OPTIMIZATION OF PAKISTAN RAILWAYS SCHEDULE

(A CASE STUDY OF A TRACK SEGMENT FROM RAWALPINDI TO LALAMUSA)

Malik Muneeb Abid

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Certified that the contents and form of thesis titled "**Optimization of Pakistan Railways Schedule (A Case Study of Track Segment from Rawalpindi to Lalamusa)**" submitted by Malik Muneeb Abid have been found satisfactory for the requirement of the degree.

Supervisor: ______________________________

Assistant Professor (Dr. Muhammad Babar Khan, PhD)

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LIST OF ACRONYMS

ABBREVIATION	DESCRIPTION
B&B	Branch and Bound
BCRP	Best Cost Priority Rule
ESPR	Early Start Priority Rule
EFPR	Early Finish Priority Rule
MPTPR	Minimum Processing Time Priority Rule
OR	Operations Research
PR	Pakistan Railways
RPR	Random Priority Rule
SPT	Shortest Path Time
DSS	Decision Support System
MCSP	Minimum Cost Scheduling Problem
PESP	Periodic Event Scheduling Problem
FCFS	First Come First Serve
FLFS	First Leave First Serve
TAS	Travel Advance Strategy

ABSTRACT

One of the most critical components in rail transportation is train schedule. Train scheduling is art of finding arrival times, departure times and dwell times of each train at every station or terminal. Efficiency of a network can be increased by efficient design of timetables. Service quality and operating cost are directly related to quality of train schedule. Train scheduling problem is interplay between different resources and shared rail network which makes it a complex optimization problem involving millions of decision variables and constraints. A good solution approach to solve this problem must consider all resources integrated. Train scheduling in Pakistan is being done manually, which is time consuming and based on thumb rules. It is required to use latest developed computer based techniques to be applied here and find profit in the form of time savings and improved schedules.

This thesis considers the train scheduling problem of single line track segment from Rawalpindi to Lalamusa, which is a busy track with 30 trains traversing this track daily. Formulation of this problem is based on job shop scheduling structure with objective to minimize total travel time. Real life constraints of this track segment are applied to this problem. To be more exact, it is optimization problem with a set of trains running over a rail network composed of set of single line segments. It is assumed that each train has pre specified departure time and travelling route. Moreover, it is also assumed that free running times at segments are constant. Travelling of trains is assumed as tasks to assign to machines (tracks and stations). To ensure safety minimum required headway is maintained on arrival of trains at same station and on departure to same track. Formulated problem is too complex to solve this problem with Branch and Bound standard combinatorial search. Cutset/ dominance rule is used to reduce search space by eliminating less promising nodes. This rule outperforms with Breadth First Search, without compromising the results quality it reduces almost 98% nodes in the search space. To simulate the human behavior priority rules are also incorporated in Branch and Bound search. Illustration of these algorithms is provided with detailed examples. Results of examples have shown that Best Cost, Early Start, Early Finish and Minimum Processing Time Priority Rules have generated almost same results to exact solution technique by evaluating less than 1% nodes as

compared to that evaluated by exact solution technique. Random Priority Rule showed results average 43.4% away from optimal solution. Actual schedule of Pakistan Railways of this track segment (Rawalpindi to Lalamusa) is optimized using Branch and Bound technique with priority rules. Optimized results have shown approximately 9 hours less total travel time as compared to actual one. Sensitivity Analysis of this track showed that 4 positions of sidings i.e., Kaliamawan, Sohawa, Ratial and Kalagujran have negligible effect on the schedule.

Chapter 1

INTRODUCTION

1.1 STUDY BACKGROUND

Railways to become and remain an attractive mode of transportation in the world, it is required to resourcefully schedule trains, travelling at different speeds, at the existing infrastructure such that capacity utilization will be maximum, while avoiding conflicts and satisfying constraints and objectives. However, to prepare train schedules for a rail network without any supporting tools and resolving conflicts "by hand" is rather a slow process. To schedule trains even over a small size rail network, a large number of experienced schedulers and ample amount of time will be required. Thus it would be difficult or impossible to look at alternative schedules, plans, operating rules, objectives, etc. Computerized aided tools are helpful to do this scheduling within seconds. A computer-aided train scheduling system can facilitate planning by systematically determining rail network capacity and identifying chokepoints. Latest research on train scheduling models and algorithms propose a variety of methods for improving the quality of the railway timetable, and thus of the railway system as a whole. Train scheduling models are being used as decision support tool and as planning tool for a train controller to evaluate the impacts of timetable change as well as railway infrastructure changes on train arrival times and train delays (Higgins, 1995b).

Pakistan railways network is comprised of 7,791 route-kilometers which consists of 1,043 km of double-track sections (in total), 285 km of electrified sections and remaining railway network is single track (JICA, 2006). Figure 1.1, shows the extent of Pakistan Railways network. Train schedulers in Pakistan are scheduling trains by manually time distance graph preparation. This type of dispatching system has so many limitations and can generate sub-optimal results (Kauppi et al, 2006). An overview by Geitz (2007) of urgent need of railway traffic management tools in emerging economies also confirm necessity of computer based tools for decision support systems in the operating and planning areas of Pakistan Railways. It is important to note that no work on the proposed topic has been carried in Pakistan. Moreover, research in other parts of the world was carried out using different conditions, therefore, cannot be applied directly and needs to be customized for local conditions in Pakistan. This study is the first of its kind in Pakistan and outcome of this research is expected to provide a valuable research material. To produce a better introduction of this thesis, a brief overview of train schedule modeling is presented in next section.

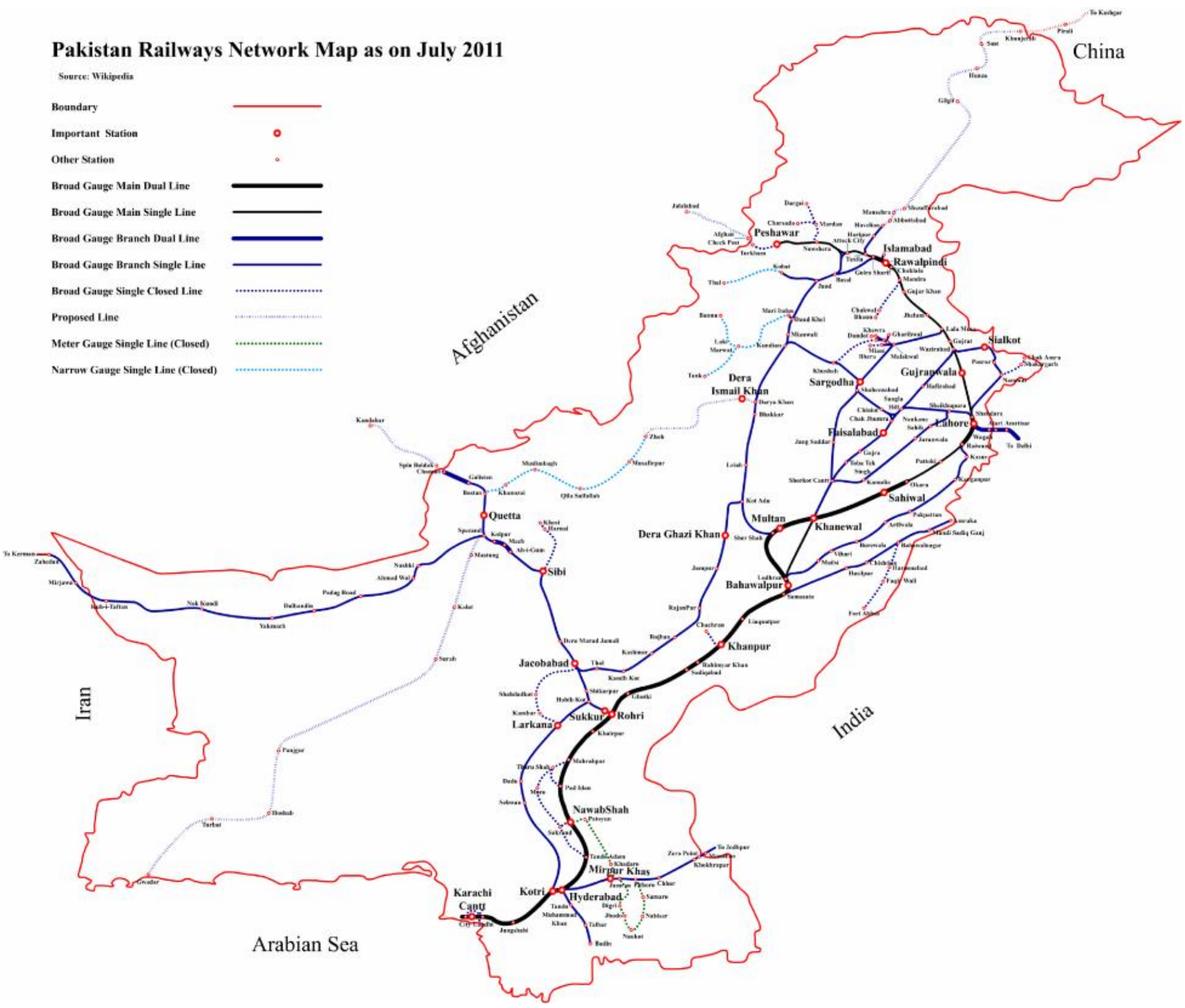


Figure 1.1: Pakistan Railways (PR) Network.

1.2 TRAIN SCHEDULE MODELING

One of the most important factor due to which level of service of railways can be improved is efficient design of Timetable. Therefore, planning and operations are fields rich in interesting optimization problems. Mathematical programming techniques as well as simulation techniques are helping tools applied to long and complex timetabling procedure to optimize the use of infrastructure capacity. According to time perspectives off-line timetabling and real-time traffic management are two main classes. Usually railways manage their service by planning all operations few months ago, which is known as off-line timetabling. During operations unexpected events disrupt the timetable and cause conflicts between train paths which must be resolved in real-time. Real-time traffic management received rather limited scientific attention, while the development of real-time decision support tools for traffic controllers enables a better use of rail infrastructure and a significant impact on train punctuality by means of effective dispatching actions. Time limitations to take decisions and complications involved in the real-time processes are among the various reasons behind this little attention. Because of the time and space limitation real-time management is mainly dependent on the timetable robustness.

Figure 1.2 shows the classifications of the railway traffic management models used to efficiently design timetables. This type of classification has been introduced recently in the field of railway by D'Ariano (2008). That is, off-line timetabling is the process to construct schedule of operations before some time, while in real-time management is modifying the existing one according to new scenario.

A detailed review of these management systems which provide the guideline for this research is discussed in detail in Chapter 2.

A synthesis of past studies on train scheduling in the context of modeling techniques, objectives and solution algorithms used are presented in Table 1.1.

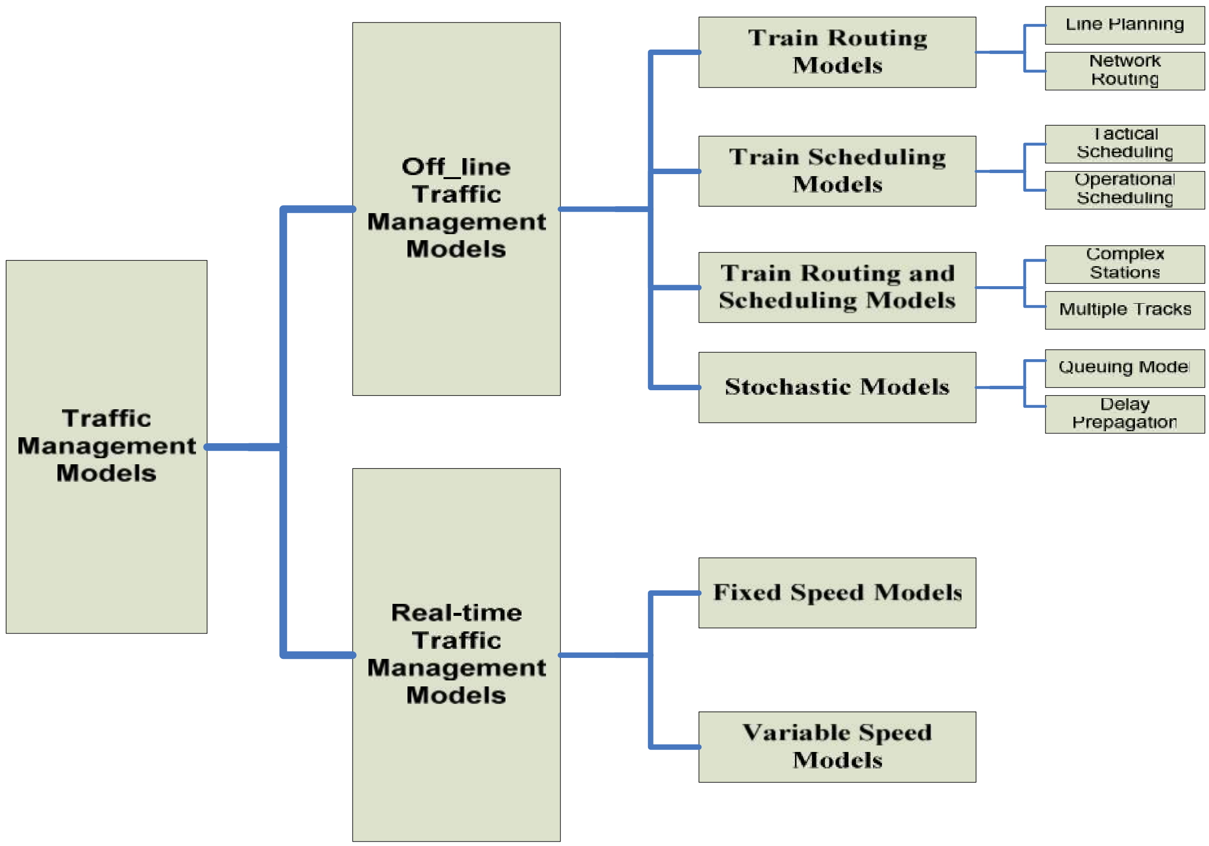


Figure 1.2: Classifications of Rail Traffic Management Models.

Table 1.1: A Synthesis of Past Research on Train Scheduling.

Publication	**Modeling Technique**	**Objectives**	**Solution Algorithm**
Tornquist and Persson(2007)	MIP	To minimize total delay and cost.	H
D'Ariano et al. (2007)	MIP	To minimize secondary delays.	B & B, H
D'Ariano et al. (2008)	MIP	To minimize the maximum and average consecutive delays in lexicographic order.	B & B, LS and PR.
D'Ariano and Pranzo(2009)	MIP,S	To minimize secondary delays for all trains over multiple timetable hours.	B & B, H and PR.
Corman et al. (2009)	MIP	To minimize average delay and average cost of train.	B & B, H
Corman et al. (2010a)	MIP	To minimize the maximum and average consecutive delays in lexicographic order.	B & B, H

Corman et al. (2010b)	S	To minimize total passengers' delay.	AG.
Corman et al. (2011)	MIP	To minimize train delay combined with the objectives of train companies.	B & B, H
Schachtebeck and Schöbel (2010)	MIP	To minimize the sum of all delays of all passengers at their final destinations.	H, D
Meng and Zhou (2011)	MIP, SP	To minimize the expected additional delay under different forecasted operational conditions.	B & B, H
Where: Mixed integer programming (MIP). Computer simulation model (S). Stochastic programming (SP).			
Branch-and-bound (B&B). Alternative graphs (AG). Heuristics (H). Dynamic programming (D). Local search (LS). Practical rules (PR).			

1.3 PROBLEM STATEMENT

The design of timetables is a complicated and recurrent problem, and typically requires many months. During operations, however, unforeseen events may disrupt the timetable and cause conflicts between train paths which must be resolved in real-time. Railway traffic management system in Pakistan is based on manual time-distance graphs preparation by traffic managers/dispatcher and removal of conflicts in control room. Figure 1.3, shows basic dispatching system, used by traffic controllers in Pakistan. This system can be improved by aiding this with some decision support systems which enable the traffic managers/dispatchers to determine the instantly favorable actions quickly by applying if-else conditions. Usually, traffic managers/dispatchers prefer to slightly change the original timetable based on their experience and knowledge instead of extensive rescheduling.

This study aims to provide an aiding tool which helps traffic managers/dispatchers in traffic management. This tool must be sophisticated and capable to estimate the effects of each and every dispatching measure taken by the controller. So that it can help rail traffic control sections in Pakistan to decide well in a short decision time by viewing the impact of their decision on the whole network. This may enable traffic controllers to modify of the actual timetable in order to adjust the sudden traffic disturbances.

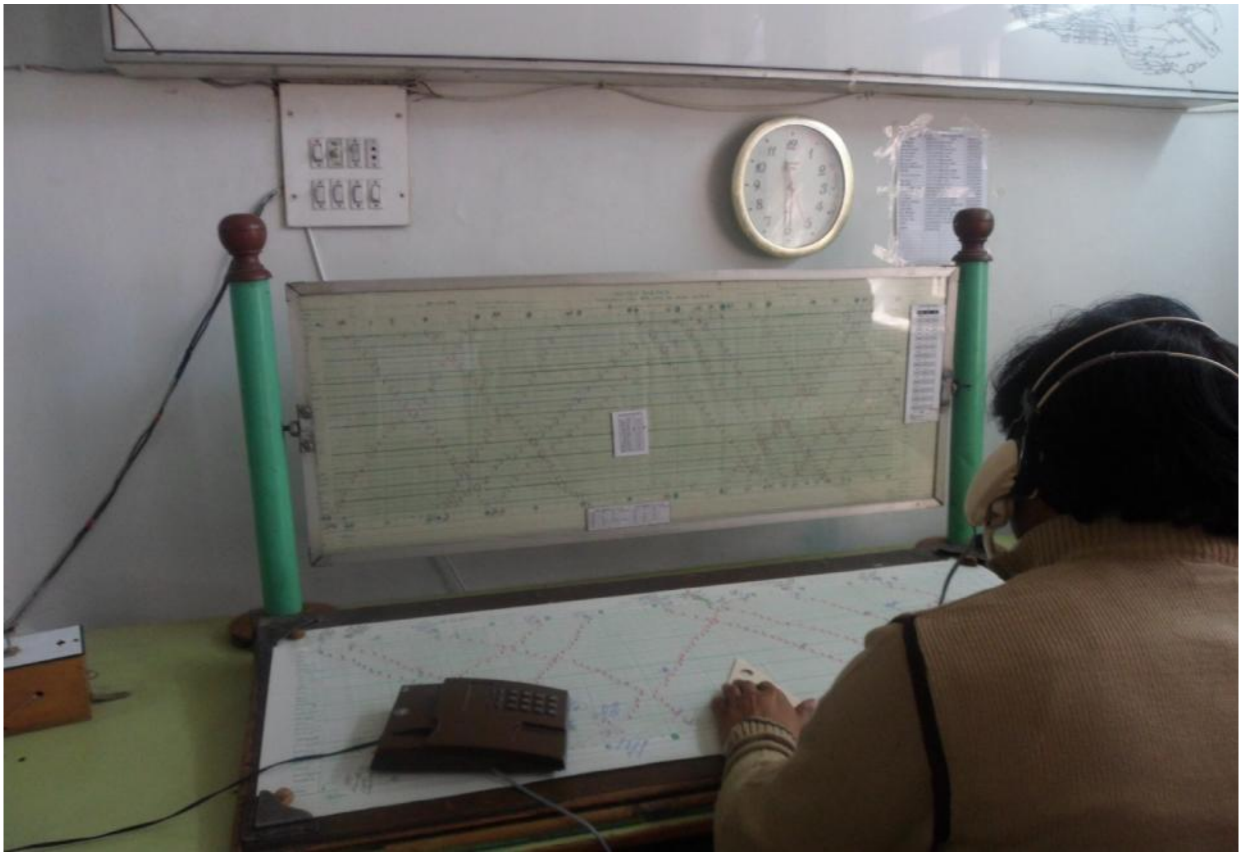


Figure 1.3: A Dispatcher Working at the Traffic Control Center in Pakistan.

1.4 BASIC COMPONENTS OF A TIMETABLE

Quality of timetable can be judged by determining how much realistic are the process times of separate activities. In real life due to variations in environmental and internal conditions process time of operations does not match with Master Plan. Probability of realization of these process times can be increased by adding some time supplements to process times. Thus, a scheduled process times contain; normal processing time, a margin to counter less favorable conditions and scheduled waiting times to remove conflicts.

Next subsection describes some definitions used in timetabling theory. After that components of timetable are discussed one by one.

1.4.1 Definitions

Some of the main terms used in this thesis are defined below.

- **Actual Schedule**: Actual Schedule is referred to as the schedule devised by the train controller after unforeseen events take place.
- **Siding**: A section of track which can be used for the crossing and passing of trains under single track operations. The terms ‘crossing loop’ or ‘passing loop’ are also used in some countries to describe such track sections. A train station on a single line track will usually contain a siding.
- **Train Conflict**: There are two situations; i) Crossing, when two trains approach each other on a single line track and continuation of either or both trains’ journey would not be possible and ii) Overtaking, when a faster train catches up to a slower train travelling in the same direction.
- **Conflict Delay**: Conflict Delay is the delay to a train if it must wait at a siding for another train to cross or overtake. From a train controller’s point of view this is not delay since it is already included in the train plan. A schedule or train plan with the least amount of conflict delay is the most efficient schedule under ideal conditions, if unforeseen events are not considered as part of the objective.
- **Inbound Train**: In this thesis an inbound train commences its journey from Lalamusa and terminates at the Rawalpindi. The outbound trains travel in the opposite direction.
- **Minimum Headway**: The minimum length of time separating two trains on a single line track. This is usually determined by signals in the case when the trains are travelling in the same direction. When travelling in opposite directions, the minimum headway is determined by the time required for one train to clear the track segment sufficiently before the opposing train can enter it.
- **Planned Schedule**: Planned Schedule is generated at a tactical level (medium term planning) by rail planners to be used on a daily or weekly basis. The actual schedule will be the same as the planned schedule if no unforeseen events occur.
- **Robustness**: The robustness of a railway system indicates the influencibilty of the system by disturbances.

- **Knock on Delays**: Secondary delays or knock-on delays are delays caused by earlier delays. These are due to the interdependencies in railway systems.

1.4.2 Running Time

Running times are usually calculated by adding nominal running times and running time margins and then rounded up to whole minutes (Schaafsma et al. (1996), Schaafsma (2001)).

- **Running Time Calculation**

Principles of train dynamics are used to calculate the nominal running time of a train. Various resistive and tractive forces are considered to determine the change of train speed by equilibrium equations (Andrews, 1996).

Figure 1.4 shows five regimes of train movement which are acceleration, Speed Holding, Coasting, Braking and Standing. These all depend on station spacing and speed limit, in some cases where stations are not much apart brakes may be applied before maximum speed attained so this phase will be missing in this case.

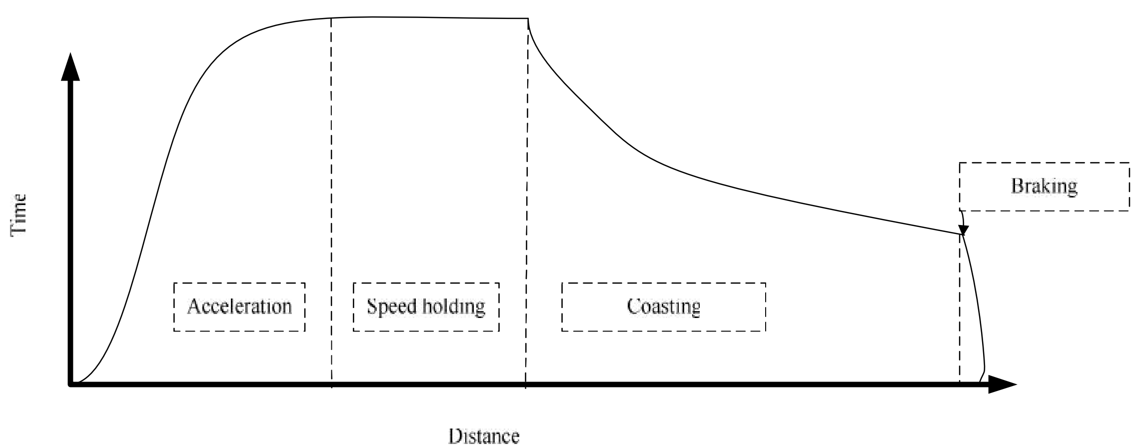
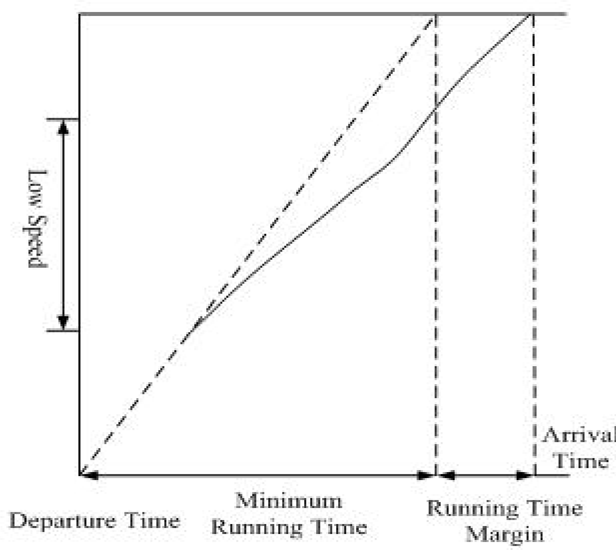


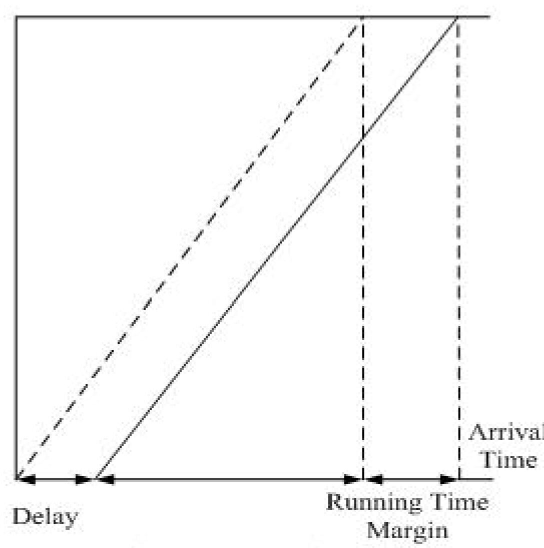
Figure 1.4: A Typical Train Speed Profile.

➢ Running Time Margins

Running time margins are added to admit train slower speed at track due to prevailing conditions. Secondly it can be used as recovery time and thirdly it can be used for energy efficient train movement by applying coasting regime (Gijsen et al. (2002), Howlett (1995)).



a) Slow Train



b) Departure Delay

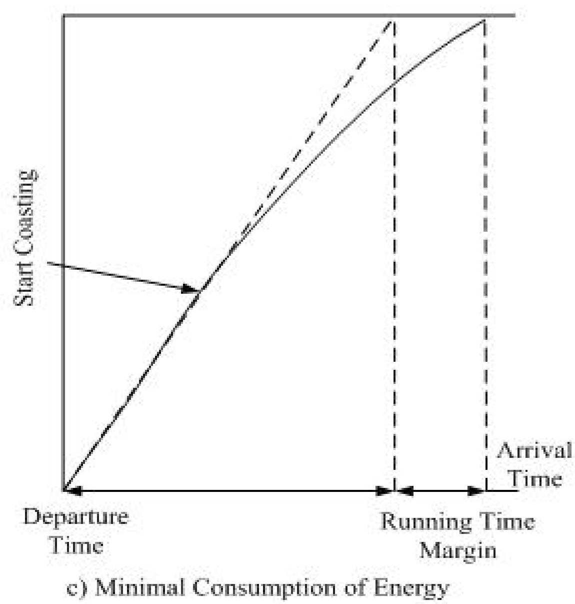


Figure 1.5: Time-Distance Diagrams Demonstrating Usage of Running Time Margins.

1.4.3 Block Time and Minimum Headways

Blocking time can be defined as time interval in which a section or block is allocated to a train and blocked for all other trains. The blocking time for a running train is the time for which a section is occupied by a train and it contains following parts (Goverde, 2005), shown in Figure 1.6.

- The switching time, is time interval to set up an interlocking route.
- Reaction time of a driver, which is running in clear weather and at minimum sight distance, to the approach signal at maximum speed.
- The approaching time, is the running time from the approach signal to the main signal.
- The block running time, is the running time between the block signals.

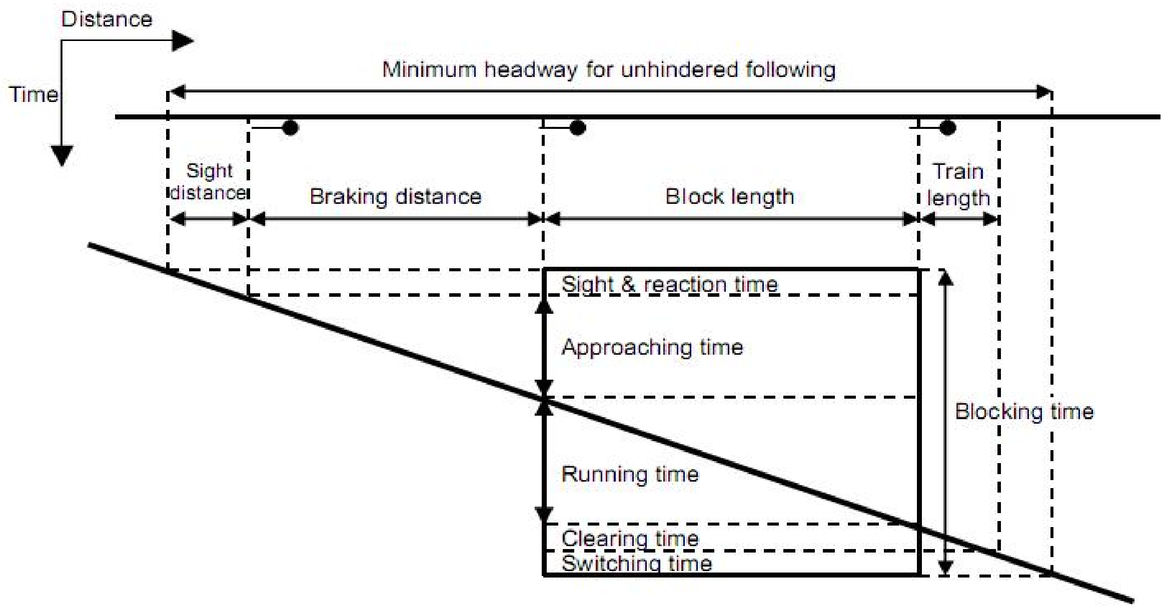


Figure 1.6: Blocking Time for a Fixed Block Signaling [Adapted from Goverde (2005)].

- The clearing time, which is the time between reaching the signal at the end of the block and the clearance of the block by the last train axle. It depend on train length.
- The switching time to release the route interlocking.

  In general headways are generally classified as (shown in figure 1.7).
- Arrival-arrival headway between two arriving trains at a junction or on conflicting inbounds routes at a station shown in Figure 1.7.
- Departure-departure headway between departing trains on conflicting outbound routes at a station or on a mutual open track.
- Arrival-departure headway between an arriving train on an inbound route and a departing train on a conflicting outbound route.
- Departure-arrival headway between a departing train on an outbound route and an arriving train on a conflicting inbound route.

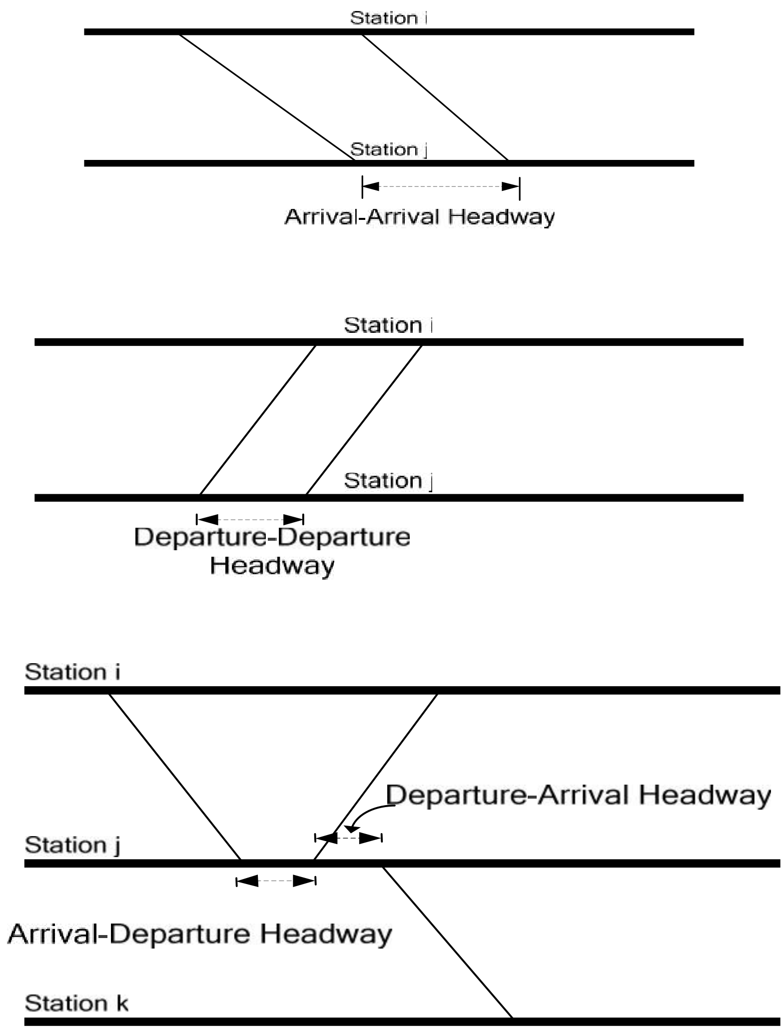


Figure 1.7: Classifications of Headways

1.4.4 Dwell Time

Time for which a train is stayed on a station to do all necessary operations e.g. alighting and boarding of passengers, coupling and uncoupling etc. Figure 1.8 shows main components of a dwell time. All factors on which this dwell time depends are variable from station to station so it is not consistent and must be calculated carefully.

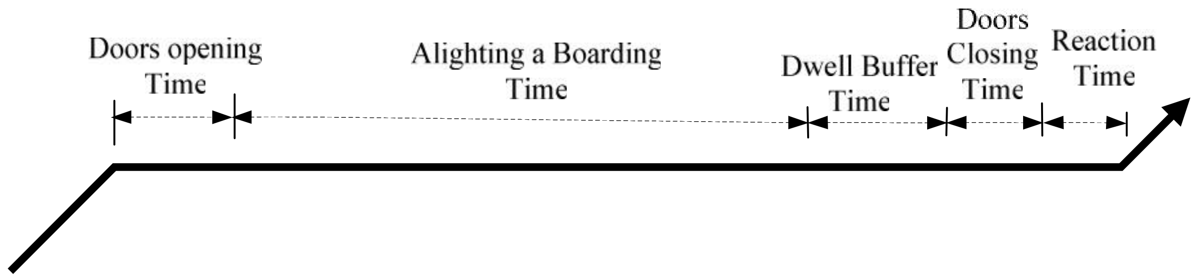


Figure 1.8: Components of Train Dwell Time.

1.4.5 Transfer Time

It is time interval in which passengers would be able to move from feeder train to connecting train service. Transfer time contains alighting, walking and boarding time. Governing factors to calculate transfer time are walking speed, distance between arrival and departure platforms and geography of station.

1.4.6 Layover Time

Time spent at terminal stations to carry out all necessary operation before the start of a new journey is called Layover time. This depends on train type and shunting activities. Minimum layover time for trains which continue their movement in opposite directions with same drivers depends on time interval for closing cabins at one end, time to walk over the length of train, and preparation time to depart at other end. Shunting and coupling activities are also considered when there is any type of rearrangement in composition of train.

1.4.7 Synchronization Time

Synchronization time is time to supplement dwell time that enables transfer of goods and passengers. Synchronization is basically coordination between arrival and departure of trains to offer a connection to transfer passengers. It is extra time than minimum dwell time that can also be used to compensate arrival delays. Synchronization time is illustrated in Figure 1.9.

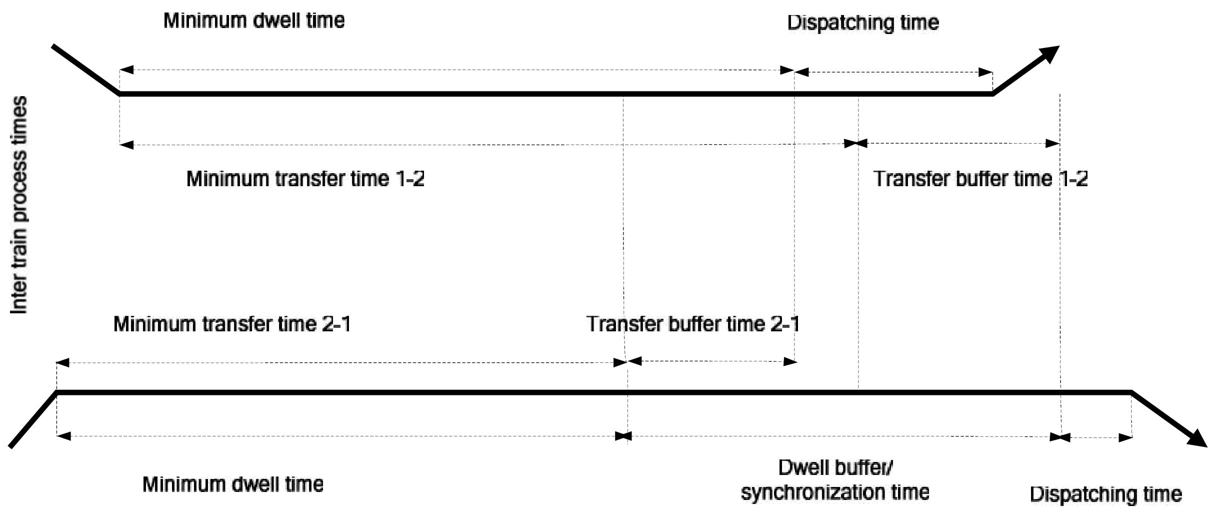


Figure 1.9: Illustration of Synchronization Time with Components.

1.5 TRAIN TIMETABLING AS PART OF RAIL OPERATIONS

In this section a connection is made between the single lines train Timetabling and rail operations as a whole. Rail operations' planning is made up of short, medium and long term planning. Longer term planning is influenced by many other areas such as marketing, environment issues, political issues, investments and human aspects. The planning hierarchy is illustrated in Figure 1.10.

In Figure 1.10, schedules are optimized at both medium and short term planning horizons. At medium term planning, a train schedule is generated off-line to be used on a regular basis. If there are no unforeseen events, trains will follow this plan exactly. However, unforeseen events do occur and require trains to be rescheduled. This is the short term planning. Other rail operations activities, for which rescheduling is performed at a short term level are locomotive scheduling and distribution of rail cars. Efficient optimal/heuristic solution techniques are required at the short term level due to the frequent occurrence of unforeseen events.

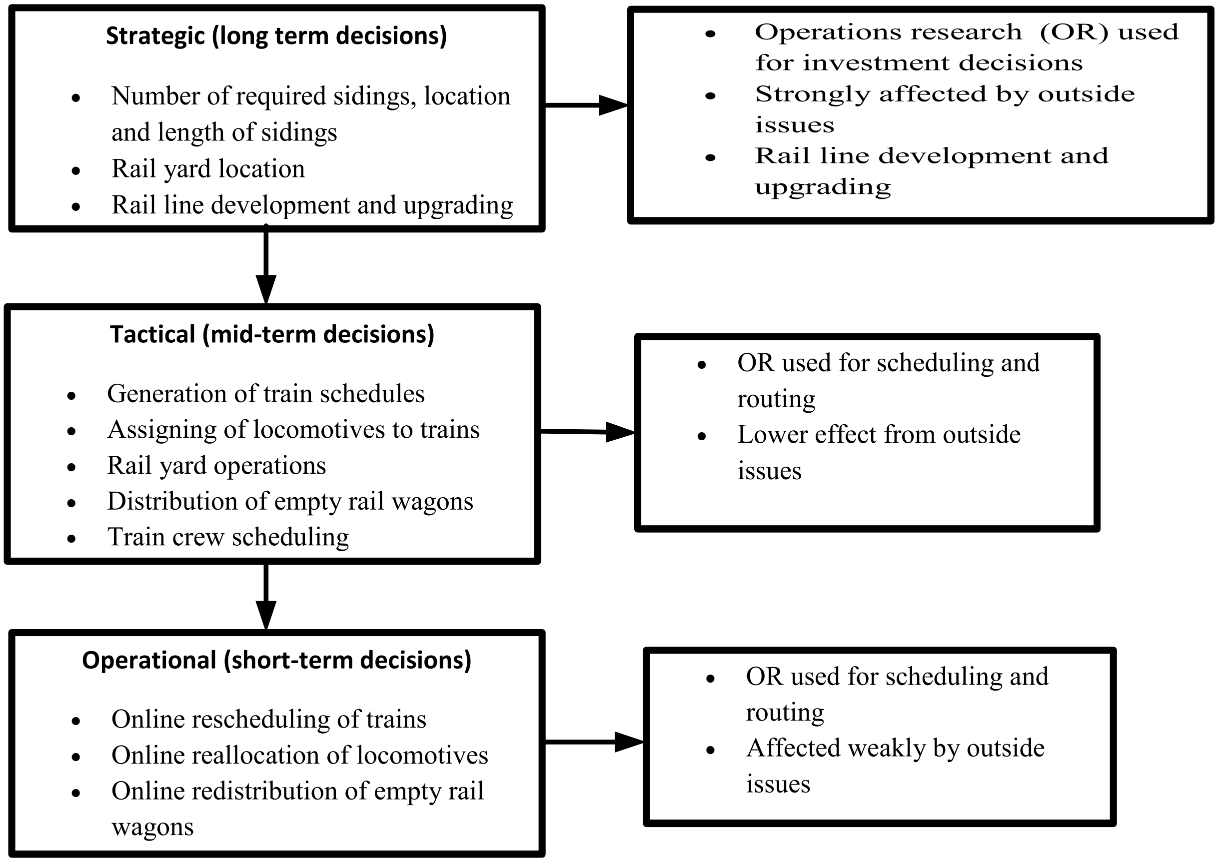


Figure 1.10: Rail Planning Hierarchy (Higgins, A., 1996b).

Train scheduling and dispatching, yard/terminal planning, scheduling of locomotives, and distribution of empty wagons are four main operational areas which are dependent upon one another and have received a great deal of research effort. It is difficult to combine single line train scheduling, locomotive scheduling, rail yard activities and distribution of rail wagons into one large problem while keeping the same level of detail as can be achieved when modeling the tasks separately. Such a formulation would involve a large number of variables and it would be difficult to mathematically decompose the problem. Because of this, researchers have concentrated on the individual tasks.

The effectiveness of using mathematical techniques for modeling each of these tasks is made more difficult by unforeseen events during a train's journey. Improving this reliability can have beneficial effects. That is a large amount of delay in rail yard activities and at terminals is due to trains not arriving close to the expected arrival time. Moreover, consistent train arrival times would allow more reliable terminal/rail yard throughput and thus more reliable departure times.

1.6 OBJECTIVES OF THESIS

The main aim of this thesis is to apply optimization models to plan operations on single line railways in Pakistan taking into account all possible constraints and to provide a helping tool to rail traffic managers in Pakistan. The models can be applied to longer term planning or short term planning such as developing a schedule to be used daily or weekly.

In order to achieve that aim, the following specific tasks were set:

- To study the train schedule generated by PR (for track segment Rawalpindi to Lalamusa).
- To find out the parameters used by PR e.g., running times, departure times, dwell time and headways etc.
- To draw schedule time distance graph generated by PR.
- To optimize this schedule using a scheduling optimization model.
- To compare both schedules, generated by PR and proposed optimizing model.

1.7 OVERVIEW OF STUDY

To achieve the stated research objectives, this dissertation follows a sequence of work activities starting with a comprehensive review of the literature of train scheduling modeling and optimization techniques. This is followed by the state of the practice, theoretical considerations, and data collection of Pakistan Railways scheduling procedure. After that, single line train operation of Pakistan Railways is modeled. This model is applied to get optimal schedule and sensitivity analysis for this track segment is done using this approach. The thesis concludes with a summary of the conclusions, and recommendations for future research. An overview of the study approach is presented in Figure 1.11.

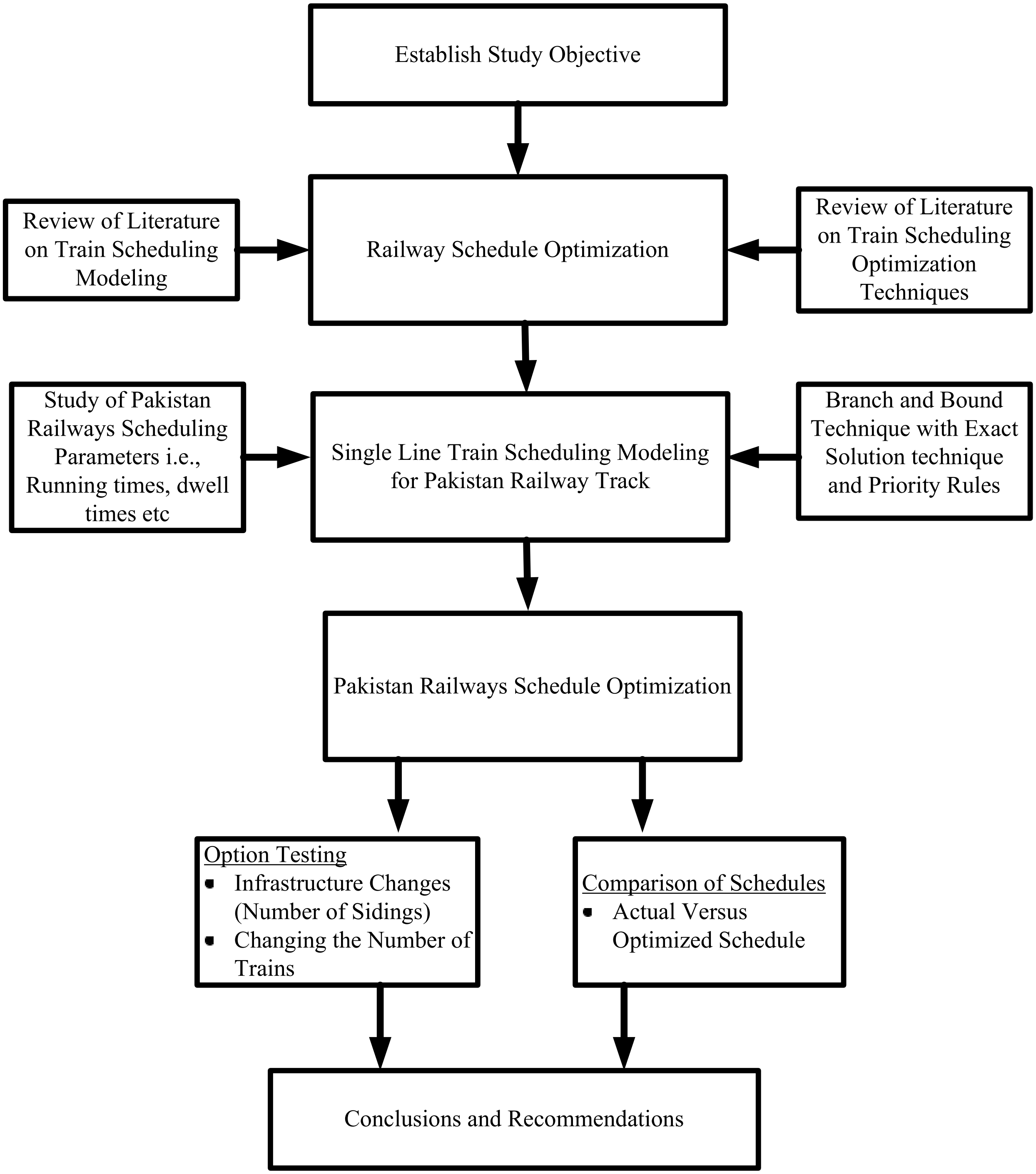


Figure 1.11: An Overview of Study Framework for Optimal Train Scheduling In Pakistan.

1.8 STRUCTURE OF THESIS

This thesis is organized in five chapters. Chapter 1 provides background for the need of train schedule modeling and necessity of application of latest computer aided techniques in railway scheduling of Pakistan. In chapter 2 detailed literature reviews of mathematical models and solution techniques used for rail operations schedule optimization are described. Chapter 3 provides the mathematical model and the schedule optimization technique used in this thesis. Comparison of different approaches used with Branch and Bound technique is presented with an example. In Chapter 4, the model parameters of PR are discussed and then model and solution technique discussed earlier are applied to an actual rail corridor of Pakistan. The purpose is to show that the developed models can be applied to actual train problems without having to make unreasonable assumptions. The usefulness of the developed model/solution procedures to rail operations is discussed. Finally in Chapter 5, the research summary, conclusions, and recommendations for the future work are presented.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Due to the growth of traffic and limited resources to enhance the infrastructure, one thing that can play a key role to improve the level of railway service is effective design of Timetable. Therefore, planning and operations are fields rich in interesting optimization problems. In fact, there is an extensive literature on Timetable design problem. This is usually a long procedure, involving intensive negotiation among different stakeholders and advantages can be taken from computer aided tools in this process. On the other hand, real-time traffic management received rather limited scientific attention, while the development of real-time decision support tools for traffic controllers enables a better use of rail infrastructure and a significant impact on train punctuality by means of effective dispatching actions. Reasons behind that are the inherent complexity of the real-time process and the strict time limitations for taking decisions, which leave small margins to computerized decision support systems. Another reason is that the management of real-time processes is often limited in time and space, and depends on the timetable robustness.

The aim of this section is to review, classify and compare various approaches for railway traffic management. According to time perspectives off-line timetabling and real-time traffic management are two main classes. That is, timetabling is the process of constructing a schedule from scratch, while in real-time a schedule already exists and may be modified. Main focus of most of the previous problems is to develop robust and optimized timetables. Researches also focus on the dispatching process of managing real-time timetable disturbances, without addressing important problems in cargo transportation such as empty car distribution, freight car management and locomotive assignment. This overview will discuss in detail only Train scheduling models which is main focus of this thesis with a little bit introduction to other types of approaches. This overview also does not include other relevant problems such as rolling stock management, train unit shunting and crew planning.

2.2 OFF-LINE TIMETABLING

To develop a timetable a scheduler has to deal between robustness and capacity utilization, which is a complex and lengthy process. This process may require several months, in which scheduler has to resolve conflicts by considering each and every factor affecting this process. Then there are so many unforeseen e.g. equipment failure in infrastructure, fluctuation of passenger volumes, weather and human behavior, which may perturb that timetable on daily basis. When only one of the scheduled trains is disturbed, so many conflicts arise due to route and signaling constraints. To compensate these delays, time reserves are usually inserted into timetables. High quality timetable generation requires precisely estimate of blocking times by considering all practical operations. The blocking time of train may be defined as the time that a train requires to operate safely without compromising the design speed over a sequence of track sections. Buffer times are margins inserted between the end and start of two blocking times; these also serve to supplement the train running times. When there is no buffer time allocation block time difference between two consecutive events represent the minimum headway. Buffer times are helpful in the reduction of Secondary delays but can't limit Primary delays. Primary delays are compensated by running time reserves and dwell time margins (Nie & Hansen, 2005). Moreover, a timetable also contains schedule stops for commercial and technical operations, non schedule waiting times also generated in practical operations. Schedule waiting times are precisely estimated times considering all operations which are likely to take place e.g. passing and overtaking and transferring of passengers and luggage from one train to another. These times are source of increase in dwell time (i.e. longer stopping time at station), timetable quality can be judged by examining this factor. Non-scheduled waiting times are delays due to unexpected delays experienced during real-time operations. Due to the randomness of disruptive events, running time reserves and other time margins should be distributed over the whole network (Hansen, 2004).

More time reserves will increase punctuality but capacity utilization will be decreased. In saturated infrastructure, due to hold back between following trains knock-on delays will be easily generated. A limited amount of time reserves can be inserted in a congested timetable. Even efficient designing of Off-line timetabling can't stop deviation in congested areas. Punctuality level of rail service is predicted by the estimation distribution of arrival and departure time delays. This estimation should be realistic as much as possible by taking into account the impact of knock-out delays due to headway and routine conflicts as well as late arriving of feeder trains. Efficient utilization of network capacity and a higher level of reliability and punctuality of train operations have been less studied and generic approach to determine optimality is still to be developed.

Reliability and robustness are two main parameters used to access the quality of a railway system. A timetable should be reliable as well as robust, which can absorb small delays and prevent or reduce the larger perturbations. Desired objectives e.g. increased quality of rail service and reduced delays can be achieved by an optimal design of a timetable.

The stability of railway systems can be defined as the ability of system to return to regular operations after disturbed situation. In unstable rail system, an unexpected event can cause irregular traffic for a long time. Delays propagate quickly in unstable system throughout the railway network, possibly causing a knock-on effect of increasing train delays. However, a common definition of stability and robustness of rail operations does not exist, also there is need to realistically model all the parameters of railway operations to predict the amount of consecutive train delays on congested rail network.

Goverde (2005) presented an analytical stability theory to evaluate the timetable robustness. He used discrete-event dynamic modeling to formulate railway network timetables on the basis of a linear system in max-plus algebra. Using max-plus spectral analysis and critical path algorithms, the stability of large-scale periodic railway systems is analyzed to support the design of robust timetables in dense railway traffic networks.

Goverde and Odijk (2002) present a tool, called PETER, for the automatic transformation of conventional periodic network timetable constraints into a max-plus state matrix of the travel times, minimal time headways and transfer times, for critical circuit and recovery time analysis. The impact of an increase or decrease of travel times and buffer times on the timetable slack and on the location of the critical circuit of periodic network timetable is estimated rapidly. PETER also computes the delay propagation of different delay scenarios in order to find the most sensitive links in the network, i.e., the time-space location of the less effective timetable time margins. However, the estimation of network timetable slack by the max-plus approach is deterministic and does not permit to change the train order of a given timetable.

To estimate precisely the punctuality, train detection devices (e.g. sensors of the safety and signaling system) are an important source of traffic flow data, i.e., the number of trains per unit of time. Goverde and Hansen (2000) have developed a tool, called TNV-Prepare, that is based on TNV-data from automatic train describers. TNV-Prepare enable accurate analysis of infrastructure utilization by matching information from safety and signaling system to train numbers. Infrastructure and train number messages are stored with a precision of one second, monitoring the change in status of a certain infrastructure element, such as a track section that gets occupied or has just been released.

Goverde (2005) used TNV-Prepare to enable accurate calculation of train movements on track section occupancy level, stability analysis of infrastructure utilization, and estimates of arrival and departure times at platform tracks in complex railway stations. A linear regression analysis and accurate empirical data are adopted to investigate the dependencies between train lines, including transfer connections and conflicting routes. Goverde (1998) introduced an innovative analytic approach for the deterministic modeling of passenger waiting times by means of recursive equations in max-plus algebra, and used this model to solve the problem of determining the wait or no wait decision of transfer connections in case of delays. In other words, for each possible connection one has to decide if a connecting train should wait for a delayed feeder train or if it is better to depart on time.

Schobel (2001) also considerd the problem of which connected train services at railway station should be maintained and which can be dropped in case of small disturbances. In Vromans (2005) and Vromans et al. (2006), a procedure to create more homogeneous timetables has been proposed by reducing the running time differences and imposing a similar number of train stops per track section. This is done to decrease the propagation of delays caused by interdependencies between trains. Some experiments on a Dutch railway corridor enable a comparison between real-life heterogeneous timetables with more homogeneous timetables. The obtained results show that the proposed measures are likely to improve the punctuality of rail operations.

Off line timetabling can be further divided into four sub areas (D'Ariano, 2008) as shown in Figure 2.1.

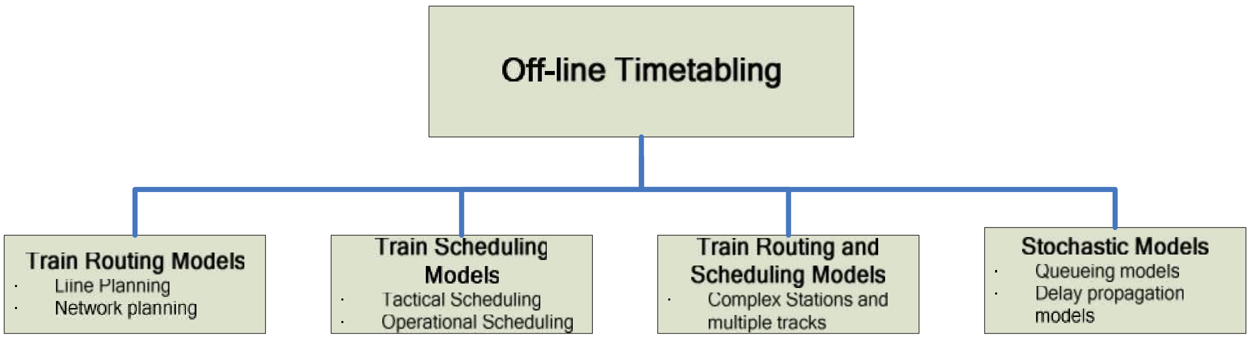


Figure 2.1: Sub-sections of Off-line Train Timetabling.

2.2.1 Train Routing Models

There are two types of optimization models addressing the routing of trains. The line planning problem is to decide the routes for passenger trains as well as the types and frequencies of each train route (Caprara et al, 2006). On the other hand, network routing models address the different problems related to freight train routing. In both cases, train scheduling models are adopted to determine the arrival and departure times of the trains at all the relevant passing and/or stopping locations.

2.2.2 Train Scheduling Models

A very large scale integer programming of the train scheduling problem is known as NP-hard (Garey & Johnson, 1979), (Ullman, 1975). On the basis of assign train routes, scheduling models find the timing and ordering of passenger and freight trains by resolving conflicts. The number of possible solutions can become very large depending on the governing factors e.g. the network structure, the amount of traffic and type of trains. The train scheduling can be done according to different time perspectives, i.e., on a tactical or operational level. Tactical level scheduling is done several months before and it involves day-to-day basis plan for a large traffic network. While, a limited and shorter time before the departure of trains is available for operational scheduling. In tactical level planning main focus is on the solution quality because the availability of ample amount of time but in the case of operational scheduling due to time limitations both the solution quality and speed are objectives. This classification has been introduced in the railway field not so long ago (see, e.g. by Harker (1995)) and sequentially mostly adopted (overviewed in Tornquist (2006)). As far as mathematical modeling and solution techniques to solve train timetable problems are concern a wide range of studies are carried out in the last three decades.

- **Tactical Scheduling**

Master Plan generated to be executed in real-time is known as tactical plan of operations. Main focus of this work is connection among all trains using the whole network with objective to allocate the track to optimize capacity utilization. Models and algorithms developed for tactical scheduling usually optimize track allocation.

Greenberg (1968) developed B&B solution technique structure to solve general machine scheduling problem based on job shop scheduling. Later on, Szpigel (1973) used the same frame structure to develop a model to solve train scheduling problem. He was first in model development to solve train scheduling problem. He used mixed integer programming in this model and the objective function was the minimization of total transit time subjected to overtaking and passing constraints.

Peterson (1974) developed model based on train priorities to control meet pass actions, based on these priorities delays can be calculated. Departure of train was taken as an independent random variable and trains were allowed to travel at different speeds. Linear equations based this model can calculate mean running time as well as delays.

Jovanovic (1989) modeled both single and double track dispatching problem as a mixed integer program. Real world complex set of constraints were applied with binary variables to indicate position of meeting points and continuous variables for arrival and departure times. This modeling aimed to minimize costs of all deviations from Master Plan.

Schedule Analysis (SCAN) proposed by Jovanovic and Harker (1990) and Jovanovic and Harker (1991), provides a system for the tactical scheduling of trains and maintenance operations. This was based on the model developed by Jovanovic (1989), combinatorial optimization and robust scheduling were main objectives. Input for SCAN was the initial schedule, feasibility check performed on various traffic scenarios. Simulation method used here to model train movements. Demonstration of this model performed using rail network containing 200 trains, 24 lines and 130 conflicts.

Carey and Lockwood (1995) presented methods and algorithms for the solution of single line dispatching problems. The network considered in this work was consisted of several links and terminals, where each line is dedicated for unidirectional traffic with trains running at different speeds. Mathematical formulation was done by mixed integer programming considering real-time constraints. First each train is scheduled to generate a plan than heuristic is applied to improve the solution. Carey (1994a) extended this work from one way to two way traffic problem and applied same technique to solve more complicated conditions.

A model to estimate risk of delays associated with a train schedule was presented by Higgins et al (1995a). They modeled track related delays, terminal\ stations delays and rolling stock related delays. Usefulness of this model was that it can be used to decide the priorities investment strategies which will improve the reliability. Moreover, effects of proposed changes in timetable as well as changes in infrastructure e.g. adding or removing sidings on the single line train operations can be assessed.

Higgins et al (1995b) modeled single line train operations to optimize train schedules, B&B technique with priority in a conflict to estimate the remaining conflict delays was used to determine optimum solution quickly. Decision support tool for dispatchers and planning tool for traffic controllers was the main two objectives behind the development of this model and solution technique.

Higgins et al (1995b, 1997a) put forward a model to determine the optimal position of sidings on a single track rail network. They use that model to find the number and position of sidings on Queensland rail network. This model allows trains to run at non constant train velocity and departure times were not taken as constants. Objective function was minimization of train operating cost and total running time for a given cyclic schedule. They decompose model to find out simultaneously optimal position of sidings and timetable for given track. Optimal resolved schedule as well as improved position of sidings is outcomes of this model. Train travel time with arrival time reliability was two operations research dealings put into that model. To find out position of sidings for a given level of service they used simulation to demonstrate the model working. Customer service and rail profitability both have considerable interdependence on the improvement of sidings in respect to number as well as position on the track.

Higgins et al (1997b) applied meta-heuristic technique to solve single line train scheduling problem. Local search heuristic, tabu search, genetic algorithm and two hybrid algorithms with new improved neighborhood frame structure were applied to solve problem. Genetic hybrid algorithm was found to generate within five percent to optimal solution for ninety percent of problems, with and without time constraints.

Newton et al. (1998) model the rail road blocking problem as a network design problem in which stations were represented by nodes and blocks by arcs. Formulation was done by mixed integer programming, branch and cut and column generation algorithms used to solve the developed shortest path model. Barnhart et al. (2000) used Lagrangian relaxation technique to decompose the same model proposed by Newton et al. (1998). They focused to find near optimal solution, results shows that for large problems computation times are not scalable.

Oliveira and Smith (2000) modeled single line train scheduling problem as job shop scheduling modeling. Train trips were taken as jobs to schedule over tracks as machines. Conflicts were taken as when two trains use same track at the same time. Objective function was the minimization of total delay and Shortest Processing Time (SPT) was used to resolve conflicts when rescheduling all tasks. Some practical constraints were also modeled in this modeling. Demonstration of this model was done by solving 19 problems of Higgins (1996b).

Caprara et al (2002) modeled single line train timetabling. Each train has two main stations on the track, origin and destination, between these stations at intermediate stations trains can stop for minimum time and can overtake each other. Proposed solution technique was direct multi-graph method in which nodes correspond to arrival and departure time at a station. Model formulation was done by integer programming with Lagrangian relaxation technique. By using this model they solved real life problems provided by Italian Railway.

Pacciarelli and Pranzo (2001) used tabu search algorithm to schedule trains by means of alternative graph method. Later on, Pacciarelli (2002) used same alternative graph solution technique to schedule complex factory activities. In this modeling an assumption was made that intermediate buffer times have infinite capacities but in real world scheduling buffer capacity has to be taken into account. This new proposed heuristic technique was discussed in relation with job-shop scheduling problem.

To solve and plot single line scheduling problems, Ingolotti et al. (2005) developed a model named as Decision Support System (DSS). Mixed integer programming was used to formulate a mathematical model which is based to satisfy constraints to generate optimized timetable.

Epstein et al. (2005) used B&B technique to solve a model developed to solve timetable issues for a complex network. Modeling was done for densely populated metropolitan area and track which have one, two and three track sections. CPLEX was used to compare the efficiency of proposed model, by comparing the results of both for a network of Los Angeles.

In collaboration with National Network of Spanish Railways (RENFE), Salido et al. (2005) developed constraints optimization technique to solve periodic train timetabling issues. In his model railways scheduling was subjected to a number of constraints describing rail infrastructure, train waiting and transit intervals and service requirements. The developed topological technique for optimization this work decomposes the model into sub problem. Each sub problem generate a traffic pattern which periodically repetition generate a full running map. Results have shown improved solution than well known constraints optimization problem solver LINGO and CPLEX.

Lindner (2004) developed a mixed integer programming model named Minimum Cost Scheduling Problem (MCSP) to find feasible least cost solution for Periodic Event Scheduling Problem (PESP). By using preprocessing techniques like lower bound estimation, B&B, cutting plane procedure, valid inequalities and a specific relaxation, he solved the real world problem within a suitable time.

Ghoseiri et al (2004) developed multi-objective optimization model for a network containing single and multiple tracks, to solve passenger train scheduling problem. Minimizing passenger time and fuel consumption were the objectives of this model, where first objective is for passenger satisfaction and second is for rail companies satisfaction. The distance based method with three types of distances used for optimization of multi-objective function.

Zhou and Zhong (2004) focused on double track high speed passenger rail line to minimize both waiting time and travel time for high speed and medium speed trains. Multimodal flow-shop scheduling problem was modeled by the application of two practical priority rules to accelerate or decelerate. Beam search algorithm with utility evaluation rules and B&B algorithm with an effective dominance rule used to generate solutions for this bicriteria scheduling problem. To demonstrate the working of model Beijing-Shinghai high speed railway was taken as case study

Linder and Zimmermann (2005) laid a corner stone for an algorithm by integrating cutting plane and B&B to optimize the German's and Netherlands' rail network. Decomposed mixed integer programming model was decomposed to solve the problems within reasonable amount of time and to get good performance. Train type related constraints were applied in the first part and the remaining constraints in other part. Objective function of this model was to minimize operating cost of schedules by choosing different types of trains at varied speed and operating cost.

Zhou and Zhong (2007) formulated resource constrained train scheduling problem considering station and segment as limited resources and constant free running times. They used B&B technique with Lagrangian relaxation and exact lower bound technique for estimation of least delays or lower bound to reduce solution space and a beam search heuristic was used to calculate upper bound. A branching scheme based on precedence relation between trains used to remove conflicts, resulting sub problem formulation was as a longest path method. This work evaluated the quality and computation cost of their lower bound rule, effectiveness of B&B technique with embedded lower bound technique and quality of priority based proposed heuristic. They consider Laizhou to Shaowu, china, 138 Km track with 18 station for this study.

D'Ariano et al (2007) modeled train scheduling problem as alternative graph formulation with B&B solution technique. Main objective of this model was to help rail infrastructure managers in real-time traffic management. According to them purpose of conflict resolution is to develop such a conflict free plan in which deviation from planned schedule is minimum. Objective function was minimization of secondary delays. Train operations were taken as node of alternative graph. Two local dispatching rules First Come First Served (FCFS) and First Leaved First Served (FLFS) and greedy algorithm were implemented to get initial value for B&B technique.

Another effective policy of timetable design focuses on cyclic timetables that have special properties of synchronization, periodicity and symmetry. Synchronization is the coordination of the departure of a train to arrivals of other trains to offer a connection for transferring passengers. Main railway stations are served by various train lines of different directions which are synchronized to offer seamless transfer opportunities. In a periodic railway timetable, train lines are operated with regular intervals throughout a day and consistent synchronized transfers are provided at stations between train lines of different type or directions. A periodic railway timetable is out of scope of this thesis.

- **Operational Scheduling**

Operational scheduling (or dispatch planning) is commonly used e.g. in North America and Australia. Whereas a master schedule is developed a long time before operations, the operational scheduling is created shortly in advance (White, 2007). In the case of freight transportation, trains sometimes operate without schedules and simply depart when potential time slots are available to them. In case a draft timetable (i.e., the train routes and the departure and arrival times at the corresponding origin and destination stations are generally fixed but not their exact timing) has been developed from a strategic point of view, the detailed movements of freight and passenger trains on the lines of the physical railway network still need to be precisely determined. The dispatch planning problem consists then of determining a feasible plan of train movements that is able to minimize train delays from the scheduled times while satisfying all the operational constrains. Specifically, trains can only overtake and cross each other at specific locations on single track lines (i.e., sidings or meet-points), and an operational schedule must order the trains while respecting the safety distance headway for trains traveling either in opposite directions or in the same direction. The main issue in train dispatching is therefore how to control trains utilizing maximally the track capacity while avoiding deadlocks. If no train on a segment of railway line can advance without causing a collision, that segment is said to be in a state of deadlock (Dorfman and Medanic, 2004). The resolution of this problem is subject to time restrictions (i.e., up to few hours) but this is still far from a real-time applicability.

A pioneer optimization model for the planning of meets and passes is the system developed at Norfolk-Southern Railroad by Sauder and Westerman (1983). This computer-aided dispatching system was implemented on a portion of the railroad. The proposed model is based on a simple partial enumeration scheme for generating an optimal meet-pass schedule for a single track rail line and selecting the one minimizing the weighted total delay.

Kraft (1987) develops a dispatching rule to order trains based on train priority, running times and a penalty function. A B&B procedure uses the proposed rule to resolve train conflicts, corresponding to the minimization a weighted sum of delays.

Kraay et al. (1991) approach a compound problem in which train velocity and interactions with the other trains are treated in sequence in order to conserve fuel and minimize train delays while satisfying scheduled arrival and departure times. They prove that some excess timetable slack could be used wisely by slowing down or pacing trains, as opposed to running trains at full speed, with important effects of reducing energy consumption, maintenance costs and the variability of expected arrival times at scheduled stops.

Kraay and Harker (1995) observe that the implementation and validation of the SCAN system (described in Jovanovic and Harker (1991) and Jovanovic and Harker (1990)) showed a limited correspondence between tactical and operation scheduling. They therefore propose a system for generating in real-time the necessary target times to be respected by train dispatching models, with particular reference to the SCAN system. A non-linear mixed integer programming model for the real-time optimization of freight train schedules is implemented and considers explicitly the current position and relative importance of each train. The resulting solution indicates the target time for each train at each relevant point. The resolution method first determines the binary variables that specify meets and overtakes. The model then reduces to a continuous variable sub-problem. A simple heuristic approach and local search methods can be used to determine feasible values for the integer variables. The approach has been tested on a North American railroad, for which local search heuristics perform better than simple heuristics but require excessive computing time.

Higgins et al. (1996) formulate the train scheduling problem as a non-linear mixed integer program aiming to the improvement of timetables and at the development of decision support systems for real-time traffic management. Their model is applied to a long single line track. The authors present a B&B algorithm based on priority rules and using a shortest path method for estimating the lower bound. The criteria for conflict resolution takes into account train priorities, current train delays and expected remaining delay due to conflicts. Successively, Higgins and Kozan (1997) and Higgins (1997) propose several meta-heuristics for the real-time train scheduling problem, including local search, genetic algorithms, tabu search and hybrid techniques.

Cai and Goh (1994) and Cai et al. (1998) describe constructive heuristics for timetabling and dispatching trains on a single railway track. Their approach incorporates fixed minimum headway constraints and resolves train conflicts at crossing and merging points on the basis of local optimality criteria. The conflict solution strategy is based on assigning trains to a position-time pair that is updated dynamically at each time instant of the traffic prediction. The proposed strategy has been implemented and adopted by a major Asian railway.

Travel advance strategy (TAS) based on local feedback was develop by Dorfman and Medanic (2004) to schedule train over a single line as well as double track corridor with variable train priorities. TAS has ability to quickly manage perturbations in a given schedule and has three times well performance that local strategy.

Sahin, G et al. (2004) model the train scheduling problem as a flexible multicommodity flow problem enabling the formulation of several practical constraints on a space-time network. Particularly, an innovative constraint permits to manage a maximum allowable delay for all the traveling trains, while traffic regulation constraints enable a correct formulation of minimum distance headway constraints. An integer programming based heuristic, a simulation-based construction heuristic and a greedy enumeration heuristic are proposed to schedule trains with the objective to minimize the total unweighted delay of all the trains.

Corman et al (2011) modeled train movements for multi class rescheduling problem via alternative graph technique. Basic objective was to help dispatcher by providing him a tool to compute feasible rescheduled plan with minimized train delays. In this model feasible train schedules are found iteratively for an order set of priority classes, from higher priority class to lower one. B&B technique was used in every iteration to find the optimal schedule. They found tradeoff between single-class and multi-class approaches, priority based classes optimized rescheduling may decrease delays of high priority but aggregate and delay of other classes may increase.

Tornquist and Persson (2007) formulate proposed rescheduling model using mixed integer linear programming for multiple track segments. They used simulation technique on a real data set with n-track bidirectional tracks. Problem consists of 80 mixed passenger and freight trains over a network of 253 segments. Results show that the proposed optimization technique was not suitable for large disruption scenarios and it is difficult to find optimum schedule within seconds. Later on, to cover the previous shortcomings Tornquist (2012) developed greedy algorithm for rescheduling quickly. This algorithm use depth first search for priority when a conflict arise. Evaluation show that greedy algorithm provide good solution within short time. In order to show effectiveness of this solution algorithm it is compared with CPLEX, a little difference found between both with CPLEX providing better feasible solutions than proposed algorithm.

Two malfunctions are common through most of scheduling model techniques developed so far: 1) Instead of so much proficient computers available, developed integer programs with constraints associated with each train on a railway track with sidings, still takes so much unreasonable more time to solve problems; and 2) when implementing a schedule, even if only one train is unable to move according to schedule, we have to reschedule all events.

2.2.3 Train Routing and Scheduling Models

It is general tendency to highly utilize rail network which requires effort for the generation of a conflict free plan of rail operations. This effort is used in satisfying constraints and objectives as well as in the search of optimal platform to stop and pass trains. Passing through a complex station with multiple tracks is also a complex and important problem which is directly linked with infrastructure capacity and robustness of a timetable. Routing and scheduling optimization modeling has a limited literature available with a foundation set by Frank (1966). Recently some approaches effectively modeled this problem in detail to adjust both of the factors.

Headway and platform occupation are the constraints when allocating trains to time slots available at platforms. Arrival time and departure time and station dwell times are customer's priorities which are to be considered in the design of timetable. This problem is directly related with station configuration, for simple station it will be easy to schedule but for a complex station with many tracks it would be difficult to find optimum route satisfying safety restrictions and reliable when perturbation occur.

Kroon (1997) investigated about the complexity of several variables of the train routing problem. They proved that routing problem is NP complete when each train has at least three routing options. They applied their polynomial algorithm for routing maximum number of trains over a fixed track layout and constraints while satisfying safety requirements.

Zwaneveld et al. (2001) modeled train routing problem as a node pecking problem with each possible train route as a node. Branch and cut algorithm applied to solve this problem optimally. This study checked the proposed algorithm on the real world instances of Dutch railways.

Carey and Carville (2003) developed scheduling heuristic technique same as "Manual method" to schedule trains at busy and complex stations. Objective function was to minimize the cost and maximization of benefits, while taking into consideration platform desirability cost, platform obstruction cost and time adjustment cost. Algorithm developed consider only one train at a time after scheduling all trains algorithm cycle back to further improve the solution.

Caimi et al (2005) also formulated the routing problem as node pecking by Zwaneveld et al. (2001). Initial solution was obtained by fixed point iteration algorithm. Case study was time table design of station where 19 trains were arriving from six different directions. Initial solution was generated in few minutes while optimized scheduling take few hours. Caimi et al. (2007) decomposed rail network into condensation and compensation zone. Main stations were taken as condensation zone while connecting lines as compensation zone. Condensation zone was the main focus for timetabling. Modeling was done as independent set problem in a conflict graph, solved by fixed point iteration algorithm.

This review shows that so many methods to assess the capacity and scheduled waiting times have been developed. However, only few of them describe the inter connection between scheduled trains and railway networks.

2.2.4 Stochastic Models

Feasible timetabling is dependent on precise determination of running and dwell times. Train services are very sensitive to disturbances but slack time and margins in timetable can mitigate this sensitivity. Normally, in optimization problem modeling running times, headways and train orders are taken as deterministic variables without variance but in stochastic modeling these variations are taken into count on the basis on assumed random distributions. Hence, non scheduled waiting time is cause of variation in track occupancy and headways. Stochastic delay propagation, queuing models and network simulators are different techniques applied to estimate non-scheduled waiting times.

Schwanhauber (1974) developed analytical methods to estimate mean queue length. Priority rules, train sequence, headway, buffer time and distribution of initial delays were main factors considered for estimation. Wakob (1985) extended the previous model to find the scheduled waiting times at stations.

Wendler (1999) proposed many extensions to the available two-train queuing model for estimation of the impact of available time difference between headways on main track. Recently, Wendler (2007) described the method to calculate scheduled waiting times for bottlenecks by assuming random train order and using semi-Markovian model.

To simulate knock-on-delays Carey and Kwiecinski (1994), modeled simple stochastic approximations for speed variations and tight headway on single link. Carey (1999) presented ex-ante stability measures to estimate schedule deviations when implementing off-line timetable or evaluating alternatives. Probability distribution function used in proposed stochastic delay propagation model to compute optimal arrival and departure time.

2.3 REAL-TIME TRAFFIC MANAGEMENT

In off-line tabling main focus is design robust timetable such that propagation of delays should be minimum. Train operations are planned several months before in detail with arrival, departure and dwell times at stations. By using smart planning rules a robust timetable can deal with minor disturbances. In case of large delays and blocking of tracks no reasonable plan is robust or reliable (Vormans et al., 2006).

Technical failures and disturbances may influence each operation of the whole network. Interaction between trains may propagate this initial delay to the whole of the network. Hence, real-time traffic management requires modification the original timetable to minimize train delays and ensure feasibility of operations. This short term process to find effective solutions is called real-time traffic management.

To control rail traffic over a complex network control section is composed of so many regional control centers. Pakistan railway network is subdivided in one main center in Lahore, six regional centers (Karachi, Sukkur, Multan, Rawalpindi, Peshawar and Quetta). Regional traffic controllers have a centralized complex control system in which local interlocking is controlled by dispatchers and movement of trains controlled by signal indication.

At least one dispatcher is working in each dispatching area of a traffic control center, which after appropriate intervals of time gets information about the status of network to which he is connected. Dispatcher after analyzing data search whether there is potential for occurrence of conflicts and if he finds some conflicts he resolve it according to his knowledge and experience. Experienced dispatchers familiar with properties of infrastructure and resources develop strategies to take compensatory actions for changing schedules to reduce delays. Possible actions a dispatchers could take are changing running speeds, dwell times, train orders at junctions and stations and passing points. He can also change routes and even cancel train runs for the sake of feasibility of schedule.

Detailed representation of the area managed by a dispatcher is very useful and essential to take feasible decisions. When time horizon is short only few trains and conflicts can be detected while in the case of longer horizons a large number of trains running on track and resulting conflicts are to be resolved. This means that there is a tradeoff between the size of the time horizon of traffic prediction and the solution quality. In fact, the solutions computed with few running trains could be myopic, since the real-time dispatching does not take into account conflicting trains further outside the time horizon. On the other hand, a conflict arising far in the future may not be as relevant as a closer conflict, since other unforeseen events could still affect the farther conflict.

Corman et al (2012) considers the dispatching problem where several dispatchers coordinate to have a global optimum solution. Figure 2.2 shows hierarchically real time traffic management two different levels consider in this model. In this model coordinator can impose constraints at the border of each dispatching area. Coordinators goal is to ensure global feasibility, local feasible schedules merge to generate global feasible. Dispatchers of each area can reschedule according to constraints and local feasible conditions. They used B&B technique to show that this technique can solve coordinator problem. Netherlands busy traffic condition used to implement the proposed algorithm. They found the ability of their algorithm to find feasible solution of real-time problems within computation time available in real-life.

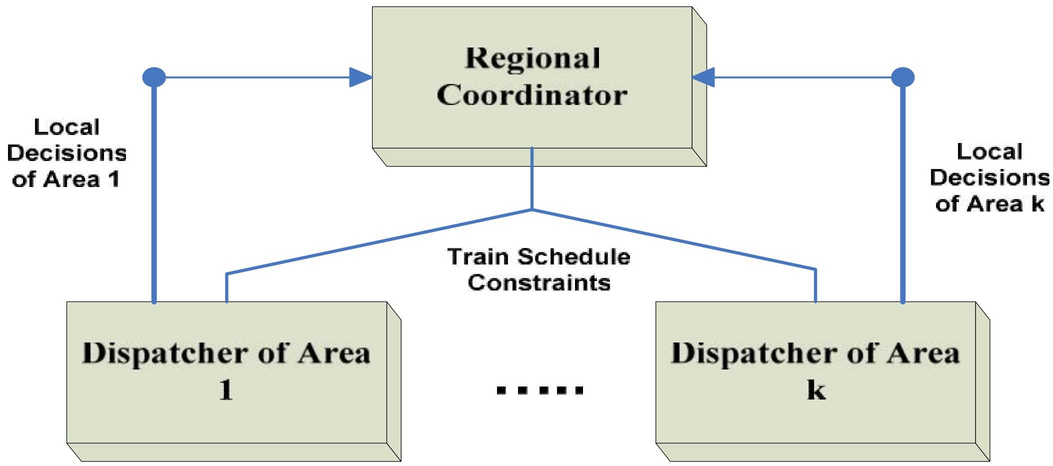


Figure 2.2: Illustration of Interaction between dispatchers and coordinators.

In Pakistan the only decision support the dispatchers have is a manually prepared time distance graph of currently running trains and the corresponding train numbers and a panoramic route layout on the wall of the traffic control center, eventually printed or oral information on perturbed trains from neighboring control areas. Coordinator has to supervise the train movements on whole network scale by estimating the impacts of delayed trains and blocked tracks in regional dispatching areas. Traffic controller has to take decisions about train's preferences, rerouting and holding after taking into consideration all factors e.g. headway times, estimated delays, severity of present and future conflicts etc. Traffic controllers evaluate mentally about pro's and con's of different control activities available within short time and costs and benefits of their interventions are unknown. They can't watch over the propagating delays in larger interconnected networks in case of large perturbations creating multiple consecutive delays and even in these cases it is difficult for them to recognize precisely the impacts of different dispatching strategies on the performance of network. They should also supported by tools and methodologies to calculate the impact of dynamic traffic management options in real time to select most beneficial option.

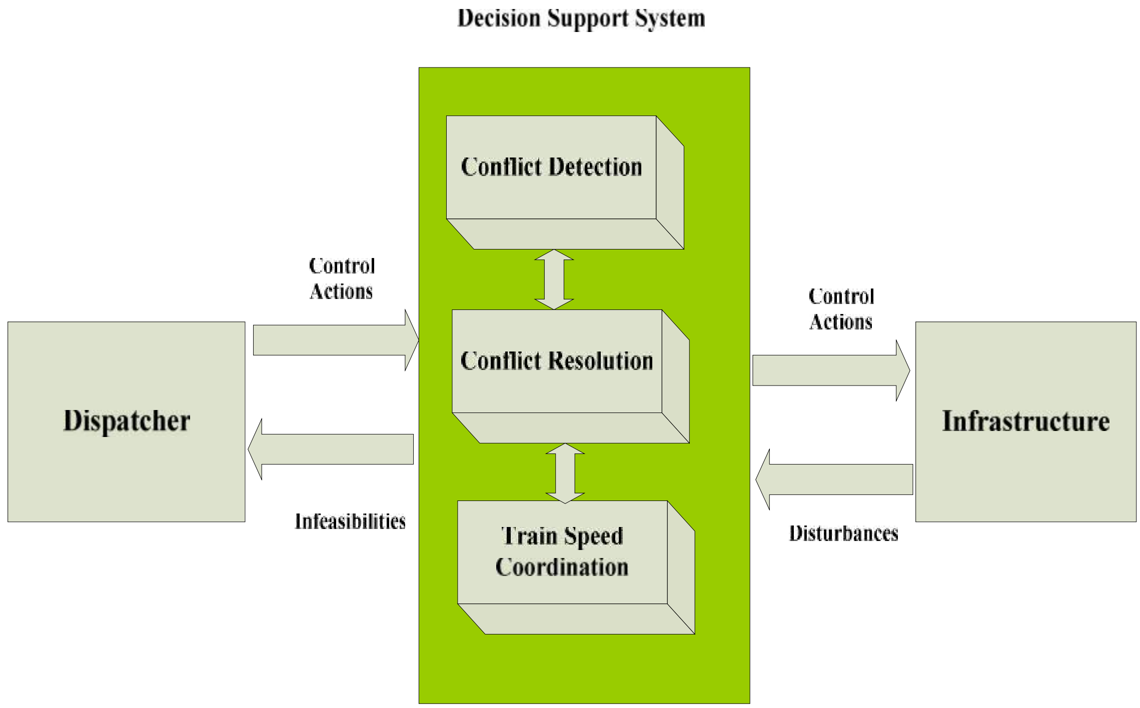


Figure 2.3: Components of Train Dispatching Support System.

A general plan of a real-time train dispatching supporting system is presented in Figure 2.3. Shoji and Igarashi (1997), Kawakami (1997), Konig and Schnieder (2001), Luthi et al. (2007) and Montigel et al. (2007) and D'Ariano (2008) describe same architecture. Network level coordination for each dispatching measure is necessary to practically implement this system. This problem is to find feasible deadlock free and conflict free solutions within a short time available to take real-time dispatching decisions. Table 2.1, summarizes the comparison between Off-line and Real-time management.

D'Ariano (2008) designed and implemented a decision support system for train dispatchers, namely ROMA, to recover schedules from disturbances automatically. By taking wait-depart decisions and priority decisions into account.

Table 2.1: Off-line Timetabling versus Real-time management (D'Ariano, 2008)

Factors of Comparison	**Off-line Time Tabling**	**Real-time traffic management**
Main Objective	Design optimal Schedule	Implement optimal control
Schedule validity	Up to some years	Up to few perturbed hours
Degree of flexibility	Any change applicable	Minor timetable modifications
Traffic conditions	Usually ideal situation	Perturbations or disruptions
Time span of prediction	Long time horizon	Up to some hours
Space span of prediction	Large traffic network	Rail junction or small network
Computation time	Up to several months	Up to few minutes

Tornquist and Persson (2007) proposed an optimization approach for rescheduling railroad traffic in an N-tracked network based on alternative graph reformulation and B&B solution algorithms. By extending optimization models proposed by Zhou and Zhong (2007) as well as Tornquist and Persson (2007), Castillo et al. (2011) further incorporated user preference into the train timetabling problem. Cordeau et al. (1998) divided train dispatching system into two classes: 1) fixed speed models and: 2) variable speed models (Figure 2.4). Fixed speed models often assume that trains running at maximum speed while variable speed models use train speed profiles to check the consequences of conflicts due to constraints imposed.

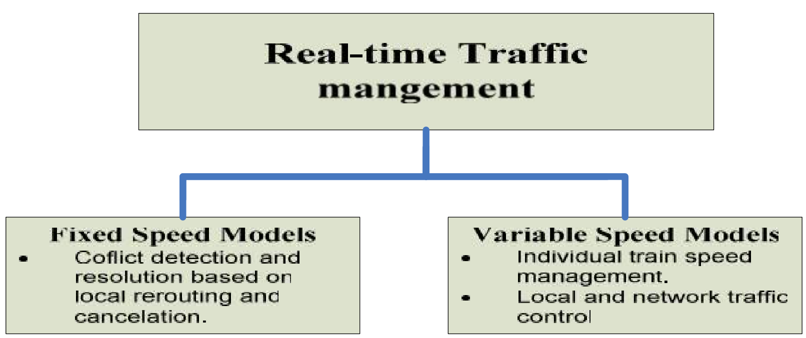


Figure 2.4: Sub-sections of Real-time Traffic Management.

2.3.1 Fixed-Speed Models

Minimization of deviations from Master Plan by conflict detection and resolution such that operational constraints are satisfied is main objective of real-time traffic management. Real-time traffic management is similar to operation scheduling however the determination of train priorities in a conflict is more complex within limited amount of time. Priority depends upon so many dynamic factors such as tardiness of trains and platform capacity. Due to these reason this complicated issue is only have a limited literature and has been solved recently.

Velocity is the decision variable in the model to find meet and pass plan of trains because arrival and departure mainly depends on speed. Most of the models available use sequential approach with a fixed speed profile for each running train. Moreover, trains are assumed to travel at maximum achievable speed. Feasibility is checked against different speed profiles for each train. A review of some recent approaches is presented here.

In rescheduling train delays are tried to minimize by changing the precedence between train in meeting and passing strategies. It can be said that in rescheduling new feasible plan of meeting and passing of train is scheduled to get deadlock free schedule with no more conflicts in order to minimize deviations and delays. Garey and Johnson (1979), Ullman (1975) classified fixed speed profiles and routes of trains as NP-complete problem. Moreover, it is necessary to solve the problem of real-time environment under severe time requirements.

Sahin (1999) investigate the single track real-time conflict resolution problem. Knock-on delay minimization was objective of this study and formulation was done as job shop scheduling problem. Ping et al. (2001) used genetic algorithm to optimize train orders and train time problem on double track line. Train departure order was set on each station to minimize delays. Guangzhou-Shenzhen high speed railway used for simulation of algorithm.

Using the blocking time theory described by Pachl (2002), Jacobs (2004) proposed a model to identify possible conflicts with high accuracy. Objective function was to minimize additional running times. Proposed algorithm detects the infeasible routes in disturbances and solves conflict by postponing the less priority train.

Tornquist and Persson (2007) modeled the train dispatching train dispatching problem on a network with several crossing and merging points. Formulation was done using mixed integer linear programming and solved with commercially available software packages. Different dispatching strategies based on reordering and local rerouting restrictions were applied to reduce the search space. They showed that checking all possible changes to train orders and routes takes too long to find a good quality solution. Tornquist (2007) proposed improvements in the available dispatching heuristics. Aim of this work was to reduce delay propagation.

It is interesting to highlight the use of rerouting instead of only rescheduling in real life where so many conflicting trains are running on network. This requires local rerouting and reordering measures to implement in real-time traffic management.

2.3.2 Variable-Speed Models

When perturbations occur variable speed models re-plan movements of trains according to current state of traffic regulations and signaling system. This consists of scheduling all movements of trains along line and at stations and modification of actual speed profiles. In literature only few studies have taken into account the possibility of speed coordination to improve train rescheduling. Advanced level traffic management systems able to consider complicated network of conflict resolution system may improve the solution by taking into consideration speed optimization. Recent approaches to dispatch at variable speeds are based on optimization of each train speed.

Hansen (2001) showed that knock on delays can be prevented by accurately monitoring position of trains and by speed prediction in advance. Khmelnitsky (2000) studied the problem to minimize the energy consumption for a train moving along given route for a given time. Objective was to determine the optimal train operations subjected to arbitrary variables speed restrictions and grade profiles.

Albrecht and Oettich (2002) presented an algorithm for dynamic schedule synchronization and energy saving for rapid transit systems. Algorithm modify the running time of train in such a manner that increase the probability to transfer to other means of public transport by arriving on-time. Objective was to minimize the overall energy consumption. Albrecht (2005b) and Albrecht and Van Luipen (2006) introduced a simulation tool for early recognition of conflicts. This was based on manual train speed control and actual state of signaling system.

Tazoniero et al. (2005) presented fuzzy rule to schedule train in freight railroad with possibility to near the reference trajectories. Dispatching rules can easily incorporate in this system to compute plan very quickly. Simulation results on Brazilian railway showed that mixed integer linear programming has ability to produce better results that fuzzy rules.

Chou et al. (2007) presented a control system which was distributed among several mutually influenced areas. To obtain a collaborative rescheduling novel time-shift strategy was proposed among the control areas. They also studied various policies for distributed control regions for the evaluation of delay cost of adopting distributed control in neighboring regions.

Literature discussed here on traffic control shows that there is little attention on the precision of simulating traffic flows. Major needs are identification of possible conflicts with accuracy and estimation of effect of different dispatching measures. If detailed information of the actual status of network is available than running times can be calculated precisely which will help in determination of conflict points and braking curves estimation. A detailed analysis of blocking times is necessary to accuracy of pre defined headways and transfer time constraints. Moreover, there is need of clearly modeling of the signaling systems in case of conflicts.

2.4 SUMMARY

A variety of optimization models used to solve off-line and real-time traffic management problems in rail transportation are discussed in this chapter. Application of these systems and methodologies may enable to solve the difficult real-world combinatorial NP-hard problems by exploiting the structure and peculiarities of each problem. Recently, mathematical programming techniques are being used to solve traffic management models, heuristics are also found very effective for several classes of discrete optimization problems. Increased level of computers and information systems also played an important role in this progression.

From the very beginning timetabling has been an active area of research in Railways. However, there is possibility that past researches which emphasis on this area may be displaced. Optimal solution may be defined as the best possible solution however any plan made must be at least feasible to be implemented. Algorithms which have been developed so far have main objectives to simplify the modeling of train conflict recognition and resolution and feasibility check, measure of reliability of a service, needed to resolve conflicts within timetable design process.

Recent works show that real-time traffic management problems in complex networks which, in the past, were only solvable by simulation are becoming tractable by mathematical optimization methods. However, due to considerable work on simulation in the last few decades, simulation techniques also useful for analysis and support in decision making. On the other hand, real-time management algorithms developed so far can manage traffic efficiently only when the disturbance to off-line timetable is small and simple. Although so many dispatching models have been developed and tested on realistic data, very few of them are implemented and used during practical operations. Hence, railway operations research must be directed to bridge the gap between theory and practice.

Chapter 3

STUDY FRAMEWORK

3.1 INTRODUCTION

This study frame work aims to provide train schedulers in Pakistan a computer aided tool to schedule trains over this track efficiently by spending very less time as compared to manual scheduling and check the practical efficiency of B&B technique as compared to theoretical efficiency given my many researchers. This chapter will provide a good mathematical model to represent train movements on railway track without making unreasonable assumptions which would be impossible to implement in practice. The proposed model is flexible so that non-routine practical events can be included. It is tried to keep the model as simple as possible and the representation as efficient such that model can be open to a wide range of different optimal and heuristic solution techniques.

3.2 DATA COLLECTION

Data pertaining to the timetable of PR is collected from PR Rawalpindi division. This division controls the rail network from Rawalpindi to Lalamusa, having 25 stations and 24 track lengths. Yearly published Pakistan Railways Time and Fare Table (2011) and Pakistan Railways Timetable for Passenger Trains (Staff Copy) (2010) are collected. Pubic use timetable contains arrival, departure and dwell time at each station and distance between the stations also given in this timetable. While staff copy of timetable contains these data sets as well as information about speed restrictions at different segments, running time at different speeds, conflict resolution data, slack time for different tracks and acceleration/deceleration data for different speeds etc.

3.3 MATHEMATICAL MODEL

This study considers single line track scheduling problem, in which a single line connects two stations and trains can meet or pass each other at specified locations known as sidings as shown in Figure 3.1. Station A and Station D are terminals and Station B and C are intermediate stations with sidings. Formulation of train scheduling problem is done as job shop scheduling problem considering a set of single track segments of rail line with a set of trains using this network.

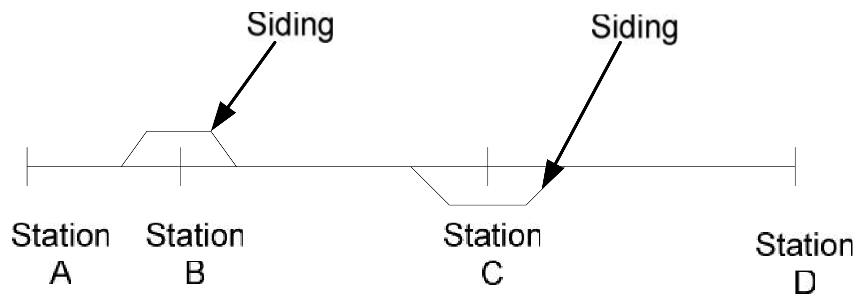


Figure 3.1: Illustration of Sidings on a Single Line Rail Track.

3.3.1 Definition of Variables

Table 3.1: Definition of Variables

Definition	Symbol
Train index	t
Segment index	s
Segment sequence number in train route	j
Station index	i
Set of trains	T
Set of segments $\lvert S \rvert = m$	S
Set of stations $\lvert J \rvert = m+1$	J
Direction indicator for train t, p(t) = 0 for an inbound train and p(t) = 1 for an outbound train	$p(t)$
Segment index of the j[th] traveling segment in a route for train i, σ (t,j) = j for outbound trains, σ (t,j) = m+1-j for inbound trains	$\sigma(t, j)$
Downstream station number of the j[th] traveling segment in a given route for train t, b(t, j) = j for outbound trains, b(t, j) = m -j for inbound trains	$b(t, j)$
Planned departure time for train t at its first station	k
Free running time for train t at segment s	$f_{(t,s)}$
Minimum required station dwell time before train t entering segment s	$d_{(t,s)}$
Maximum allowed station dwell time before train i entering segment j	$\overline{d}_{(t,s)}$
Minimum headway between arrival and departure times of two consecutive trains	h_s
Minimum headway between arrival times of two consecutive trains at station u	g_i
Entering time for train t at segment s, i.e., start time for job t on machine s	$o_{t,s}$

Leaving time for train t at segment s, i.e., end time for job t on machine s	$c_{t,s}$
Binary Variable,1 if train t is scheduled before train t' on segment s, 0 otherwise	$A_{t,t',s}$
Sufficiently large constant	M

3.3.2 Assumptions and Inputs

Assumptions used in this thesis are as follows:

- The track is considered to be composed of segments, separated by sidings.
- It is assumed that each train has pre specified direction and route.
- Free running times are assumed to be constant for a track segment.
- Travelling of trains are assumed as tasks to be assigned to machines (here tracks and stations are taken as machines).
- Sidings are places where trains can cross each other.
- A minimum headway will be maintained for trains to follow each other on a track segment.
- Trains can have maximum 30 minutes conflict delay otherwise this option will be neglected.
- A station may have capacity to be occupied by more than one trains but only one train capacity per station is considered in this thesis.

The model will require the following data as input to the model:

- Fixed running times are calculated for each segment according to PR calculation method. Given in Appendix II.
- According to timetable of PR planned departure times of all trains to be scheduled.
- Maximum time a train can wait for other train at a siding.

3.3.3 The Objective Function of Model

$$MinZ = \sum_{t=1}^{n} c_{t,\sigma(t,m)} \tag{3.1}$$

Objective function of model is to minimize the total of completion time of each activity which will give result in the minimization of total travel time.

3.3.4 Constraints

- **Departure Time Constraint**

$$o_{t,\sigma(t,1)} \geq k_t \qquad \forall t \in T \tag{3.2}$$

This constrains ensures that planned departure time is not more than the actual departure time.

- **Free Running Time Constraint**

$$c_{t,\sigma(t,j)} = f_{t,\sigma(t,j)} + o_{t,\sigma(t,j)} \quad \forall t \in T, j = 1,2,...m \tag{3.3}$$

This equation states that leaving time of a section must be equal to the entering time plus free running time. Free running time used here is the time counted by PR taking into account acceleration and deceleration and speed restrictions of each track.

- **Minimum Dwell Time Constraint**

$$o_{t,\sigma(t,j)} \geq c_{t,\sigma(t,j-1)} + \underline{d}_{t,\sigma(t,j)} \quad \forall t \in T, j = 2,...m \tag{3.4}$$

This constraint is ensuring that scheduled stop is more than minimum dwell time which is practically required to load and unload passengers and freight trains.

- **Headway Constraint at Track Segment**

$$o_{t,s} \geq c_{t',s} + h_s \text{ Or } o_{t',s} \geq c_{t,s} + h_s \quad \forall t', t \in T, t \neq t', s \in S \tag{3.5}$$

Minimum headway is required for safe operation of trains running in opposite or same direction on the same track. This constraint ensures safe operations at the rail corridor.

- **Headway Constraint on Arrival Time at Stations**

$$c_{t,\sigma(t,j)} \geq c_{t',\sigma(t',j')} + g_i \text{ Or } c_{t',\sigma(t',j')} \geq c_{t,\sigma(t,j)} + g_i, \quad \forall t', t \in T, t \neq t', b(t,j) = b(t',j') = s \tag{3.6}$$

This constraint imposes that minimum headway on two consecutive trains approaching at same station.

- **Maximum Dwell Time Constraint**

$$o_{t,\sigma(t,j)} \le c_{t,\sigma(t,j-k)} + \overline{d}_{t,o(t,j)} \quad \forall t \in T, j = 1,2,...m \tag{3.7}$$

This constraint gives the upper bound of time which a train can wait for other train.

- **Either-or Relationship**

$$o_{t,s} \ge c_{t',s} + h_s - M \times A_{t,t',s}$$

$$o_{t',s} \ge c_{t,s} + h_s - M \times (1 - A_{t,t',s}) \tag{3.8}$$

Either – or relations are decision variables which will decide which train will traverse segment first.

3.4 BRANCH AND BOUND TECHNIQUE

Branch and Bound (B&B) is a general algorithm applied to many areas to find optimum solution of various optimization problems. It consists of enumeration of all candidate solution systematically while a large amount of fruitless candidates are discarded based on upper and lower bound estimation of quantity to optimized. Some of the basic definitions of B&B technique are

- **Search Tree**: Graphically B&B technique is represented by search tree. It represents the solution space of the problem. It contains all possible permutations of scheduling and conflict resolution.
- **Node**: Every possible solution is represented by a node on search tree. Parent nodes are generating children nodes at each exploration level.
- **Goal Node**: Complete solution of search tree is known as goal node, which schedules all tasks on given machines.
- **Feasible Solution**: Any solution which is acceptable according to optimality level is known as feasible solution.
- **Intermediate Node**: Partial solution of problem in search tree is known as intermediate node.
- **Level/ Depth of Search**: Number of tasks scheduled prior to the considered node in this solution of search tree.

- **Cost**: Quality of schedule represented by this node. This can be in the form of lateness, tiredness etc.
- **Order of Search**: This is order in which nodes are explored, so many preset rules are available e.g., Depth first search, Breadth first search etc.
- **Upper Bound**: It is the maximum value a function can attain with in solution space. It is used to initialize the root node. If upper bound is calculated accurately it will increase the performance of B&B search as it will prune more nodes in each step.
- **Lower Bound**: It is the minimum value a function can attain with in solution space.
- **Bounding**: It is a tool which calculates upper and lower bound of given function for given values of solution space.
- **Branching**: It is a tool with the help of which splitting of solution space S is done in a manner that union of new subsets covers S.
- **Fathoming/ Pruning**: Based on bounding functions some of the nodes are discarded to search further within its child nodes. This is called Fathoming or pruning.

B&B technique is process of generating child nodes by branching and bounding function evaluates the cost of newly generated/ active nodes for further exploration. The node with best objective value is saved as incumbent. The algorithm uses the best objective of the remaining nodes to be fathomed to update the best bound. Each time the algorithm finds a new incumbent, it computes the relative difference between its objective and the current best bound, yielding an upper bound on the improvement in the objective that might be obtained by continuing the solution process.

To illustrate the implementation of the branch-and-bound method for a MILP, an example presented by (Wolsey, A. L., 1998) is as follows:

Consider the problem

$$z = \max(cx : x \in S)$$

Basic concept is that to decompose S into series of smaller problems that are easy to solve. Solve that sub problems and put that information together to solve the original problem.

Let $S = S_i \cup ...... \cup S_k$

$$z^k = \max(cx : x \in S_k)\, for\, k = 1,2,.....K$$

$$z = \max_k z^k$$

Typically this problem is represented by enumeration tree. For instance, if $S \subseteq (0,1)^3$, we might construct tree as Figure 3.2. Here, first S is divided into $S_0 = \{x \in S : x_1 = 0\}$ and $S_1 = \{x \in S : x_1 = 1\}$ then $S_{00} = \{x \in S_0 : x_2 = 0\} = \{x \in S : x_1 = x_2 = 0\}$, $S_{01} = \{x \in S_0 : x_2 = 1\}$ and so on.

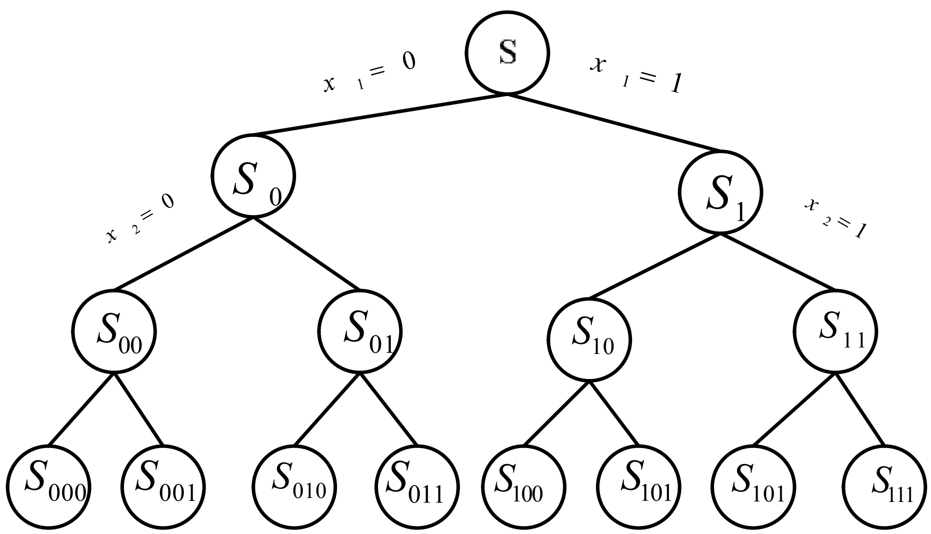


Figure 3.2: Illustration of Binary Tree Enumeration

It is impossible to completely enumerate tree when the number of variables in integer program or nodes in graph exceed 20 or 30 (Wolsey, A. L., 1998). So instead of just dividing some bounds on the value of z^k are also used. $\bar{z}^k$ be an upper bound and $\underline{z}^k$ be a lower bound on z^k. Now with the help of three examples working of lower and upper bound will be elaborated.

- **Example 1**:

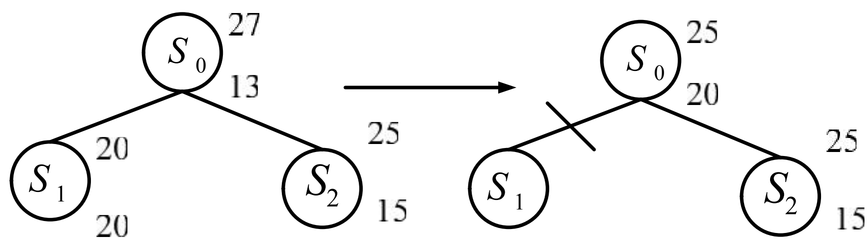


Figure 3.3: Illustration of Pruning by Priority.

Here $\bar{z} = \max_k \bar{z}^k = \max(20, 25) = 25$

And $\underline{z} = \max_k \underline{z}^k = \max(20,15) = 20$

In the S_1 lower bound and upper bound are same = 20. This shows that there is no further reason to examine S_1. Therefore, S_1 is eliminated.

- **Example 2:**

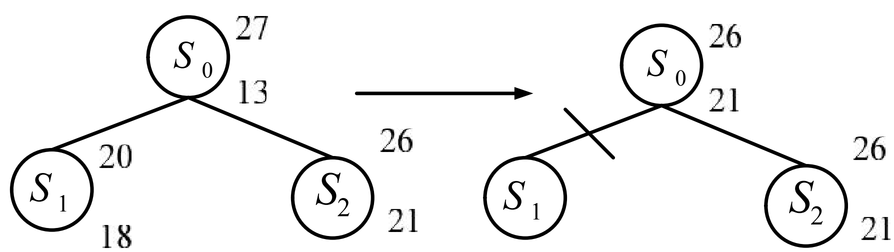


Figure 3.4: Illustration of Example Pruning by Bound.

First note that here $\bar{z} = \max_k \bar{z}^k = \max(20, 26) = 26$

And $\underline{z} = \max_k \underline{z}^k = \max(18, 21) = 21$

Second, observe that optimal value has least 21 and $\bar{z}_1 = 20$, shows that no optimal can lie in S_1. Therefore, the branch S_1 of the enumeration tree can be pruned by bound.

- **Example 3:**

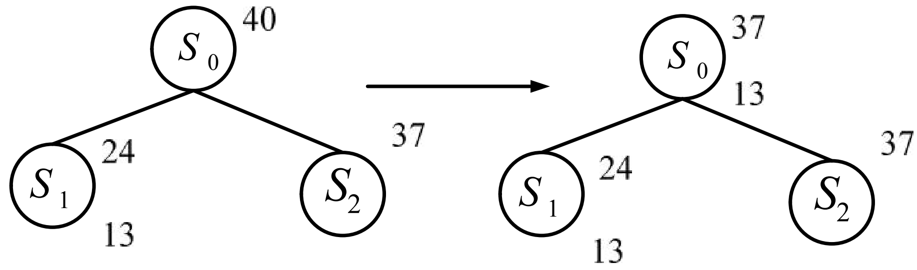


Figure 3.5: Illustration of Example of No Pruning.

First note that here $\bar{z} = \max_k \bar{z}^k = \max(24,37) = 37$

And $\underline{z} = \max_k \underline{z}^k = \max(13,-) = 13$

Here, no other conclusion can be drawn so we need to explore both S_1 and S_2.

Based on examples we can conclude that there are three reasons of pruning the tree, as shown in Figure 3.6.

i. Pruning by optimality $z_t = (\max cx : x \in S_t)$ has been solved.

ii. Pruning by bound $\bar{z} \le \underline{z}$.

iii. Pruning by infeasibility $S_t = \Phi$.

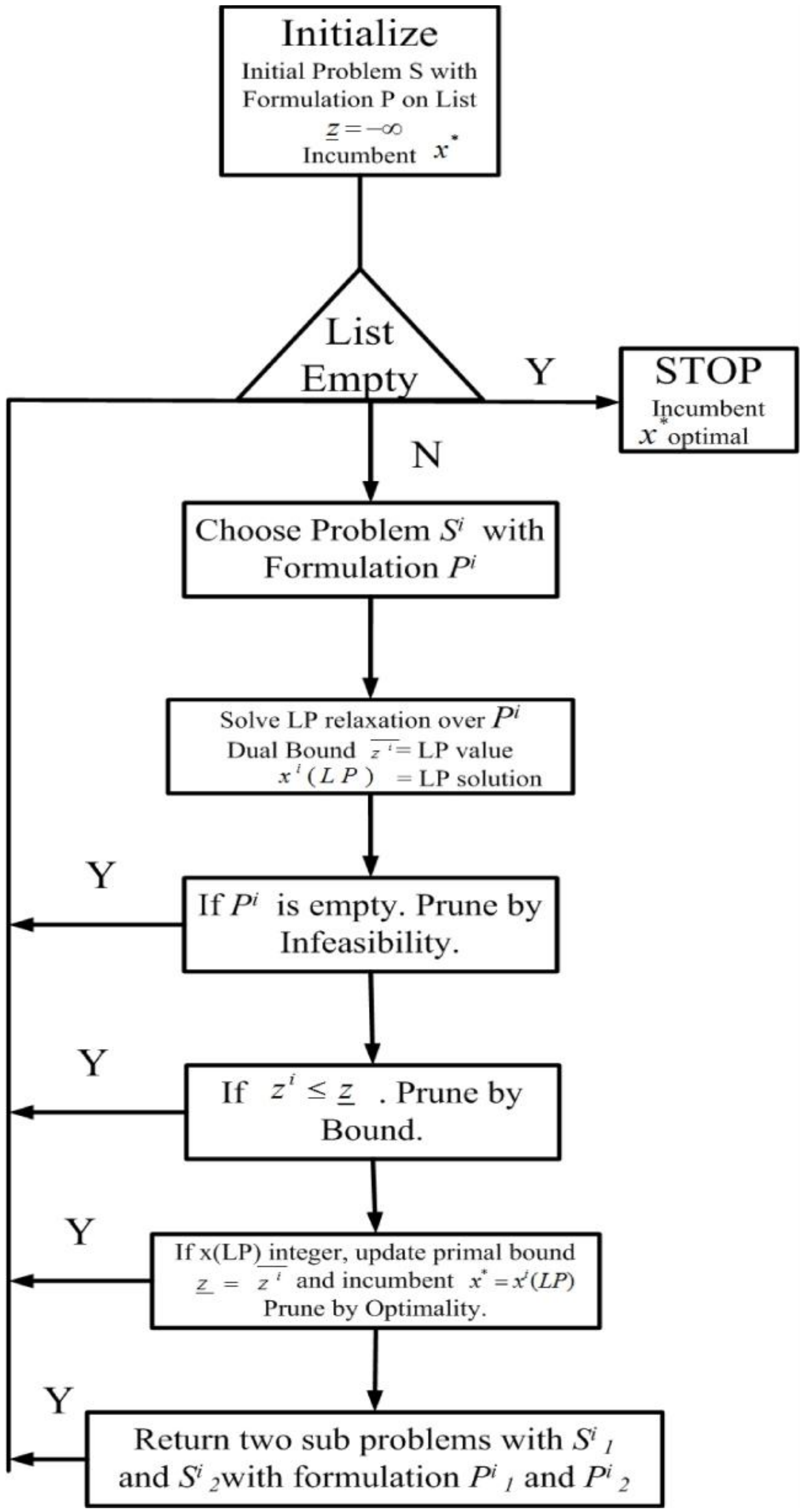


Figure 3.6: Flow Chart for Branch and Bound Tree Enumeration.

3.4.1 Search Techniques

Search techniques are used to find the specified item with in a set of items. These techniques are useful to find the solution early. There are so many algorithms applied for searching some of those used in this thesis for B&B searching are as follows:

- **Depth First Search**: It is a search technique used for traverse the search tree this technique start search from root and terminates at leaf and then go next unvisited node. Rule is if a node is not pruned than next search node will be its children node.
- **Breadth First Search**: It is a search technique used for traverse the search tree this technique start search from root and visit all nodes at same level first than go to next level nodes. Rule of this search is exploring all nodes of given level before proceeding to next level.

3.4.2 Branch and Bound with Priority Rules

It is practically impossible to attain optimal solution of large scale network of NP-hard train scheduling problem (Cai et al (1998), Caprara et al (2002)). To find the feasible solutions of these problems within a reasonable time limit heuristic techniques are generally applied. Priority rules are also incorporated which decides, according to predefined objectives, the next train to be scheduled from a pair of conflicting trains. For simulation of human behavior we implement the simple dispatching priority rules (Zhou et al (2007), D'Ariano et al (2007)).

These priority rules order the running trains by using the decision criteria adopted by traffic controllers at each junction. We are using most commonly used rules which are elaborated in more detail in the example of this chapter.

- **Random Priority Rule (RPR)**

This rule as the name indicates that will give priority to any one of the conflicting trains. Results of this rule may be somewhat suboptimal as compared to other rules.

- **Best Cost Priority Rule (BCPR)**

This rule compares the cost of each alternating option and gives priority to train which provides best cost (in terms of delay) among the trains.

- **Early Start Priority Rule (ESPR)**

This is mostly used rule in railway practice to resolve train conflicts. This rule simple gives precedence to a train which enters the conflicting track first. No dispatching action is required in this as trains are passing through the crossing and merging points according to their actual order.

- **Early Finish Priority Rule (EFPR)**

This rule first calculates the entering and traversing time of both trains claiming to use same track. Precedence will be given to train which will leave the track first. It incorporates two rules (i) priority to train which enters the track first, (ii) priority to train which running fast as compared to slow one.

- **Minimum Processing Time Priority Rule (MPTPR)**

This rule calculates the traversing time of trains trying to use track same time and gives precedence to train with low processing time. Most researches in the past consider the same constant free running time for all track segments hence this rule is not incorporated mostly.

3.4.3 Lower bound Calculation

In this work simple lower bound rule proposed by Higgins (1995b) and later on modified and used by Zhou and Zhong (2007) is used. This rule simply estimates the additional delay required for resolving the remaining crossing conflicts in a partial schedule, it ignores the existing overtaking and new generated conflicts in schedule. Figure 3.7; differentiate between crossing and overtaking conflicts. When two trains are in opposite direction than it will be crossing conflict while in the case of overtaking they are running in the same direction.

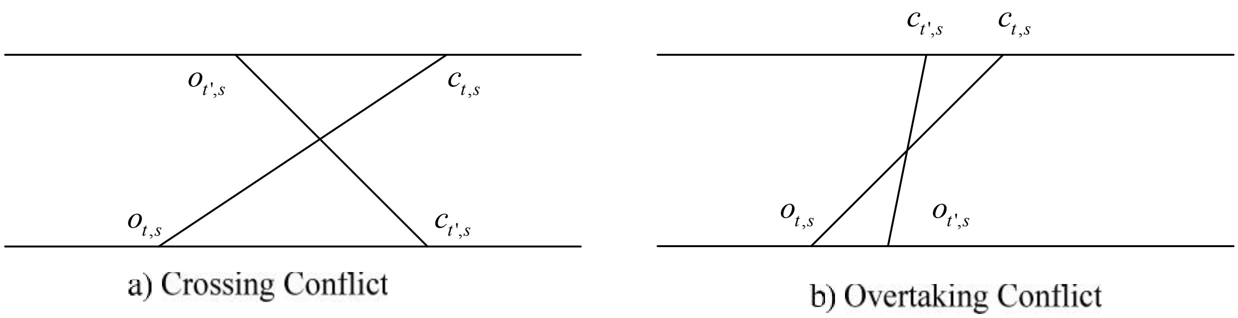


Figure 3.7: Illustration of Crossing and Overtaking Conflicts.

First minimum additional delay to resolve a single crossing conflict is estimated and then it can be used to calculate the total additional delay for all conflicts in a partial schedule.

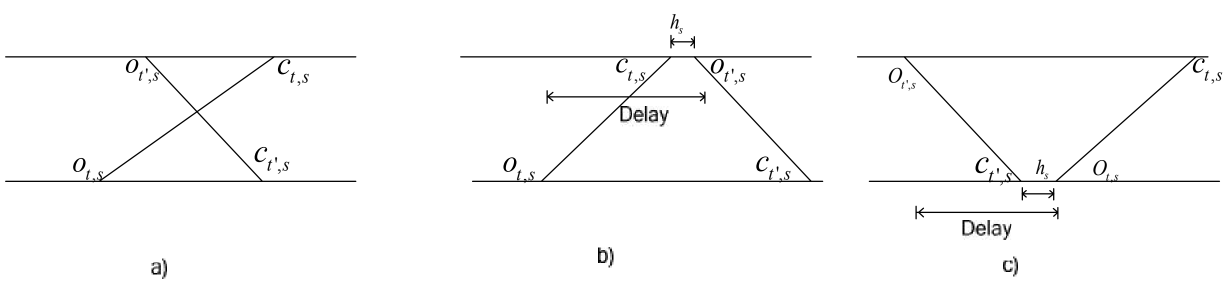


Figure 3.8: Calculation of Additional Delay for Resolving a Conflict.

Figure 3.8, shows a conflict between two trains at segment s. If train t' is delayed first and train t is allowed to traverse track first than resulting delay to t' will be $h_s + c_{t,s} - o_{t',s}$. Otherwise, train t will be delayed for $h_s + c_{t',s} - o_{t,s}$. From the above explanation it can be concluded that minimum additional delay for resolving a single conflict at segment s will be

$$\min(h_s + c_{t,s} - o_{t',s}, h_s + c_{t',s} - o_{t,s}) = h_s + \min(c_{t,s} - o_{t',s}, c_{t',s} - o_{t,s}) \geq h_s \qquad (3.10)$$

When resolving a conflict at intermediate siding minimum headways of both upstream and downstream segments should maintained. Figure 3.9, conflict resolution of two trains running in opposite directions at intermediate siding. From both cases it can be concluded that minimum additional delay for conflict resolution at intermediate siding will be $g + h$.

It is clear from Figure 3.9 that additional delay has two components. First, headway between the arrival times of two trains at a station J. Second, headway between the departure times of trains. h time units are the accurate estimation of second part of lower bound because the only constraint applied over the departure time of second train is minimum headway. On the contrary, arrival time of trains is dependant of path trajectories of trains which may lead a train to arrive a station much earlier than other. Hence, in first part g units delay underestimates the additional delay. Alternatively, it would be suitable to change meeting station if actual delay of first part is greater than the free running time of consecutive segment.

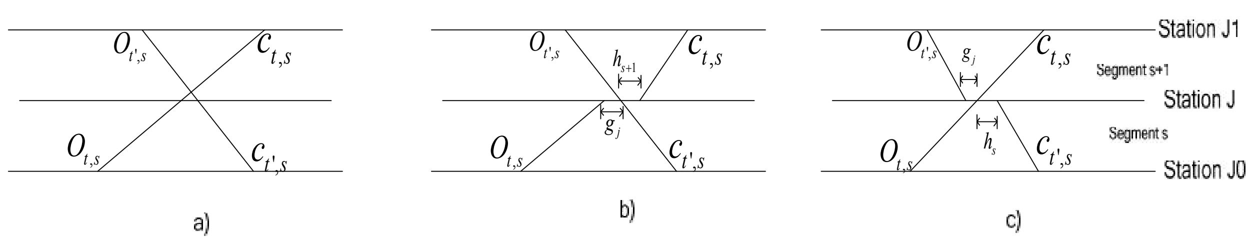


Figure 3.9: Calculation of Additional Delay for Resolving a Conflict at Intermediate Siding.

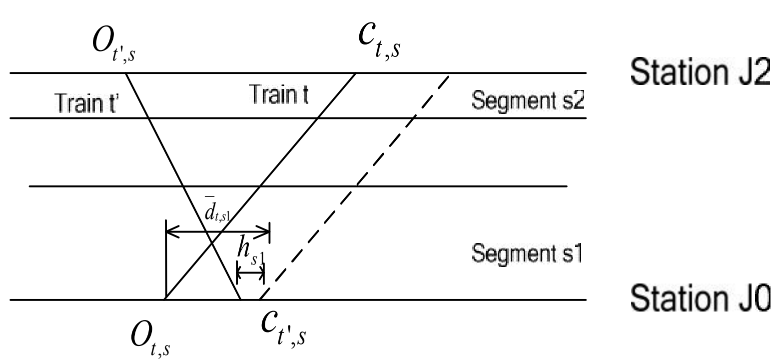


Figure 3.10: Estimation of Feasible Region for Conflict Resolution.

Based on the dwell time window of both trains conflicting, possible region of their conflict can be estimated. As shown in Figure 3.10, if $c_{t',J1} \geq o_{t,J1} + \bar{d}_{t,J1}$ and $c_{t,J2} \geq o_{t',J2} + \bar{d}_{t',J2}$ then $c_{t',J1} \geq o_{t,J1}$ and $c_{t,J2} \geq o_{t',J2}$ indicates that conflict is to be resolved at some where intermediate siding.

Summarizing, the above discussion the conflict based lower bound at any node n is

$$LB(n) = \sum c_{t,\sigma(t,s)} + \sum_{t,t'} \Theta_{t,t'} \qquad (3.11)$$

$\Theta_{t,t'}$ can be determined from following expressions:

if $c_{t',J1} \geq o_{t,J1} + \overline{d}_{t,J1}$ and $c_{t,J2} \geq o_{t',J2} + \overline{d}_{t',J2}$

$\Theta_{t,t'} = g + h$

Else if $c_{t',J1} \leq o_{t,J1}$ and $c_{t,J2} \leq o_{t',J2}$

$\Theta_{t,t'} = h$

End.

3.4.4 Node Elimination Rule

Node elimination rules are incorporated to reduce the search space by pruning those nodes which are not providing the promising results. Function value is calculated at each node and it is eliminated if it does not provide solution leading to feasible solution.

- **Cut set /Dominance Rule**

This rule calculates the function value of each child and active nodes and compares it with current best solution. If cost of this node is equal or greater than the current best solution than it will eliminated.

It compares two nodes only if these conditions are satisfied:

i. Finish set of trains at both nodes are same.
ii. Departure time of considered train is same at both nodes, $k_i(n_1) = k_i(n_2)$.
iii. $z(n_1) < z(n_2)$, z is objective function value at nodes.

Than n_2 is dominated by n_1.

Figure 3.11 gives example of cut set rule. Train 3 is the last scheduled high speed train with $k_i(n_1) = k_i(n_2)$. Both nodes have same set of scheduled trains which include high speed trains 1, 2, 2 and medium speed train 8. Both active nodes n_2 and n_1 has to schedule train 9, which yields to train 3 at station 3. Furthermore, it is easy to verify that $z(n_1) < z(n_2)$ for two schedules. This concludes that node n_1 dominates n_2.

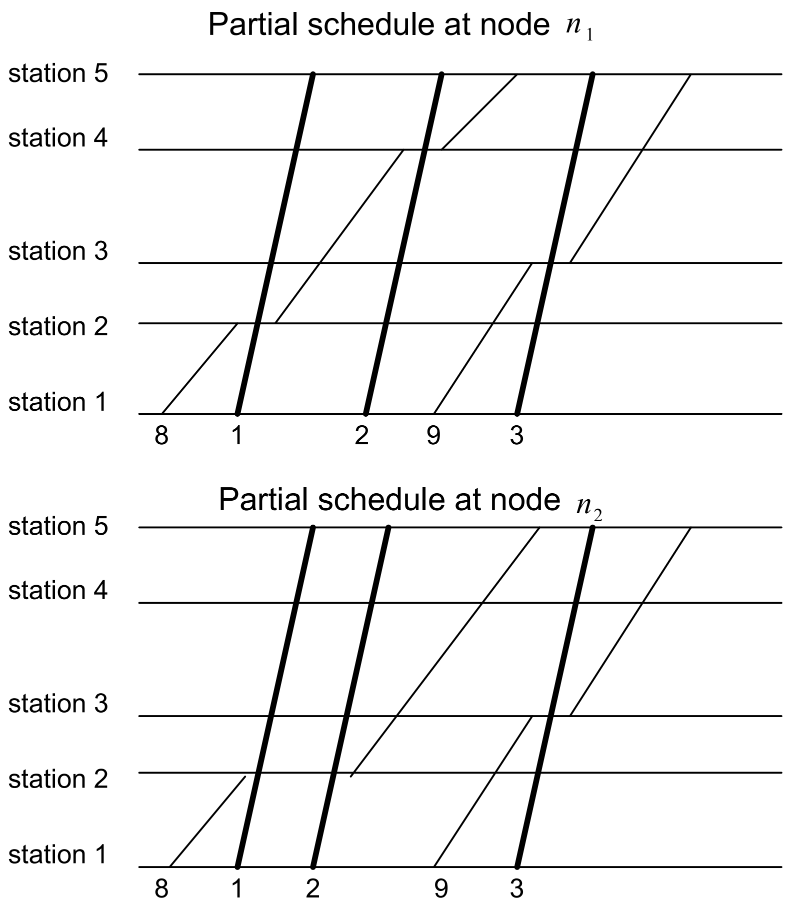


Figure 3.11: Example of Cut Set Rule.

- **Lower bound Rule**

Lower bound value of each newly generated node is calculated. If value of lower bound of a node does not fall within Optimality gap of upper bound function than it is pruned.

$$LB(n) \geq UB(optimality\ gap\%) \tag{3.9}$$

3.5 APPLICATION OF BRANCH AND BOUND SOLUTION TECHNIQUE

Since the single line train scheduling problem is NP-Hard, a straight forward application of common optimization techniques would not allow realistic size problems to be solved in a reasonable time span. There are so many heuristics, meta-heuristics and exact solution techniques applied to train scheduling problem. Latest research works are shown in Table 1.1 with solution techniques applied. The most often used method for solving mixed integer linear programs (MILP) is the branch and-bound (B&B) algorithm, which was first proposed by Land and Doig (1960). The effectiveness of this method has substantially increased with recent algorithmic and computational development. Here we will apply the B&B solution technique to the train scheduling problem.

3.5.1 Solution Procedure

B&B solution procedure with depth and breadth first search technique is described in this section to resolve conflicts. Each node in the B&B tree represents a partial solution (i.e. partially resolved schedule) and the depth (in terms of number of levels) in the tree determines the number of conflicts resolved in this partial solution. For example, a node at the ninth level of the tree will be a partially resolved schedule where the first nine conflicts are resolved. Each node will have two branches as either of the two trains in the conflict can be delayed. A train is delayed at the nearest feasible siding. The B&B technique is as follows:

- Initialize the root node with an empty schedule with data given as input i.e., Departure time, free running time of each track, direction of train etc. Set the upper bound to 999999.
- Apply constraints to trains running at track segments and find the conflict (where two or more trains want to use same resource). Identify the segment and trains of conflict.
- Generate child nodes from each of the option available.
- Node selection rule (DFS, BFS etc) is applied to select active node for branching.
- Calculate lower bound estimate for each of the node.
- Apply node elimination rule if applicable to reduce the search space.

- Move further with remaining child nodes.
- Loop until no more nodes are remaining in list of active nodes or until stop condition of node selection rule is satisfied.

3.5.2 Example:

Schedule 3 trains using B&B technique, with running speed 60 km/h over a single line track with five segments and six sidings/terminals. One train is inbound and two are outbound. Track lengths are 10, 10, 10, 15 and 10 km. Departure times of each train at terminal stations is given in Table 3.2.

Table 3.2: Problem Input Data

Train Number	**Departure time**	**Direction**
0	0:05	Outbound
1	0:17	Inbound
2	0:35	Outbound

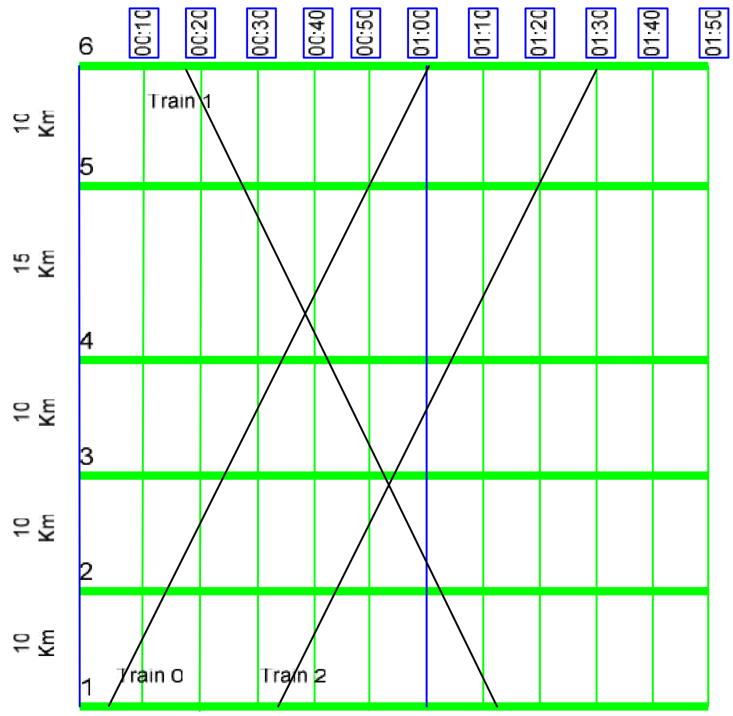


Figure 3.12: Problem Representation

- **Depth First Search**

DFS technique will take the last generated node as active node. Here, we have started with Node No.0 with an empty schedule and proceed further by scheduling tasks on the available tracks until we find a conflict among the trains. Than the available options will be new nodes of search tree. Train 0 and Train 1 are conflicting at section 3 which will give two child nodes, one node when Train 1 is allowed to traverse the track segment first and other when Train 1 is waiting for Train 0. Train 1 is trying to use the track 27 to 42 minutes and Train 0 is 35 to 50 minutes. According to time Node No.1 will be option when Train 1 traverses the track 27 to 42 minutes and other one is Node No.2.

Node No.2 will be evaluated first because it is the last one node generated in search space. At level 2 Node No.2 is generating two more nodes 3 and 4 with different available options. Now Node No.4 will be evaluated giving 5 and 6 root nodes of this search tree. First Node No.6 is evaluated giving optimum value 49 and then Node No.5 gave 35. No more child node available now here than it will move one step back at level 2 and evaluate Node No.3 which gives two root nodes 7 and 8. Node No.8 will be first one to get evaluated but it will be pruned as it is not giving good results as compared to previous results than Node No.7 evaluation gives 31. Next, algorithm will move back to unexplored nodes as no more nodes are available after this root node in this path. At level 1 Node No.1 is evaluated it is giving two options Node No.9 and Node No.10. DFS will evaluate Node No.10 first with optimum value 28 and then finally it will go to the last available option Node No.9 which will give optimum value 14, which is less than all previous values. Hence, result of this search tree is 11 nodes generated with depth 4 and optimum value 14 minutes delay.

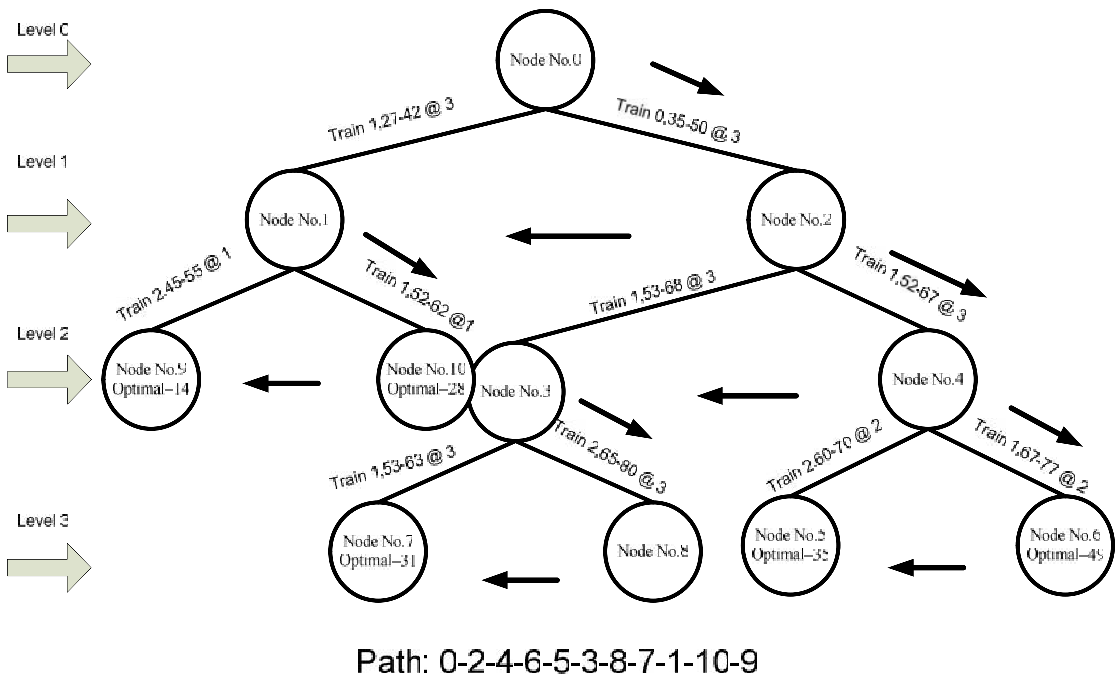


Figure 3.13: Search Tree of Depth First Search Technique.

- **Breadth First Search**

BFS technique traverse the search tree in a such manner that node generated first will be evaluated first and all nodes at the same level are evaluated before going to next level. When considering the above problem given with BFS (as compared to DFS), Node No.1 will be explored first here. Node No.1 gives birth to 2 child nodes Node No.3 and 4. Next, Node No.2 is explored with two options available Node No.5 and 6. All the nodes at level 1 are evaluated now algorithm will go to next level where Node No.3 comes first, which gives optimal value 14. Than search algorithm will evaluate Node No.4, 5 and 6 but these all available options will not update solution. It concludes that this search algorithm has evaluated 7 nodes up to depth level 3 and generated optimum solution 14 minutes delay to trains.

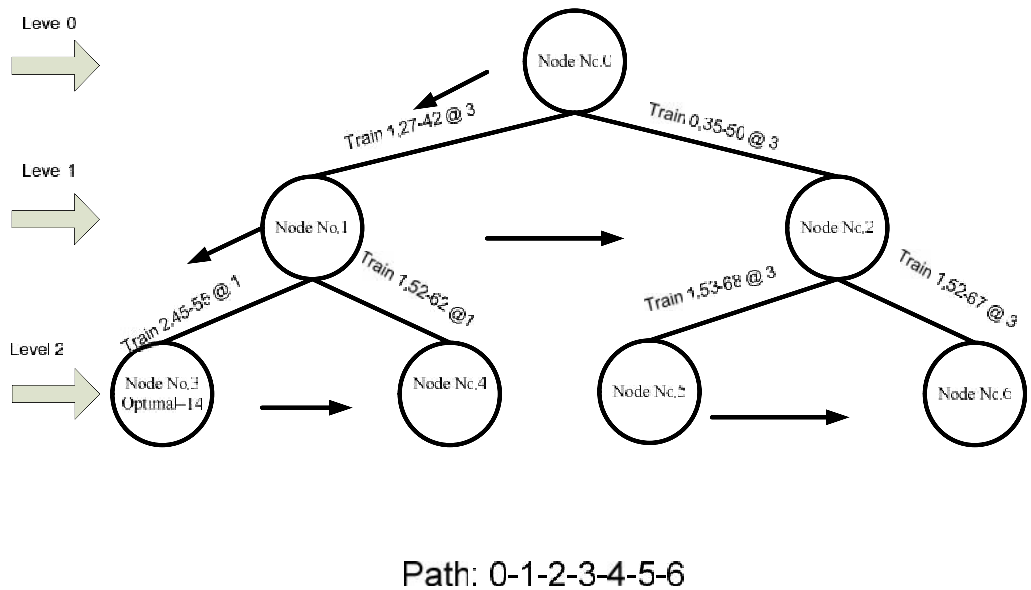


Figure 3.14: Search Tree of Breadth First Search Technique.

Table 3.3: Output of B&B technique with exact solution techniques (DFS, BFS) and BCPR, ESPR, EFPR, MPTPR.

Section	Train Number	Start Time	End Time
Section 0	Train0	5	15
Section 0	Train1	67	77
Section 0	Train2	35	45
Section 1	Train0	15	25
Section 1	Train1	57	67
Section 1	Train2	45	55
Section 2	Train0	25	35
Section 2	Train1	42	52
Section 2	Train2	55	65
Section 3	Train0	44	59
Section 3	Train1	27	42

Section 3	Train2	65	80
Section 4	Train0	59	69
Section 4	Train1	17	27
Section 4	Train2	80	90

- **Priority Rules**

Random priority rule select active node from the child nodes randomly and evaluate only one node at each level and all others remain unexplored. Result of random priority rule is given in Table No. 3.4 and Figure No 3.16. All other rules are generating same results because here free running time of each track segment is fixed and only one type of train is consider in this example so early arrival and early departure and processing times will be same. Here this example only describes the working of different techniques in the next chapter in the application of this model; two different types of trains are considered which will evaluate the effect of different priority rules. Table No 3.3 and Figure No 3.18 shows the results of DFS, BFS, early arrival, early finish, early departure and minimum processing times

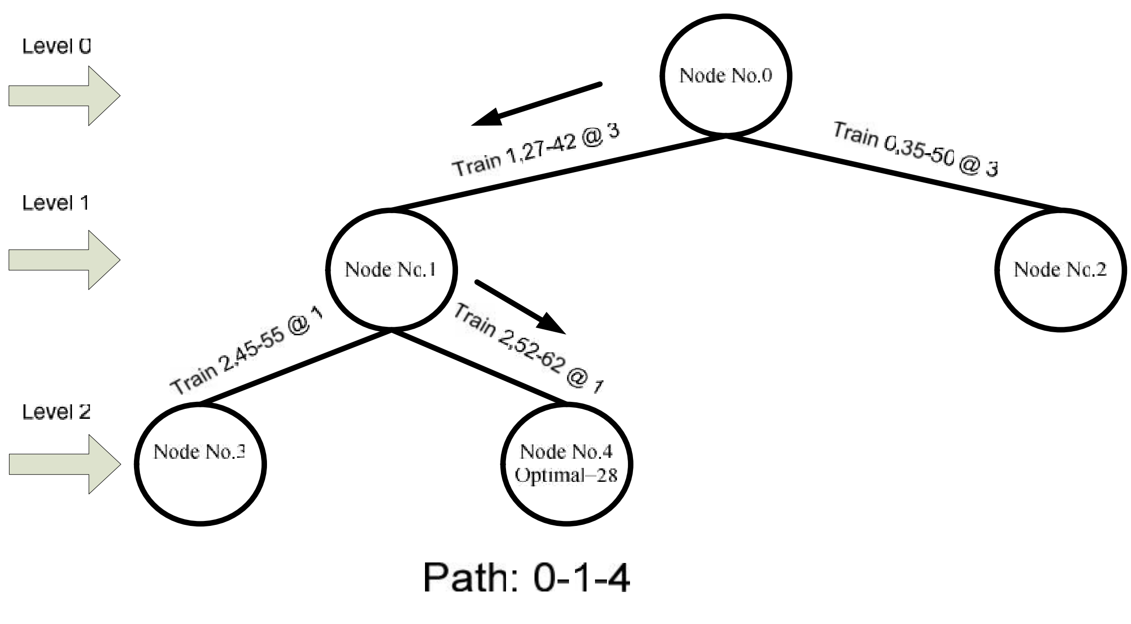


Figure 3.15: Search Tree of Random Priority Rule.

Table 3.4: Output of Random Priority Rule.

Section	Train number	Start Time	End Time
Section 0	Train0	5	15
Section 0	Train1	62	72
Section 0	Train2	35	45
Section 1	Train0	15	25
Section 1	Train1	52	62
Section 1	Train2	64	74
Section 2	Train0	25	35
Section 2	Train1	42	52
Section 2	Train2	74	84
Section 3	Train0	44	59
Section 3	Train1	27	42
Section 3	Train2	84	99
Section 4	Train0	59	69
Section 4	Train1	17	27
Section 4	Train2	99	109

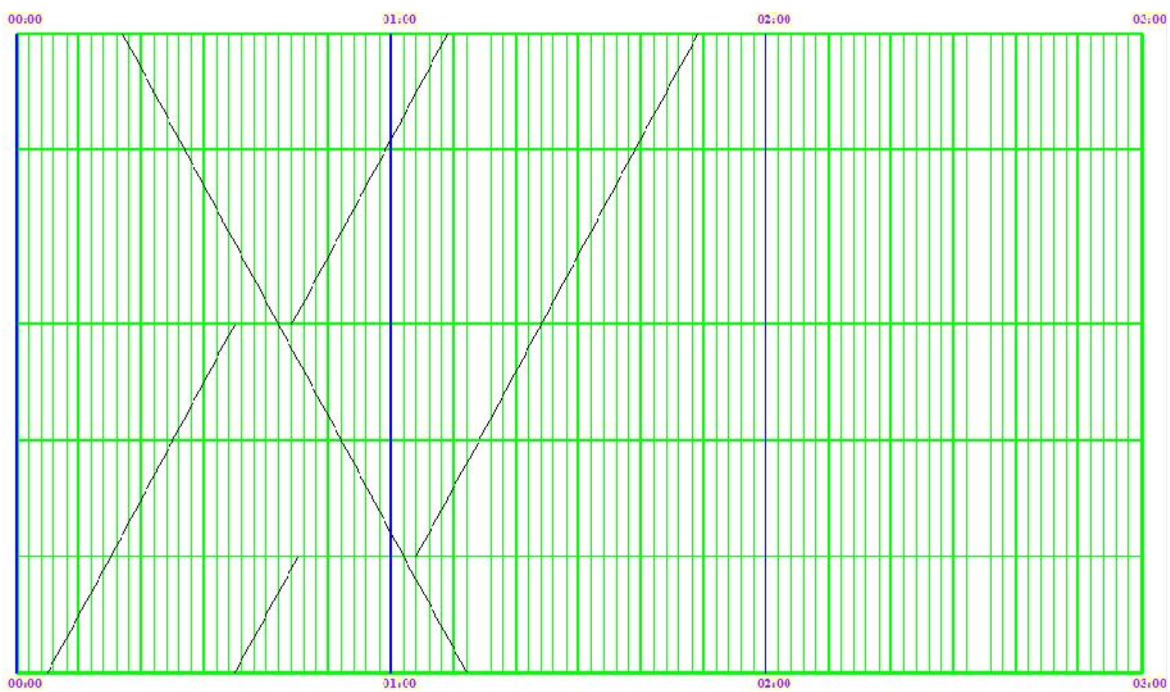


Figure 3.16: Software Output for Optimum Solution by Random Priority Rule.

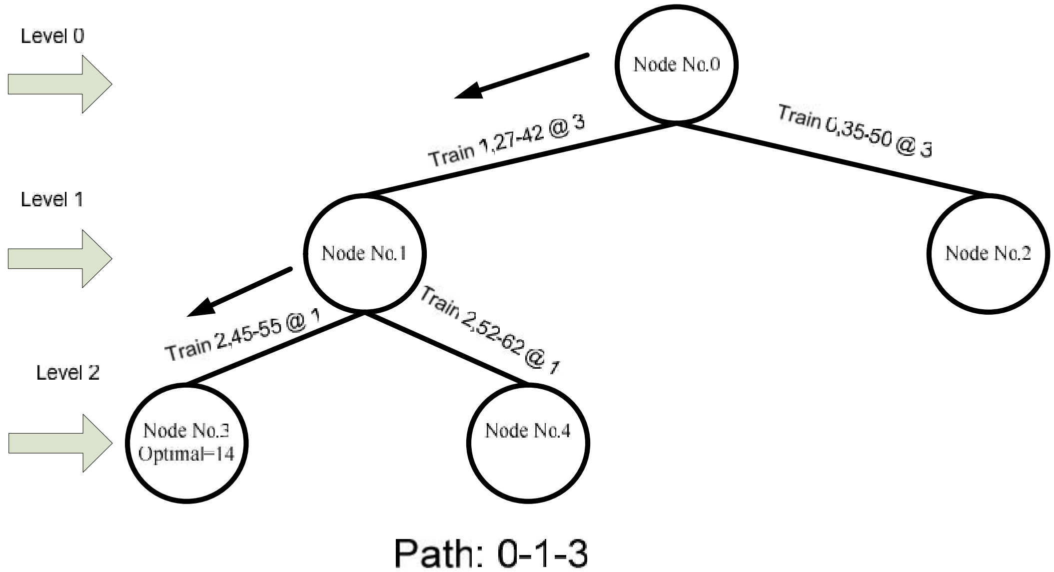


Figure 3.17: Search Tree of BCPR, ESPR, EFPR, MPTPR.

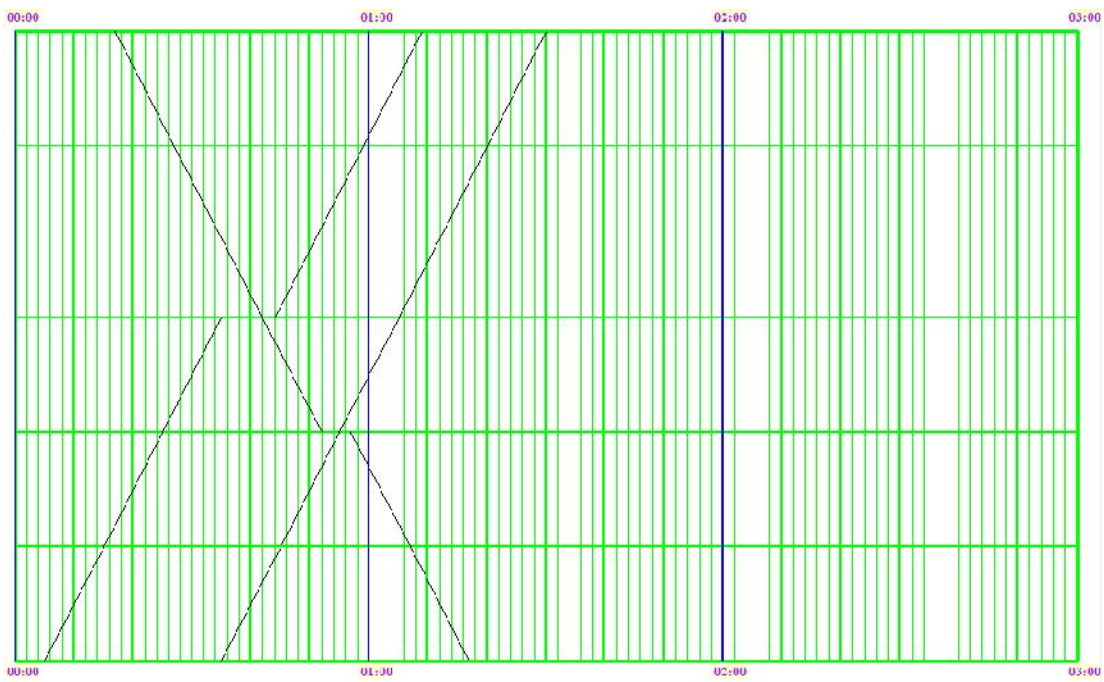


Figure 3.18: Software Output for Optimum Solution by Exact solution technique and BCPR, ESPR, EFPR, MPTPR.

3.6 COMPARISON OF DIFFERENT APPROACHES

The B&B technique with different search techniques (Depth first search and Breadth first search) and local simple dispatching rules (priorities based on arrival, departure and processing times) to simulate general human behavior is implemented in Visual C++ 2008. The model was tested on a train schedule of 5 sections track segments with 3 to 15 trains running with constant segment running times shown in Table 3.5.

Table 3.5: Segment Running Times

Segment	**Running Time(min)**
1	13
2	13
3	11
4	9
5	9

Figure 3.19 and 3.20 shows the summary of results in terms of number of nodes evaluated by DFS and BFS search techniques and Figure 3.21 shows the number of nodes evaluated by different priority rules. Appendix III give details of each method and number of nodes generated and explored by different priority rules. Results are generated after considering all nodes because the optimality gap used in Lower bound rule is 100%, which do not prune any node. Dominance or cutest rule performs well with breadth first technique. Data set assumed here contains constant running times so best cost, late arrival, late departure and minimum processing time priority rules are generating same results. BFS with dominance rule has generated 98.7% less nodes as compared to other approaches. Priority rules has generated less than 1% nodes as compared to exact solution techniques with 43.4% and 2.71% optimality gap in random and other rules.

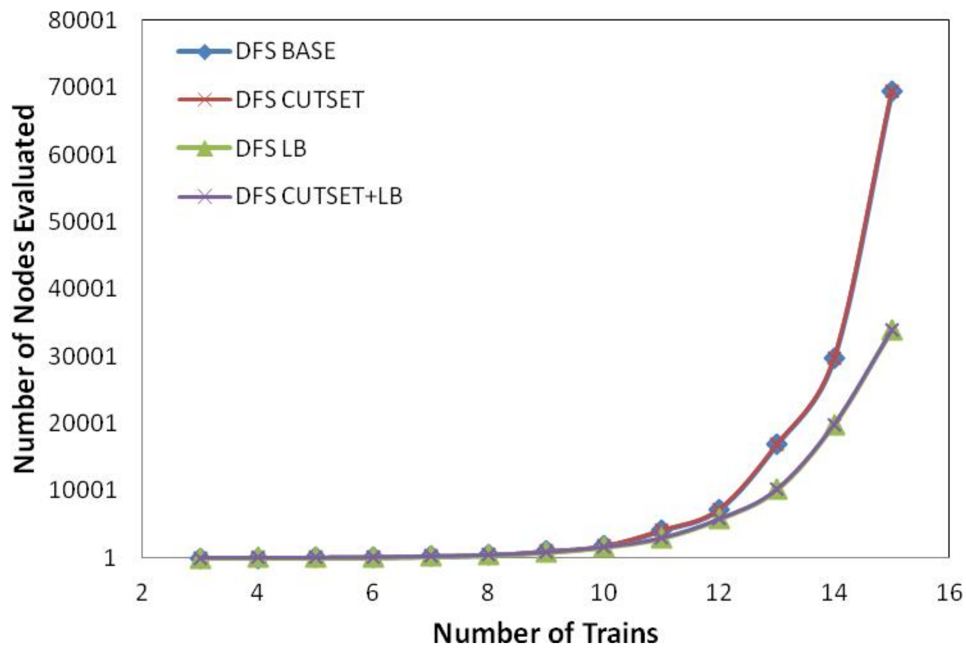


Figure 3.19: Number of Nodes Evaluated by Depth First Search Technique.

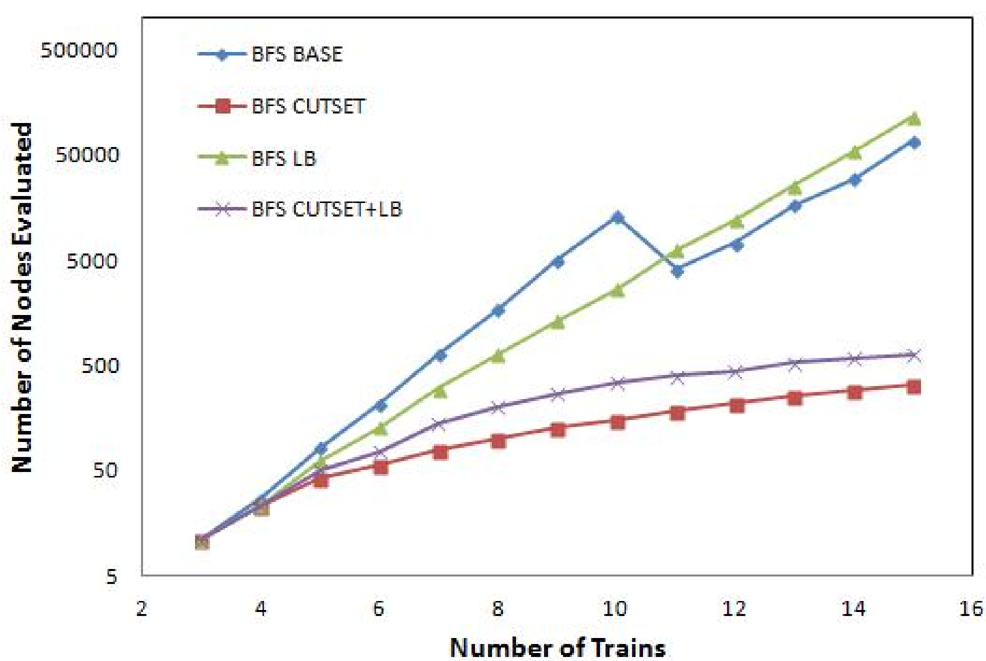


Figure 3.20: Number of Nodes Evaluated by Breadth First Search Technique.

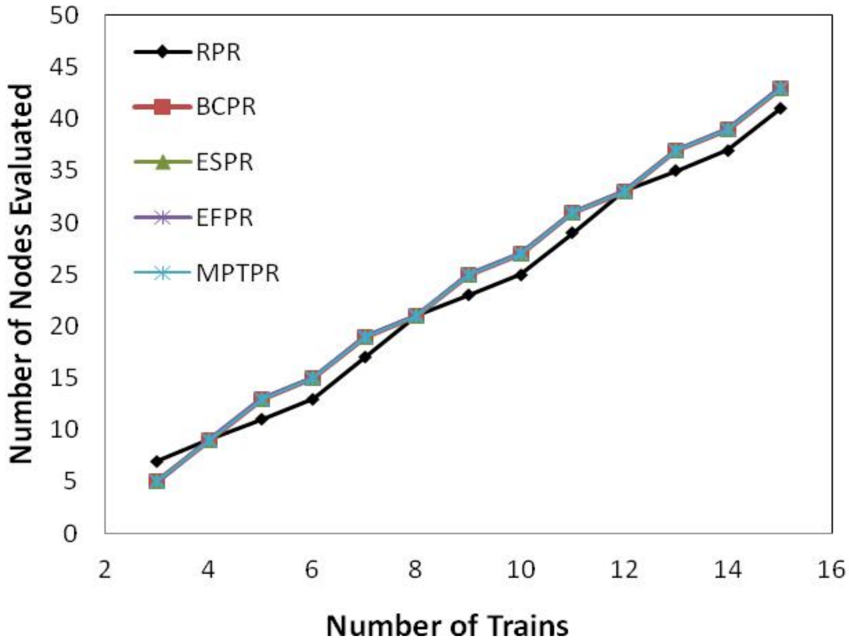


Figure 3.21: Number of Nodes by Evaluated Priority Rules.

3.7 SUMMARY

Mathematical modeling of rail operation in Pakistan is done here with very simple and reasonable assumptions. Objective of this modeling was to minimize the sum of end time of all activities which ultimately results in minimization of conflict delays. Actual constraints of rail corridor are applied to ensure safety and real working environment. Results shows that B&B exact solution techniques take more time as compared to simple priority rules and difference in their results is not considerable. Cutest or dominance rule outperforms with BFS technique, it reduced nodes of search space to 98.7% as compared to other exact solution approaches.

Priority rules are generating results almost same as B&B exact solution techniques within so much less time except RPR. They generate less than 1% nodes as compared to exact solution techniques. Here, we considered constant fixed running times of each track and trains traversing the rail corridor are of same type. All priority rules except RPR produced same type of results because in the each case train entering first will be the train finishing first and the same will be the train providing best cost. As far as MPTPR is concern, all trains have same running times here, to implement this rule trains with different running speeds are required.

Chapter 4

PRACTICAL APPLICATION OF MODEL

4.1 INTRODUCTION

In this chapter B&B solution with priority rules is applied to get optimize schedule of PR schedule of track segment Rawalpindi to Lalamusa. Practical issues which are associated with this problem also discussed. Detailed description of problem and input of parameters are given in Section 4.2. In Section 4.3 actual schedule is compared with optimized results and in Section 4.4 sensitivity analysis is performed.

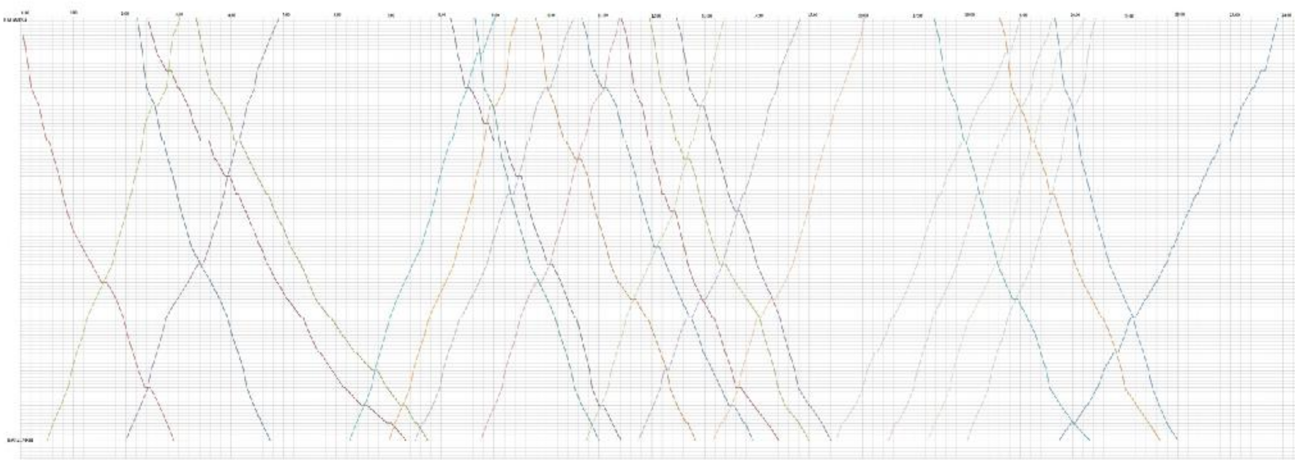


Figure 4.1: Actual Train Schedule of Track Segment from Rawalpindi to Lalamusa.

4.2 PAKISTAN RAILWAY SCHEDULE

The track chosen to apply the model and get optimized results is from Rawalpindi to Lalamusa. Track chosen is mainly single line track with length 156 Km. On the busiest day of week about 30 trains traverse this track. There are four different types of trains scheduled over this track, namely; Mail and Express, Intercity, Passenger and Mixed trains. To ensure safety minimum 3 minute headway between the departure time of two trains to a track and 2 minutes between arrival times of two trains at a station is maintained.

Figure 4.1 shows train schedule of the track segment between Rawalpindi to Lalamusa. Description of each train and their input values in the model to get optimum results are given in

Table 4.1. Appendix IV and V shows the details of actual schedule and optimized output of model.

Table 4.1: Description of Trains using Track segment

Inbound train						Outbound Train					
Train no	**Train No input**	**Type**	**Origin**	**Destination**	**Start time**	**Train no**	**Train No input**	**Type**	**Origin**	**Destination**	**Start time**
105	3	A-C/P,A-C/L & EC	LLM	RWP	2:13	106	1	A-C/P,A-C/L & EC	RWP	LLM	0:30
327	4	MIXED	LLM	RWP	2:25	2	2	A-C,A-C/B & EC	RWP	LLM	2:00
131	5	EC	LLM	RWP	3:20	46	6	EC	RWP	LLM	6:15
11	9	EC	LLM	RWP	8:10	110	7	A-C/P,A-C/L & EC	RWP	LLM	7:00
107	10	A-C/P,A-C/L & EC	LLM	RWP	8:38	104	8	A-C/P,A-C/L & EC	RWP	LLM	7:30
101	12	A-C/P,A-C/L & EC	LLM	RWP	9:47	8	11	A-C,A-C/B & EC	RWP	LLM	8:45
13	13	A-C/L & EC	LLM	RWP	10:40	40	14	A-C,A-C/B & EC	RWP	LLM	10:45
23	15	1ST & EC	LLM	RWP	11:25	24	16	1ST & EC	RWP	LLM	11:45
39	17	A-C,A-C/B & EC	LLM	RWP	11:57	14	19	A-C/L,EC	RWP	LLM	13:10
45	18	EC	LLM	RWP	12:28	132	20	EC	RWP	LLM	15:30
7	23	A-C,A-C/B & EC	LLM	RWP	17:22	102	21	A-C/P,A-C/L & EC	RWP	LLM	16:30
103	25	A-C/P,A-C/L & EC	LLM	RWP	18:37	12	22	EC	RWP	LLM	17:15
109	26	A-C/P,A-C/L & EC	LLM	RWP	19:40	108	24	A-C/P,A-C/L & EC	RWP	LLM	18:00
1	0	A-C,A-C/B & EC	LLM	RWP	0:00	328	27	MIXED 2ND	RWP	LLM	19:45

A-C=Air conditioned, B=Business, EC=Economy, 1^{ST}=First Class, L=Standard, P=Parlour.

Unobstructed times of trains running at different operating speed on each track segments are taken as constant are given in Appendix II. These train times are obtained from Pakistan Railways Timetable for Passenger Trains (Staff Copy) (2010).

Figure 4.2 shows the main screen simulating the time distance graph for track segment Lalamusa to Rawalpindi. Horizontal axis shows time in hours from 0 to 24 and vertical axis shows distance among stations.

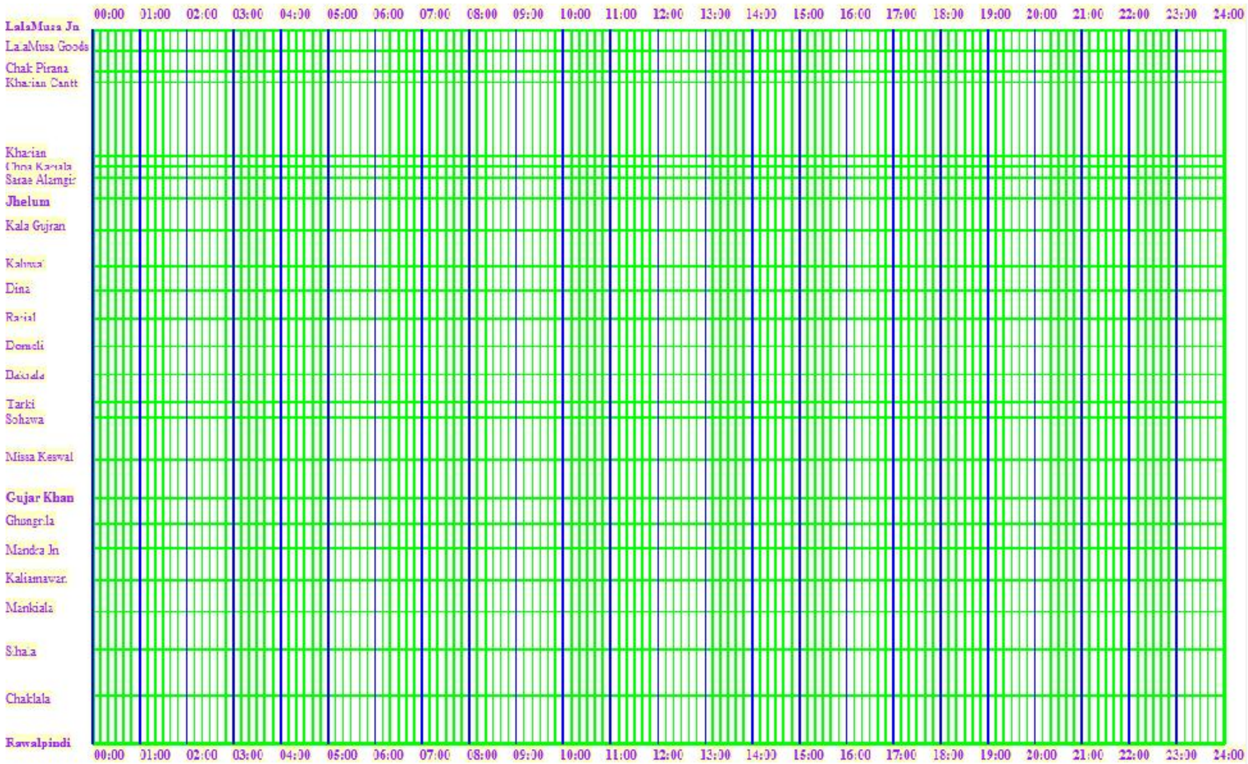


Figure 4.2: Main Screen of Train Scheduler, Simulating Track Segment from Rawalpindi to Lalamusa.

4.3 SCHEDULE OPTIMIZATION

4.3.1 Comparison of Optimal with Actual Planned Schedule

The objective function was to minimize total travel time by optimizing the conflicts of trains running over track segment taken for case study. The actual train schedule generated by train scheduler is displayed in Figure 4.1. There is total running time 85 hours 52 minutes with 304 minutes conflict delay and 238 minutes scheduled stops. The schedule was optimized using B&B technique with priority rules. The optimal schedule generated by BCPR is displayed in Figure 4.3. This has total 72 hours and 36 minutes and 291 minutes conflict delay. All other priority rules optimize this schedule with 72 hours and 40 minutes with 295 minutes conflict delay, as shown in Figure 4.4. Efficiency of optimal schedules can be found by visual inspection of both schedules. For a detailed analysis Appendix IV and V are attached.

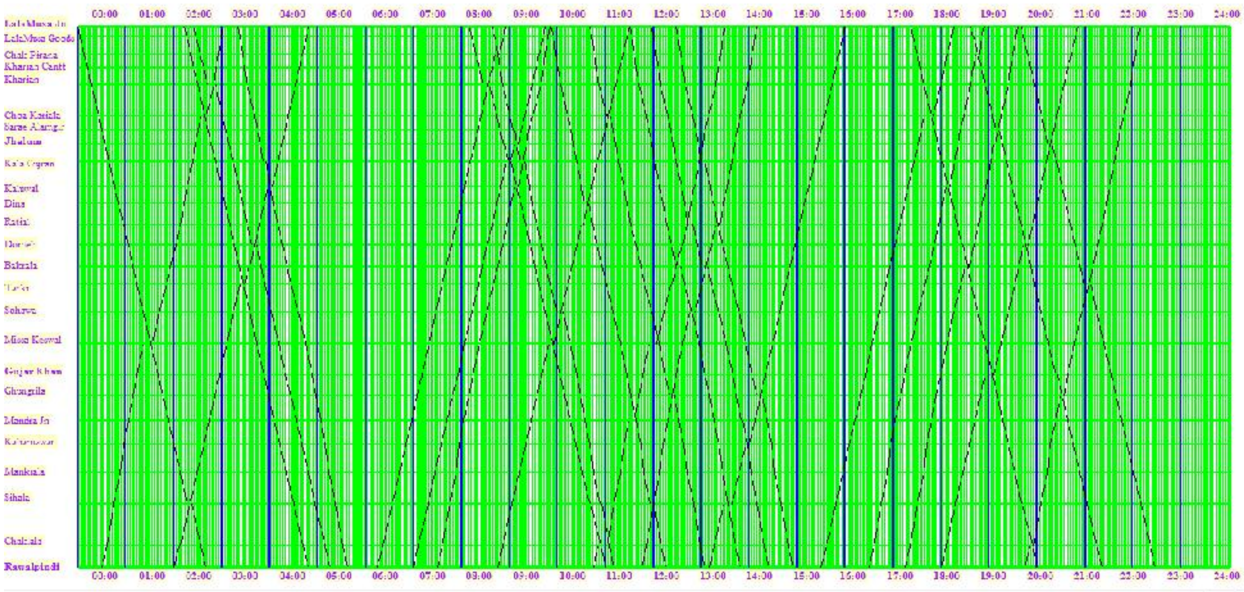


Figure 4.3: Optimize schedule with BCPR for Track Segment Rawalpindi to Lalamusa.

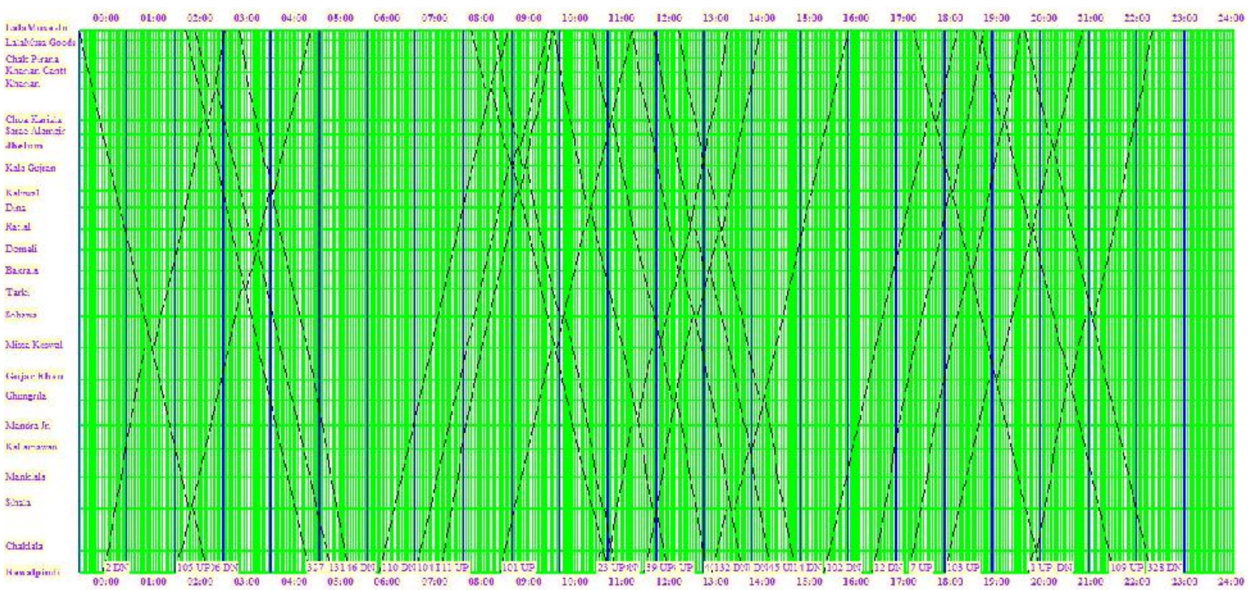


Figure 4.4: Optimize schedule with ESPR, EFPR and MPTPR for Track Segment Rawalpindi to Lalamusa.

In Figure 4.1 there are unnecessary delays to train 327 and 131, conflicts of these trains can be reduced considerably without causing extra delay to other trains. Figure 4.5 to Figure 4.10

is providing us with comparison of conflict delays, total travel and running time of inbound and outbound trains separately.

It can be seen from comparison of actual and optimized schedules that conflict delay to inbound Train 11 and outbound Train 104 are much more than other trains in actual schedule.In actual schedule, at the start of Train 104 's path conflicts are with Train 327 and Train 131. While in optimized schedule because conflict resolution of inbound Train 327 and Train 131 with outbound Train 106 and Train2 path are adjusted in such a way that the path trajectaries of these trains (Train 327 and Train 131) end before the departure of Train104. In case of Train 11, in actual schedule it is conflicting with four outbound trains (Train 46, Train 110, Train 104 and Train 8). In all conflicts it is delayed and it is also overtaken by Train107 (Fast train), which cause more delay to this path. In optimized schedule, in conflict with Train 46 is given priority over this and in all other crossing comflicts it is given priority over other three outbound trains. This arrangement also omited overtaking conflict with Train 107.

Conflicts between inbound Train 327, Train 131, Train 105 and outbound Train 106 and Train 2 are adjusted such that in optimzed schedule inbound trains are given priority over outbound trains, which reduces next conflicts of these trains with Train 46, Train 110 and Train 104.

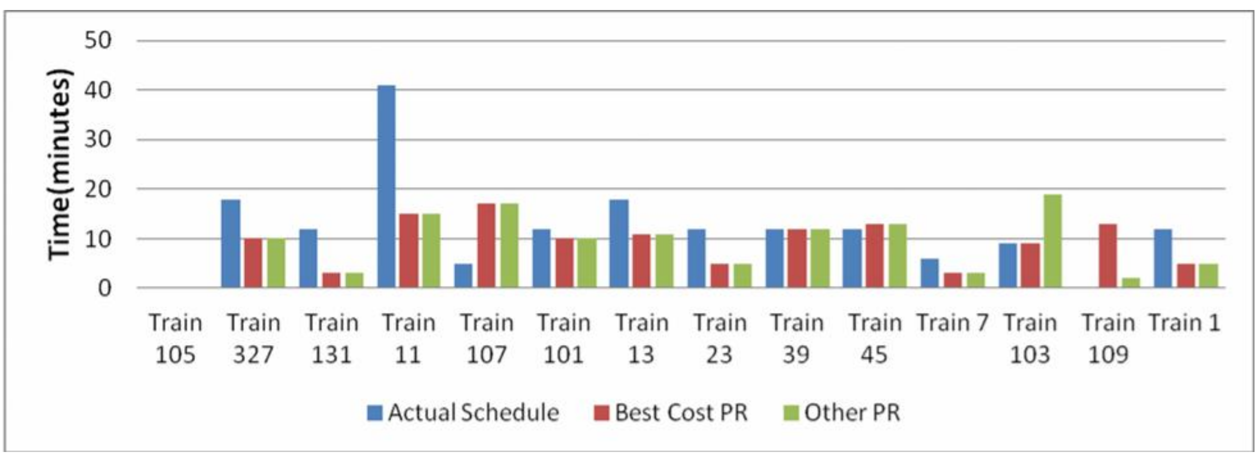


Figure 4.5: Comparison of Conflict Delays of Inbound Trains for Actual and Optimized Schedule.

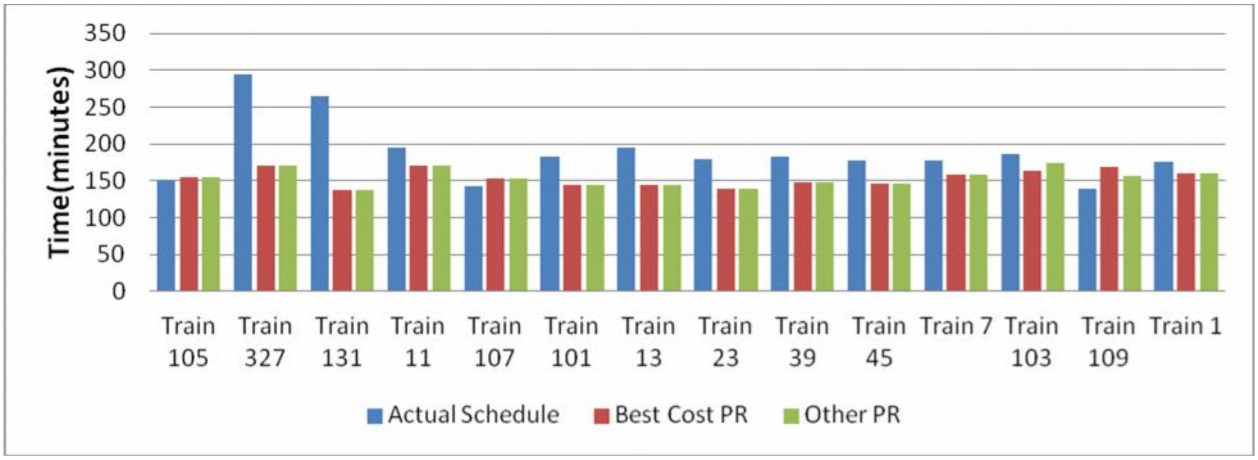


Figure 4.6: Comparison of Total Travel Time of Inbound Trains for Actual and Optimized Schedule.

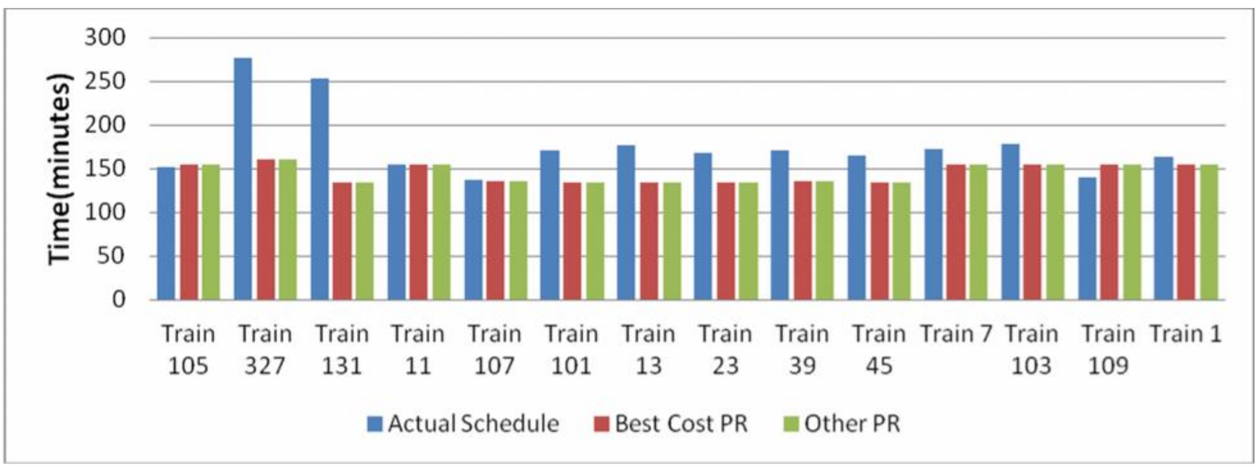


Figure 4.7: Comparison of Running Time of Inbound Trains for Actual and Optimized Schedule.

In actual schedule outboud Train 40 is given priority over inbound Train 11, Train 107, Train 101, Train 13, Train 23, Train 39 and Train 45. This delay of 7 inbound trains is generating more conflicts with next outbound trains. In optimized schedule these inbound trains are given priority over Train 40, which results in omission of conflict of Train 13 and Train 14, Train 45 and Train 132.

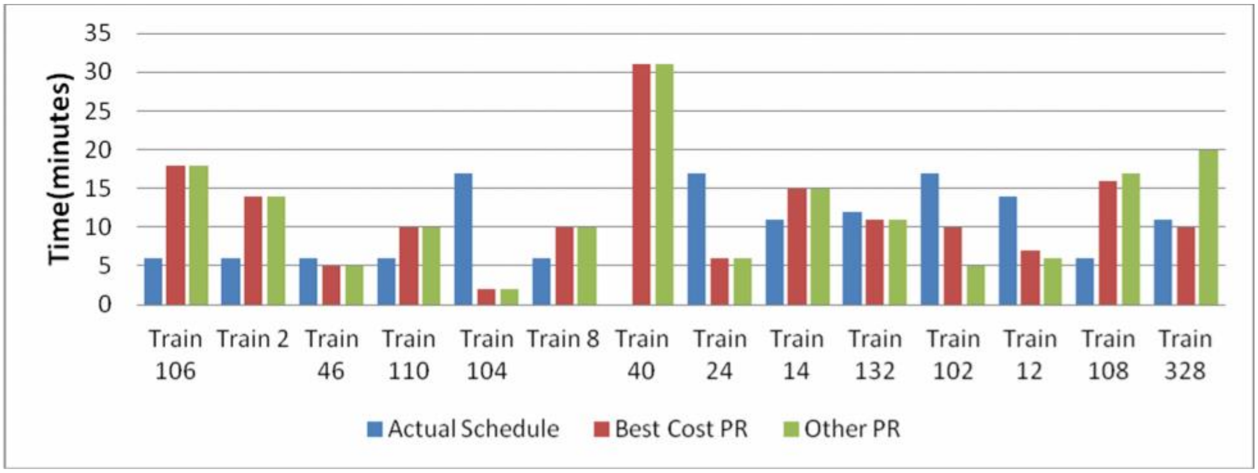


Figure 4.8: Comparison of Conflict Delays of Outbound Trains for Actual and Optimized Schedule.

Figure 4.9: Comparison of Total Travel Time of Inbound Trains for Actual and Optimized Schedule.

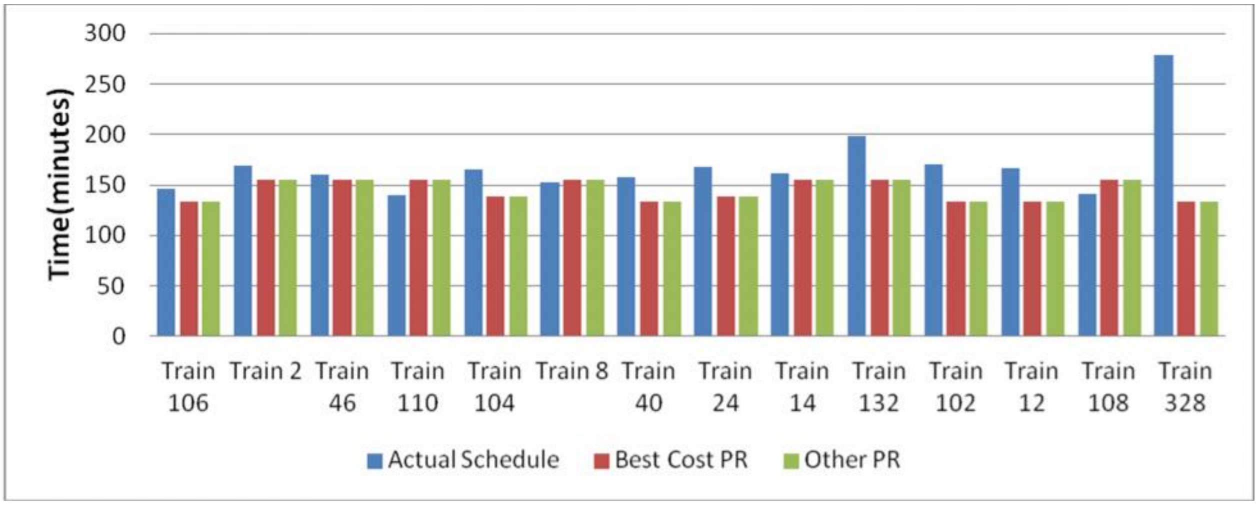


Figure 4.10: Comparison of Running Time of Inbound Trains for Actual and Optimized Schedule.

4.4 OPTION TESTING

Different operating changes are tested on the test track by using same B&B technique. Decreases in number of sidings, where conflicts can be resolved, change in running speed and increase in numbers of trains to demonstrate increase in demand are different changes that can be tested to demonstrate the effects of operational changes.

Taking the number of siding variable here, computational effort and conflict delays are calculated. Figure 4.11 shows the number of conflicts resolved on all the stations between Lalamusa and Rawalpindi according to PR’s schedule. Some intermediate sidings do not have any conflict and some has as many as 5 per day.

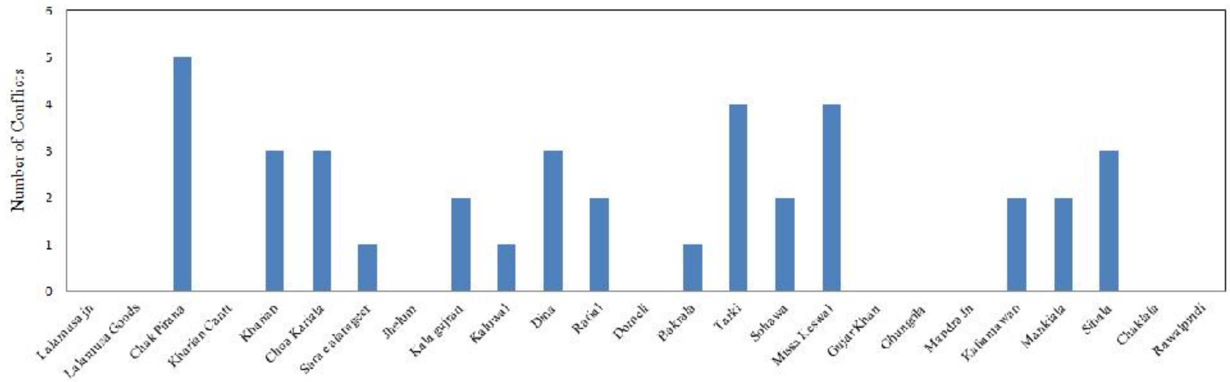


Figure 4.11: Number of Conflicts on Each Siding in Actual Schedule

In the sensitivity analysis of this track, we first consider only 15 intermediate sidings with two terminal stations, which are being used to resolve conflicts. Than starting from Lalamusa terminal all those sidings which have only one conflict, are ignored one by one.

Table 4.2: Results of Option Testing

Siding	8 Trains		9 Trains		10 Trains		11 trains		12 trains	
	Nodes	Delay	Nodes	Delay	Nodes	Delay	Nodes	Delay	Nodes	Delay
17	486	40	1716	57	14563	84	54389	99	179742	111
16	301	52	1021	69	5633	95	17185	110	64014	127
15	361	58	967	74	5335	102	14048	116	66433	138
14	473	67	1271	83	6664	111	18385	125	91798	148
13	253	82	1383	133	8710	186	14479	202	64472	231
12	197	82	1105	133	6400	186	9188	202	35420	231
11	197	82	1105	133	6400	186	8956	202	46878	242
10	311	99	1029	141	5527	194	8229	210	35005	250
9	409	138	837	174	3766	227	6017	242	24693	279

After that we ignored the sidings which have two conflicts to get resolved. Appendix VI shows the arrangement of different options which were tested with varying number of trains to calculate the impact of extra sidings available. Details of different testing schemes are provided in Appendix VI.

Figure 4.12 shows graphically the results of Table 4.2. It can be seen that decreasing the number of locations is resulting increase in conflict delays but the track with 10 to 13 sidings arrangement are producing exactly same results. Appendix VI shows that these are four options Kaliamawan, Sohawa, Ratial and Kalagujran which are omitted from list of conflict resolving sidings when 10 to 13 sidings are obtained. This elaborate the fact that these are arranged without any such type of conflict delay estimation or it may also be possible that the system available at that time when investments on this track was planned, may not be efficient like this modern one.

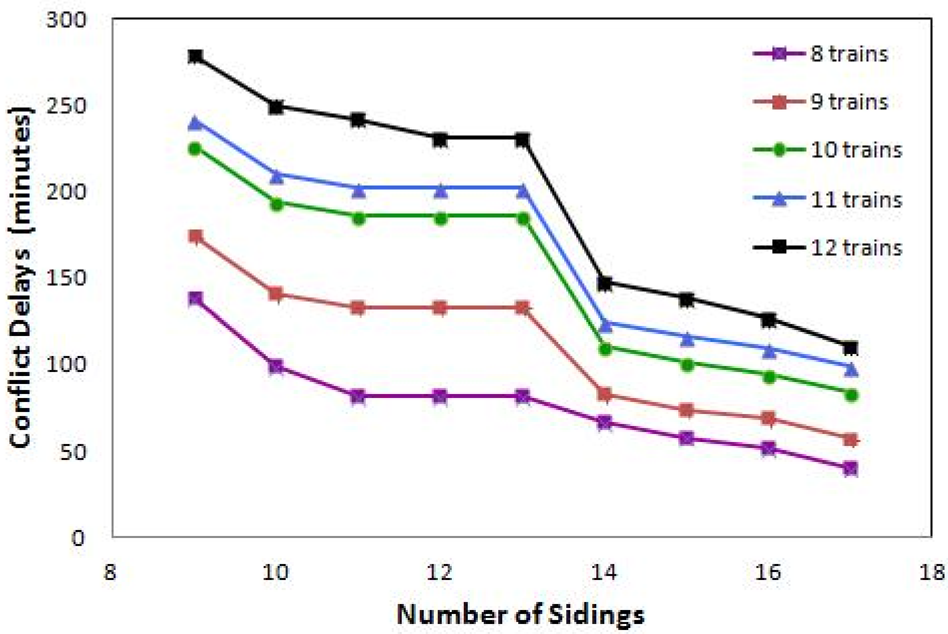


Figure 4.12: Illustration of Increase in Delay with Decrease in Number of sidings.

Figure 4.13 shows the impact of decrease in the number of locations where conflicts can be resolved on the computational effort involved in solving the problem. By decreasing sidings number of nodes to be evaluated decreases but the conflict delay increases. Impact of siding on the whole schedule can be judged by this manner. Here the results, shows that curve is almost same for 10 to 13 sidings with curves of 12 and 13 sidings lying exactly on each other, strengthening the conclusion of previous discussion that sidings Kaliamawan, Sohawa, Ratial and Kalagujran have a very little effect on the schedule. It also elaborates that by fixing some necessary places for sidings large scale problem of train scheduling can be reduced to a simple one but results may be suboptimal.

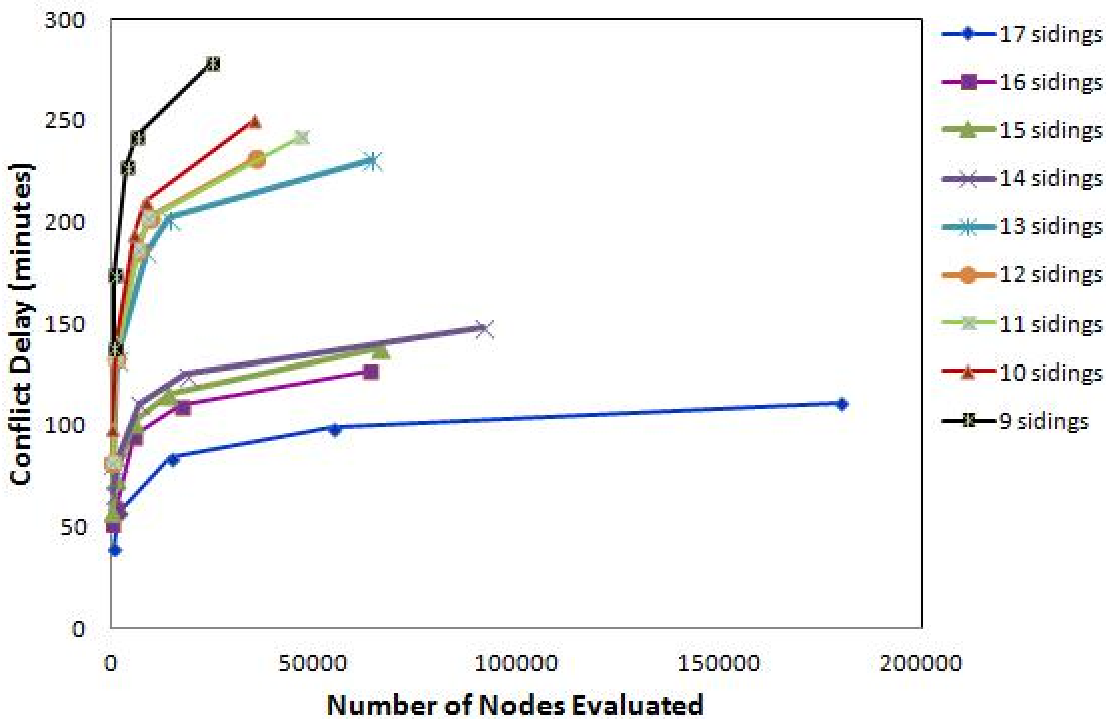


Figure 4.13: Analysis of Computation Effort Involved in Option Testing.

4.5 SUMMARY

Mathematical model developed in last chapter is applied over a real rail corridor of track segment from Rawalpindi to Lalamusa. Actual schedule of this track is optimized here using priority rules, while considering both slow and fast trains traversing this track segment daily. Results have shown that these rules generate optimized schedule with approximately 9 hours less running time as compared to actual one, which was the objective function of this modeling.

Sensitivity analysis was done with changing the number of sidings and trains. Sidings with no conflicts are ignored first and then those sidings have one conflicts are ignored, to decrease the number of conflict resolution places. Results show that with decrease in the number of sidings delay increases but the computation effort decreases. Some of sidings which don't have any impact on scheduling of this track are mentioned using this analysis. This shows that this technique can be used to determine the investments in terms of location and number of sidings because conflict related delays has direct relation with number and position of sidings.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, research conclusions and recommendations are presented. Based on the study results, the conclusions are drawn and recommendations are made.

5.2 CONCLUSIONS

The major findings of this study are concluded as follows:

5.2.1 Optimization Techniques

Exact and priority based solution techniques for schedule optimization has been presented in this work. Experimental analysis revealed the following facts:

- B&B technique with node elimination rules gave best solution within less time. Cutset or dominance rule outperforms with BFS technique with 98.7 % less node generation without compromising the results.
- Lower bound rule embedded in B&B to reduce search space also performed well with DFS.
- BCPR, ESPR, EFPR and MPTPR priority rules generated results near to exact solution techniques by exploring less than 1% nodes as compared to exact solution technique and 2.71 % optimality gap.
- RPR showed results that have 43.4 % optimality gap.
- Priority rules were found the viable options to find the feasible solutions of these problems within a reasonable time.

5.2.2 Schedule Optimization

Actual schedule of track segment Lalamusa to Rawalpindi is optimized using the model developed in this work. Experimental analysis revealed the following facts:

- Optimized results showed that the objective function of model that was minimization of total travel time is achieved. Actual schedule has 9 hours more travel time as compared to optimal one.
- Actual schedule has some trains causing delays to other trains while in optimized schedule they were scheduled properly.

5.2.3 Sensitivity Analysis

Option testing was done by changing the number of sidings and finding the resulting delay and computational effort. Conclusions from sensitivity analysis are as follows:

- By decreasing sidings number of nodes to be evaluated decreases but the conflict delay increases.
- By fixing some necessary sidings for scheduling, large scale problem of train scheduling can be reduced to a simple one but results may be suboptimal.
- Track segment with 10 to 13 sidings arrangement is producing exactly same results showing that sidings Kaliamawan, Sohawa, Ratial and Kalagujran have a negligible effect on the schedule.

5.3 RECOMMENDATIONS

It is practically impossible to attain optimal solution of large scale network of NP-hard train scheduling problem. To find the suboptimal and feasible solutions of these problems within a reasonable time limit heuristic techniques are generally applied. Although so many time and computational cost saving heuristic techniques have been developed but often their results are not so much accurate. There is tradeoff between computation effort and solution quality of problem and we should focus to establish heuristic techniques which give optimal solution within seconds. Optimal solution works in two ways, first, it provides a benchmark for evaluation of the heuristic technique and second it provides us with upper bound for sensitivity testing i.e., impact of changing the values of design attributes on the solution. It is suggested that user friendly software should be developed for railway scheduling in order to increase efficiency of Train scheduler/Dispatchers in Pakistan.

5.4 FUTURE DIRECTIONS

This work assumed constant free running time to make this more realistic its extension would be inclusion of variable running time into this model. By using this approach in modeling, this may lead to more complex problem formulation hence there will be necessity of an efficient heuristic technique which will solve it with in less time.

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APPENDICES

Appendix I: Types of Trains Traversing Network

TRAINS	TYPES	TOTAL
105-131-107-101-103-109-106-110-104-132-102-108	INTERCITY TRAINS	12
11-13-23-39-45-7-1-2-46-8-40-24-14-12	MAIL & EXPRESS	14
327-328	MIXED TRAINS	2
Total		28

Appendix II: Train Running Times at Different Segments.

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -LALA MUSA GOODS	3	3
LALA MUSA GOODS -CHAK PIRANA	3	5
CHAK PIRANA -KHARIAN CANTT	3	4
KHARIAN CANTT -KHARIAN	3	5
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -SERAI ALAMGEER	4	4
SERAI ALAMGEER -JHELUM	3	4
JHELUM -KALA GUJRAN	4	5
KALA GUJRAN -KALUWAL	6	7
KALUWAL -DINA	4	5
DINA -RATIAL	5	6
RATIAL -DOMILI	6	6
DOMILI -BAKRALA	6	6
BAKRALA -TARKI	5	5
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -GUJAR KHAN	8	9
GUJAR KHAN -GHUNGILA	5	6
GHUNGILA -MARDAN JN	6	7
MARDAN JN -KALIAMAWAN	6	7
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -CHAKLALA	9	12
CHAKLALA -RAWALPINDI	6	6

Appendix III: Comparative Tables of Different Approaches.

- **Comparison of Exact Solution Techniques**

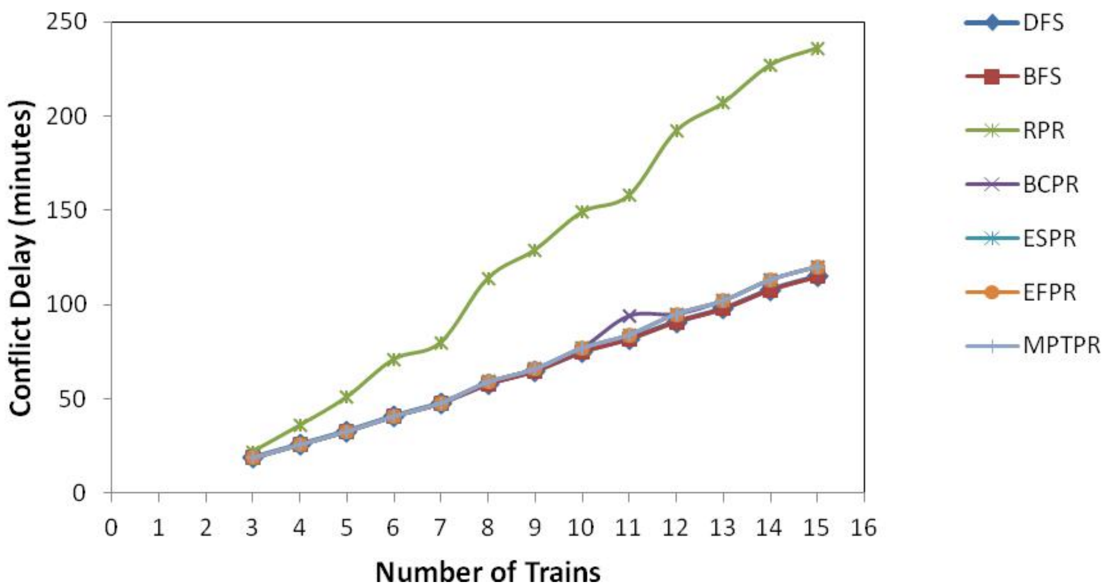
Trains	Depth First Search				Breadth First Search			
	Base	Cut set Rule	Lower Bound	Cutset+ Lower bound	Base	Cut set Rule	Lower Bound	Cutset+ Lower bound
3	11	11	11	11	11	11	11	11
4	23	23	25	25	27	23	23	23
5	57	57	57	57	83	43	63	51
6	99	99	111	111	219	57	129	77
7	235	235	247	247	647	79	299	143
8	421	421	433	433	1711	101	647	205
9	987	987	851	851	5003	127	1333	269
10	1751	1751	1613	1613	13245	153	2625	351
11	4085	4085	2959	2959	4085	187	6223	397
12	7215	7215	5769	5769	7215	217	11931	437
13	16831	16831	10155	10155	16831	255	25663	529
14	29745	29745	19867	19867	29745	293	54703	581
15	69383	69383	33891	33891	69383	333	116645	631

- **Comparison of Priority Rules**

Trains	Priority Rule Search									
	RPR		BCPR		ESPR		EFPR		MPTPR	
	Nodes	Unexplored	Nodes	Unexplored	Nodes	Unexplored	Nodes	Unexplored	Nodes	Unexplored
3	7	2	5	2	5	2	5	2	5	2
4	9	3	9	4	9	4	9	4	9	4
5	11	4	13	6	13	6	13	6	13	6
6	13	5	15	7	15	7	15	7	15	7
7	17	6	19	9	19	9	19	9	19	9
8	21	8	21	10	21	10	21	10	21	10
9	23	9	25	12	25	12	25	12	25	12
10	25	10	27	13	27	13	27	13	27	13
11	29	11	31	11	31	11	31	11	31	11
12	33	13	33	12	33	12	33	12	33	12

13	35	14	37	13	37	13	37	13	37	13
14	37	15	39	14	39	14	39	14	39	14
15	41	16	43	15	43	15	43	15	43	15

- Solution Quality of Priority Rules in Terms of Conflict Delay.



Appendix IV: Details of Actual Schedule

➢ Inbound Trains

Stations	Train 105	Train 327	Train 131	Train 11	Train 107	Train 101	Train 13	Train 23	Train 39	Train 45	Train 7	Train 103	Train 109	Train 1
Lalamusa jn		2:00	3:15	8:05		9:45	10:35	11:20	11:55	12:26	17:20	18:35		23:55
Lalamusa jn	2:13	2:25	3:20	8:10	8:38	9:47	10:40	11:25	11:57	12:28	17:22	18:37	19:40	23:58
Lalamusa Goods														
Lalamusa Goods	2:16	2:30	3:24	8:15	8:41	9:53	10:46	11:31	12:02	12:34	17:27	18:43	19:43	0:03
Chak Pirana														
Chak Pirana	2:19	2:35	3:28	8:18	8:44	9:56	10:49	11:34	12:05	12:37	17:30	18:46	19:46	0:06
Kharian Cantt		2:46					10:53							
Kharian Cantt	2:21	2:52	3:32	8:23	8:46	9:58	10:55	11:37	12:08	12:40	17:33	18:48	19:48	0:09
Kharian		2:59		8:27			11:03							
Kharian	2:24	3:01	3:38	8:33	8:49	10:01	11:09	11:40	12:11	12:43	17:39	18:51	19:51	0:12
Choa Kariala		3:11								12:53				
Choa Kariala	2:33	3:12	3:51	8:43	8:59	10:10	11:20	11:49	12:20	12:59	17:48	19:00	20:00	0:21
Sara e alamgeer		3:17		8:48										
Sara e alamgeer	2:37	3:18	4:00	8:54	9:03	10:14	11:24	11:53	12:24	13:05	17:52	19:08	20:04	0:25
Jhelum	2:41	3:25	4:04	9:00		10:20	11:28	11:56	12:28	13:09	17:56	19:13		0:30
Jhelum	2:43	3:35	4:10	9:12	9:06	10:22	11:30	11:58	12:30	13:11	17:58	19:16	20:07	0:32
Kala gujran		3:41				10:33			12:37					
Kala gujran	2:48	3:42	4:20	9:18	9:09	10:39	11:36	12:02	12:43	13:17	18:04	19:24	20:10	0:38
Kaluwal		3:53		9:25										
Kaluwal	2:54	3:59	4:30	9:31	9:15	10:47	11:42	12:08	12:50	13:23	18:10	19:30	20:16	0:44
Dina		4:06	4:40					12:12				19:34		
Dina	2:58	4:08	4:42	9:36	9:19	10:51	11:46	12:14	12:54	13:27	18:14	19:39	20:20	0:48

Ratial		4:16						12:21		13:35				
Ratial	3:03	4:17	4:50	9:41	9:24	10:56	11:51	12:27	12:59	13:41	18:19	19:46	20:25	0:53
Domeli		4:25												
Domeli	3:09	4:26	5:00	9:47	9:30	11:02	11:57	12:32	13:05	13:49	18:24	19:52	20:31	0:59
Bakrala		4:33					12:03							
Bakrala	3:15	4:34	5:08	9:55	9:36	11:08	12:09	12:37	13:11	13:55	18:30	19:58	20:37	1:10
Tarki		4:41		10:01					13:18					
Tarki	3:25	4:42	5:20	10:07	9:41	11:13	12:16	12:41	13:24	14:00	18:35	20:03	20:42	1:21
Sohawa		4:52												1:32
Sohawa	3:37	4:53	5:28	10:16	9:51	11:22	12:25	12:48	13:35	14:09	18:43	20:12	20:51	1:38
Missa Keswal		5:04				11:36					18:52			
Missa Keswal	3:47	5:05	5:37	10:24	10:01	11:42	12:34	12:58	13:49	14:18	18:58	20:22	21:00	1:49
Gujar Khan		5:20	5:52	10:32		11:53	12:43	13:09				20:33		
Gujar Khan	3:56	5:22	5:54	10:34	10:10	11:55	12:45	13:11	14:03	14:26	19:08	20:35	21:09	1:57
Ghungrila														
Ghungrila	4:01	5:30	6:07	10:39	10:15	12:03	12:53	13:18	14:08	14:31	19:18	20:43	21:14	2:02
Mandra Jn		5:40	6:21											
Mandra Jn	4:08	5:42	6:23	10:44	10:22	12:10	12:59	13:24	14:14	14:37	19:24	20:50	21:21	2:08
Kaliamawan			6:41											
Kaliamawan	4:14	5:55	6:47	10:49	10:28	12:17	13:09	13:31	14:20	14:43	19:30	20:56	21:27	2:14
Mankiala		6:09						13:36						2:22
Mankiala	4:18	6:10	6:58	10:52	10:32	12:21	13:19	13:42	14:24	14:47	19:34	21:00	21:31	2:28
Sihala		6:29	7:13	11:00			13:28							
Sihala	4:26	6:35	7:19	11:05	10:40	12:29	13:34	13:56	14:32	15:00	19:47	21:13	21:39	2:38
Chaklala		6:58	7:30			12:39	13:45							
Chaklala	4:35	7:03	7:32	11:15	10:51	12:41	13:47	14:12	14:48	15:14	20:01	21:27	21:48	2:47
Rawalpindi	4:45	7:20	7:45	11:25	11:00	12:50	13:55	14:25	15:00	15:25	20:20	21:40	22:00	2:55

Rawalpindi		8:00	11:50	11:10	14:20	14:45				3:20

➢ Inbound Trains Total Delays

Stations	Train 105	Train 327	Train 131	Train 11	Train 107	Train 101	Train 13	Train 23	Train 39	Train 45	Train 7	Train 103	Train 109	Train 1
Lalamusa jn	0	25	5	5	0	2	5	5	2	2	2	2	0	3
Lalamusa Goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chak Pirana	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kharian Cantt	0	6	0	6	0	0	2	0	0	0	0	0	0	0
Kharian	0	2	0	0	0	0	6	0	0	0	0	0	0	0
Choa Kariala	0	1	0	6	0	0	0	0	0	6	0	0	0	0
Sara e alamgeer	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Jhelum	2	1	6	12	0	2	2	2	2	2	2	3	0	2
Kala gujran	0	1	0	0	0	6	0	0	6	0	0	0	0	0
Kaluwal	0	6	0	6	0	0	0	0	0	0	0	0	0	0
Dina	0	2	2	0	0	0	0	2	0	0	0	5	0	0
Ratial	0	1	0	0	0	0	0	6	0	6	0	0	0	0
Domeli	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Bakrala	0	1	0	0	0	0	6	0	0	0	0	0	0	0
Tarki	0	1	0	6	0	0	0	0	6	0	0	0	0	0
Sohawa	0	1	0	0	0	0	0	0	0	0	0	0	0	6
Missa Keswal	0	1	0	0	0	6	0	0	0	0	6	0	0	0
Gujar Khan	0	2	2	2	0	2	2	2	0	0	0	2	0	0
Ghungrila	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mandra Jn	0	2	2	0	0	0	0	0	0	0	0	0	0	0
Kaliamawan	0	0	6	0	0	0	0	0	0	0	0	0	0	0
Mankiala	0	1	0	0	0	0	0	6	0	0	0	0	0	6
Sihala	0	6	6	5	5	0	6	0	0	0	0	0	0	0

Chaklala	0	5	2	0	0	2	2	0	0	0	0	0	0	0
Total	2	67	31	48	5	20	31	23	16	16	10	12	0	17

➢ Inbound Trains Conflict Delays

Stations	**Train 105**	**Train 327**	**Train 131**	**Train 11**	**Train 107**	**Train 101**	**Train 13**	**Train 23**	**Train 39**	**Train 45**	**Train 7**	**Train 103**	**Train 109**	**Train 1**
Lalamusa jn	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lalamusa Goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chak Pirana	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kharian Cantt	0	6	0	0	0	0	0	0	0	0	0	0	0	0
Kharian	0	0	0	6	0	0	6	0	0	0	0	0	0	0
Choa Kariala	0	0	0	0	0	0	0	0	0	6	0	0	0	0
Sara e alamgeer	0	0	0	6	0	0	0	0	0	0	0	0	0	0
Jhelum	0	0	0	12	0	0	0	0	0	0	0	3	0	0
Kala gujran	0	0	0	0	0	6	0	0	6	0	0	0	0	0
Kaluwal	0	6	0	6	0	0	0	0	0	0	0	0	0	0
Dina	0	0	0	0	0	0	0	0	0	0	0	6	0	0
Ratial	0	0	0	0	0	0	0	6	0	6	0	0	0	0
Domeli	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bakrala	0	0	0	0	0	0	6	0	0	0	0	0	0	0
Tarki	0	0	0	6	0	0	0	0	6	0	0	0	0	0
Sohawa	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Missa Keswal	0	0	0	0	0	6	0	0	0	0	6	0	0	0
Gujar Khan	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ghungrila	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mandra Jn	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kaliamawan	0	0	6	0	0	0	0	0	0	0	0	0	0	0

Mankiala	0	0	0	0	0	0	0	6	0	0	0	0	0	6
Sihala	0	6	6	5	0	0	6	0	0	0	0	0	0	0
Chaklala	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Rawalpindi	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	18	12	41	5	12	18	12	12	12	6	9	0	12

➢ Outbound Trains

Stations	Train 106	Train 2	Train 46	Train 110	Train 110	Train 104	Train 8	Train 40	Train 24	Train 14	Train 132	Train 102	Train 12	Train 108	Train 328
Lalamusa jn		5:00	9:03		9:26	10:37	11:28	13:25	14:52	16:05	19:05	19:42	20:20	20:27	0:00
Lalamusa jn	3:02	4:55	9:01			10:32	11:23	13:23	14:50	16:03	19:00	19:37	20:15		23:55
Lalamusa Goods		4:46	8:54		9:20	10:22	11:19	13:18	14:42	15:59	18:55	19:32	20:05	20:21	23:50
Lalamusa Goods	2:54														
Chak Pirana		4:38	8:47		9:17	10:16	11:12	13:13	14:34	15:52	18:49	19:23	19:49	20:18	23:45
Chak Pirana	2:51		8:41								18:43		19:43		
Kharian Cantt		4:30	8:35		9:15	10:11	11:09	13:08	14:26	15:45	18:36	19:16	19:38	20:16	23:40
Kharian Cantt	2:49														23:35
Kharian		4:27	8:30		9:12	10:04	11:06	13:05	14:23	15:38	18:27	19:13	19:35	20:13	23:27
Kharian	2:46					9:58									23:25
Choa Kariala	2:36	4:18	8:21		9:02	9:48	10:52	12:56	14:14	15:29	18:14	19:03	19:25	20:03	23:14
Choa Kariala	2:30				8:56							18:57		19:57	23:13
Sara e alamgeer		4:14	8:17		8:52	9:44	10:48	12:52	14:10	15:25	18:05	18:48	19:21	19:53	23:07
Sara e alamgeer	2:22														23:06
Jhelum		4:09	8:12		8:49	9:40	10:43	12:47	14:05	15:20	18:00	18:39	19:16	19:50	23:00
Jhelum	2:19	4:07	8:10			9:38	10:41	12:45	14:03	15:18	17:54	18:37	19:13		22:50
Kala gujran		4:02	8:04		8:46	9:34	10:36	12:40	13:58	15:13	17:46	18:30	19:09	19:47	22:41
Kala gujran	2:16														22:40
Kaluwal		3:56	7:58		8:40	9:28	10:30	12:34	13:52	15:07	17:36	18:23	19:03	19:41	22:31
Kaluwal	2:10														22:30
Dina		3:52	7:54		8:36	9:22	10:26	12:30	13:46	15:03	17:30	18:17	18:59	19:37	22:23
Dina	2:06					9:16			13:44		17:28	18:11			22:21

Ratial		3:47	7:49	8:31	9:09	10:21	12:25	13:38	14:58	17:21	18:06	18:54	19:31	22:13
Ratial	2:01													22:12
Domeli		3:41	7:43	8:25	9:03	10:15	12:16	13:32	14:52	17:14	18:00	18:48	19:25	22:04
Domeli	1:55													22:03
Bakrala		3:35	7:37	8:19	8:57	10:09	12:06	13:26	14:46	17:08	17:54	18:42	19:19	21:55
Bakrala	1:49													21:54
Tarki		3:28	7:27	8:14	8:52	10:04	11:57	13:21	14:41	17:03	17:49	18:37	19:14	21:47
Tarki	1:44	3:22										18:32		21:46
Sohawa		3:11	7:18	8:05	8:43	9:54	11:48	13:12	14:32	16:55	17:40	18:23	19:05	21:36
Sohawa	1:35					9:48								21:35
Missa Keswal		2:58	7:09	7:55	8:33	9:38	11:39	13:01	14:21	16:46	17:30	18:14	18:55	21:24
Missa Keswal	1:25							12:55	14:15					21:23
Gujar Khan		2:46	7:01	7:46	8:23	9:30	11:31	12:46	14:05	16:36	17:21	18:04	18:46	21:12
Gujar Khan	1:16				8:21			12:40	14:00	16:34		18:02		21:06
Ghungrila		2:41	6:56	7:41	8:15	9:25	11:26	12:32	13:55	16:27	17:16	17:56	18:41	21:00
Ghungrila	1:11													
Mandra Jn		2:35	6:50	7:34	8:08	9:19	11:20	12:26	13:49	16:17	17:09	17:50	18:34	20:52
Mandra Jn	1:04									16:15				20:47
Kaliamawan		2:29	6:44	7:28	8:02	9:13	11:14	12:19	13:43	16:06	17:03	17:44	18:28	20:36
Kaliamawan	0:58							12:14						
Mankiala		2:25	6:40	7:24	7:58	9:09	11:10	12:10	13:39	16:01	16:59	17:40	18:24	20:29
Mankiala	0:54													20:28
Sihala		2:17	6:32	7:16	7:50	9:01	11:02	12:02	13:31	15:52	16:51	17:32	18:16	20:17
Sihala	0:46													20:16
Chaklala		2:08	6:23	7:07	7:40	8:52	10:53	11:53	13:21	15:39	16:40	17:23	18:07	20:03
Chaklala	0:37				7:38				13:19	15:37	16:38			19:58

Rawalpindi		2:00	6:15	7:00	7:30	8:45	10:45	11:45	13:10	15:30	16:30	17:15	18:00	19:45
Rawalpindi	0:30	1:35						11:25	12:50			16:45	17:40	19:05

➢ Outbound Trains Total Delays

Stations	Train 106	Train 2	Train 46	Train 110	Train 104	Train 8	Train 40	Train 24	Train14	Train 132	Train 102	Train 12	Train 108	Train 328
Lalamusa jn	0	5	2	0	5	5	2	2	2	5	5	5	0	15
Lalamusa Goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chak Pirana	0	0	6	0	0	0	0	0	0	6	0	6	0	0
Kharian Cantt	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Kharian	0	0	0	0	6	0	0	0	0	0	0	0	0	2
Choa Kariala	6	0	0	6	0	0	0	0	0	0	6	0	6	1
Sara e alamgeer	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Jhelum	0	0	2	0	2	2	2	0	2	6	2	3	0	10
Kala gujran	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Kaluwal	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Dina	0	0	0	0	6	0	0	2	0	2	6	0	0	2
Ratial	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Domeli	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Bakrala	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Tarki	0	6	0	0	0	0	0	0	0	0	0	5	0	1
Sohawa	0	0	0	0	0	6	0	0	0	0	0	0	0	1
Missa Keswal	0	0	0	0	0	0	0	6	6	0	0	0	0	1
Gujar Khan	0	0	0	0	2	0	0	6	5	2	0	0	0	6
Ghungrila	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mandra Jn	0	0	0	0	0	0	0	0	0	2	0	0	0	5
Kaliamawan	0	0	0	0	0	0	0	5	0	0	0	0	0	0

Mankiala	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sihala	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Chaklala	0	0	0	0	2	0	0	0	2	2	2	0	0	5
Total	6	11	10	6	23	13	4	21	17	25	21	19	6	62

➢ **Outbound Trains Conflict Delays**

Stations	Train 106	Train 2	Train 46	Train 110	Train 104	Train 8	Train 40	Train 24	Train14	Train 132	Train 102	Train 12	Train 108	Train 328
Lalamusa jn	0	0	0	0	5	0	0	0	0	0	5	0	0	0
Lalamusa Goods	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chak Pirana	0	0	6	0	0	0	0	0	0	6	0	6	0	0
Kharian Cantt	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kharian	0	0	0	0	6	0	0	0	0	0	0	0	0	0
Choa Kariala	6	0	0	6	0	0	0	0	0	0	6	0	6	0
Sara e alamgeer	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jhelum	0	0	0	0	0	0	0	0	0	6	0	3	0	0
Kala gujran	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kaluwal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dina	0	0	0	0	6	0	0	0	0	0	6	0	0	0
Ratial	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Domeli	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bakrala	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tarki	0	6	0	0	0	0	0	0	0	0	0	5	0	0
Sohawa	0	0	0	0	0	6	0	0	0	0	0	0	0	0
Missa Keswal	0	0	0	0	0	0	0	6	6	0	0	0	0	0
Gujar Khan	0	0	0	0	0	0	0	6	5	0	0	0	0	6
Ghungrila	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Mandra Jn	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Kaliamawan	0	0	0	0	0	0	0	5	0	0	0	0	0	0
Mankiala	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sihala	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chaklala	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rawalpindi	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	6	6	6	6	17	6	0	17	11	12	17	14	6	11

Appendix V: Details of Computer Output

- **Software Output for ESPR, EFPR, MPTPR**

Section #	Train#	Start Time (minutes)	End Time (minutes)
Section 0	Train0	154	160
Section 0	Train1	30	36
Section 0	Train2	120	126
Section 0	Train3	282	288
Section 0	Train4	309	315
Section 0	Train5	331	337
Section 0	Train6	375	381
Section 0	Train7	420	426
Section 0	Train8	450	456
Section 0	Train9	654	660
Section 0	Train10	665	671
Section 0	Train11	525	531
Section 0	Train12	730	736
Section 0	Train13	779	785
Section 0	Train14	645	651
Section 0	Train15	823	829
Section 0	Train16	705	711
Section 0	Train17	859	865
Section 0	Train18	889	895
Section 0	Train19	790	796
Section 0	Train20	930	936
Section 0	Train21	990	996
Section 0	Train22	1035	1041
Section 0	Train23	1194	1200
Section 0	Train24	1080	1086
Section 0	Train25	1285	1291
Section 0	Train26	1331	1337
Section 0	Train27	1185	1191
Section 1	Train0	142	154
Section 1	Train1	36	45
Section 1	Train2	128	140
Section 1	Train3	270	282
Section 1	Train4	297	309
Section 1	Train5	322	331
Section 1	Train6	381	393
Section 1	Train7	426	438
Section 1	Train8	456	465
Section 1	Train9	642	654
Section 1	Train10	656	665
Section 1	Train11	531	543
Section 1	Train12	721	730
Section 1	Train13	770	779
Section 1	Train14	662	671
Section 1	Train15	814	823
Section 1	Train16	711	720
Section 1	Train17	850	859
Section 1	Train18	880	889
Section 1	Train19	796	808
Section 1	Train20	936	948
Section 1	Train21	996	1005
Section 1	Train22	1041	1050
Section 1	Train23	1182	1194
Section 1	Train24	1086	1098
Section 1	Train25	1273	1285
Section 1	Train26	1319	1331
Section 1	Train27	1196	1205
Section 2	Train0	128	137
Section 2	Train1	45	53
Section 2	Train2	140	149
Section 2	Train3	261	270
Section 2	Train4	288	297
Section 2	Train5	314	322
Section 2	Train6	393	402
Section 2	Train7	438	447
Section 2	Train8	465	473
Section 2	Train9	631	640
Section 2	Train10	645	653
Section 2	Train11	543	552
Section 2	Train12	708	716
Section 2	Train13	762	770
Section 2	Train14	671	679
Section 2	Train15	806	814
Section 2	Train16	720	728
Section 2	Train17	842	850

Section 2	Train18	872	880
Section 2	Train19	818	827
Section 2	Train20	948	957
Section 2	Train21	1005	1013
Section 2	Train22	1050	1058
Section 2	Train23	1172	1181
Section 2	Train24	1098	1107
Section 2	Train25	1264	1273
Section 2	Train26	1310	1319
Section 2	Train27	1205	1213
Section 3	Train0	120	128
Section 3	Train1	53	57
Section 3	Train2	149	157
Section 3	Train3	253	261
Section 3	Train4	280	288
Section 3	Train5	310	314
Section 3	Train6	402	410
Section 3	Train7	447	455
Section 3	Train8	473	477
Section 3	Train9	623	631
Section 3	Train10	641	645
Section 3	Train11	552	560
Section 3	Train12	704	708
Section 3	Train13	758	762
Section 3	Train14	679	683
Section 3	Train15	802	806
Section 3	Train16	728	732

Section 3	Train17	838	842
Section 3	Train18	868	872
Section 3	Train19	827	835
Section 3	Train20	957	965
Section 3	Train21	1013	1017
Section 3	Train22	1058	1062
Section 3	Train23	1164	1172
Section 3	Train24	1107	1115
Section 3	Train25	1256	1264
Section 3	Train26	1302	1310
Section 3	Train27	1213	1217
Section 4	Train0	113	120
Section 4	Train1	57	63
Section 4	Train2	157	164
Section 4	Train3	246	253
Section 4	Train4	273	280
Section 4	Train5	304	310
Section 4	Train6	410	417
Section 4	Train7	455	462
Section 4	Train8	477	483
Section 4	Train9	616	623
Section 4	Train10	635	641
Section 4	Train11	560	567
Section 4	Train12	698	704
Section 4	Train13	752	758
Section 4	Train14	683	689
Section 4	Train15	796	802

Section 4	Train16	732	738
Section 4	Train17	832	838
Section 4	Train18	862	868
Section 4	Train19	840	847
Section 4	Train20	965	972
Section 4	Train21	1017	1023
Section 4	Train22	1062	1068
Section 4	Train23	1157	1164
Section 4	Train24	1115	1122
Section 4	Train25	1249	1256
Section 4	Train26	1295	1302
Section 4	Train27	1217	1223
Section 5	Train0	106	113
Section 5	Train1	63	69
Section 5	Train2	164	171
Section 5	Train3	239	246
Section 5	Train4	266	273
Section 5	Train5	298	304
Section 5	Train6	417	424
Section 5	Train7	462	469
Section 5	Train8	483	489
Section 5	Train9	609	616
Section 5	Train10	629	635
Section 5	Train11	567	574
Section 5	Train12	692	698
Section 5	Train13	746	752
Section 5	Train14	696	702

Section 5	Train15	790	796
Section 5	Train16	738	744
Section 5	Train17	824	830
Section 5	Train18	856	862
Section 5	Train19	847	854
Section 5	Train20	972	979
Section 5	Train21	1023	1029
Section 5	Train22	1068	1074
Section 5	Train23	1150	1157
Section 5	Train24	1122	1129
Section 5	Train25	1242	1249
Section 5	Train26	1288	1295
Section 5	Train27	1223	1229
Section 6	Train0	100	106
Section 6	Train1	69	74
Section 6	Train2	171	177
Section 6	Train3	233	239
Section 6	Train4	260	266
Section 6	Train5	293	298
Section 6	Train6	424	430
Section 6	Train7	469	475
Section 6	Train8	489	494
Section 6	Train9	603	609
Section 6	Train10	624	629
Section 6	Train11	574	580
Section 6	Train12	687	692
Section 6	Train13	735	740
Section 6	Train14	702	707
Section 6	Train15	785	790
Section 6	Train16	744	749
Section 6	Train17	819	824
Section 6	Train18	844	849
Section 6	Train19	854	860
Section 6	Train20	979	985
Section 6	Train21	1029	1034
Section 6	Train22	1074	1079
Section 6	Train23	1144	1150
Section 6	Train24	1129	1135
Section 6	Train25	1236	1242
Section 6	Train26	1282	1288
Section 6	Train27	1229	1234
Section 7	Train0	91	100
Section 7	Train1	74	82
Section 7	Train2	177	186
Section 7	Train3	224	233
Section 7	Train4	251	260
Section 7	Train5	285	293
Section 7	Train6	430	439
Section 7	Train7	475	484
Section 7	Train8	494	502
Section 7	Train9	594	603
Section 7	Train10	616	624
Section 7	Train11	580	589
Section 7	Train12	679	687
Section 7	Train13	727	735
Section 7	Train14	707	715
Section 7	Train15	777	785
Section 7	Train16	749	757
Section 7	Train17	811	819
Section 7	Train18	836	844
Section 7	Train19	860	869
Section 7	Train20	985	994
Section 7	Train21	1034	1042
Section 7	Train22	1079	1087
Section 7	Train23	1135	1144
Section 7	Train24	1146	1155
Section 7	Train25	1227	1236
Section 7	Train26	1273	1282
Section 7	Train27	1239	1247
Section 8	Train0	82	91
Section 8	Train1	93	102
Section 8	Train2	186	195
Section 8	Train3	215	224
Section 8	Train4	242	251
Section 8	Train5	276	285
Section 8	Train6	439	448
Section 8	Train7	484	493
Section 8	Train8	502	511
Section 8	Train9	585	594
Section 8	Train10	607	616
Section 8	Train11	596	605

Section 8	Train12	670	679
Section 8	Train13	718	727
Section 8	Train14	724	733
Section 8	Train15	768	777
Section 8	Train16	757	766
Section 8	Train17	802	811
Section 8	Train18	827	836
Section 8	Train19	869	878
Section 8	Train20	994	1003
Section 8	Train21	1042	1051
Section 8	Train22	1087	1096
Section 8	Train23	1126	1135
Section 8	Train24	1155	1164
Section 8	Train25	1216	1225
Section 8	Train26	1264	1273
Section 8	Train27	1247	1256
Section 9	Train0	74	82
Section 9	Train1	102	111
Section 9	Train2	195	203
Section 9	Train3	207	215
Section 9	Train4	234	242
Section 9	Train5	267	276
Section 9	Train6	448	456
Section 9	Train7	493	501
Section 9	Train8	511	520
Section 9	Train9	577	585
Section 9	Train10	591	600

Section 9	Train11	605	613
Section 9	Train12	661	670
Section 9	Train13	709	718
Section 9	Train14	733	742
Section 9	Train15	759	768
Section 9	Train16	772	781
Section 9	Train17	793	802
Section 9	Train18	818	827
Section 9	Train19	878	886
Section 9	Train20	1003	1011
Section 9	Train21	1051	1060
Section 9	Train22	1096	1105
Section 9	Train23	1118	1126
Section 9	Train24	1164	1172
Section 9	Train25	1208	1216
Section 9	Train26	1256	1264
Section 9	Train27	1266	1275
Section 10	Train0	69	74
Section 10	Train1	111	116
Section 10	Train2	209	214
Section 10	Train3	202	207
Section 10	Train4	229	234
Section 10	Train5	262	267
Section 10	Train6	456	461
Section 10	Train7	501	506
Section 10	Train8	520	525
Section 10	Train9	572	577

Section 10	Train10	586	591
Section 10	Train11	613	618
Section 10	Train12	656	661
Section 10	Train13	704	709
Section 10	Train14	744	749
Section 10	Train15	754	759
Section 10	Train16	781	786
Section 10	Train17	788	793
Section 10	Train18	813	818
Section 10	Train19	886	891
Section 10	Train20	1011	1016
Section 10	Train21	1060	1065
Section 10	Train22	1105	1110
Section 10	Train23	1113	1118
Section 10	Train24	1172	1177
Section 10	Train25	1203	1208
Section 10	Train26	1251	1256
Section 10	Train27	1275	1280
Section 11	Train0	63	69
Section 11	Train1	116	122
Section 11	Train2	215	221
Section 11	Train3	196	202
Section 11	Train4	223	229
Section 11	Train5	256	262
Section 11	Train6	461	467
Section 11	Train7	506	512
Section 11	Train8	525	531

Section 11	Train9	566	572
Section 11	Train10	580	586
Section 11	Train11	618	624
Section 11	Train12	650	656
Section 11	Train13	698	704
Section 11	Train14	749	755
Section 11	Train15	743	749
Section 11	Train16	786	792
Section 11	Train17	775	781
Section 11	Train18	807	813
Section 11	Train19	891	897
Section 11	Train20	1016	1022
Section 11	Train21	1065	1071
Section 11	Train22	1115	1121
Section 11	Train23	1107	1113
Section 11	Train24	1177	1183
Section 11	Train25	1197	1203
Section 11	Train26	1245	1251
Section 11	Train27	1280	1286
Section 12	Train0	57	63
Section 12	Train1	122	128
Section 12	Train2	221	227
Section 12	Train3	190	196
Section 12	Train4	212	218
Section 12	Train5	250	256
Section 12	Train6	467	473
Section 12	Train7	512	518

Section 12	Train8	531	537
Section 12	Train9	560	566
Section 12	Train10	574	580
Section 12	Train11	624	630
Section 12	Train12	644	650
Section 12	Train13	692	698
Section 12	Train14	756	762
Section 12	Train15	737	743
Section 12	Train16	792	798
Section 12	Train17	769	775
Section 12	Train18	801	807
Section 12	Train19	897	903
Section 12	Train20	1022	1028
Section 12	Train21	1071	1077
Section 12	Train22	1121	1127
Section 12	Train23	1100	1106
Section 12	Train24	1184	1190
Section 12	Train25	1191	1197
Section 12	Train26	1239	1245
Section 12	Train27	1286	1292
Section 13	Train0	51	57
Section 13	Train1	128	133
Section 13	Train2	227	233
Section 13	Train3	184	190
Section 13	Train4	206	212
Section 13	Train5	245	250
Section 13	Train6	473	479

Section 13	Train7	518	524
Section 13	Train8	537	542
Section 13	Train9	554	560
Section 13	Train10	569	574
Section 13	Train11	632	638
Section 13	Train12	639	644
Section 13	Train13	687	692
Section 13	Train14	762	767
Section 13	Train15	732	737
Section 13	Train16	803	808
Section 13	Train17	759	764
Section 13	Train18	796	801
Section 13	Train19	903	909
Section 13	Train20	1028	1034
Section 13	Train21	1077	1082
Section 13	Train22	1127	1132
Section 13	Train23	1094	1100
Section 13	Train24	1190	1196
Section 13	Train25	1180	1186
Section 13	Train26	1233	1239
Section 13	Train27	1292	1297
Section 14	Train0	46	51
Section 14	Train1	133	137
Section 14	Train2	233	238
Section 14	Train3	179	184
Section 14	Train4	201	206
Section 14	Train5	241	245

Section 14	Train6	479	484
Section 14	Train7	524	529
Section 14	Train8	542	546
Section 14	Train9	549	554
Section 14	Train10	565	569
Section 14	Train11	638	643
Section 14	Train12	630	634
Section 14	Train13	683	687
Section 14	Train14	767	771
Section 14	Train15	728	732
Section 14	Train16	808	812
Section 14	Train17	755	759
Section 14	Train18	791	795
Section 14	Train19	909	914
Section 14	Train20	1034	1039
Section 14	Train21	1082	1086
Section 14	Train22	1132	1136
Section 14	Train23	1089	1094
Section 14	Train24	1196	1201
Section 14	Train25	1175	1180
Section 14	Train26	1228	1233
Section 14	Train27	1297	1301
Section 15	Train0	39	46
Section 15	Train1	137	143
Section 15	Train2	243	250
Section 15	Train3	172	179
Section 15	Train4	194	201

Section 15	Train5	235	241
Section 15	Train6	484	491
Section 15	Train7	529	536
Section 15	Train8	551	557
Section 15	Train9	542	549
Section 15	Train10	559	565
Section 15	Train11	643	650
Section 15	Train12	624	630
Section 15	Train13	677	683
Section 15	Train14	772	778
Section 15	Train15	722	728
Section 15	Train16	812	818
Section 15	Train17	749	755
Section 15	Train18	785	791
Section 15	Train19	914	921
Section 15	Train20	1039	1046
Section 15	Train21	1091	1097
Section 15	Train22	1136	1142
Section 15	Train23	1082	1089
Section 15	Train24	1201	1208
Section 15	Train25	1168	1175
Section 15	Train26	1221	1228
Section 15	Train27	1301	1307
Section 16	Train0	34	39
Section 16	Train1	143	147
Section 16	Train2	250	255
Section 16	Train3	167	172

Section 16	Train4	189	194
Section 16	Train5	228	232
Section 16	Train6	491	496
Section 16	Train7	541	546
Section 16	Train8	557	561
Section 16	Train9	534	539
Section 16	Train10	549	553
Section 16	Train11	650	655
Section 16	Train12	620	624
Section 16	Train13	673	677
Section 16	Train14	778	782
Section 16	Train15	718	722
Section 16	Train16	818	822
Section 16	Train17	745	749
Section 16	Train18	776	780
Section 16	Train19	921	926
Section 16	Train20	1046	1051
Section 16	Train21	1097	1101
Section 16	Train22	1142	1146
Section 16	Train23	1076	1081
Section 16	Train24	1208	1213
Section 16	Train25	1163	1168
Section 16	Train26	1216	1221
Section 16	Train27	1307	1311
Section 17	Train0	30	34
Section 17	Train1	147	150
Section 17	Train2	255	259

Section 17	Train3	163	167
Section 17	Train4	185	189
Section 17	Train5	225	228
Section 17	Train6	496	500
Section 17	Train7	551	555
Section 17	Train8	561	564
Section 17	Train9	528	532
Section 17	Train10	546	549
Section 17	Train11	655	659
Section 17	Train12	617	620
Section 17	Train13	670	673
Section 17	Train14	782	785
Section 17	Train15	715	718
Section 17	Train16	822	825
Section 17	Train17	742	745
Section 17	Train18	773	776
Section 17	Train19	926	930
Section 17	Train20	1051	1055
Section 17	Train21	1101	1104
Section 17	Train22	1146	1149
Section 17	Train23	1072	1076
Section 17	Train24	1218	1222
Section 17	Train25	1159	1163
Section 17	Train26	1212	1216
Section 17	Train27	1311	1314
Section 18	Train0	26	30
Section 18	Train1	150	154

Section 18	Train2	259	263
Section 18	Train3	159	163
Section 18	Train4	181	185
Section 18	Train5	221	225
Section 18	Train6	500	504
Section 18	Train7	555	559
Section 18	Train8	564	568
Section 18	Train9	524	528
Section 18	Train10	540	544
Section 18	Train11	660	664
Section 18	Train12	613	617
Section 18	Train13	666	670
Section 18	Train14	785	789
Section 18	Train15	711	715
Section 18	Train16	825	829
Section 18	Train17	738	742
Section 18	Train18	769	773
Section 18	Train19	930	934
Section 18	Train20	1055	1059
Section 18	Train21	1104	1108
Section 18	Train22	1150	1154
Section 18	Train23	1068	1072
Section 18	Train24	1222	1226
Section 18	Train25	1155	1159
Section 18	Train26	1206	1210
Section 18	Train27	1314	1318
Section 19	Train0	17	26

Section 19	Train1	161	170
Section 19	Train2	263	272
Section 19	Train3	150	159
Section 19	Train4	172	181
Section 19	Train5	212	221
Section 19	Train6	504	513
Section 19	Train7	559	568
Section 19	Train8	570	579
Section 19	Train9	515	524
Section 19	Train10	531	540
Section 19	Train11	664	673
Section 19	Train12	604	613
Section 19	Train13	652	661
Section 19	Train14	789	798
Section 19	Train15	702	711
Section 19	Train16	829	838
Section 19	Train17	729	738
Section 19	Train18	760	769
Section 19	Train19	934	943
Section 19	Train20	1070	1079
Section 19	Train21	1108	1117
Section 19	Train22	1154	1163
Section 19	Train23	1059	1068
Section 19	Train24	1226	1235
Section 19	Train25	1141	1150
Section 19	Train26	1197	1206
Section 19	Train27	1318	1327

Section 20	Train0	12	17
Section 20	Train1	170	173
Section 20	Train2	272	277
Section 20	Train3	145	150
Section 20	Train4	157	162
Section 20	Train5	209	212
Section 20	Train6	513	518
Section 20	Train7	568	573
Section 20	Train8	579	582
Section 20	Train9	502	507
Section 20	Train10	528	531
Section 20	Train11	673	678
Section 20	Train12	601	604
Section 20	Train13	649	652
Section 20	Train14	798	801
Section 20	Train15	699	702
Section 20	Train16	838	841
Section 20	Train17	726	729
Section 20	Train18	757	760
Section 20	Train19	943	948
Section 20	Train20	1079	1084
Section 20	Train21	1117	1120
Section 20	Train22	1163	1166
Section 20	Train23	1054	1059
Section 20	Train24	1235	1240
Section 20	Train25	1136	1141
Section 20	Train26	1192	1197

Section 20	Train27	1327	1330
Section 21	Train0	8	12
Section 21	Train1	173	176
Section 21	Train2	277	281
Section 21	Train3	141	145
Section 21	Train4	153	157
Section 21	Train5	206	209
Section 21	Train6	518	522
Section 21	Train7	573	577
Section 21	Train8	582	585
Section 21	Train9	498	502
Section 21	Train10	525	528
Section 21	Train11	678	682
Section 21	Train12	598	601
Section 21	Train13	646	649
Section 21	Train14	801	804
Section 21	Train15	696	699
Section 21	Train16	841	844
Section 21	Train17	723	726
Section 21	Train18	754	757
Section 21	Train19	948	952
Section 21	Train20	1084	1088
Section 21	Train21	1120	1123
Section 21	Train22	1166	1169
Section 21	Train23	1050	1054
Section 21	Train24	1240	1244
Section 21	Train25	1132	1136

Section 21	Train26	1188	1192
Section 21	Train27	1330	1333
Section 22	Train0	3	8
Section 22	Train1	176	179
Section 22	Train2	281	286
Section 22	Train3	136	141
Section 22	Train4	148	153
Section 22	Train5	203	206
Section 22	Train6	527	532
Section 22	Train7	577	582
Section 22	Train8	585	588
Section 22	Train9	493	498
Section 22	Train10	522	525
Section 22	Train11	682	687
Section 22	Train12	595	598
Section 22	Train13	643	646
Section 22	Train14	804	807
Section 22	Train15	693	696
Section 22	Train16	844	847
Section 22	Train17	720	723
Section 22	Train18	751	754
Section 22	Train19	952	957
Section 22	Train20	1088	1093
Section 22	Train21	1123	1126
Section 22	Train22	1169	1172
Section 22	Train23	1045	1050
Section 22	Train24	1244	1249

Section 22	Train25	1127	1132
Section 22	Train26	1183	1188
Section 22	Train27	1333	1336
Section 23	Train0	0	3
Section 23	Train1	179	182
Section 23	Train2	286	289
Section 23	Train3	133	136
Section 23	Train4	145	148
Section 23	Train5	200	203
Section 23	Train6	532	535
Section 23	Train7	582	585
Section 23	Train8	588	591
Section 23	Train9	490	493
Section 23	Train10	518	521
Section 23	Train11	687	690
Section 23	Train12	592	595
Section 23	Train13	640	643
Section 23	Train14	807	810
Section 23	Train15	690	693
Section 23	Train16	847	850
Section 23	Train17	717	720
Section 23	Train18	748	751
Section 23	Train19	957	960
Section 23	Train20	1093	1096
Section 23	Train21	1126	1129
Section 23	Train22	1172	1175
Section 23	Train23	1042	1045
Section 23	Train24	1249	1252
Section 23	Train25	1117	1120
Section 23	Train26	1180	1183
Section 23	Train27	1336	1339

- **Software Output for BCPR**

Section #	Train#	Start Time (minutes)	End Time (minutes)
Section 0	Train0	154	160
Section 0	Train1	30	36
Section 0	Train2	120	126
Section 0	Train3	282	288
Section 0	Train4	309	315
Section 0	Train5	331	337
Section 0	Train6	375	381
Section 0	Train7	420	426
Section 0	Train8	450	456
Section 0	Train9	654	660
Section 0	Train10	665	671
Section 0	Train11	525	531
Section 0	Train12	730	736
Section 0	Train13	779	785
Section 0	Train14	645	651
Section 0	Train15	823	829
Section 0	Train16	705	711
Section 0	Train17	859	865
Section 0	Train18	889	895
Section 0	Train19	790	796
Section 0	Train20	930	936
Section 0	Train21	990	996
Section 0	Train22	1035	1041
Section 0	Train23	1194	1200
Section 0	Train24	1080	1086
Section 0	Train25	1275	1281
Section 0	Train26	1342	1348
Section 0	Train27	1185	1191
Section 1	Train0	142	154
Section 1	Train1	36	45
Section 1	Train2	128	140
Section 1	Train3	270	282
Section 1	Train4	297	309
Section 1	Train5	322	331
Section 1	Train6	381	393
Section 1	Train7	426	438
Section 1	Train8	456	465
Section 1	Train9	642	654
Section 1	Train10	656	665
Section 1	Train11	531	543
Section 1	Train12	721	730
Section 1	Train13	770	779
Section 1	Train14	662	671
Section 1	Train15	814	823
Section 1	Train16	711	720
Section 1	Train17	850	859
Section 1	Train18	880	889
Section 1	Train19	796	808
Section 1	Train20	936	948
Section 1	Train21	996	1005
Section 1	Train22	1041	1050
Section 1	Train23	1182	1194
Section 1	Train24	1086	1098
Section 1	Train25	1263	1275
Section 1	Train26	1330	1342
Section 1	Train27	1196	1205
Section 2	Train0	128	137
Section 2	Train1	45	53
Section 2	Train2	140	149
Section 2	Train3	261	270
Section 2	Train4	288	297
Section 2	Train5	314	322
Section 2	Train6	393	402
Section 2	Train7	438	447
Section 2	Train8	465	473
Section 2	Train9	631	640
Section 2	Train10	645	653
Section 2	Train11	543	552
Section 2	Train12	708	716
Section 2	Train13	762	770
Section 2	Train14	671	679
Section 2	Train15	806	814
Section 2	Train16	720	728
Section 2	Train17	842	850
Section 2	Train18	872	880
Section 2	Train19	818	827
Section 2	Train20	948	957

Section 2	Train21	1005	1013
Section 2	Train22	1050	1058
Section 2	Train23	1172	1181
Section 2	Train24	1098	1107
Section 2	Train25	1254	1263
Section 2	Train26	1321	1330
Section 2	Train27	1205	1213
Section 3	Train0	120	128
Section 3	Train1	53	57
Section 3	Train2	149	157
Section 3	Train3	253	261
Section 3	Train4	280	288
Section 3	Train5	310	314
Section 3	Train6	402	410
Section 3	Train7	447	455
Section 3	Train8	473	477
Section 3	Train9	623	631
Section 3	Train10	641	645
Section 3	Train11	552	560
Section 3	Train12	704	708
Section 3	Train13	758	762
Section 3	Train14	679	683
Section 3	Train15	802	806
Section 3	Train16	728	732
Section 3	Train17	838	842
Section 3	Train18	868	872
Section 3	Train19	827	835

Section 3	Train20	957	965
Section 3	Train21	1013	1017
Section 3	Train22	1058	1062
Section 3	Train23	1164	1172
Section 3	Train24	1107	1115
Section 3	Train25	1246	1254
Section 3	Train26	1313	1321
Section 3	Train27	1213	1217
Section 4	Train0	113	120
Section 4	Train1	57	63
Section 4	Train2	157	164
Section 4	Train3	246	253
Section 4	Train4	273	280
Section 4	Train5	304	310
Section 4	Train6	410	417
Section 4	Train7	455	462
Section 4	Train8	477	483
Section 4	Train9	616	623
Section 4	Train10	635	641
Section 4	Train11	560	567
Section 4	Train12	698	704
Section 4	Train13	752	758
Section 4	Train14	683	689
Section 4	Train15	796	802
Section 4	Train16	732	738
Section 4	Train17	832	838
Section 4	Train18	862	868

Section 4	Train19	840	847
Section 4	Train20	965	972
Section 4	Train21	1017	1023
Section 4	Train22	1062	1068
Section 4	Train23	1157	1164
Section 4	Train24	1115	1122
Section 4	Train25	1239	1246
Section 4	Train26	1306	1313
Section 4	Train27	1217	1223
Section 5	Train0	106	113
Section 5	Train1	63	69
Section 5	Train2	164	171
Section 5	Train3	239	246
Section 5	Train4	266	273
Section 5	Train5	298	304
Section 5	Train6	417	424
Section 5	Train7	462	469
Section 5	Train8	483	489
Section 5	Train9	609	616
Section 5	Train10	629	635
Section 5	Train11	567	574
Section 5	Train12	692	698
Section 5	Train13	746	752
Section 5	Train14	696	702
Section 5	Train15	790	796
Section 5	Train16	738	744
Section 5	Train17	824	830

Section 5	Train18	856	862
Section 5	Train19	847	854
Section 5	Train20	972	979
Section 5	Train21	1023	1029
Section 5	Train22	1068	1074
Section 5	Train23	1150	1157
Section 5	Train24	1122	1129
Section 5	Train25	1232	1239
Section 5	Train26	1299	1306
Section 5	Train27	1223	1229
Section 6	Train0	100	106
Section 6	Train1	69	74
Section 6	Train2	171	177
Section 6	Train3	233	239
Section 6	Train4	260	266
Section 6	Train5	293	298
Section 6	Train6	424	430
Section 6	Train7	469	475
Section 6	Train8	489	494
Section 6	Train9	603	609
Section 6	Train10	624	629
Section 6	Train11	574	580
Section 6	Train12	687	692
Section 6	Train13	735	740
Section 6	Train14	702	707
Section 6	Train15	785	790
Section 6	Train16	744	749

Section 6	Train17	819	824
Section 6	Train18	844	849
Section 6	Train19	854	860
Section 6	Train20	979	985
Section 6	Train21	1029	1034
Section 6	Train22	1074	1079
Section 6	Train23	1144	1150
Section 6	Train24	1129	1135
Section 6	Train25	1226	1232
Section 6	Train26	1293	1299
Section 6	Train27	1234	1239
Section 7	Train0	91	100
Section 7	Train1	74	82
Section 7	Train2	177	186
Section 7	Train3	224	233
Section 7	Train4	251	260
Section 7	Train5	285	293
Section 7	Train6	430	439
Section 7	Train7	475	484
Section 7	Train8	494	502
Section 7	Train9	594	603
Section 7	Train10	616	624
Section 7	Train11	580	589
Section 7	Train12	679	687
Section 7	Train13	727	735
Section 7	Train14	707	715
Section 7	Train15	777	785

Section 7	Train16	749	757
Section 7	Train17	811	819
Section 7	Train18	836	844
Section 7	Train19	860	869
Section 7	Train20	985	994
Section 7	Train21	1034	1042
Section 7	Train22	1079	1087
Section 7	Train23	1135	1144
Section 7	Train24	1146	1155
Section 7	Train25	1214	1223
Section 7	Train26	1284	1293
Section 7	Train27	1239	1247
Section 8	Train0	82	91
Section 8	Train1	93	102
Section 8	Train2	186	195
Section 8	Train3	215	224
Section 8	Train4	242	251
Section 8	Train5	276	285
Section 8	Train6	439	448
Section 8	Train7	484	493
Section 8	Train8	502	511
Section 8	Train9	585	594
Section 8	Train10	607	616
Section 8	Train11	596	605
Section 8	Train12	670	679
Section 8	Train13	718	727
Section 8	Train14	724	733

Section 8	Train15	768	777
Section 8	Train16	757	766
Section 8	Train17	802	811
Section 8	Train18	827	836
Section 8	Train19	869	878
Section 8	Train20	994	1003
Section 8	Train21	1042	1051
Section 8	Train22	1087	1096
Section 8	Train23	1126	1135
Section 8	Train24	1155	1164
Section 8	Train25	1205	1214
Section 8	Train26	1275	1284
Section 8	Train27	1247	1256
Section 9	Train0	74	82
Section 9	Train1	102	111
Section 9	Train2	195	203
Section 9	Train3	207	215
Section 9	Train4	234	242
Section 9	Train5	267	276
Section 9	Train6	448	456
Section 9	Train7	493	501
Section 9	Train8	511	520
Section 9	Train9	577	585
Section 9	Train10	591	600
Section 9	Train11	605	613
Section 9	Train12	661	670
Section 9	Train13	709	718
Section 9	Train14	733	742
Section 9	Train15	759	768
Section 9	Train16	772	781
Section 9	Train17	793	802
Section 9	Train18	818	827
Section 9	Train19	878	886
Section 9	Train20	1003	1011
Section 9	Train21	1051	1060
Section 9	Train22	1096	1105
Section 9	Train23	1118	1126
Section 9	Train24	1164	1172
Section 9	Train25	1197	1205
Section 9	Train26	1267	1275
Section 9	Train27	1256	1265
Section 10	Train0	69	74
Section 10	Train1	111	116
Section 10	Train2	209	214
Section 10	Train3	202	207
Section 10	Train4	229	234
Section 10	Train5	262	267
Section 10	Train6	456	461
Section 10	Train7	501	506
Section 10	Train8	520	525
Section 10	Train9	572	577
Section 10	Train10	586	591
Section 10	Train11	613	618
Section 10	Train12	656	661
Section 10	Train13	704	709
Section 10	Train14	744	749
Section 10	Train15	754	759
Section 10	Train16	781	786
Section 10	Train17	788	793
Section 10	Train18	813	818
Section 10	Train19	886	891
Section 10	Train20	1011	1016
Section 10	Train21	1060	1065
Section 10	Train22	1105	1110
Section 10	Train23	1113	1118
Section 10	Train24	1172	1177
Section 10	Train25	1192	1197
Section 10	Train26	1254	1259
Section 10	Train27	1265	1270
Section 11	Train0	63	69
Section 11	Train1	116	122
Section 11	Train2	215	221
Section 11	Train3	196	202
Section 11	Train4	223	229
Section 11	Train5	256	262
Section 11	Train6	461	467
Section 11	Train7	506	512
Section 11	Train8	525	531
Section 11	Train9	566	572
Section 11	Train10	580	586
Section 11	Train11	618	624

Section 11	Train12	650	656
Section 11	Train13	698	704
Section 11	Train14	749	755
Section 11	Train15	743	749
Section 11	Train16	786	792
Section 11	Train17	775	781
Section 11	Train18	807	813
Section 11	Train19	891	897
Section 11	Train20	1016	1022
Section 11	Train21	1065	1071
Section 11	Train22	1115	1121
Section 11	Train23	1107	1113
Section 11	Train24	1177	1183
Section 11	Train25	1186	1192
Section 11	Train26	1248	1254
Section 11	Train27	1270	1276
Section 12	Train0	57	63
Section 12	Train1	122	128
Section 12	Train2	221	227
Section 12	Train3	190	196
Section 12	Train4	212	218
Section 12	Train5	250	256
Section 12	Train6	467	473
Section 12	Train7	512	518
Section 12	Train8	531	537
Section 12	Train9	560	566
Section 12	Train10	574	580

Section 12	Train11	624	630
Section 12	Train12	644	650
Section 12	Train13	692	698
Section 12	Train14	756	762
Section 12	Train15	737	743
Section 12	Train16	792	798
Section 12	Train17	769	775
Section 12	Train18	801	807
Section 12	Train19	897	903
Section 12	Train20	1022	1028
Section 12	Train21	1071	1077
Section 12	Train22	1121	1127
Section 12	Train23	1100	1106
Section 12	Train24	1188	1194
Section 12	Train25	1180	1186
Section 12	Train26	1242	1248
Section 12	Train27	1276	1282
Section 13	Train0	51	57
Section 13	Train1	128	133
Section 13	Train2	227	233
Section 13	Train3	184	190
Section 13	Train4	206	212
Section 13	Train5	245	250
Section 13	Train6	473	479
Section 13	Train7	518	524
Section 13	Train8	537	542
Section 13	Train9	554	560

Section 13	Train10	569	574
Section 13	Train11	632	638
Section 13	Train12	639	644
Section 13	Train13	687	692
Section 13	Train14	762	767
Section 13	Train15	732	737
Section 13	Train16	803	808
Section 13	Train17	759	764
Section 13	Train18	796	801
Section 13	Train19	903	909
Section 13	Train20	1028	1034
Section 13	Train21	1077	1082
Section 13	Train22	1127	1132
Section 13	Train23	1094	1100
Section 13	Train24	1194	1200
Section 13	Train25	1174	1180
Section 13	Train26	1236	1242
Section 13	Train27	1282	1287
Section 14	Train0	46	51
Section 14	Train1	133	137
Section 14	Train2	233	238
Section 14	Train3	179	184
Section 14	Train4	201	206
Section 14	Train5	241	245
Section 14	Train6	479	484
Section 14	Train7	524	529
Section 14	Train8	542	546

Section 14	Train9	549	554
Section 14	Train10	565	569
Section 14	Train11	638	643
Section 14	Train12	630	634
Section 14	Train13	683	687
Section 14	Train14	767	771
Section 14	Train15	728	732
Section 14	Train16	808	812
Section 14	Train17	755	759
Section 14	Train18	791	795
Section 14	Train19	909	914
Section 14	Train20	1034	1039
Section 14	Train21	1082	1086
Section 14	Train22	1132	1136
Section 14	Train23	1089	1094
Section 14	Train24	1200	1205
Section 14	Train25	1169	1174
Section 14	Train26	1231	1236
Section 14	Train27	1287	1291
Section 15	Train0	39	46
Section 15	Train1	137	143
Section 15	Train2	243	250
Section 15	Train3	172	179
Section 15	Train4	194	201
Section 15	Train5	235	241
Section 15	Train6	484	491
Section 15	Train7	529	536

Section 15	Train8	551	557
Section 15	Train9	542	549
Section 15	Train10	559	565
Section 15	Train11	643	650
Section 15	Train12	624	630
Section 15	Train13	677	683
Section 15	Train14	772	778
Section 15	Train15	722	728
Section 15	Train16	812	818
Section 15	Train17	749	755
Section 15	Train18	785	791
Section 15	Train19	914	921
Section 15	Train20	1039	1046
Section 15	Train21	1091	1097
Section 15	Train22	1136	1142
Section 15	Train23	1082	1089
Section 15	Train24	1205	1212
Section 15	Train25	1162	1169
Section 15	Train26	1224	1231
Section 15	Train27	1291	1297
Section 16	Train0	34	39
Section 16	Train1	143	147
Section 16	Train2	250	255
Section 16	Train3	167	172
Section 16	Train4	189	194
Section 16	Train5	228	232
Section 16	Train6	491	496

Section 16	Train7	541	546
Section 16	Train8	557	561
Section 16	Train9	534	539
Section 16	Train10	549	553
Section 16	Train11	650	655
Section 16	Train12	620	624
Section 16	Train13	673	677
Section 16	Train14	778	782
Section 16	Train15	718	722
Section 16	Train16	818	822
Section 16	Train17	745	749
Section 16	Train18	776	780
Section 16	Train19	921	926
Section 16	Train20	1046	1051
Section 16	Train21	1097	1101
Section 16	Train22	1142	1146
Section 16	Train23	1076	1081
Section 16	Train24	1212	1217
Section 16	Train25	1157	1162
Section 16	Train26	1219	1224
Section 16	Train27	1297	1301
Section 17	Train0	30	34
Section 17	Train1	147	150
Section 17	Train2	255	259
Section 17	Train3	163	167
Section 17	Train4	185	189
Section 17	Train5	225	228

Section 17	Train6	496	500
Section 17	Train7	551	555
Section 17	Train8	561	564
Section 17	Train9	528	532
Section 17	Train10	546	549
Section 17	Train11	655	659
Section 17	Train12	617	620
Section 17	Train13	670	673
Section 17	Train14	782	785
Section 17	Train15	715	718
Section 17	Train16	822	825
Section 17	Train17	742	745
Section 17	Train18	773	776
Section 17	Train19	926	930
Section 17	Train20	1051	1055
Section 17	Train21	1101	1104
Section 17	Train22	1148	1151
Section 17	Train23	1072	1076
Section 17	Train24	1217	1221
Section 17	Train25	1153	1157
Section 17	Train26	1210	1214
Section 17	Train27	1301	1304
Section 18	Train0	26	30
Section 18	Train1	150	154
Section 18	Train2	259	263
Section 18	Train3	159	163
Section 18	Train4	181	185

Section 18	Train5	221	225
Section 18	Train6	500	504
Section 18	Train7	555	559
Section 18	Train8	564	568
Section 18	Train9	524	528
Section 18	Train10	540	544
Section 18	Train11	660	664
Section 18	Train12	613	617
Section 18	Train13	666	670
Section 18	Train14	785	789
Section 18	Train15	711	715
Section 18	Train16	825	829
Section 18	Train17	738	742
Section 18	Train18	769	773
Section 18	Train19	930	934
Section 18	Train20	1055	1059
Section 18	Train21	1104	1108
Section 18	Train22	1151	1155
Section 18	Train23	1068	1072
Section 18	Train24	1221	1225
Section 18	Train25	1144	1148
Section 18	Train26	1206	1210
Section 18	Train27	1304	1308
Section 19	Train0	17	26
Section 19	Train1	161	170
Section 19	Train2	263	272
Section 19	Train3	150	159

Section 19	Train4	172	181
Section 19	Train5	212	221
Section 19	Train6	504	513
Section 19	Train7	559	568
Section 19	Train8	570	579
Section 19	Train9	515	524
Section 19	Train10	531	540
Section 19	Train11	664	673
Section 19	Train12	604	613
Section 19	Train13	652	661
Section 19	Train14	789	798
Section 19	Train15	702	711
Section 19	Train16	829	838
Section 19	Train17	729	738
Section 19	Train18	760	769
Section 19	Train19	934	943
Section 19	Train20	1070	1079
Section 19	Train21	1108	1117
Section 19	Train22	1155	1164
Section 19	Train23	1059	1068
Section 19	Train24	1225	1234
Section 19	Train25	1135	1144
Section 19	Train26	1197	1206
Section 19	Train27	1308	1317
Section 20	Train0	12	17
Section 20	Train1	170	173
Section 20	Train2	272	277

Section 20	Train3	145	150
Section 20	Train4	157	162
Section 20	Train5	209	212
Section 20	Train6	513	518
Section 20	Train7	568	573
Section 20	Train8	579	582
Section 20	Train9	502	507
Section 20	Train10	528	531
Section 20	Train11	673	678
Section 20	Train12	601	604
Section 20	Train13	649	652
Section 20	Train14	798	801
Section 20	Train15	699	702
Section 20	Train16	838	841
Section 20	Train17	726	729
Section 20	Train18	757	760
Section 20	Train19	943	948
Section 20	Train20	1079	1084
Section 20	Train21	1117	1120
Section 20	Train22	1164	1167
Section 20	Train23	1054	1059
Section 20	Train24	1234	1239
Section 20	Train25	1130	1135
Section 20	Train26	1192	1197
Section 20	Train27	1317	1320
Section 21	Train0	8	12
Section 21	Train1	173	176

Section 21	Train2	277	281
Section 21	Train3	141	145
Section 21	Train4	153	157
Section 21	Train5	206	209
Section 21	Train6	518	522
Section 21	Train7	573	577
Section 21	Train8	582	585
Section 21	Train9	498	502
Section 21	Train10	525	528
Section 21	Train11	678	682
Section 21	Train12	598	601
Section 21	Train13	646	649
Section 21	Train14	801	804
Section 21	Train15	696	699
Section 21	Train16	841	844
Section 21	Train17	723	726
Section 21	Train18	754	757
Section 21	Train19	948	952
Section 21	Train20	1084	1088
Section 21	Train21	1120	1123
Section 21	Train22	1167	1170
Section 21	Train23	1050	1054
Section 21	Train24	1239	1243
Section 21	Train25	1126	1130
Section 21	Train26	1188	1192
Section 21	Train27	1320	1323
Section 22	Train0	3	8

Section 22	Train1	176	179
Section 22	Train2	281	286
Section 22	Train3	136	141
Section 22	Train4	148	153
Section 22	Train5	203	206
Section 22	Train6	527	532
Section 22	Train7	577	582
Section 22	Train8	585	588
Section 22	Train9	493	498
Section 22	Train10	522	525
Section 22	Train11	682	687
Section 22	Train12	595	598
Section 22	Train13	643	646
Section 22	Train14	804	807
Section 22	Train15	693	696
Section 22	Train16	844	847
Section 22	Train17	720	723
Section 22	Train18	751	754
Section 22	Train19	952	957
Section 22	Train20	1088	1093
Section 22	Train21	1128	1131
Section 22	Train22	1170	1173
Section 22	Train23	1045	1050
Section 22	Train24	1243	1248
Section 22	Train25	1121	1126
Section 22	Train26	1183	1188
Section 22	Train27	1323	1326

Section 23	Train0	0	3
Section 23	Train1	179	182
Section 23	Train2	286	289
Section 23	Train3	133	136
Section 23	Train4	145	148
Section 23	Train5	200	203
Section 23	Train6	532	535
Section 23	Train7	582	585
Section 23	Train8	588	591
Section 23	Train9	490	493
Section 23	Train10	518	521
Section 23	Train11	687	690
Section 23	Train12	592	595
Section 23	Train13	640	643
Section 23	Train14	807	810
Section 23	Train15	690	693
Section 23	Train16	847	850
Section 23	Train17	717	720
Section 23	Train18	748	751
Section 23	Train19	957	960
Section 23	Train20	1093	1096
Section 23	Train21	1131	1134
Section 23	Train22	1173	1176
Section 23	Train23	1042	1045
Section 23	Train24	1248	1251
Section 23	Train25	1117	1120
Section 23	Train26	1180	1183
Section 23	Train27	1326	1329

Details of Optimized Schedule (Software Output Converted into Schedule)

- **Results of ESPR, EFPR, MPTPR**
- **Inbound Trains**

Scheduler Train Input Numbers		Train 3	Train 4	Train 5	Train 9	Train 10	Train 12	Train 13	Train 15	Train 17	Train 18	Train 23	Train 25	Train 26
Actual Train Numbers		**Train 105**	**Train 327**	**Train 131**	**Train 11**	**Train 107**	**Train 101**	**Train 13**	**Train 23**	**Train 39**	**Train 45**	**Train 7**	**Train 103**	**Train 109**
Segments		288	315	337	660	671	736	785	829	865	895	1200	1291	1337
Section 0	**Rwp-Chaklala**	282	309	331	654	665	730	779	823	859	889	1194	1285	1331
Section 1	**Chaklala-Sihala**	282	309	331	654	665	730	779	823	859	889	1194	1285	1331
		270	297	322	642	656	721	770	814	850	880	1182	1273	1319
Section 2	**Sihala-Mankiala**	270	297	322	640	653	716	770	814	850	880	1181	1273	1319
		261	288	314	631	645	708	762	806	842	872	1172	1264	1310
Section 3	**Mankiala-Kaliamawan**	261	288	314	631	645	708	762	806	842	872	1172	1264	1310
		253	280	310	623	641	704	758	802	838	868	1164	1256	1302
Section 4	**Kaliamawan-Mandra Jn**	253	280	310	623	641	704	758	802	838	868	1164	1256	1302
		246	273	304	616	635	698	752	796	832	862	1157	1249	1295
Section 5	**Mandra Jn - Ghungrila**	246	273	304	616	635	698	752	796	830	862	1157	1249	1295
		239	266	298	609	629	692	746	790	824	856	1150	1242	1288
Section 6	**Ghungrila-Gujjar Khan**	239	266	298	609	629	692	740	790	824	849	1150	1242	1288
		233	260	293	603	624	687	735	785	819	844	1144	1236	1282
Section 7	**Gujjar Khan - Missa Keswal**	233	260	293	603	624	687	735	785	819	844	1144	1236	1282
		224	251	285	594	616	679	727	777	811	836	1135	1227	1273
Section 8	**Missa Keswal - Sohawa**	224	251	285	594	616	679	727	777	811	836	1135	1225	1273
		215	242	276	585	607	670	718	768	802	827	1126	1216	1264
Section 9	**Sohawa-Tarki**	215	242	276	585	600	670	718	768	802	827	1126	1216	1264

		207	234	267	577	591	661	709	759	793	818	1118	1208	1256
Section 10	**Tarki-Bakrala**	207	234	267	577	591	661	709	759	793	818	1118	1208	1256
		202	229	262	572	586	656	704	754	788	813	1113	1203	1251
Section 11	**Bakrala-Domeli**	202	229	262	572	586	656	704	749	781	813	1113	1203	1251
		196	223	256	566	580	650	698	743	775	807	1107	1197	1245
Section 12	**Domeli-Ratial**	196	218	256	566	580	650	698	743	775	807	1106	1197	1245
		190	212	250	560	574	644	692	737	769	801	1100	1191	1239
Section 13	**Ratial-Dina**	190	212	250	560	574	644	692	737	764	801	1100	1186	1239
		184	206	245	554	569	639	687	732	759	796	1094	1180	1233
Section 14	**Dina-Kaluwal**	184	206	245	554	569	634	687	732	759	795	1094	1180	1233
		179	201	241	549	656	630	683	728	755	791	1089	1175	1228
Section 15	**Kaluwal-Kala Gujran**	179	201	241	549	565	630	683	728	755	791	1089	1175	1228
		172	194	235	542	559	624	677	722	749	785	1082	1168	1221
Section 16	**Kala Gujran - Jhelum**	172	194	232	539	553	624	677	722	749	780	1081	1168	1221
		167	189	228	534	549	620	673	718	745	776	1076	1163	1216
Section 17	**Jhelum-Sarae Alamgir**	167	189	228	532	549	620	673	718	745	776	1076	1163	1216
		163	185	225	528	546	617	670	715	742	773	1072	1159	1212
Section 18	**Sarai Alamgir - Choa Kariala**	163	185	225	528	544	617	670	715	742	773	1072	1159	1210
		159	181	221	524	540	613	666	711	738	769	1068	1155	1206
Section 19	**Choa Kariala-Kharian**	159	181	221	524	540	613	661	711	738	769	1068	1150	1206
		150	172	212	515	531	604	652	702	729	760	1059	1141	1197
Section 20	**Kharian-Kharian Cantt**	150	162	212	507	531	604	652	702	729	760	1059	1141	1197
		145	157	209	502	528	601	649	699	726	757	1054	1136	1192
Section 21	**Kharian Cantt - Chak Pirana**	145	157	209	502	528	601	649	699	726	757	1054	1136	1192
		141	153	206	498	525	598	646	696	723	754	1050	1132	1188
Section 22	**Chak Pirana-LalaMusa Goods**	141	153	206	498	525	598	646	696	723	754	1050	1132	1188
		136	148	203	493	522	595	643	693	720	751	1045	1127	1183

Section 23	**LalaMusa Goods - LLM**	136	148	203	493	521	595	643	693	720	751	1045	1120	1183
		133	145	200	490	518	592	640	690	717	748	1042	1117	1180

➢ Outbound Trains

Scheduler Train Input Numbers		Train 1	Train 2	Train 6	Train 7	Train 8	Train 11	Train 14	Train 16	Train 19	Train 20	Train 21	Train 22	Train 24	Train 27
Actual Train Numbers		Train 106	Train 2	Train 46	Train 110	Train 104	Train 8	Train 40	Train 24	Train 14	Train 132	Train 102	Train 12	Train 108	Train 328
Segments		30	120	375	420	450	525	645	705	790	930	990	1035	1080	1185
Section 0	Rwp-Chaklala	36	126	381	426	456	531	651	711	796	936	996	1041	1086	1191
Section 1	Chaklala-Sihala	36	128	381	426	456	531	662	711	796	936	996	1041	1086	1196
		45	140	393	438	465	543	671	720	808	948	1005	1050	1098	1205
Section 2	Sihala-Mankiala	45	140	393	438	465	543	671	720	818	948	1005	1050	1098	1205
		53	149	402	447	473	552	679	728	827	957	1013	1058	1107	1213
Section 3	Mankiala-Kaliamawan	53	149	402	447	473	552	679	728	827	957	1013	1058	1107	1213
		57	157	410	455	477	560	683	732	835	965	1017	1062	1115	1217
Section 4	Kaliamawan-Mandra Jn	57	157	410	455	477	560	683	732	840	965	1017	1062	1115	1217
		63	164	417	462	483	567	689	738	847	972	1023	1068	1122	1223
Section 5	Mandra Jn - Ghungrila	63	164	417	462	483	567	696	738	847	972	1023	1068	1122	1223
		69	171	424	469	489	574	702	744	854	979	1029	1074	1129	1229
Section 6	Ghungrila-Gujjar Khan	69	171	424	469	489	574	702	744	854	979	1029	1074	1129	1229
		74	177	430	475	494	580	707	749	860	985	1034	1079	1135	1234
Section 7	Gujjar Khan - Missa Keswal	74	177	430	475	494	580	707	749	860	985	1034	1079	1146	1239
		82	186	439	484	502	589	715	757	869	994	1042	1087	1155	1247
Section 8	Missa Keswal - Sohawa	93	186	439	484	502	596	724	757	869	994	1042	1087	1155	1247
		102	195	448	493	511	605	733	766	878	1003	1051	1096	1164	1256
Section 9	Sohawa-Tarki	102	195	448	493	511	605	733	772	878	1003	1051	1096	1164	1266
		111	203	456	501	520	613	742	781	886	1011	1060	1105	1172	1275
Section 10	Tarki-Bakrala	111	209	456	501	520	613	744	781	886	1011	1060	1105	1172	1275
		116	214	461	506	525	618	749	786	891	1016	1065	1110	1177	1280
Section 11	Bakrala-Domeli	116	215	461	506	525	618	749	786	891	1016	1065	1115	1177	1280

		122	221	467	512	531	624	755	792	897	1022	1071	1121	1183	1286
Section 12	**Domeli-Ratial**	122	221	467	512	531	624	756	792	897	1022	1071	1121	1184	1286
		128	227	473	518	537	630	762	798	903	1028	1077	1127	1190	1292
Section 13	**Ratial-Dina**	128	227	473	518	537	632	762	803	903	1028	1077	1127	1190	1292
		133	233	479	524	542	638	767	808	909	1034	1082	1132	1196	1297
Section 14	**Dina-Kaluwal**	133	233	479	524	542	638	767	808	909	1034	1082	1132	1196	1297
		137	238	484	529	546	643	771	812	914	1039	1086	1136	1201	1301
Section 15	**Kaluwal-Kala Gujran**	137	243	484	529	551	643	772	812	914	1039	1091	1136	1201	1301
		143	250	491	536	557	650	778	818	921	1046	1097	1142	1208	1307
Section 16	**Kala Gujran - Jhelum**	143	250	491	541	557	650	778	818	921	1046	1097	1142	1208	1307
		147	255	496	546	561	655	782	822	926	1051	1101	1146	1213	1311
Section 17	**Jhelum-Sarae Alamgir**	147	255	496	551	561	655	782	822	926	1051	1101	1146	1218	1311
		150	259	500	555	564	659	785	825	930	1055	1104	1149	1222	1314
Section 18	**Sarai Alamgir - Choa Kariala**	150	259	500	555	564	660	785	825	930	1055	1104	1150	1222	1314
		154	263	504	559	568	664	789	829	934	1059	1108	1154	1226	1318
Section 19	**Choa Kariala-Kharian**	161	263	504	559	570	664	789	829	934	1070	1108	1154	1226	1318
		170	272	513	568	579	673	798	838	943	1079	1117	1163	1235	1327
Section 20	**Kharian-Kharian Cantt**	170	272	513	568	579	673	798	838	943	1079	1117	1163	1235	1327
		173	277	518	573	582	678	801	841	948	1084	1120	1166	1240	1330
Section 21	**Kharian Cantt - Chak Pirana**	173	277	518	573	582	678	801	841	948	1084	1120	1166	1240	1330
		176	281	522	577	585	682	804	844	952	1088	1123	1169	1244	1333
Section 22	**Chak Pirana-LalaMusa Goods**	176	281	527	577	585	682	804	844	952	1088	1123	1169	1244	1333
		179	286	532	582	588	687	807	847	957	1093	1126	1172	1249	1336
Section 23	**LalaMusa Goods - LLM**	179	286	532	582	588	687	807	847	957	1093	1126	1172	1249	1336
		182	289	535	585	591	690	810	850	960	1096	1129	1175	1252	1339

- **Results of BCPR**
- **Inbound Trains**

Scheduler Train Input Numbers		**Train 3**	**Train 4**	**Train 5**	**Train 9**	**Train 10**	**Train 12**	**Train 13**	**Train 15**	**Train 17**	**Train 18**	**Train 23**	**Train 25**	**Train 26**	**Train 0**
Actual Train Numbers		**Train 105**	**Train 327**	**Train 131**	**Train 11**	**Train 107**	**Train 101**	**Train 13**	**Train 23**	**Train 39**	**Train 45**	**Train 7**	**Train 103**	**Train 109**	**Train 1**
	Sections	288	315	337	660	671	736	785	829	865	895	1200	1281	1348	160
Section 0	**Rwp-Chaklala**	282	309	331	654	665	730	779	823	859	889	1194	1275	1342	154
Section 1	**Chaklala-Sihala**	282	309	331	654	665	730	779	823	859	889	1194	1275	1342	154
		270	297	322	642	656	721	770	814	850	880	1182	1263	1330	142
Section 2	**Sihala-Mankiala**	270	297	322	640	653	716	770	814	850	880	1181	1263	1330	137
		261	288	314	631	645	708	762	806	842	872	1172	1254	1321	128
Section 3	**Mankiala-Kaliamawan**	261	288	314	631	645	708	762	806	842	872	1172	1254	1321	128
		253	280	310	623	641	704	758	802	838	868	1164	1246	1313	120
Section 4	**Kaliamawan-Mandra Jn**	253	280	310	623	641	704	758	802	838	868	1164	1246	1313	120
		246	273	304	616	635	698	752	796	832	862	1157	1239	1306	113
Section 5	**Mandra Jn - Ghungrila**	246	273	304	616	635	698	752	796	830	862	1157	1239	1306	113
		239	266	298	609	629	692	746	790	824	856	1150	1332	1299	106
Section 6	**Ghungrila-Gujjar Khan**	239	266	298	609	629	692	740	790	824	849	1150	1232	1299	106
		233	260	293	603	624	687	735	785	819	844	1144	1226	1293	100
Section 7	**Gujjar Khan - Missa Keswal**	233	260	293	603	624	687	735	785	819	844	1144	1223	1293	100
		224	251	285	594	616	679	727	777	811	836	1135	1214	1284	91
Section 8	**Missa Keswal - Sohawa**	224	251	285	594	616	679	727	777	811	836	1135	1214	1284	91
		215	242	276	585	607	670	718	768	802	827	1126	1205	1275	82
Section 9	**Sohawa-Tarki**	215	242	276	585	600	670	718	768	802	827	1126	1205	1275	82
		207	234	267	577	591	661	709	759	793	818	1118	1197	1267	74
Section 10	**Tarki-Bakrala**	207	234	267	577	591	661	709	759	793	818	1118	1197	1259	74

		202	229	262	572	586	656	704	754	788	813	1113	1192	1254	69
Section 11	**Bakrala-Domeli**	202	229	262	572	586	656	704	749	781	813	1113	1192	1254	69
		196	223	256	566	580	650	698	743	775	807	1107	1186	1248	63
Section 12	**Domeli-Ratial**	196	218	256	566	580	650	698	743	775	807	1106	1186	1248	63
		190	212	250	560	574	644	692	737	769	801	1100	1180	1242	57
Section 13	**Ratial-Dina**	190	212	250	560	574	644	692	737	764	801	1100	1180	1242	57
		184	206	245	554	569	639	687	732	759	796	1094	1174	1236	51
Section 14	**Dina-Kaluwal**	184	206	245	554	569	634	687	732	759	795	1094	1174	1236	51
		179	201	241	549	656	630	683	728	755	791	1089	1169	1231	46
Section 15	**Kaluwal-Kala Gujran**	179	201	241	549	565	630	683	728	755	791	1089	1169	1231	46
		172	194	235	542	559	624	677	722	749	785	1082	1162	1224	39
Section 16	**Kala Gujran - Jhelum**	172	194	232	539	553	624	677	722	749	780	1081	1162	1224	39
		167	189	228	534	549	620	673	718	745	776	1076	1157	1219	34
Section 17	**Jhelum-Sarae Alamgir**	167	189	228	532	549	620	673	718	745	776	1076	1157	1214	34
		163	185	225	528	546	617	670	715	742	773	1072	1153	1210	30
Section 18	**Sarai Alamgir - Choa Kariala**	163	185	225	528	544	617	670	715	742	773	1072	1148	1210	30
		159	181	221	524	540	613	666	711	738	769	1068	1144	1206	26
Section 19	**Choa Kariala-Kharian**	159	181	221	524	540	613	661	711	738	769	1068	1144	1206	26
		150	172	212	515	531	604	652	702	729	760	1059	1135	1197	17
Section 20	**Kharian-Kharian Cantt**	150	162	212	507	531	604	652	702	729	760	1059	1135	1197	17
		145	157	209	502	528	601	649	699	726	757	1054	1130	1192	12
Section 21	**Kharian Cantt - Chak Pirana**	145	157	209	502	528	601	649	699	726	757	1054	1130	1192	12
		141	153	206	498	525	598	646	696	723	754	1050	1126	1188	8
Section 22	**Chak Pirana-LalaMusa Goods**	141	153	206	498	525	598	646	696	723	754	1050	1126	1188	8
		136	148	203	493	522	595	643	693	720	751	1045	1121	1183	3
Section 23	**LalaMusa Goods - LLM**	136	148	203	493	521	595	643	693	720	751	1045	1120	1183	3
		133	145	200	490	518	592	640	690	717	748	1042	1117	1180	0

➢ Outbound Trains

Scheduler Train Input Numbers		Train 1	Train 2	Train 6	Train 7	Train 8	Train 11	Train 14	Train 16	Train 19	Train 20	Train 21	Train 22	Train 24	Train 27
Actual Train Numbers		**Train 106**	**Train 2**	**Train 46**	**Train 110**	**Train 104**	**Train 8**	**Train 40**	**Train 24**	**Train 14**	**Train 132**	**Train 102**	**Train 12**	**Train 108**	**Train 328**
	Sections	30	120	375	420	450	525	645	705	790	930	990	1035	1080	1185
Section 0	**Rwp-Chaklala**	36	126	381	426	456	531	651	711	796	936	996	1041	1086	1191
Section 1	**Chaklala-Sihala**	36	128	381	426	456	531	662	711	796	936	996	1041	1086	1196
		45	140	393	438	465	543	671	720	808	948	1005	1050	1098	1205
Section 2	**Sihala-Mankiala**	45	140	393	438	465	543	671	720	818	948	1005	1050	1098	1205
		53	149	402	447	473	552	679	728	827	957	1013	1058	1107	1213
Section 3	**Mankiala-Kaliamawan**	53	149	402	447	473	552	679	728	827	957	1013	1058	1107	1213
		57	157	410	455	477	560	683	732	835	965	1017	1062	1115	1217
Section 4	**Kaliamawan-Mandra Jn**	57	157	410	455	477	560	683	732	840	965	1017	1062	1115	1217
		63	164	417	462	483	567	689	738	847	972	1023	1068	1122	1223
Section 5	**Mandra Jn - Ghungrila**	63	164	417	462	483	567	696	738	847	972	1023	1068	1122	1223
		69	171	424	469	489	574	702	744	854	979	1029	1074	1129	1229
Section 6	**Ghungrila-Gujjar Khan**	69	171	424	469	489	574	702	744	854	979	1029	1074	1129	1234
		74	177	430	475	494	580	707	749	860	985	1034	1079	1135	1239
Section 7	**Gujjar Khan - Missa Keswal**	74	177	430	475	494	580	707	749	860	985	1034	1079	1146	1239
		82	186	439	484	502	589	715	757	869	994	1042	1087	1155	1247
Section 8	**Missa Keswal - Sohawa**	93	186	439	484	502	596	724	757	869	994	1042	1087	1155	1247
		102	195	448	493	511	605	733	766	878	1003	1051	1096	1164	1256
Section 9	**Sohawa-Tarki**	102	195	448	493	511	605	733	772	878	1003	1051	1096	1164	1256
		111	203	456	501	520	613	742	781	886	1011	1060	1105	1172	1265
Section 10	**Tarki-Bakrala**	111	209	456	501	520	613	744	781	886	1011	1060	1105	1172	1265
		116	214	461	506	525	618	749	786	891	1016	1065	1110	1177	1270
Section 11	**Bakrala-Domeli**	116	215	461	506	525	618	749	786	891	1016	1065	1115	1177	1270

		122	221	467	512	531	624	755	792	897	1022	1071	1121	1183	1276
Section 12	**Domeli-Ratial**	122	221	467	512	531	624	756	792	897	1022	1071	1121	1188	1276
		128	227	473	518	537	630	762	798	903	1028	1077	1127	1194	1282
Section 13	**Ratial-Dina**	128	227	473	518	537	632	762	803	903	1028	1077	1127	1194	1282
		133	233	479	524	542	638	767	808	909	1034	1082	1132	1200	1287
Section 14	**Dina-Kaluwal**	133	233	479	524	542	638	767	808	909	1034	1082	1132	1200	1287
		137	238	484	529	546	643	771	812	914	1039	1086	1136	1205	1291
Section 15	**Kaluwal-Kala Gujran**	137	243	484	529	551	643	772	812	914	1039	1091	1136	1205	1291
		143	250	491	536	557	650	778	818	921	1046	1097	1142	1212	1297
Section 16	**Kala Gujran - Jhelum**	143	250	491	541	557	650	778	818	921	1046	1097	1142	1212	1297
		147	255	496	546	561	655	782	822	926	1051	1101	1146	1217	1301
Section 17	**Jhelum-Sarae Alamgir**	147	255	496	551	561	655	782	822	926	1051	1101	1148	1217	1301
		150	259	500	555	564	659	785	825	930	1055	1104	1151	1221	1304
Section 18	**Sarai Alamgir - Choa Kariala**	150	259	500	555	564	660	785	825	930	1055	1104	1151	1221	1304
		154	263	504	559	568	664	789	829	934	1059	1108	1155	1225	1308
Section 19	**Choa Kariala-Kharian**	161	263	504	559	570	664	789	829	934	1070	1108	1155	1225	1308
		170	272	513	568	579	673	798	838	943	1079	1117	1164	1234	1317
Section 20	**Kharian-Kharian Cantt**	170	272	513	568	579	673	798	838	943	1079	1117	1164	1234	1317
		173	277	518	573	582	678	801	841	948	1084	1120	1167	1239	1320
Section 21	**Kharian Cantt - Chak Pirana**	173	277	518	573	582	678	801	841	948	1084	1120	1167	1239	1320
		176	281	522	577	585	682	804	844	952	1088	1123	1170	1243	1323
Section 22	**Chak Pirana-LalaMusa Goods**	176	281	527	577	585	682	804	844	952	1088	1128	1170	1243	1323
		179	286	532	582	588	687	807	847	957	1093	1131	1173	1248	1326
Section 23	**LalaMusa Goods - LLM**	179	286	532	582	588	687	807	847	957	1093	1131	1173	1248	1326
		182	289	535	585	591	690	810	850	960	1096	1134	1176	1251	1329

Appendix VI: Sensitivity Analysis Options

- **Running Times at Different Segments for 17 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -SERAI ALAMGEER	4	4
SERAI ALAMGEER -KALA GUJRAN	7	9
KALA GUJRAN -KALUWAL	6	7
KALUWAL -DINA	4	5
DINA -RATIAL	5	6
RATIAL -BAKRALA	12	12
BAKRALA -TARKI	5	5
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 16 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -KALA GUJRAN	11	13
KALA GUJRAN -KALUWAL	6	7
KALUWAL -DINA	4	5
DINA -RATIAL	5	6
RATIAL -BAKRALA	12	12
BAKRALA -TARKI	5	5
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8

MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 15 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -KALA GUJRAN	11	13
KALA GUJRAN -DINA	10	12
DINA -RATIAL	5	6
RATIAL -BAKRALA	12	12
BAKRALA -TARKI	5	5
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 14 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -KALA GUJRAN	11	13
KALA GUJRAN -DINA	10	12
DINA -RATIAL	5	6
RATIAL -TARKI	17	17
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 13 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -DINA	21	25
DINA -RATIAL	5	6
RATIAL -TARKI	17	17
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 12 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -DINA	21	25
DINA -TARKI	22	23
TARKI -SOHAWA	9	8
SOHAWA -MISSAKASWAL	9	9
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 11 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9

CHOA KARIALA -DINA	21	25
DINA -TARKI	22	23
TARKI -MISSAKASWAL	18	17
MISSAKASWAL -KALIAMAWAN	25	29
KALIAMAWAN -MANKIALA	4	8
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 10 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -DINA	21	25
DINA -TARKI	22	23
TARKI -MISSAKASWAL	18	17
MISSAKASWAL -MANKIALA	29	37
MANKIALA -SIHALA	8	9
SIHALA -RAWALPINDI	15	18

- **Running Times at Different Segments for 9 Sidings**

SEGMENTS	105/65Km/h	65 Km/h
LALA MUSA JN -CHAK PIRANA	6	8
CHAK PIRANA -KHARIAN	6	9
KHARIAN -CHOA KARIALA	9	9
CHOA KARIALA -DINA	21	25
DINA -TARKI	22	23
TARKI -MISSAKASWAL	18	17
MISSAKASWAL -SIHALA	37	46
SIHALA -RAWALPINDI	15	18