.28%

Results show that due to the dwell times capacity is reduced by 18.28%.

4.2.5 Case 5: Effect of infrastructure expansion on Railroad capacity

Duplicating all the sections of the network is capital extensive and time-consuming. So it is best to adopt the incremental infrastructure expansion strategy. Therefore, bottleneck sections are duplicated first and resolved the model to find the effect of duplicating the section. This course of action is supported by the existing theory of bottlenecks. Therefore, in the current network, the length of longest section is 17 KM so, it will be duplicate first by adding one track and resolved the capacity model. Capacity results by adding single and two tracks are summarized in Table 4.13.

In this case, dwell times are not considered, and Percentage flow of train types on corridors is considered according to following values. The effect on capacity by adding new single and double tracks are shown in Figure 6.

PF = [0.06 0.32 0.11 0.19 0.12 0.20]

Table 4.13: Increase in capacity due to infrastructure expansion

S. No.	Track addition	Length of sections (in KMS)	Cumulative sections	Capacity by adding one track	Capacity by adding two track
1	0		0	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]

2	Section- 61	17	1	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]	23.734 126.58 43.513 75.159 47.469 79.115 [395.573]
3	Section- 57 Section- 70 Section- 92 Section- 93	15 15 15 15	5	24.637 131.4 45.168 78.017 49.274 82.123 [410.615]	24.637 131.4 45.168 78.017 49.274 82.123 [410.615]
4	Section- 15 Section- 37 Section- 38 Section- 84 Section- 95	14 14 14 14 14	10	27.311 145.66 50.071 86.486 54.623 91.038 [455.191]	27.311 145.66 50.071 86.486 54.623 91.038 [455.191]
5	Section- 13 Section- 48 Section- 58 Section- 60 Section- 110 Section- 112 Section- 114	13 13 13 13 13 13 13	17	28.72 153.17 52.654 90.947 57.44 95.734 [478.67]	28.72 153.17 52.654 90.947 57.44 95.734 [478.67]
6	Section- 33 Section- 69 Section- 71 Section- 96 Section- 102	12 12 12 12 12	23	28.72 153.17 52.654 90.947	28.72 153.17 52.654 90.947

	Section- 117	12		57.44	57.44
				95.734	95.734
				[478.67]	[478.67]
7	Section- 14	11	39	28.72	28.72
	Section- 21	11		153.17	153.17
	Section- 26	11		52.654	52.654
	Section- 34	11		90.947	90.947
	Section- 42	11		57.44	57.44
	Section- 47	11		95.734	95.734
	Section- 52	11		[478.67]	[478.67]
	Section- 53	11			
	Section- 56	11			
	Section- 59	11			
	Section- 72	11			
	Section- 83	11			
	Section- 105	11			
	Section- 108	11			
	Section- 115	11			
	Section- 119	11			
8	Section- 4	10	54	35.602	35.9
	Section- 5	10		189.88	191.47
	Section- 11	10		65.27	65.817
	Section- 12	10		112.74	113.68
	Section- 17	10		71.203	71.8
	Section-18	10		118.67	119.67
	Section- 19	10		[593.36]	[598.337]
	Section- 31	10			
	Section- 36	10			
	Section- 44	10			
	Section- 100	10			
	Section- 103	10			
	Section- 107	10			
	Section- 113	10			

	Section- 120	10			
9	Section- 22	9	66	35.602	35.9
	Section- 23	9		189.88	191.47
	Section- 39	9		65.27	65.817
	Section- 43	9		112.74	113.68
	Section- 45	9		71.203	71.8
	Section-54	9		118.67	119.67
	Section-68	9		[593.36]	[598.337]
	Section-80	9			
	Section-98	9			
	Section-104	9			
	Section-116	9			
	Section- 118	9			
10	Section- 2	8	83	35.602	41.029
	Section-16	8		189.88	218.82
	Section-24	8		65.27	75.22
	Section-25	8		112.74	129.92
	Section-28	8		71.203	82.058
	Section-35	8		118.67	136.76
	Section-41	8		[593.36]	[683.814]
	Section-46	8			
	Section-49	8			
	Section-50	8			
	Section-55	8			
	Section-81	8			
	Section-82	8			
	Section-87	8			
	Section-97	8			
	Section-99	8			
	Section-111	8			
11	Section-7	7	97	35.602	47.469
	Section-8	7		189.88	253.17
	Section-9	7		65.27	87.026

	Section-20	7		112.74	150.32
	Section-29	7		71.203	94.938
	Section-30	7		118.67	158.23
	Section-51	7		[593.36]	[791.146]
	Section-63	7			
	Section-67	7			
	Section-76	7			
	Section-86	7			
	Section-89	7			
	Section-101	7			
	Section-106	7			
12	Section-1	6	111	35.602	47.469
	Section-27	6		189.88	253.17
	Section-40	6		65.27	87.026
	Section-64	6		112.74	150.32
	Section-66	6		71.203	94.938
	Section-73	6		118.67	158.23
	Section-74	6		[593.36]	[791.146]
	Section-75	6			
	Section-78	6			
	Section-79	6			
	Section-85	6			
	Section-90	6			
	Section-91	6			
	Section-109	6			
13	Section-3	5	119	35.602	47.469
	Section-6	5		189.88	253.17
	Section-10	5		65.27	87.026
	Section-32	5		112.74	150.32
	Section-62	5		71.203	94.938
	Section-65	5		118.67	158.23
	Section-77	5		[593.36]	[791.146]
	Section-88	5			

14	Section- 94	4	120	35.602 189.88 65.27 112.74 71.203 118.67 [593.36]	47.469 253.17 87.026 150.32 94.938 158.23 [791.146]

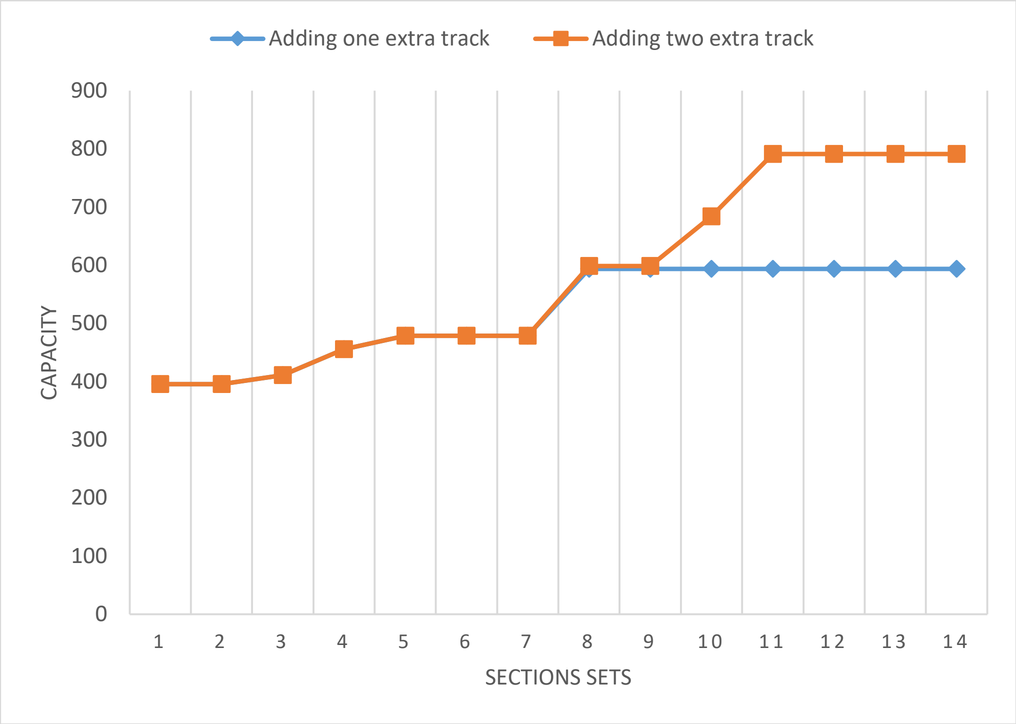


Figure 4.4. Effect on capacity when single and double tracks added

Table 4.14 and Table 4.15 show the improvement in capacity when single and double track added in a line section. The results show that when there is a restriction of single track addition, then the capacity of the network is increased to 593.36. However, when two tracks are added to the network then capacity is reached to 791.146. It is also observed that after duplicating the 53 sections network capacity is not increased further. In case of two track addition, the process of increasing the capacity also stops after 97 duplicating sections. Change in capacity due to duplication of sections is not uniform. Furthermore, some incremental changes do not increase the capacity of the network.

Table 4.14 Improvement in capacity when single track added

S. no.	Single track added		
	Total track length added (Km)	**Network capacity**	**% improvement in capacity**
1	0	395.573	0.00
2	77	410.615	3.80
3	147	455.191	15.07
4	238	478.67	21.00
5	636	593.36	50.00

Table 4.15 Improvement in capacity when double track added

S. no.	Double track added		
	Total track length added (Km)	**Network capacity**	**% improvement in capacity**
1	0	395.573	0.00
2	77	410.615	3.80
3	147	455.191	15.07
4	238	478.67	21.00
5	636	598.337	51.25
6	880	683.814	72.86
7	978	791.146	100.00

CHAPTER 5

RESEARCH CONCLUSION

5.1 Main contribution of thesis

An optimization model for calculation of railroad capacity and, evaluation of train type interactions on railroad capacity is presented here. The proposed model considers infrastructure and operating parameters. The objective of the proposed model is to maximize the number of trains in railway line and line section in the specific period. The inputs of the models are railway line and train type attributes, which are typically available to planners. To evaluate the proposed model, it is implemented in Indian Railways.

When the proportional distribution of train types is considered than network capacity is reduced by 11%. The results also show that the network capacity is highly affected by low-speed trains (Train type 1). If the speed of low-speed trains increase up to 9 KMPH than 20% excess capacity can be generated, and extra trains can be run on the same infrastructure. As the investment in making extra tracks are high so it can be economical to increase the operational speed of low-performing trains.

The results show that when we consider the dwell time the capacity is reduced by 18.28 %. Incremental improvement in infrastructure is also analyzed, which shows that when the restriction of a single track addition, then capacity cannot be increased beyond 593.36 trains. When the restriction of a single track addition per section is relaxed to two, then the capacity does increase. In comparison, the increase is quite significant because of the capacity changes from 593.36 to 791.146 trains.

5.2 Recommendations for future research

This research work has focused on developing a model for capacity determination and improving the capacity of existing railway networks. There are many avenues that still need to be investigated in future studies. The most significant areas for further research are as below:

- An investigation of other methods, other than track addition for capacity expansion should be performed.

- The feasible combination of various parameters should be found out and analysed on rail road capacity.
- A cost analysis of infrastructure expansion strategy should also be performed to identify the best and the most cost-effective way of performing capacity expansion in railway networks.

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APPENDIX I

NETWORK DATA

D-E-F CORRIDOR				
SEC. NO.	FROM	TO	SECTION LENGTH (KMS)	LINE
1	AJMER(AII)	MADAR JN(MDJN)	6	2
2	MADAR JN(MDJN)	LADPURA(LR)	8	2
3	LADPURA(LR)	GEGAL AKHRI(GEK)	5	2
4	GEGAL AKHRI(GEK)	KISHANGARH(KSG)	10	2
5	KISHANGARH(KSG)	TILONIYA(TL)	10	2
6	TILONIYA(TL)	GAHLOTA(GLTA)	5	2
7	GAHLOTA(GLTA)	SAHELI(SALI)	7	2
8	SAHELI(SALI)	SAKHUN(SK)	7	2
9	SAKHUN(SK)	DANTRA(DTRA)	7	2
10	DANTRA(DTRA)	NARAINA(NRI)	5	2
11	NARAINA(NRI)	PHULERA JN(FL)	10	2
12	PHULERA JN(FL)	KHANDEL(KNDL)	10	1
13	KHANDEL(KNDL)	BHESLANA(BILA)	13	1
14	BHESLANA(BILA)	RENWAL(RNW)	11	1
15	RENWAL(RNW)	BADHAL(BDHL)	14	1
16	BADHAL(BDHL)	KISHANMANPURA(KMNP)	8	1
17	KISHANMANPURA(KMNP)	RINGAS JN(RGS)	10	1
18	RINGAS JN(RGS)	SHRI MADHOPUR(SMPR)	10	1
19	SHRI MADHOPUR(SMPR)	KHACHERA(KHRA)	10	1
20	KHACHERA(KHRA)	KANWAT(KAWT)	7	1
21	KANWAT(KAWT)	BHAGEGA(BAGA)	11	1
22	BHAGEGA(BAGA)	NIM KA THANA(NMK)	9	1
23	NIM KA THANA(NMK)	MANDOLA(MADA)	9	1
24	MANDOLA(MADA)	JHILO(JLLO)	8	1
25	JHILO(JLLO)	DABLA(DBLA)	8	1
26	DABLA(DBLA)	NIZAMPUR(NIP)	11	1
27	NIZAMPUR(NIP)	AMARPUR JORASI(APJ)	6	1
28	AMARPUR JORASI(APJ)	NARNAUL(NNL)	8	1

29	NARNAUL(NNL)	MIRZAPUR BACHHAUD(MBV)	7	1
30	MIRZAPUR BACHHAUD(MBV)	ATELI(AEL)	7	1
31	ATELI(AEL)	KATHUWAS(KTWS)	10	1
32	KATHUWAS(KTWS)	KUND(KUND)	5	1
33	KUND(KUND)	KHORI(KORI)	12	1
34	KHORI(KORI)	REWARI(RE)	11	1
		Total length of corridor D-E-F	**235 KMS**	

D-E-A CORRIDOR

SEC. NO.	FROM	TO	SECTION LENGTH (KMS)	LINE
1	AJMER(AII)	MADAR JN(MDJN)	6	2
2	MADAR JN(MDJN)	LADPURA(LR)	8	2
3	LADPURA(LR)	GEGAL AKHRI(GEK)	5	2
4	GEGAL AKHRI(GEK)	KISHANGARH(KSG)	10	2
5	KISHANGARH(KSG)	TILONIYA(TL)	10	2
6	TILONIYA(TL)	GAHLOTA(GLTA)	5	2
7	GAHLOTA(GLTA)	SAHELI(SALI)	7	2
8	SAHELI(SALI)	SAKHUN(SK)	7	2
9	SAKHUN(SK)	DANTRA(DTRA)	7	2
10	DANTRA(DTRA)	NARAINA(NRI)	5	2
11	NARAINA(NRI)	PHULERA JN(FL)	10	2
35	PHULERA JN(FL)	HIRNODA(HDA)	8	2
36	HIRNODA(HDA)	ASALPUR JOBNER(JOB)	10	2
37	ASALPUR JOBNER(JOB)	SHEOSINGHPURA(SHNX)	14	2
38	SHEOSINGHPURA(SHNX)	KANAKPURA(KKU)	14	2
39	KANAKPURA(KKU)	JAIPUR(JP)	9	2
		Total length of corridor D-E-A	**135 KMS**	

C-B-A CORRIDOR

SEC. NO.	FROM	TO	SECTION LENGTH (KMS)	LINE
40	KOTA JN(KOTA)	GURLA(GQL)	6	2
41	GURLA(GQL)	KESHORAI PATAN(KPTN)	8	2
42	KESHORAI PATAN(KPTN)	ARNETHA(ARE)	11	2
43	ARNETHA(ARE)	KAPREN(KPZ)	9	2
44	KAPREN(KPZ)	GHATAKA VARANA(GKB)	10	2
45	GHATAKA VARANA(GKB)	LABAN(LBN)	9	2
46	LABAN(LBN)	LAKHERI(LKE)	8	2
47	LAKHERI(LKE)	INDARGARH(IDG)	11	2
48	INDARGARH(IDG)	AMLI(AMLI)	13	2
49	AMLI(AMLI)	RAWANIA DUNGAR(RWJ)	8	2
50	RAWANIA DUNGAR(RWJ)	KUSHTALA(KTA)	8	2
51	KUSHTALA(KTA)	SAWAI MADHOPUR(SWM)	7	2
52	SAWAI MADHOPUR(SWM)	DEVPURA(DPZ)	11	1
53	DEVPURA(DPZ)	CHAUTH KA BRWRA(CKB)	11	1
54	CHAUTH KA BRWRA(CKB)	SURELI(SURL)	9	1
55	SURELI(SURL)	ISARDA(ISA)	8	1
56	ISARDA(ISA)	SIRAS(SRAS)	11	1
57	SIRAS(SRAS)	BANSTHALI NIWAI(BNLW)	15	1
58	BANSTHALI NIWAI(BNLW)	CHANNANI(CHNN)	13	1
59	CHANNANI(CHNN)	CHAKSU(CKS)	11	1
60	CHAKSU(CKS)	SHEOSDASPURA(SAS)	13	1
61	SHEOSDASPURA(SAS)	SANGANER(SNGN)	17	1
62	SANGANER(SNGN)	DURGAPURA(DPA)	5	1
63	DURGAPURA(DPA)	JAIPUR(JP)	7	1
		Total length of corridor C-B-A	**239 KMS**	

A-G-F CORRIDOR				
SEC. NO.	FROM	TO	SECTION LENGTH (KMS)	LINE
64	JAIPUR(JP)	GANDHINAGAR JPR(GADJ)	6	2
65	GANDHINAGAR JPR(GADJ)	GETOR JAGATPURA(GTJT)	5	2
66	GETOR JAGATPURA(GTJT)	KHATIPURA(KWP)	6	2
67	KHATIPURA(KWP)	KANAUTA(KUT)	7	2
68	KANAUTA(KUT)	BASSI(BAI)	9	2
69	BASSI(BAI)	BANSKHO(BSKO)	12	2
70	BANSKHO(BSKO)	JATWARA(JW)	5	2
71	JATWARA(JW)	DAUSA(DO)	12	2
72	DAUSA(DO)	BHAN KARI(BAK)	11	2
73	BHAN KARI(BAK)	KOLVAGRAM(KVGM)	6	2
74	KOLVAGRAM(KVGM)	ARNIA(ARNA)	6	2
75	ARNIA(ARNA)	BANDIKUI JN(BKI)	6	2
76	BANDIKUI JN(BKI)	GULANA(GLNA)	7	2
77	GULANA(GLNA)	BASWA(BU)	5	2
78	BASWA(BU)	SURERGOTH(SRRG)	6	2
79	SURERGOTH(SRRG)	RAJGARH(RHG)	6	2
80	RAJGARH(RHG)	DHIGAWARA(DGW)	9	2
81	DHIGAWARA(DGW)	MALAKHERA(MKH)	8	2
82	MALAKHERA(MKH)	MAHWA(MWW)	8	2
83	MAHWA(MWW)	ALWAR JN(AWR)	11	2
84	ALWAR JN(AWR)	PARISAL(PSL)	14	2
85	PARISAL(PSL)	GHATLA(GAL)	6	2
86	GHATLA(GAL)	KHAIRTHAL(KRH)	7	2
87	KHAIRTHAL(KRH)	HARSAULI(HSI)	8	2
88	HARSAULI(HSI)	KHANPUR AHIR(KNAR)	5	2
89	KHANPUR AHIR(KNAR)	AJARAKA(AIA)	7	2
90	AJARAKA(AIA)	MAJRI NANGAL(MJNL)	6	2
91	MAJRI NANGAL(MJNL)	BAWAL(BWL)	6	2
92	BAWAL(BWL)	REWARI(RE)	15	2
		Total length of corridor A-G-F	**225 KMS**	

A-G-H CORRIDOR				
SEC. NO.	FROM	TO	SECTION LENGTH (KMS)	LINE
64	JAIPUR(JP)	GANDHINAGAR JPR(GADJ)	6	2
65	GANDHINAGAR JPR(GADJ)	GETOR JAGATPURA(GTJT)	5	2
66	GETOR JAGATPURA(GTJT)	KHATIPURA(KWP)	6	2
67	KHATIPURA(KWP)	KANAUTA(KUT)	7	2
68	KANAUTA(KUT)	BASSI(BAI)	9	2
69	BASSI(BAI)	BANSKHO(BSKO)	12	2
70	BANSKHO(BSKO)	JATWARA(JW)	5	2
71	JATWARA(JW)	DAUSA(DO)	12	2
72	DAUSA(DO)	BHAN KARI(BAK)	11	2
73	BHAN KARI(BAK)	KOLVAGRAM(KVGM)	6	2
74	KOLVAGRAM(KVGM)	ARNIA(ARNA)	6	2
75	ARNIA(ARNA)	BANDIKUI JN(BKI)	6	2
93	BANDIKUI JN(BKI)	BIWAI(BW)	15	1
94	BIWAI(BW)	BHAJERA(BJRA)	4	1
95	BHAJERA(BJRA)	MANDAWAR M RD(MURD)	14	1
96	MANDAWAR M RD(MURD)	DATIA(DTF)	12	1
97	DATIA(DTF)	KHERLI(KL)	8	1
98	KHERIL(KL)	TARCHHERA BARAOLIRAN(TBL)	9	1
99	TARCHHERA BARAOLIRAN(TBL)	NADBAI(NBI)	8	1
100	NADBAI(NBI)	PAPARERA(PPEA)	10	1
101	PAPARERA(PPEA)	HELAK(HK)	7	1
102	HELAK(HK)	BHARATPUR JN(BTE)	12	1
		Total length of corridor A-G-H	**190 KMS**	

C-B-H CORRIDOR

SEC. NO.	FROM	TO	SECTION LENGTH (KMS)	LINE
40	KOTA JN(KOTA)	GURLA(GQL)	6	2
41	GURLA(GQL)	KESHORAI PATAN(KPTN)	8	2
42	KESHORAI PATAN(KPTN)	ARNETHA(ARE)	11	2
43	ARNETHA(ARE)	KAPREN(KPZ)	9	2
44	KAPREN(KPZ)	GHATAKA VARANA(GKB)	10	2
45	GHATAKA VARANA(GKB)	LABAN(LBN)	9	2
46	LABAN(LBN)	LAKHERI(LKE)	8	2
47	LAKHERI(LKE)	INDARGARH(IDG)	11	2
48	INDARGARH(IDG)	AMLI(AMLI)	13	2
49	AMLI(AMLI)	RAWANIA DUNGAR(RWJ)	8	2
50	RAWANIA DUNGAR(RWJ)	KUSHTALA(KTA)	8	2
51	KUSHTALA(KTA)	SAWAI MADHOPUR(SWM)	7	2
103	SAWAI MADHOPUR(SWM)	RANTHAMBHORE(RNT)	10	2
104	RANTHAMBHORE(RNT)	MOKHOLI(MXL)	9	2
105	MOKHOLI(MXL)	MALARNA(MLZ)	11	2
106	MALARNA(MLZ)	NOMODA(NMD)	7	2
107	NOMODA(NMD)	NRYNPUR TATWAR(NNW)	10	2
108	NRYNPUR TATWAR(NNW)	LALPUR UMRI(LRU)	11	2
109	LALPUR UMRI(LRU)	GANGAPUR CITY(GGC)	6	2
110	GANGAPUR CITY(GGC)	CHHOTI ODAI(COO)	13	2
111	CHHOTI ODAI(COO)	PILIODA(PDZ)	8	2
112	PILIODA(PDZ)	SHRI MAHABIRJI(SMBJ)	13	2
113	SHRI MAHABIRJI(SMBJ)	HINDAUN CITY(HAN)	10	2
114	HINDAUN CITY(HAN)	FATEH SINGHPURA(FSP)	13	2
115	FATEH SINGHPURA(FSP)	DUMARIYA(DY)	11	2

116	DUMARIYA(DY)	BAYANA JN(BXN)	9	2
117	BAYANA JN(BXN)	KELA DEVI(KEV)	12	2
118	KELA DEVI(KEV)	PINGORA(PNGR)	9	2
119	PINGORA(PNGR)	SEWAR(SWAR)	11	2
120	SEWAR(SWAR)	BHARATPUR JN(BTE)	10	2
Total length of corridor C-B-H			**291 KMS**	

APPENDIX II

DWELL TIME DATA

Location	Dwell Times (in Minutes)				
	Train Types				
	1	2	3	4	5
1	1	0	0	0	0
2	1	0	0	0	0
3	1	0	0	0	0
4	1	2	2	2	0
5	1	0	0	0	0
6	1	0	0	0	0
7	1	0	0	0	0
8	1	0	0	0	0
9	1	0	0	0	0
10	1	0	0	0	0
11	5	5	2	0	0
12	1	0	0	0	0
13	1	0	0	0	0
14	1	0	0	0	0
15	1	0	0	0	0
16	1	0	0	0	0
17	3	0	0	0	0
18	2	0	0	0	0
19	1	0	0	0	0
20	1	0	0	0	0
21	1	0	0	0	0

22	1	0	0	0	0
23	1	0	0	0	0
24	1	0	0	0	0
25	1	0	0	0	0
26	1	0	0	0	0
27	1	0	0	0	0
28	1	0	0	0	0
29	1	0	0	0	0
30	1	0	0	0	0
31	1	0	0	0	0
32	1	0	0	0	0
33	1	0	0	0	0
34	0	0	0	0	0
35	1	0	0	0	0
36	2	0	0	0	0
37	1	0	0	0	0
38	1	2	0	0	0
39	0	0	0	0	0
40	0	0	0	0	0
41	2	0	0	0	0
42	0	0	0	0	0
43	0	0	0	0	0
44	0	0	0	0	0
45	0	0	0	0	0
46	2	0	0	0	0
47	2	2	0	0	0

48	0	0	0	0	0
49	0	0	0	0	0
50	0	0	0	0	0
51	20	20	10	0	2
52	0	0	0	0	0
53	2	0	0	0	0
54	0	0	0	0	0
55	2	0	0	0	0
56	0	0	0	0	0
57	2	2	0	0	0
58	0	0	0	0	0
59	0	0	0	0	0
60	0	0	0	0	0
61	2	0	0	0	0
62	5	2	1	0	0
63	0	0	0	0	0
64	2	3	2	2	0
65	1	2	0	0	0
66	1	0	0	0	0
67	0	0	0	0	0
68	1	0	0	0	0
69	1	0	0	0	0
70	0	0	0	0	0
71	2	2	2	0	0
72	0	0	0	0	0
73	1	0	0	0	0

74	1	0	0	0	0
75	21	2	2	2	0
76	1	0	0	0	0
77	1	0	0	0	0
78	1	0	0	0	0
79	1	2	1	0	0
80	1	0	0	0	0
81	1	0	0	0	0
82	1	0	0	0	0
83	3	3	3	2	0
84	1	0	0	0	0
85	1	0	0	0	0
86	1	1	1	0	0
87	1	0	0	0	0
88	1	0	0	0	0
89	1	0	0	0	0
90	1	0	0	0	0
91	1	0	0	0	0
92	0	0	0	0	0
93	0	0	0	0	0
94	0	0	0	0	0
95	0	2	2	0	0
96	0	0	0	0	0
97	0	2	2	0	0
98	0	0	0	0	0
99	0	2	2	0	0

100	0	0	0	0	0
101	0	0	0	0	0
102	0	0	0	0	0
103	1	0	0	0	0
104	1	0	0	0	0
105	1	2	0	0	0
106	1	0	0	0	0
107	1	2	0	0	0
108	1	0	0	0	0
109	5	5	2	2	0
110	1	0	0	0	0
111	1	0	0	0	0
112	1	2	0	2	0
113	1	5	2	2	0
114	1	2	0	0	0
115	1	0	0	0	0
116	5	5	2	2	0
117	1	0	0	0	0
118	1	0	0	0	0
119	1	0	0	0	0
120	0	0	0	0	0

APPENDIX III

COMPUTAIONAL MODEL FOR DETERMINATION OF RAILRAOD CAPACITY

```
/********************************************
 * OPL 12.7.1.0 Model
 * Author:
 * Creation Date: 23-Feb-2017 at 2:40:11 pm
 ********************************************/
//===========================================================
// Constants
//===========================================================
int T = ...; // The specified time for study
int nbTrain = ...; // Number of train types
int nbSec = ...; // Total number of sections
int nbL = ...; // Total number of location
int nbCor = ...; // Number of corridors in network
int nbIO = ...; // Number of Input Output points in network
//===========================================================
// Ranges
//===========================================================
range Train = 1 .. nbTrain; // Range of train types
range Sec = 1 .. nbSec; // Range of sections present in network
range Cor = 1 .. nbC; // Range of corridors in network
//===========================================================
// Sets
//===========================================================
{int} SECT = {s | s in Sec};
{int} TRAIN = {t | t in Train};
//===========================================================
// Parameters
//===========================================================
float SPEED[Train] = ...; //Speed of train types
```

```
float LOS[Sec] = ...; // Length of line sections
{int} CORS_SECT [Cor] = ...; // Corresponding sections present in each corridor
float SRT[Sec][Train]; // Sectional running time
float SOT[Sec][Train]; // Section occupation time
float DD[Cor][Train] = ...; // Directional distribution of train types on corridors
float PD[Cor][Train] = ...; // Proportional distribution of train types on corridors
float PF[Cor] = ...; // Percentage flow of trains on each corridor
int MAX_TRK[Sec] = ...; // Maximum number of tracks that can be added in a section
int TRK[Sec] = ...; // Number of tracks present in a section
float DT[Sec][Train] = ...;//Dwell times
//==========================================================
// Decision Variables
//==========================================================
dvar float CAPACITY; // Capacity of network
dvar float NC_f[Cor][Train]; // The number of trains utilising each corridor – in
                               forward direction
dvar float NC_r[Cor][Train]; // The number of trains utilising each corridor – in
                               backward direction
dvar float NS _f[Sec][Train]; // The number of trains utilising each section
dvar float NS _r[Sec][Train]; // The number of trains utilising each section
dvar float NC[Cor]; // The number of trains running on each corridor
dvar float used[Sec][Train]; // Time used by train types on each section
dvar float usedTot[Sec]; // Time occupied on each section
//==========================================================
// Pre_processing
//==========================================================
execute INITIALISE
{
var s,i;
for(s in SECT)
for(i in Train)
{
SRT[s][i] = 60.0 *LOS[s] / SPD[i];
SOT[s][i] = SRT[s][i] + DT[s][i]
```

```
}
}

//=======================================================
// Mathematical Formulation
//=======================================================
// Objective function
maximize CAPACITY;
subject to
{
CAPACITY == sum(c in Cor,i in Train) (NC_f[c][i] + xNC_r[c][i]);
// Constraint 0: relationship between NC and NS
forall(s in Sec, i in TRAIN)
{
NS_f[s][i] == sum(c in Cor: s in CORS_SECT[c]) NC_f[c][i];
NS_r[s][i] == sum(c in Cor: s in CORS_SECT[c]) NC_r[c][i];

};
forall(c in Cor)
NC[c] == sum(i in TRAIN) (NC_f[c][i] + NC_r[c][i]);

// Constraint 1: proportional distribution of train types across corridor
forall(c in Cor, i in TRAIN)
(NC_f[c][i] + NC_r[c][i]) == (PD[c][i]*NC[c]);
// Constraint 2: directional distribution of train types across corridor
forall(c in Cor, i in TRAIN)
NC_f[c][i] == DD[c][i] * (NC_f[c][i] + NC_r[c][i]);
// Constraint 3: Restrictions on sectional occupation time
forall(s in Sec)
sum(i in TRAIN) used[s][i] <= TIME*((TRK[s]) + MAX_TRK[s]);
forall(s in Sec)
usedTot[s] == sum(i in TRAIN) used[s][i];
forall(s in Sec,i in TRAIN)
used[s][i] == SOT[s][i]*NS_f[s][i] + SOT[s][i]*NS_r[s][i];
```

```
forall(c in Cor, i in TRAIN)
sum(i in TRAIN) (NC_f[c][i] + NC_r[c][i]) == PF[c]*sum(c in Cor,i in T) (NC_f[c][i]
+ NC_r[c][i]);

// Constraint 5: Satisfied condition of positivity
forall(i in TRAIN)
{
forall(s in Sec) NS_f[s][i] >= 0;
forall(s in Sec) NS_r[s][i] >= 0;
forall(c in Cor) NC_f[c][i] >= 0;
forall(c in Cor) NC_r[c][i] >= 0;
};
}
```

RESEARCH PUBLICATIONS

Journals

1. Neeraj Saini and G. Agarwal, An Optimization Model to analyze the Railway Capacity, International Journal of Mechanical Engineering and Technology 8(8), 2017, pp. 1327–1333. (Scopus Indexed)
   http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=8

2. Neeraj Saini and G. Agarwal, A Review on Railroad Capacity Assessment Techniques, International Journal of Innovative Research in Science, Engineering and Technology 8(6), 2017, pp. 16878–16882. (UGC approved)
   DOI:10.15680/IJIRSET.2016.0608166

3. Neeraj Saini and G. Agarwal, An optimization model to determine the absolute capacity of railway networks, Journal of Emerging Technologies and Innovative Research 8(4), 2017, pp. 80–82. (UGC approved)
   DOI: http://doi.one/10.1717/JETIR.17022

Conference

1. Neeraj Saini and G. Agarwal, An Optimization Model to Estimate Railway Network Capacity, 4th International Conference on New Frontiers of Engineering, Science, Management and Humanities (ICNFESMH-2017), Hyderabad, India.