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Effective signaling system management on an upgraded railway:

The case study of Ghana Western Line

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Master's Degree in Transport Systems Engineering

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Abstract

Railway can be considered one of the best way to move goods and people all over the worlds, because of the low costs, high regularity and punctuality as well as the minimal environmental impact, in comparison with other transportation systems.

The railway system is one the most efficient and environmentally friendly transportation systems regarding to highly energy efficient, safe operation, and low CO_2 emission.

Train control is an important part of the railway operations management system. The railway signaling is a complex and fascinating subject and it is the key system to ensure the safe operation of railway traffic and it used to direct railway traffic and keep trains clear of each other at all times. Therefore, it is important to have a safe and reliable railway signaling system.

Railway signaling systems from the structural point of view are divided into two main categories named as Fixed-block signaling system and Moving-block signaling systems. In fixed-block railway systems, railway lines are divided into blocks with fixed-length and trains are moving according to the route reservation procedure whereas in moving-block railway systems, each train is regarded as a moving-block and more than one train occupancy is allowed in the same railway block.

Furthermore, this dissertation compares Moving-block signaling system with Fixed-block signaling system to show the differences of these two signaling systems according to some factors such as delay and running time for showing the result of this comparison in the research by applying the optimum timetable to the case study project.

The thesis illustrates simulation of the case study railway line (Western-line Ghana Railway) with optimal situation according to the existing demand with applying OpenTrack simulation software.

Finally, the research examines the effect of changing signaling system (the moving-block signaling system and fixed-block signaling system) in case study project with two separate railway lines, without any effect of opposite traffic on the project.

To summarize, the thesis demonstrates that the differences between two signaling systems (Fixed-block signaling system and Moving-block signaling system) and represents the more efficient signaling system according to some factors such as delay and running time in base on case study project.

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Chapter 1

1 Introduction

1.1 Railway Systems

The railway system is one the most efficient and environmentally friendly transportation systems. For example, some of the most significant characteristics of railway system are highly energy efficient, safe in operation, and low in CO_2 emission. Railway operation should be highly reliable.

Two major worldwide markets in railways are Main Line Railways and Urban Rail Transportation Systems (Metro, LRT (Light Rail Transit), Tramway).

Train control is an important part of the railway operations management system. Train movement safety and the control and management of trains depend on signaling system. Over the years many signaling and train control systems have been evolved so that today a highly technical and complex industry has developed.

1.2 Signaling Systems in Railway

Railway signaling is a complex and fascinating subject in research and development area in the railways. The purpose of a signaling system is to facilitate the safe and efficient movement of trains on the railway and ensuring the safe operation of railway traffic. Therefore, it is important to have a safe and reliable railway signaling system.

Signaling is one of the most important components of the railway system. Signaling is Mechanism by which the station master conveys information to the Loco driver to Stop, go with Caution or Proceed.

Railway signaling systems from the structural point of view are divided into two main categories named as fixed block (conventional) and moving-block signaling systems. In fixed-block railway systems, railway lines are divided into blocks with fixed-length and trains are moving according to the route reservation procedure whereas in moving-block railway systems, each train is regarded as a moving-block and more than one train occupancy is allowed in the same railway block.

Furthermore, there are many infrastructure and superstructure components in railway. However, Independent of the signaling category, the vital component of railway systems which provides safe travel and transportation is the signaling system is the interlocking system. Nowadays, by increasing speed and density of railway, the need of reliable and safe signaling systems in railway is much more important and crucial.

1.3 Aims and Objectives

The objective of this thesis is to find a more efficient signaling system for railway systems (between Fixed-block signaling system and Moving-block signaling system) in order to improve the railway control and signaling (RCS) systems along railway line. For this purpose, some factors such as delay and running time by applying a optimum timetable in the case study project (Western-line Ghana Railway) will be examined in this research. For simulating both fixed-block and moving-block signaling system in the case study project, the Opentrack simulation software will be used.

1.4 Structure of the Thesis

As first a brief overview of railway systems and signaling systems for railway including Fixed-block signaling system and Moving-Block signaling system are explained. Secondly, some factors such as delay and running time in different signaling systems in railways presented (chapter 2). As next it follows by description of case study project. (Chapter 3). This chapter represents some information about case study project (Western-line Ghana Railway) and a brief description of simulation software (Opentrack). In chapter 4, simulation of case study model for both signaling system (Fixed-block and Moving-block signaling systems) is presented. Then, the results of these two simulation model were analyzed according some factors such as delay and cost. Consequently, the best option is selected according to be more efficient and cost analysis. Finally, the conclusions, included in chapter 5, where results are analyzed and commented.

Chapter 2

2 Literature Review

2.1 Railway Systems

The railway network is a complex and distributed system with several technologies working together to fulfill the demands on capacity, speed and mobility to transport goods and passengers. The railway system can be divided into different systems depending on functionality, such as the rolling stock, the track, the power supply, the signaling system, etc. (1)

Railway can be considered one of the best way to move goods and people all over the worlds, because of the low costs, high (nominal) regularity and punctuality as well as the minimal environmental impact, in comparison with other transportation systems (2).

In general, a rail system consists of four domains: (3)

- the infrastructure on which the trains run (including its power supply, telecommunication, safety and traffic control systems);
- the rolling stock;
- the schedule, which defines the agreed offer; and
- the operation rules.

Operation rules thus impact the design and construction of both infrastructure and rolling stock and they decisively affect the rail system's performance and efficiency. Depending on technological or regulatory developments, the operation rules are adjusted continuously to enhance the effectiveness and competitiveness of rail traffic. Nowadays, infrastructure, rolling stock, and operation rules are designed in a way that passengers and goods can be transported to their destination as safely, quickly, punctually, cheaply and comfortably as possible. It must therefore not be forgotten that several principles are still based on ideas and solutions from the early beginnings of railway operation. Also infrastructure elements, applied technologies and rolling stock have been in use for many decades. Upgrading adjustments are thus not always possible (3).

The structure of the railway system and its processes are designed as a pyramid with several layers (Figure 2.1). The functional structure consists of several layers with an integrated control and communication system. This general structure is transferred from other automation industries and adjusted to the specific requirements and particularities of railway systems (3).

Figure 2-1: Functional structure for railway operations and planning

The bottom operational layer consists of the immediate production and its safety supervision. The transport product - the movement of passengers and goods by trains - is thus generated by commanding and controlling infrastructure and trains. The large geographical distribution of the network and the enormous amount of actions taking place at the same time are the specific characteristics of the operation of trains and infrastructure. A signaling system prevents or minimizes accidents and hazardous situations due to human errors or technical failures. A signalman in a local interlocking system or movement inspectors with remote control in centralized traffic control centers control the trains by setting routes. Thereby, also the sequence of trains on tracks can be set based on the specifications on the timetable and the actual situation (3).

The tactical layer within a railway system is used to supervise the network and to solve deviations, failures, interruptions or unplanned events. The superior overview of the location of all trains and infrastructure status allows conflicts to be identified and solved. This so-called dispatching process is executed by a few traffic management centers. Thereby, connections to be held and decisions with large impacts on trains are defined. Nowadays, dispatching and operation is functionally strictly separated for railway systems. Communication to give orders and measures is mainly carried out verbally by phone; system states and status reports can only be monitored but not directly accessed between the operational and the tactical layers. A closer connection or merging of both layers into a single unit is foreseeable and will improve rail operation’s efficiency (3).

Timetables are the basis of operations. Planning the schedule is a strategic task. However, the planning process can also be divided into several sub-levels, starting with long-term tasks and ending with the daily schedule. Experience based on past operational data analysis is used as an important input to enhance the schedule. Furthermore, the top-layer includes management tasks (for example investment strategies, archiving or accounting). These activities are not directly connected with the daily operational work and the time horizon can cover up to several decades (3).

The resulting hierarchical technical structure is visualized in Figure 2.2. Communication and information exchange between the layers depends on various requirements, for example safety, reliability, availability, or temporal demands and the actors involved. Use is made of telecommunication systems for oral and data exchange, computer networks with data-bus systems, documents as handouts, bulletins or leaflets, visual displays like signals, and so on (3).

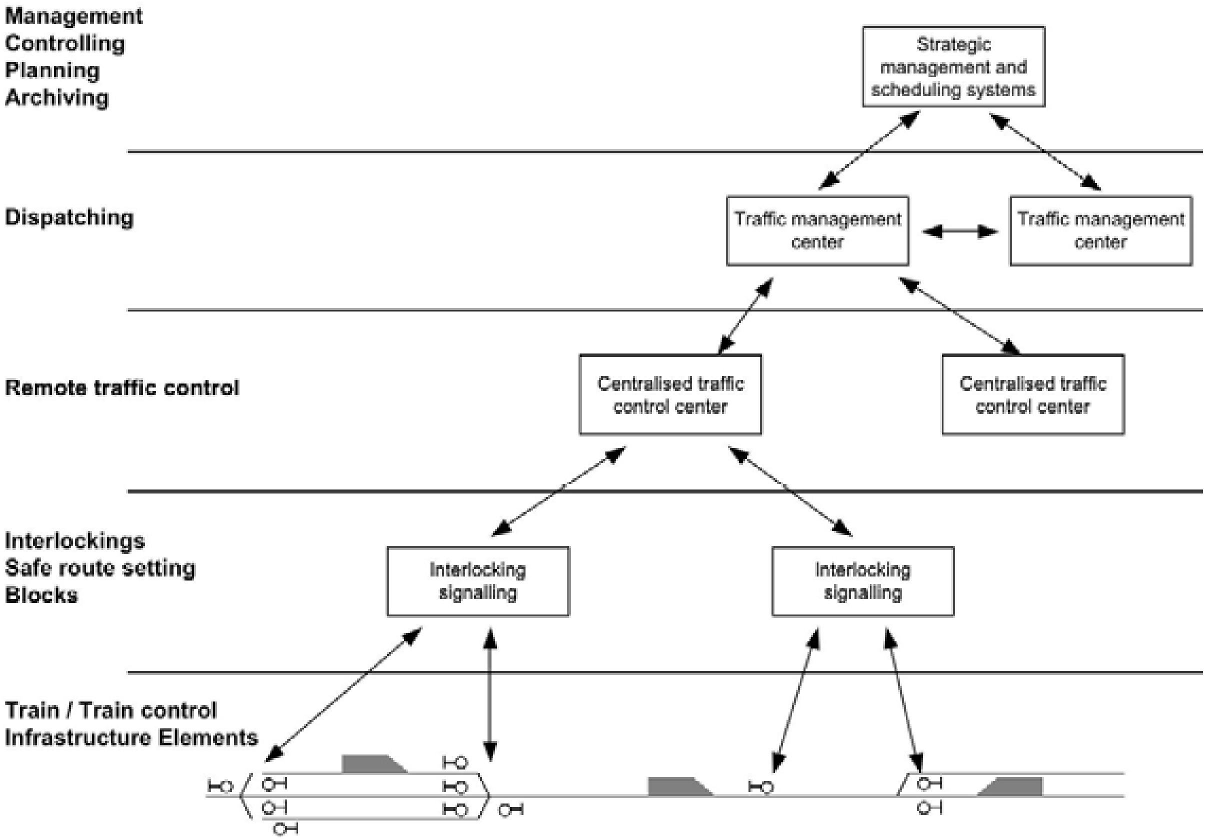


Figure 2-2: Hierarchical system structure for railway operations

The system structure is influenced by operating rules and developments in many fields but mainly in electrical engineering, telecommunication, and computer science. These principles result in the fact that rail operation is an extremely safe transportation mode even for high speed and hazardous goods. And additionally, up to a certain level of operated trains, the pyramidal structure also allows fast and flexible intervention whenever an error or disturbance occurs.

Safe, efficient and cost-effective operation is thus assured. Of course, the technical structure differs for rail networks with low traffic density, less automation or a different traffic management concept.

2.2 Railway Signaling Systems

Railway signaling systems are composed of several different systems; each has its own purpose, but the main functionality of the overall system is determined by the interoperability between them. Railway signaling systems ensure the safe operation of the railway network, and their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains. The functionality of the signaling system is based on the principle of “fail safe”; this means that the railway section where a failure is located will be not fully operative until the failure is repaired (since safety cannot be ensured). Hence, the dependability of these systems directly affects the capacity of the network (4).

Signaling systems are complex combinations of software and hardware; they play an important role in the control, supervision and protection of rail traffic, and their availability affects the performance of the whole system. Further complicating the issue is the fact that signaling systems are composed of several different systems; each has its own purpose, but the main functionality of the overall system is determined by the interoperability between them (4).

The primary purpose of a signaling is to keep trains safely separated by providing enough distance to stop the train in case of failure. However, this distance cannot be too long, otherwise delay can happen and instead of a train arriving every three minutes, trains may arrive every five minutes, it means that headway between trains will be increased.

Railway signaling system is needed for ensuring the safe operation in rail traffic. The signal devices are located on the side of railway line to give information of the state of railway line ahead to train drivers. A generic interpretation of the control loop of the railway signaling system is presented in Figure 2.3. (5)

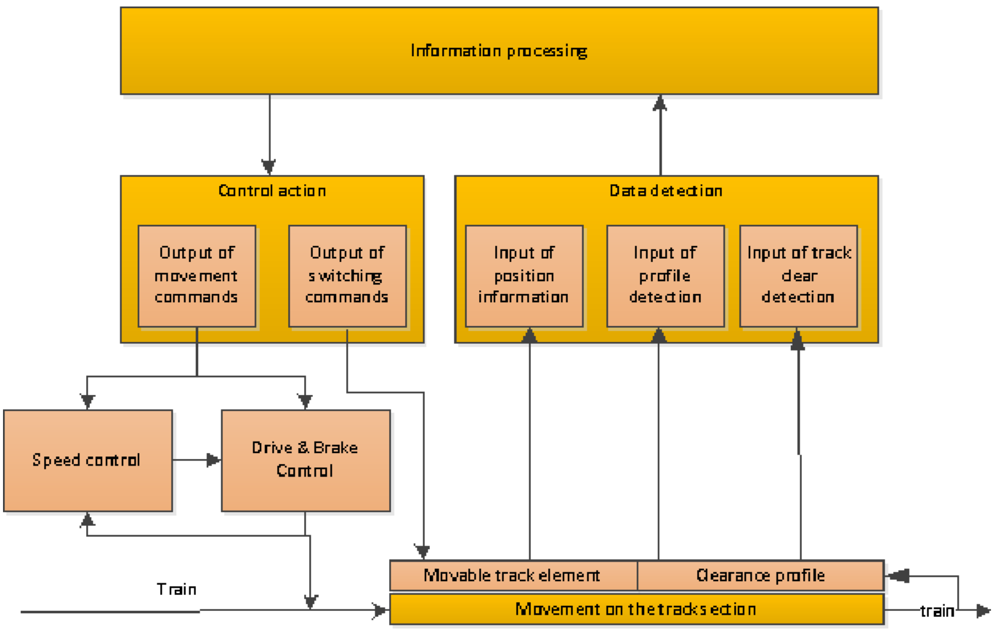


Figure 2-3: Control loop of the railway signaling system (6)

The development of signaling is closely linked to the development of railways. It began as a manual system determining access to a line, but the growing demand for transportation and the increasing number of trains made this system inadequate. Advanced technologies were implemented to supervise and control railway lines. These were mainly analogue systems, based on relay technology (e.g. track circuit, axle counter, relay interlocking). Today these systems are being replaced by digital control systems based on electronics (e.g. balise, electronic interlocking, lineside electronic unit – LEU), but both systems coexist in most of the railway network. Over the years, many signaling and train control systems have evolved, creating a highly technical and complex industry. Every country has developed different solutions over the years. The operation of trains must not be country-dependent, however, and the creation of a unified signaling system would prevent the need to make changes between countries. In order to achieve interoperability between the control and supervision systems, several contributions via standardization have been made (UNISIG SUBSET 026, 2011; EIRENE SRS, 2006). Standards have been developed for the RAMS of the different railway systems (EN 50126, 1999), with special focus on the systems for signaling, communications and processing systems on the railway (EN 50128, 2001; EN 50129, 2003). These standards aim to enable interoperability while ensuring safety (4).

There are a number of items within the larger category of signaling systems. For example, track circuits, axle counters and GPS-based systems can be used to locate a train. Track circuits and signals can help to control the traffic on the railway line to prevent collisions. Balises and radio based systems allow the train control centre to restrict the movement of trains, and advanced systems i.e. European Rail Traffic Management System (ERTMS) or Automatic train control system (ATC), supervise and control the railway network. They interpret the inputs from the other systems, creating restrictions on the train route to ensure safe operation. An example of the parts of a signaling system and their relationship is shown in Figure 2.4 (4).

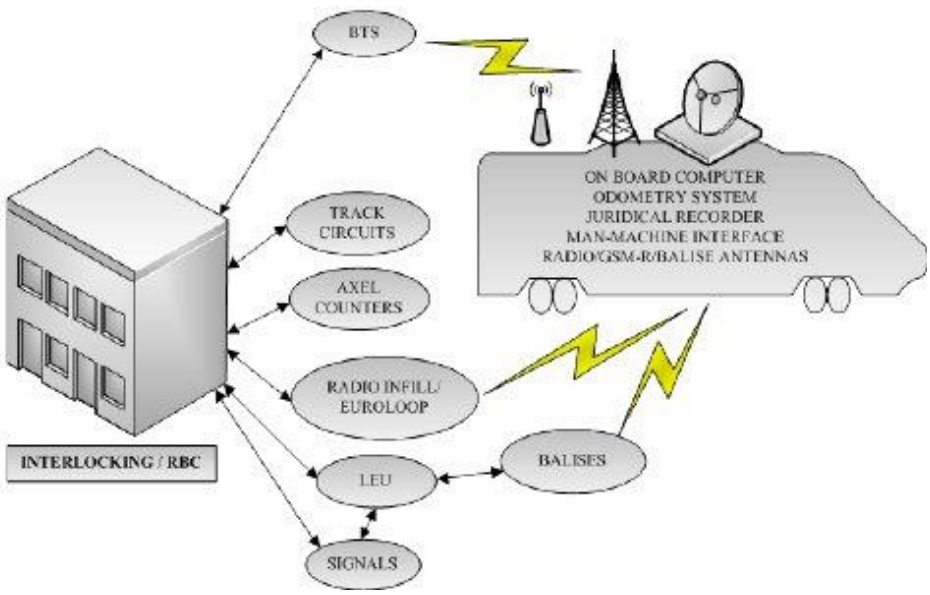


Figure 2-4: Different signaling systems and their interfaces

The various systems, such as track circuits or level crossings, provide input to interlocking systems and radio block centre systems (RBC). Interlocking systems receive information, process it and make new restrictions on system components. For example, they can provide information to onboard signaling systems through the GSM-R system, by means of the base transceiver stations (BTS) located along the railway network. The onboard signaling system is composed of a centralized computer that processes the different inputs, giving supervision during the train's operation. An odometry system constantly measures the speed and acceleration of the train. The balise antenna reads the information from the balises placed on the track. The man-machine interface allows the driver to interact with the onboard computer. The juridical recorder records the information generated during the operation (e.g. driver operations, balises and odometry information, etc.). Other systems, such as the GSM-R or the radio infill, exchange information between the wayside signaling system and the onboard signaling system. Some auxiliary systems, such as the Lineside electronic unit (LEU) whose purpose is to exchange information between wayside systems, do not depend on the interlocking system to process information (4).

Railway signaling systems are composed of several different systems that have their own purpose but the main functionality is given by the interoperability between them: the supervision and protection of the railway network will not be possible if any of the items of the signaling system do not work properly or there is a lack of interoperability between them. Signaling systems are challenging to model, given the amount of information derived from both software and hardware in the various locations of the systems' many devices (7).

Previous studies have shown the importance of signaling systems on the dependability of the railway network. Signaling systems supervise and control the railway operation with different technologies installed both in the infrastructure along the track and in the rolling stock. To operate on a specific railway corridor, the signaling systems of train and infrastructure must be interoperable (4).

The signaling system is composed of the following sub-systems: (8)

- Interlocking (IXL) / Radio Block Center (RBC): receives input from the different systems (e.g. track circuits, level crossings, signals, TMS), calculates and returns as an output the train operation restrictions to ensure safe traffic operation.
- Track circuits: responsible for the train location.
- Balise group: input from the track to the onboard signaling system (e.g. speed limits, driving mode, etc.).
- Level crossings: coordinate the road traffic crossing the railroad.
- Traffic management system (TMS): interface between the traffic operator and the railway network.

- Signals: give or restrict permission to the train to enter a track section.
- Signaling boards: inform the train of fixed information (e.g. tunnels, bridges, speed restriction area, etc.).

2.2.1 Interlocking Systems

The methods behind railway signaling system are information transmission and information processing. The function of information processing is typically realized by interlocking. The purpose of interlocking is to connect the track elements and signals. This can be achieved by means of data detection and control action. Here data detection includes discovering the position information of the movable track elements and information of track occupation. Control action involves evaluating the received information and giving instructions to the train drivers via signals. These two actions form the basic principles for interlocking functions (6) :

- A train movement can be permitted only if all track elements are in desired positions and locked.
- It is only allowed to enter a section for one train, no other train may be permitted to enter that section.

An interlocking system has many functions. Generally, they can be categorized into three levels of functions: operation control level, interlocking level and element control level. They are defined as (6):

- The **operation control level** includes the interface to the signaler and may include different non-vital functions of automatic operation control such as automatic train routing etc.
- The **interlocking level** includes the vital functions to interlock signals, routes, movable track elements, block applications with each other.
- The **element control level** includes functions of commanding, power and information transmission to and from the field elements, such as signals, movable track elements, track sections, level crossing etc.

Since the safe operation of railway is always primary concern, different technologies have been implemented for those interlocking systems to ensure the safety worldwide in the rail transport. They are human interlocking, mechanical interlocking, electric (relay) interlocking and electronic interlocking (5).

The oldest solution for interlocking is the human interlocking. Human is in charge of checking the preconditions for clearing signals, switching movable track elements and for transmitting information to the field elements by walking between them (6).

The mechanical interlocking system was introduced in the late 1800's, see Figure 2-5. In mechanical interlocking system, the mechanical levels that are interlocked with each other are operated by signaler. The safety of this system is secured by using robust mechanical and/or electrical components (6).

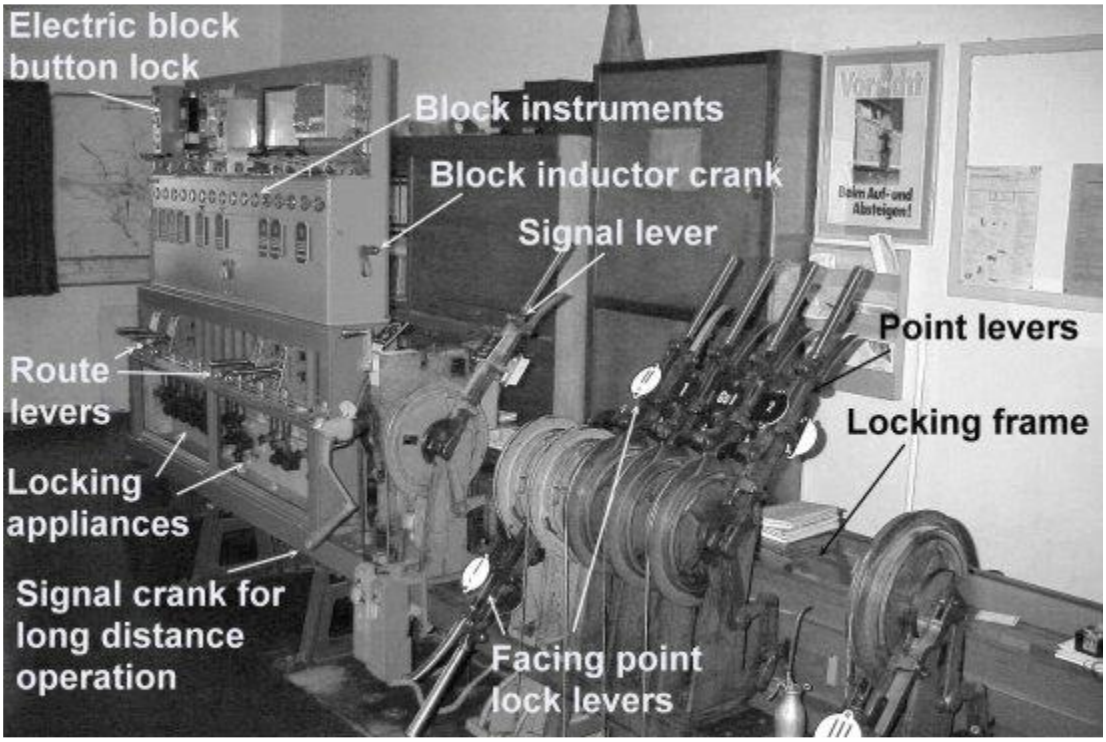


Figure 2-5: Mechanical Interlocking System (9)

Relay-based interlocking system was introduced after mechanical interlocking system. A signal relay is specially designed for the safety-related operation. The interlocking consists of complex circuitry implemented by relays and the field elements are operated and controlled purely electrically.

Electronic interlocking systems became prevailing after 1980s. The systems have high degree of complexity and are easily affected by external influences. The interlocking functions are programmed by software, and the hardwares are made by electronic components which are not robust as mechanical components. These cause that the inherent fail-safe design is hardly applied to electronic interlocking systems as before. To increase the reliability, hardware dependency are widely used in electronic interlocking systems. There are three major forms of system redundancy, depended on special national requirements, in various electronic interlocking systems. (5)

Signals and switches are controlled from signal boxes as they are known. Points and routes are thus interlocked to ensure safe movements. In most signal boxes, the interlocking apparatus only controls points and signals over a short distance. For modern (relay and electronic) interlocking systems, it is technically possible to remotely control several interlocking together from a single central command center by movement inspectors (3).

Several additional features can thus help to increase the level of automation (3):

- a track clear detection systems is needed to detect whether a block section is occupied or available for a next train;
- a train describer system is needed in order to assign a train number to the occupation of a block; and
- an automated route setting system where alternative routes are stored and can be set automatically in the case of a conflict or occupancy.

Consequently, automation and, in particular, the remote control of interlocking is an important precondition for efficient and cost-effective rail operation (3).

2.2.2 Track Circuits

Track circuit is the fundamental method of train detection. The first track circuit, based on a DC technology, has been invented at the end of nineteenth. Over the years, the continuous technological development has enabled to realize track circuits in an increasingly performing way by using AC technology and modulations, but the basic principle for train detection is still the same. An alternative approach is the Axle Counter system, which uses a "check-in/check-out" logic. By comparing the result for the axles counted in a block section with the result for those counted out, it is possible to know the status of the track section (free or occupied). Track circuits contributes also for the vehicle's speed control, since the electrical signals used for train detection can be exchanged between wayside and on-board for the transmission of speed commands. This can be realized through a modulation of the track signal and is known as "coded track circuits". Perhaps, no single invention in the history of the development of railway transportation has contributed more towards safety and dispatch in that field than the track circuit. (10)

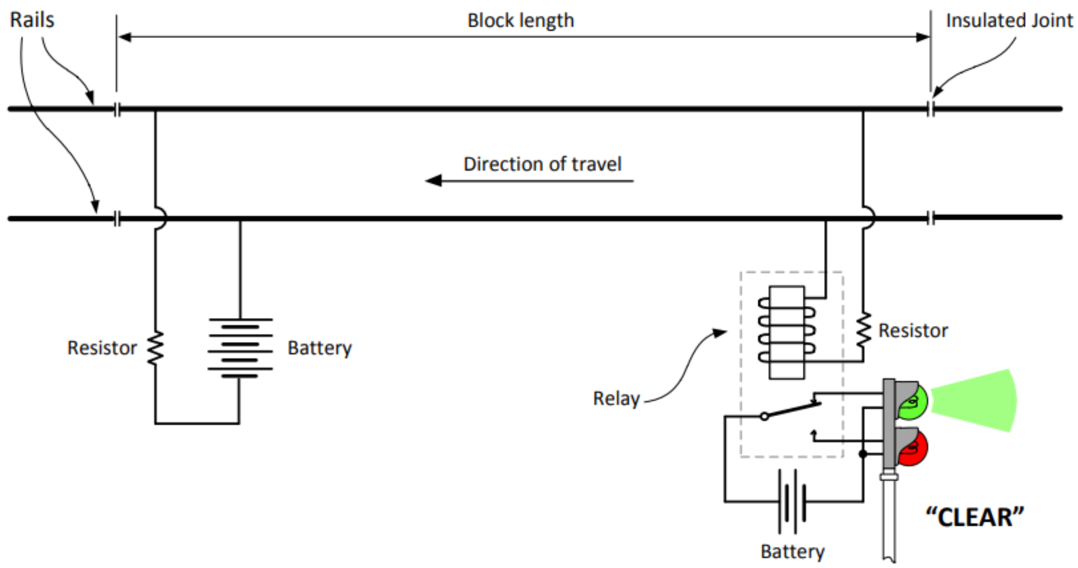


Figure 2-6: Unoccupied Block

When a train approaches the block, its wheels and axles connect the two running rails together shorting the battery and thereby reducing to zero the current through the relay. This causes the relay to "drop" (Figure 2-7), turning off the green signal light and turning on the red light to indicate that the block is occupied by a train. A series resistor with the battery protects it by limiting the current that it must provide when a train is present. (10)

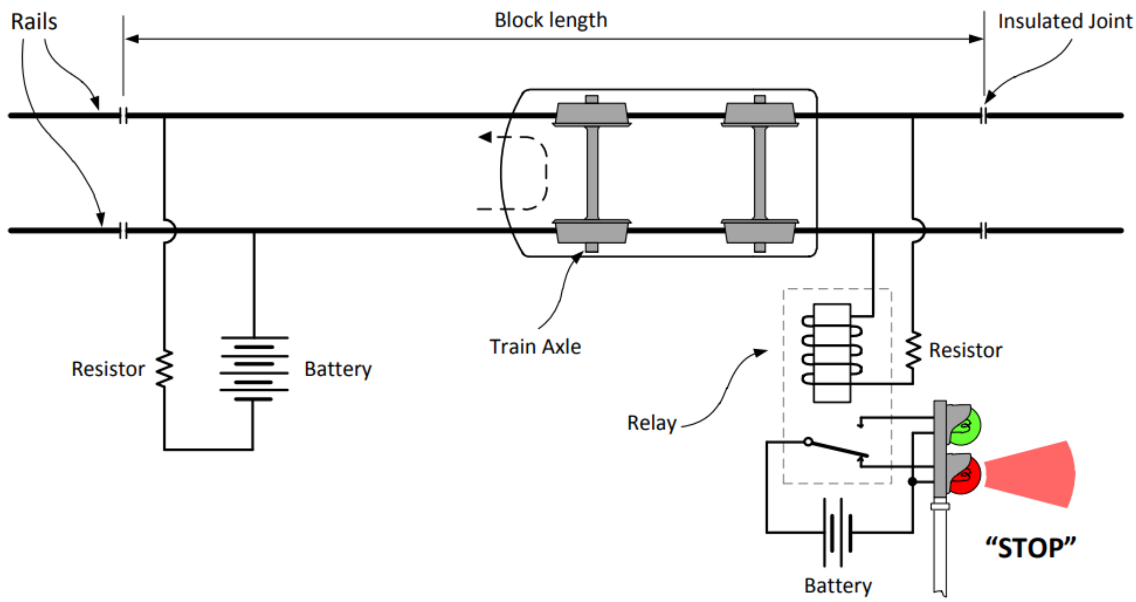


Figure 2-7: Occupied Block

2.2.3 Balise Group

A balise is a physical equipment installed on a sleeper (e.g. wood or concrete sleeper). The balise does not require external power supply; it is activated/energized by a specific equipment and related antenna installed on a train. The function of a balise is mainly to send information (fixed or variable) to the on-board that energizes/activates it. (11)

Figure 2-8: Balise

Balise is an electronic beacon or transponder placed between the rails of a railway as part of an automatic train protection (ATP) system. Transmission device (passive transponder) that can send telegrams (or tele-powering) to an on-Board subsystem passing over it. The on-board system tracks the train's location by counting wheel rotations, and correcting at fixed locations known as balises. Balises constitute an integral part of the European Train Control System, where they serve as "beacons" giving the exact location of a train. A balise which complies with the European Train Control System specification is called a Eurobalise.

2.2.4 Level Crossing

A level crossing is a place where a railway is crossed by another type of way on the same level. There are about 120,000 level crossings in the EU. On average, there are five level crossings per 10 line-km in the EU. Level crossings represent the largest single risk of catastrophic train accident on European railways. In 2010, 619 significant level crossing accidents occurred in the EU resulting in 359 fatalities and 327 serious injuries. Level crossing accidents represent 27 % of all significant railway accidents and 28 % of all fatalities on railway, suicides excluded. At the same time, only one in one hundred of road users that die each year on EU roads dies on level crossing. Economic impact of fatalities and serious injuries in level crossing accidents in 2010 is estimated at EUR 350 million. Costs of delays due to level crossing accidents are not available at EU level, but level crossing accidents have damaging impact on the key strengths of the rail transport: safety, reliability and speed.

In physical terms, a level crossing is a comparatively simple thing. Legally, it is much more complicated. The legislation governing level crossings is complex and antiquated, much of it dating back to the nineteenth century when the main railways were constructed. The provisions relevant to level crossings are difficult to access. This arises partly because they are spread across legislation relating to a number of different subject areas – railways, highways/roads, health and safety, planning and criminal law. Furthermore, the provisions are contained in a combination of public general Acts, private Acts, bye-laws, and subordinate legislation in the form of Orders and Regulations, many of which have been amended heavily in recent years. More specifically, under the current system, the procedure for making generic changes to the protective measures at level crossings is cumbersome and expensive. In addition, the procedures for closure of level crossings are complicated and time-consuming. (12)

2.2.5 Traffic Management System (TMS)

TMS is an autonomous system for the complete real-time management of railway traffic over a given network.

The goal of the TMS is to execute a predefined plan as well as possible, given a certain optimization criterion. The TMS detects and solves future conflicts and generates a new conflict free plan by shifting timetable target times and exploiting alternative routes. The TMS also supports the implementation of this plan by giving advisory speeds (or time-location-speed slots) to train drivers and advices about routes, route setting times and order changes to dispatchers.

The TMS is highly suitable to support dispatchers, solving routine conflicts with a high level of automation (which can be adapted to the desires of a dispatcher), thus freeing the dispatcher of this work so that he/she can focus on tactical decisions and also preventing that small deviations become large ones by intervening at an early stage.

Even problems with a limited number of trains on a limited network (e.g. 5 trains approaching's Hertogenbosch from different directions) have many solution possibilities and involve many relevant details, while there can be large differences in quality between various solutions. This quickly grows beyond human capabilities and response times. At the same time, computers are very good at this.
On the other hand, humans are very good at a tactical level, requiring a broader overview and creativity, dealing with problems that as yet cannot easily be formulated in mathematical terms or are too complex to solve.

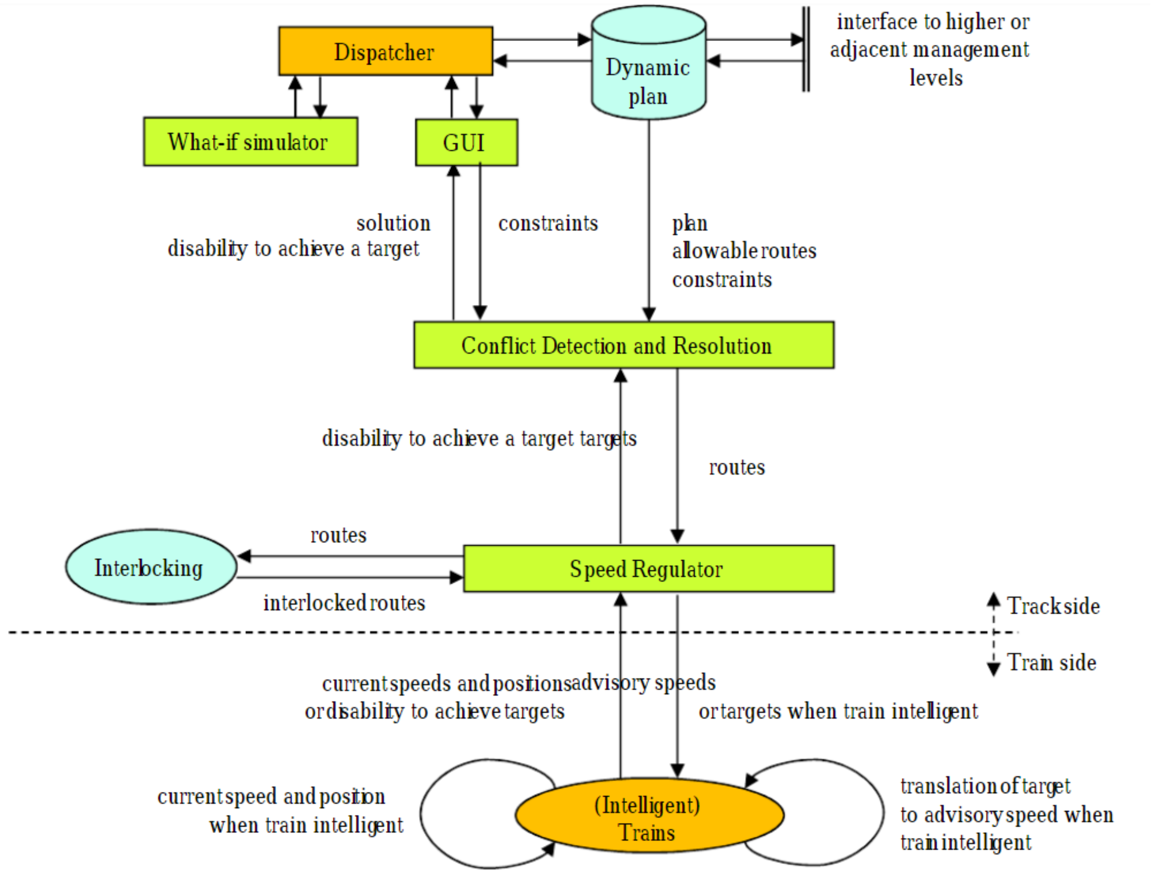


Figure 2-9: Traffic Management System (TMS)

The Rail system is not unique, not in process, not in complexity, not in operator interfacing needs. Decision support and control systems have been implemented successfully for similar systems. Clearly, a step by step approach in implementation is advisable. Due to its modularity TMS is suitable for this.

In simulation studies and a pilot implementation TMS already has shown its value, increasing punctuality, reducing energy consumption and reducing the number of non-commercial stops for freight trains.

2.2.6 Signals

Railway signal is a visual display device that conveys instructions or provides advance warning of instructions regarding the driver's authority to proceed. The driver interprets the signal's indication and acts accordingly. Typically, a signal might inform the driver of the speed at which the train may safely proceed or it may instruct the driver to stop.

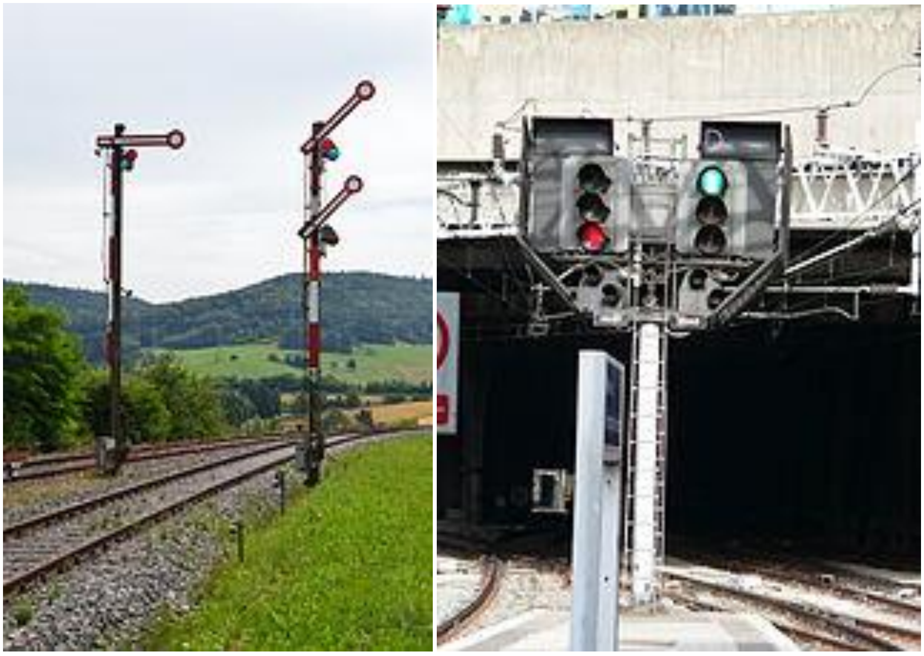


Figure 2-10: Semaphore Signals (left) & Color-light Signals (right)

Originally, signals displayed simple stop or proceed indications. As traffic density increased, this proved to be too limiting and refinements were added. One such refinement was the addition of distant signals on the approach to stop signals. The distant signal gave the driver warning that he was approaching a signal which might require a stop. This allowed for an overall increase in speed, since train drivers no longer had to drive at a speed within sighting distance of the stop signal.

Under timetable and train order operation, the signals did not directly convey orders to the train crew. Instead, they directed the crew to pick up orders, possibly stopping to do so if the order warranted it.

Signals are used to indicate one or more of the following:

- That the line ahead is clear (free of any obstruction) or blocked
- That the driver has permission to proceed
- That points (also called switch or turnout in the US) are set correctly
- Which way points are set
- The speed the train may travel
- The state of the next signal
- That the train orders are to be picked up by the crew

Signals can be placed:

- At the start of a section of track
- On the approach to a movable item of infrastructure, such as points or switches or a swingbridge
- In advance of other signals
- On the approach to a level crossing
- At a switch or turnout
- Ahead of platforms or other places that trains are likely to be stopped
- At train order stations

'Running lines' are usually continuously signaled. Each line of a double track railway is normally signaled in one direction only, with all signals facing the same direction on either line. Where bidirectional signaling is installed, signals face in both directions on both tracks (sometimes known as 'reversible working' where lines are not normally used for bidirectional working). Signals are generally not provided for controlling movements within sidings or yard areas.

Signals were originally controlled by levers situated at the signals, and later by levers grouped together and connected to the signal by wire cables, or pipes supported on rollers (US). Often these levers were placed in a special building, known as a signal box (UK) or interlocking tower (US), and eventually they were mechanically interlocked to prevent the display of a signal contrary to the alignment of the switch points. Automatic traffic control systems added track circuits to detect the presence of trains and alter signal aspects to reflect their presence or absence.

2.2.7 Signaling Boards

Signaling boards give the driver fixed information (e.g. tunnels, bridges, speed restriction area, etc.) (13).

To ensure safe operation, a track section is supervised by an interlocking located at the end of that section, usually at a station. Signals are placed at the entrance of every section and sometimes in the middle to allow or restrict the passing of a train into that section. Signals restrict the passing of a train when a failyre occurs on a track circuit or an interlocking, and warns it to circulate with caution when there is a failure in a level crossing. When a signal fails, the balise group associated with it will force the train to stop. If a balise does not work properly, it will produce an emergency brake (EB). A single TMS fails, the operation has an automatic mode that allows normal operation for a maximum of 2 hours. After that time, operation is not possible. If there is a stoppage of operation caused by a failure on the signaling system of a track section, railway operation can still be possible on that section if the dispatcher allows the driver to circulate with caution in a degraded operational mode. In this case, the maximum speed is 40 km/h and the driver's visual supervision is required to ensure safe circulation (e.g. there is no damage in the track; the switch is in the correct position etc.). (13)

The operation time between failure is represented by the total duration of operation time between two consecutive restorations. Signaling systems supervise the railway at all times, not only when a train passes, making them continuously operating items. Therefore, all maintenance time will affect the operation of the signaling system. (13)

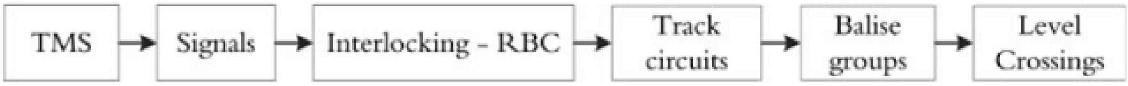


Figure 2-11: RBD of a Signaling System

Railway signaling systems are mainly divided into two main groups on a railway block basis, which is consist of **Fixed-block signaling systems** (conventional railway signaling systems), in that railway lines are partitioned into blocks with fixed length, and **Moving-block signaling systems**, in that the sum of the length of train and its braking distance is considered as a moving block. In this chapter, basic definitions of these two signaling systems are presented.

2.3 Fixed-Block Signaling Systems

Fixed-block signaling is a solution based on a technology invented in the 1860's.

Fixed-block signaling creates an artificial separation between trains. Fixed-block signaling divides the track into small blocks which determines how far apart trains will be kept for safety and how frequently stations will be serviced.

Looking back over the past few decades, railway signaling technology has been based mainly on the so called "Conventional Fixed-Block System" principle.

Traditional signaling systems are based on fixed blocks: the railway is divided into sections of track, which are separated by signals. A train is not allowed to enter a given track section (=block) before the preceding train has cleared it.

This system has a number of disadvantages, one being its lack of flexibility: the block size is the same for all trains regardless of their speed and braking performance. Thus the big safety distances required by fast trains are imposed on slower trains as well. Obviously this reduces track capacity.

The fixed-block technology inherently imposed a service limitation because of the need to reserve buffer block(s) for train separation. With increasing patronage, demand grew to achieve higher line capacities on existing rail infrastructures. In order to realize this requirement without major upgrades to the rolling stock and rail infrastructure, intelligent signaling and train control systems have become a crucial technology for the new age of rail systems and services. The distance-to-go principle has therefore been developed on the "Fixed-Block System," which provides flexible control of the buffer block(s) for train separation.

In fixed-block railway signaling systems, railway lines are divided into fixed length subsections, named as railway blocks. The length of a railway block is determined according to different variables such as the permitted line speed and the gradient of the railway line. Each block has entrance and exit signals with different types depending on the location of the signal (14). Dispatchers (responsible officers) request routes for incoming and outgoing trains in the region of their responsibility (15).

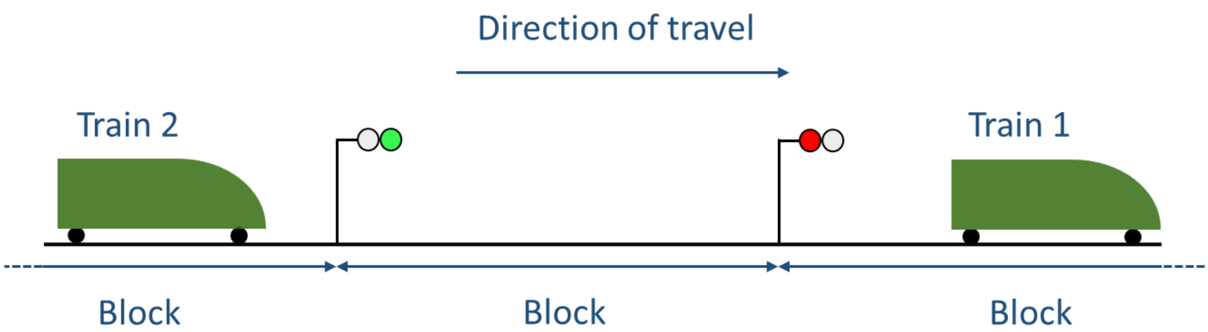


Figure 2-12: Fixed-block Signaling System (16)

Figure 2-12 represents blocks are defined as the distance between two signals. Trains are prevented from colliding by ensuring that only one train is allowed into a block at once (16).

In fixed block signaling, movement authority is provided by signals that instruct train divers on whether to stop or to progress through a block. Movement authority is given to a fixed point on the track - i.e. the location of the next signal. Train detection equipment, for example electrical circuits built into the track, can detect whether a train is occupying a particular block. Other track-side equipment (known as interlocking) analyses information from the train detection equipment to determine whether a block is available for a train to move into, before the signals can give a train permission to move (16).

Typically, the lengths of the blocks on a particular route are chosen to safely accommodate the fastest trains with the longest stopping distances. Stopping distances vary between trains because of a number of factors, such as the speed of the train, the age of the brakes and the weight of the freight being transported. Fixed block signaling therefore prevents better-performing trains with shorter stopping distances from travelling closer together. In some cases, block lengths are chosen to optimize capacity for the trains that use the line most frequently. Trains with longer stopping distances can still use the line, but are run at a reduced speed (16).

An automatic fixed block signaling system consists of lineside signals and train detection devices (axle counters). In its basic form, it uses fixed block sections, which are protected by signals. Signals allow control of the traffic on the network, and to avoid collisions among trains. A block section is a track segment between two signals, which may be red, yellow or green. A red signal means either another train occupies the subsequent block or it is not in use, a yellow signal means that the subsequent block section is empty but the following block section is occupied, and a green signal means the next two block sections are empty ensuring the train ride without any obstruction. Thus, a train is allowed to occupy a certain block section either the signal released is green or yellow. The later indicates the train driver to decelerate to 40 km/h, keeping this “sight” speed until the next indication. Due to safety reasons, it is assumed that a block section must be at least as long as the braking distance required for a train running at the maximum allowed speed.

Travelling time in each block section is called block running time, calculated according to the physical characteristics of the railway infrastructure and rolling stock, and also the running time supplements added as scheduled running times to recover the planned operation. Besides, this running time can also include dwell time at stops and surrounding acceleration or deceleration times.

The time interval in which a block is allocated to a train and blocked for other trains is called blocking time (17) the blocking time is the most important design variable to estimate infrastructure capacity and to design schedules. The minimum time between two succeeding trains, or headway as it is known, is determined by the blocking time (3). The headway is the interval between two following trains. The minimum headway on a line with a fixed block system depends on the blocking time, the time interval in which a section of track is exclusively allocated to a train and therefore blocked for all other trains. In this sense, the blocking times describe the occupation of the infrastructure sections. The blocking time is longer than the block running time, and it consists of:

- Time for clearing the signal
- Sight and Reaction time to view the signal aspect
- Approach Time between the signal that provides the approach indication and the entrance signal
- Time between block signals: Block Running Time
- Time to clear the block section, including safety margin of one train length
- Release time to "unlock" the block system

Figure 2-13 illustrates that the blocking time is significantly longer than the time used to pass the block distance. The occupation and clearance of a track section is detected by a track clear detection device, which could either be implemented by axle counters or track circuits, or by human staff (3).

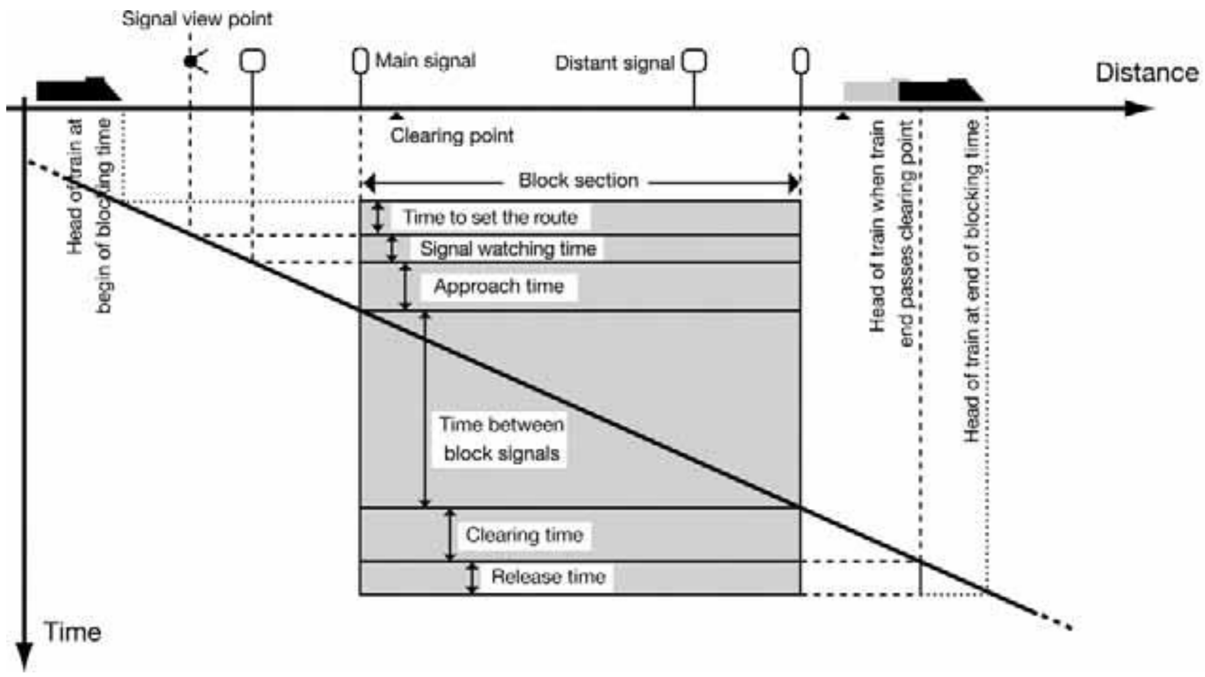


Figure 2-13: Elements of the blocking time

It is possible to detect the position of a train using track clear detection devices. This information is used by dispatchers to detect deviations and possible consequential conflicts. This position and time information is discrete data in general. Between two detection points no information about a train is therefore available. Continuous train detection systems are available, but are not widespread due to their high cost (3).

Automated route setting and releasing based on track clear detection systems helps to minimize the fixed, train-independent system times for route setting and releasing. Having a total route setting and release time of almost two minutes for mechanical interlocking and manual block systems in the 1970s [43], these times are minimized for automatic systems to a few seconds nowadays depending on the complexity of interlocking area and conflicting routes (3).

In the case of a cab signaling system, the fixed minimum approach time (depending on the distance between the distant and main signal and the track speed) can be replaced by the duration based on the braking time depending on the actual, specific speed and position (braking curves). Therefore, the use of cab signaling systems can reduce blocking times.

By stringing together, the blocking times along the line on which a train is running, the blocking time stairways in the time-distance diagram represent the use of the infrastructure perfectly (Figure 2-14). The minimum headway of two trains between two stations, overtaking or crossing points may accordingly be determined. In addition, conflicts in the schedule or during operations can be identified (3).

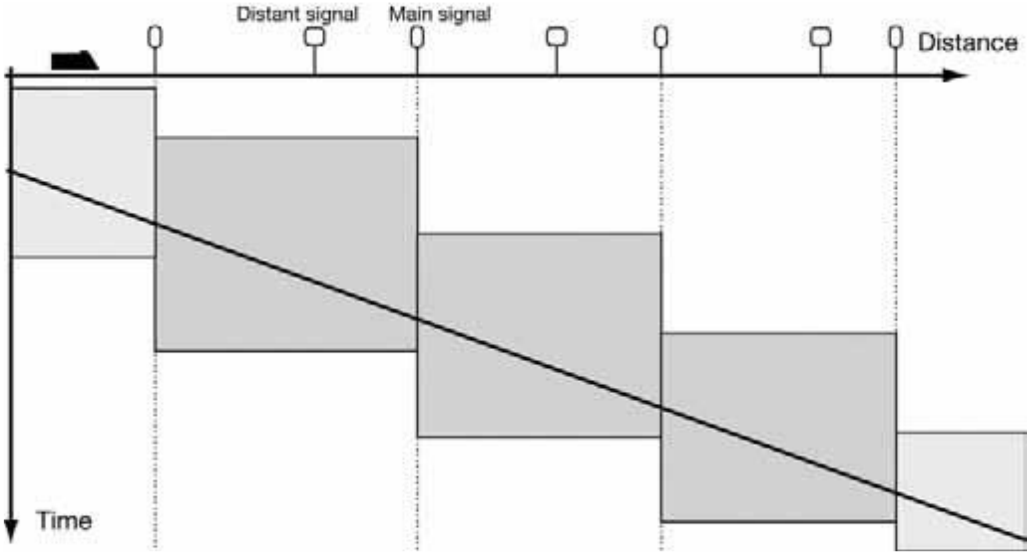


Figure 2-14: Blocking time stairways

Blocking time stairways show that the number of trains operating on a track section is maximized when the blocking time for each train and the speed differences between the trains are minimum. Another insight is that capacity is improved by reducing the block distance. And finally, blocking times depend on train speeds. Higher speeds, on the one hand, reduce the occupation time for the block section, but increase approach time because of the braking distance extension on the other hand. This leads to a non-linear dependency between travel speed and minimum headway time. Depending on the safety system (especially the fixed block length) and braking coefficient, the optimum travel speed to minimize the headway (and maximize capacity) is between 60 and 100 kilometers per hour (18)

2.3.1 Components Fixed-Block Signaling Systems

The components of fixed-block signaling systems are given in below: (19)

Traffic Control Center: is responsible for all railway traffic by providing an interface between the interlocking system and the dispatchers. Dispatchers (responsible officer) may send several requests to the interlocking system for evaluation such as route reservation request, point machine position request or field component blocking requests. Another main responsibility of the traffic control center is to log and monitor the train movements. (19)

Interlocking system (Signaling System Control Software): The signaling system control software, namely, the interlocking system (IS) receives the requests of the traffic control center, and evaluates these requests of the dispatchers for a final decision. The requests of the dispatchers can be accepted or rejected according to the safety restrictions. Then, it sends proper commands to the railway field equipment, if necessary. The design, development and the testing process of the interlocking system should be carefully handled and realized with respect to the related functional safety requirements (20).

Railway blocks (RBs): are the subsections of the railway lines with fixed-length. The entrance and exit of a RB is equipped with signals to inform train drivers. The location of the trains are detecting by using simple electrical circuits know as track circuits or devices known as axle counters. (19) The occupation of a train in a railway block is detected by the help of track circuits or axle counters (21). Depending on the length of the block, one or more track circuits are used. Track circuits operate according to the short-circuit principle. By the entrance of a train into a railway block, the track circuit is short-circuited by the axles of the train. In this situation, the interlocking system considers that the related block is occupied. TCDD uses three different types of track circuits, namely, DC-type, AC-type, and Jointless-type track circuits (14). On the other hand, axle counters can be used to detect the train locations. The counter heads of the axle counters are located at the intersection points of the railway blocks and count the train axles. The railway block is assumed to be occupied until the total number of the incoming axles becomes equal to the total number of the outgoing axles. (15)

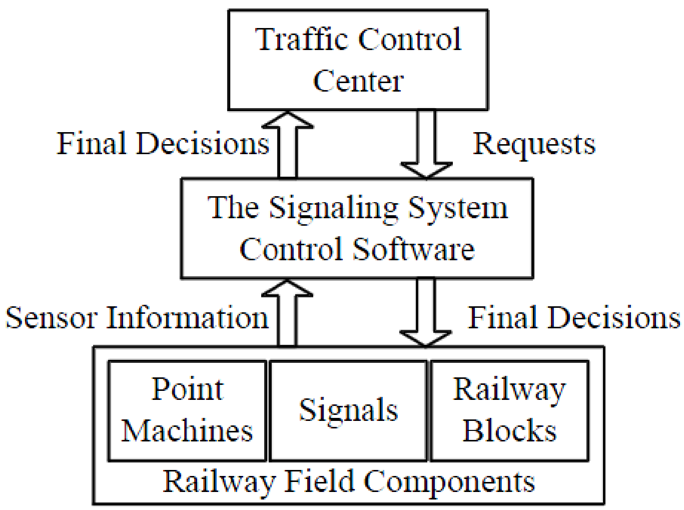


Figure 2-15: General Block Diagram of a Fixed-block Signaling System

Signals (SLs): are used to inform the train drivers about the situation of their way. Even different colors and their combinations are in use and differ from country to country, the red color and the green color have similar meanings. Turkish State Railways use the red color to denote the next two RBs are occupied whereas the green color denotes the next two RBs are free. The yellow color denotes the next RB is unoccupied but not the RB after the next. Depending on the topology of the railway field, an additional yellow color is also used by Turkish State Railway to denote the line change. Generally, this additional yellow color is placed at the bottom of the signal before entering point machine regions. (19)

Since every country has its own signaling principles and safety standards, the use of colors of railway signals and their combinations may vary from country to country. Railway signals inform train drivers of the occupation of the next block. The train drivers have to pay attention to the signals on the right side with respect to their direction of movement. For example, in the TCDD, the meaning of the red color is that the next block is occupied, whereas the yellow color means that the next block is free but not after the next block. The yellow color also permits a train to proceed with reduced speed. The green color indicates that the next two blocks are free and the train can proceed. The Japanese Railways uses red, yellow, and green signals with their combinations and the North American Railways uses purple and amber signals. Signals are generally located at the entrance and exit of railway blocks. (15)

Point machines (PMs (Points, Railway Switches)): are devices which enable trains to pass from one railway line to another. They are established in certain locations where track change is needed. They have two location indicators known as normal and reverse. A PM can be operated either by a route reservation request or manually via traffic control center. The position of a PM can be controlled by the TCC either manually or automatically. PMs can also be controlled by the officers in the railway field by using a metal bar (lever). (19)

General representation of a fixed-block signaling system is illustrated in Figure 2-16. (19)

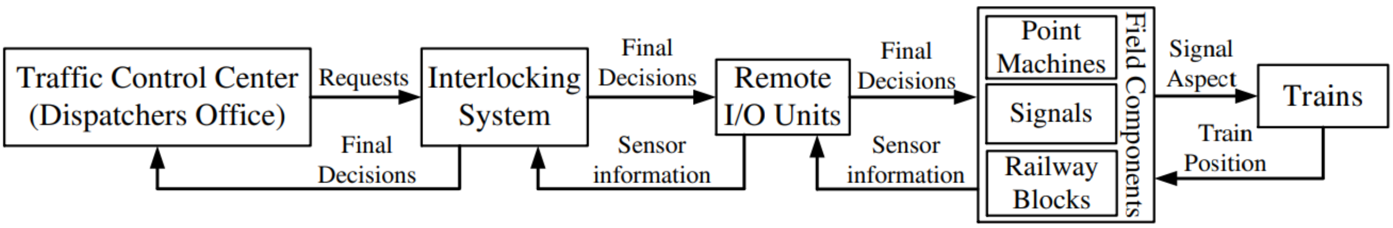


Figure 2-16: General Representation of a Fixed-block Signaling System

2.4 Moving-Block Signaling Systems

Today with the power of microprocessor based systems, there is another option called Moving-block signaling systems. It was a changing process from the traditional view of signaling for the new concept.

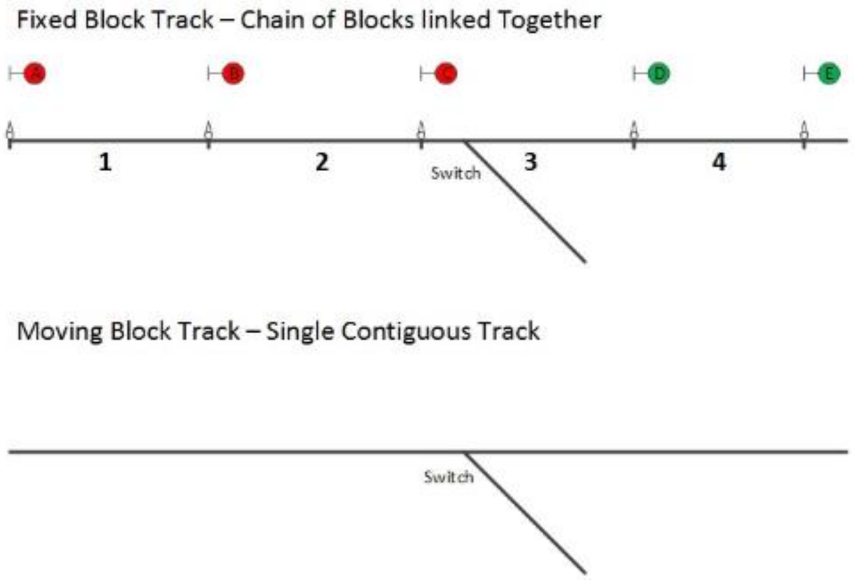


Figure 2-17: Different between Fixed-block & Moving-block signaling systems in schematic view

Trains are moving according to a route reservation procedure in fixed-block signaling systems. Trains cannot enter the same railway line in opposite directions and must leave at least one block while moving on the same railway line in the same direction. Briefly, for each block, at most one train is allowed to move. Since trains need a long stopping distance that depends on different variables such as mass of train, brake reaction time, or type of brakes etc., the length of the blocks have to be determined carefully. As it is obvious, it is not possible to use the overall capacity of the railway lines efficiently (14).

Moving-block signaling systems provide more efficient use of the railway lines by enabling multiple train movements on the same block, especially on metro and urban lines. Moreover, the moving-block signaling system increases the transport capacity and reduces headways. A moving block is defined as the sum of the length of the train and the safe braking distance (15).

Moving-Block System, which also operates on the distance-to-go principle, has evolved. Moving block systems require less wayside equipment than fixed block systems. They provide considerable cost reductions for personnel and maintenance due to a strong reduction in way-side equipment.

A moving block system (often called CBTC = Communications Based Train Control) does not require traditional fixed-block track circuits for determining train position. Instead, it relies on continuous two-way digital communication between each controlled train and a wayside control centre. On a moving block equipped railway, the line is usually divided into areas or regions, each area under the control of a computer and each with its own radio transmission system. Each train transmits its identity, location, direction and speed to the area computer which makes the necessary calculations for safe train separation and transmits this to the following train. The radio link between each train and the area computer is continuous so the computer knows the location of all the trains in its area all the time. It transmits to each train the location of the train in front and gives it a braking curve to enable it to stop before it reaches that train. In effect, it is a dynamic distance-to-go system. As long as each train is travelling at the same speed as the one in front and they all have the same braking capabilities, they can, in theory, run as close together as a few meters (e.g. about 50 meters at 50 km/h). This, of course, would contradict the railways safety policies. Instead, one safety feature of fixed block signaling is usually retained - the requirement for a full speed braking distance between trains. This ensures that, if the radio link is lost, the latest data retained on board the following train will cause it to stop before it reaches the preceding train. What distinguishes moving block from fixed block is that it makes the block locations and lengths consistent with train location and speed, i.e. making them movable rather than fixed.

In moving-block signaling, trains are given permission to move to a specific position anywhere on the track, as defined by a computer system. This is in contrast to the fixed block signaling (in which trains are granted permission to move to a pre-defined, fixed position — i.e. the next signal) (16).

Moving block signaling effectively maintains a safe 'envelope' of empty track around each train, which moves with that train. This envelope can be tailored to match the breaking performance and speed of that specific train, optimizing line capacity in different situations. For example, the same track could be used to run lower-speed commuter trains (with shorter stopping distances) closer together, and high-speed trains (with longer stopping distances) further apart (16).

Although moving block signaling can increase the capacity of railway routes compared to fixed block signaling, in practice there are still constraints, largely due to train braking performance and timetabling restrictions. This means that the increase in capacity provided by moving block signaling differs between routes (16).

ERTMS application level 3 and Communication Based Train Control (CBTC) systems are examples of moving-block signaling systems and already in use, in different regions in worldwide. Unlike fixed-block signaling systems, track circuits and wayside signals are removed from the railway lines. As a result of this, the total maintenance costs of railway lines are significantly decreased (15).

ERTMS can be considered as a standard for safety signaling and communication systems for railways across Europe and also world-wide. ERTMS increases railway capacity, decreases energy consumption, and optimizes train speeds. Another main purpose of ERTMS is to unify different national signaling and train control systems in Europe. In addition to European countries, ERTMS is also in use in Mexico, South Korea, China, Thailand, Taiwan, Australia, and Turkey (22).

European Train Control System (ETCS) has mainly three application levels from 1 to 3. The application levels 1 and 2 can be regarded as fixed-block signaling systems with ATS (Automatic Train Stop) and ATP (Automatic Train Protection) features, respectively (23) whereas the application level 3 is considered as moving block signaling systems (24).

Detailed explanations can be found in the following subchapters. (15)

2.4.1 European Train Control System

The basic of ETCS was defined by cooperation of railway people in Europe such as UIC (International Union of Railways), UNIFE/UNISIG (European Rail Industry/ Union Industry of Signaling), and ERA (European Railway Agency) (15).

ETCS levels are defined below in detail:

2.4.1.1 Application Level 0

In this application level, train drivers should obey the national rules and requirements. It is assumes as level 0 when an ETCS equipped vehicle is used on a route without ETCS equipment (15).

2.4.1.2 Application Level 1

In this application level, wayside signals and track circuits are used to inform train drivers of the occupation of the track in front of them. The communication between the train and the railway block (railway track) is realized over balises (Eurobalise) or beacons [64]. The on-board train computer named Eurocab receives the movement authority (MA) over balises, compares with the actual speed of the train, and calculates the train braking distance, if necessary. All essential information is displayed to the driver over Driver Machine Interface (DMI) (25).

Track circuits are used to detect the occupation in railway blocks. Trains cannot pass the balise as long as the next signal is red. If the train passes the related balise while the related signal is red, then it will stop automatically by the Eurocab, or if the driver does not react in time for a signal change then the train will slow down by its own (15).

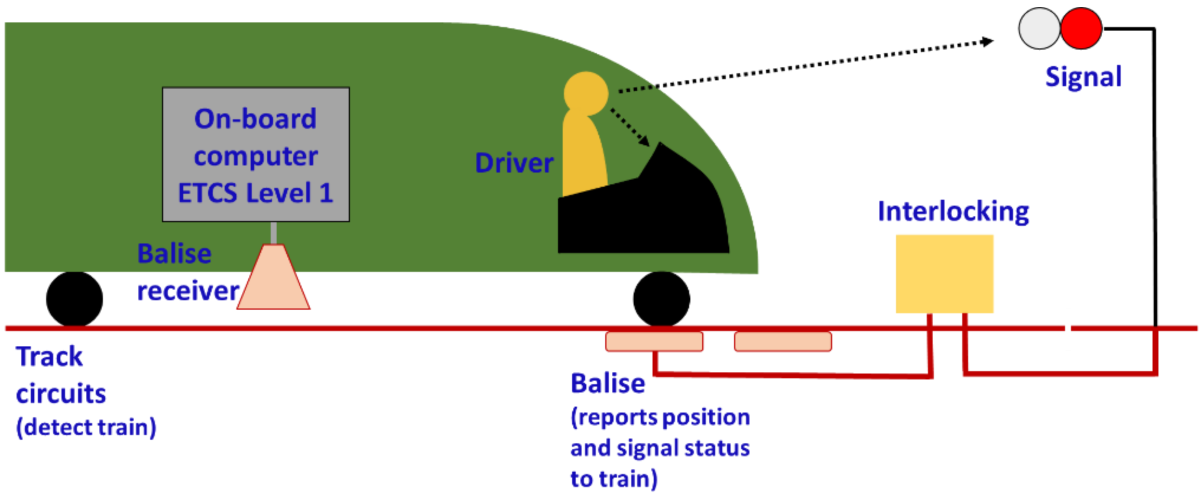


Figure 2-18: ETCS – Level 1

2.4.1.3 Application Level 2

In this application level, MA is sent to the on-board train computer directly from Radio Block Center (RBC) via GSM-R instead of balises. There is no need for wayside signals and Eurocab is always up to date over GSM-R. Balises are used as position markers and send fixed messages such as location and gradient (15).

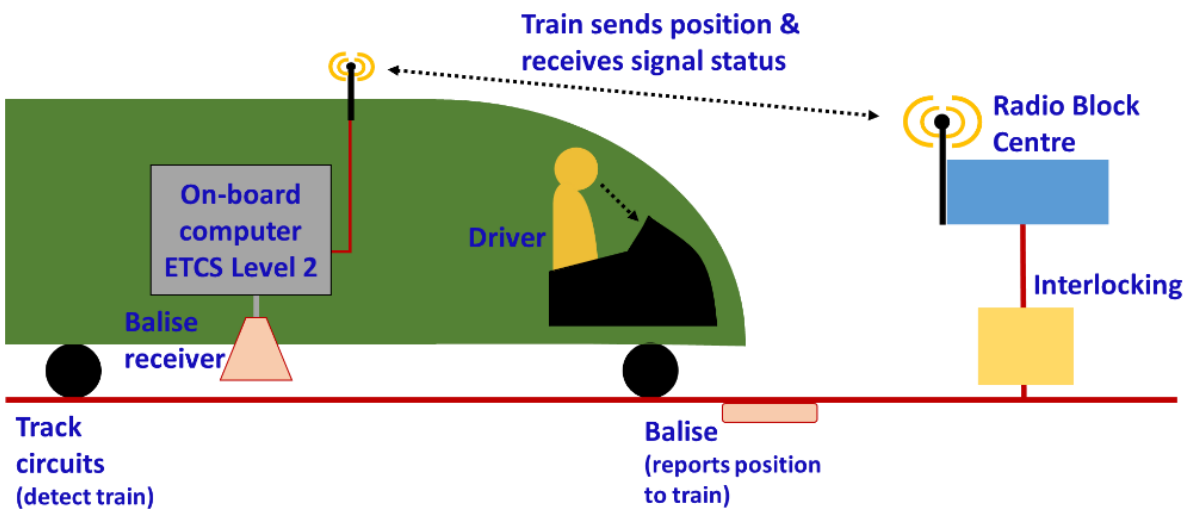


Figure 2-19: ETCS – Level 2

2.4.1.4 Application Level 3

In this application level, all necessary information from the control center to a train is sent directly to on-board train computers over GSM-R and vice versa whereas CBTC uses the bidirectional radio frequency (26). The location of a train is detected by the help of balises placed on proper positions on the railway line. Balises provide information to a train to check the actual train location and to calibrate its odometer.

It is mentioned in (27) that the proper balise position also reduces train headways and corrects speed errors (15).

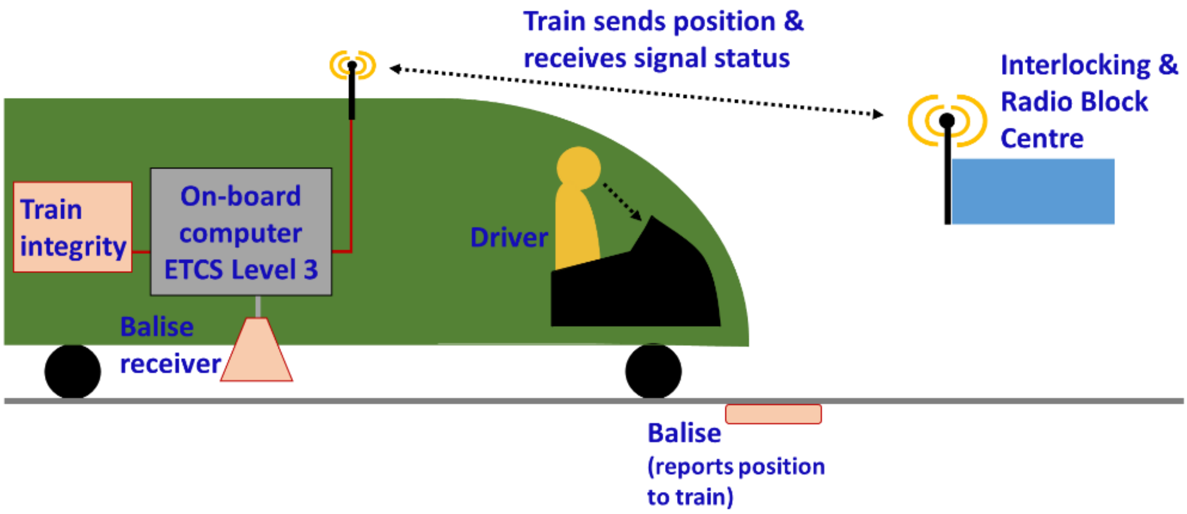


Figure 2-20: ETCS – Level 3

For this application level, while moving on a railway line, depending on the conditions, End of Authority (EOA) messages could be received by the train from the control center and new MA will be uploaded to train on-board computers via GSM-R. The control center and the interlocking system communicate with the GSMR network by using the nearest RBC. As mentioned before, more than one train can share the same block while moving on the same railway line in the same direction but trains have to leave a sufficient gap between them to prevent from collision. This gap is calculated by considering the braking distances and the safety distance which can be chosen as the length of the train. The movement of trains is illustrated in Figure 2-21. (15)

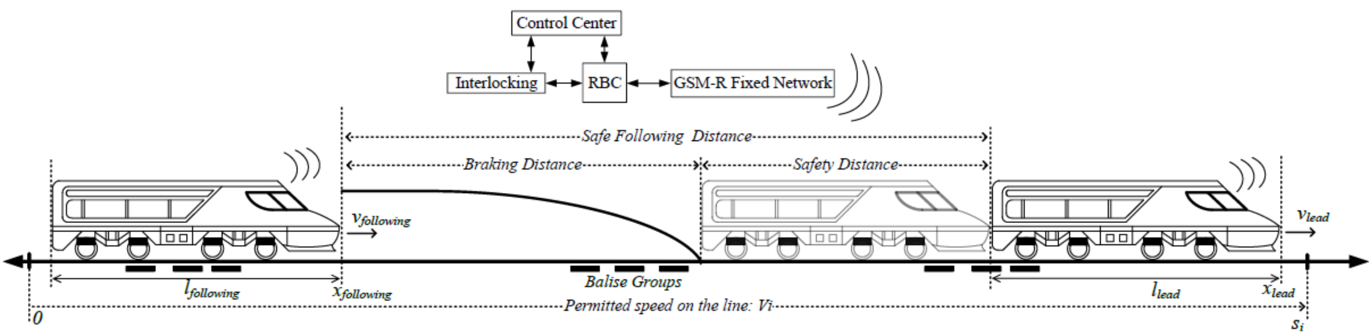


Figure 2-21: Movement of Trains in a Railway Line

2.5 Punctuality and Delay

One of the most important quality indicators of public transportation is punctuality. Deviations from schedule reduce the level of service (25).

Efficiency and level of quality can be improved by minimizing the “gaps” between the elements of the quality loop. Provision of passenger information significantly affects the quality perception, which helps smoothing the possible quality “gaps” (25).

Delay is defined as the deviation from the planned departure/arrival time registered on the railway stations. Based on the data the level of the service can be evaluated and the different lines are to be compared. Identification of the delay events and their causes helps the future planning of service and it can be used for traffic forecast (25):

- on operational side: in view of delay trends, the schedule and connections are to be modified;
- on passenger side: in view of the certain factors (weather conditions, lines, service type, etc.) the punctuality of vehicles (departure and arrival time) are predictable. These values can be used for passenger information on stations as well as on personalized travel information applications (journey planners).

The most frequent reason for delay is guaranteeing connections. Delays above average value have been caused by other railway companies and in case of extraordinary weather conditions (25).

There are two specific situations in which a functional relation between train delays and characteristics of the railway system would be useful for tactical planning:

- **Investment planning.** Managers are interested in reducing train arrival delays at a station by investing in the infrastructure. The investments may include track renewal to increase the speed profile along some routes, building an overpass to avoid train conflicts, or introducing more advanced signaling systems that resolve rights-of-way more efficiently. A functional relation between train delays and characteristics of the infrastructure would enable the planners to evaluate the effects that different infrastructure projects (or their combination) would have on delays. This would assist the management in selecting the most effective investment plan, given the available budget (26).
- **Simulation analysis.** Planners are interested in examining effects of changes in the railway system on bottlenecks, capacity utilization, or delay propagation. Such analysis is typically conducted by simulating specific traffic scenarios, given the information about the infrastructure and train movements (30). Since trains often deviate from their timetables, simulation models must account for delays to validly represent the real-world operations. A functional relation between train delays and characteristics of

the system can be used to estimate initial arrival delays to the observed section or intersection. These initial delays can be used further as inputs to a simulation model to obtain more realistic estimates of the capacity utilization, delay propagation, or bottleneck effects at downstream locations (26).

Models for real-time prediction of train delays are used to detect potential instabilities in the timetable and alert the dispatchers to reschedule some trains. Train delays are predicted from data describing arrivals and departures, which are gathered in real-time (31). Train movement data are collected from the infrastructure track occupation records, sensors in rolling-stock, or mobile GPS devices. Flier et al. (32) apply an algorithm that sweeps through the delay of the incoming trains and efficiently finds systematic dependencies in large-scale railway delay data (26).

Some models are defined with several variables (i.e., influencing factors) that are correlated with the type of delay that is analyzed. For example, the punctuality of trains in Norwegian railways is correlated with the number of passengers, occupancy ratio, departure punctuality and operational priority rules (32) (26).

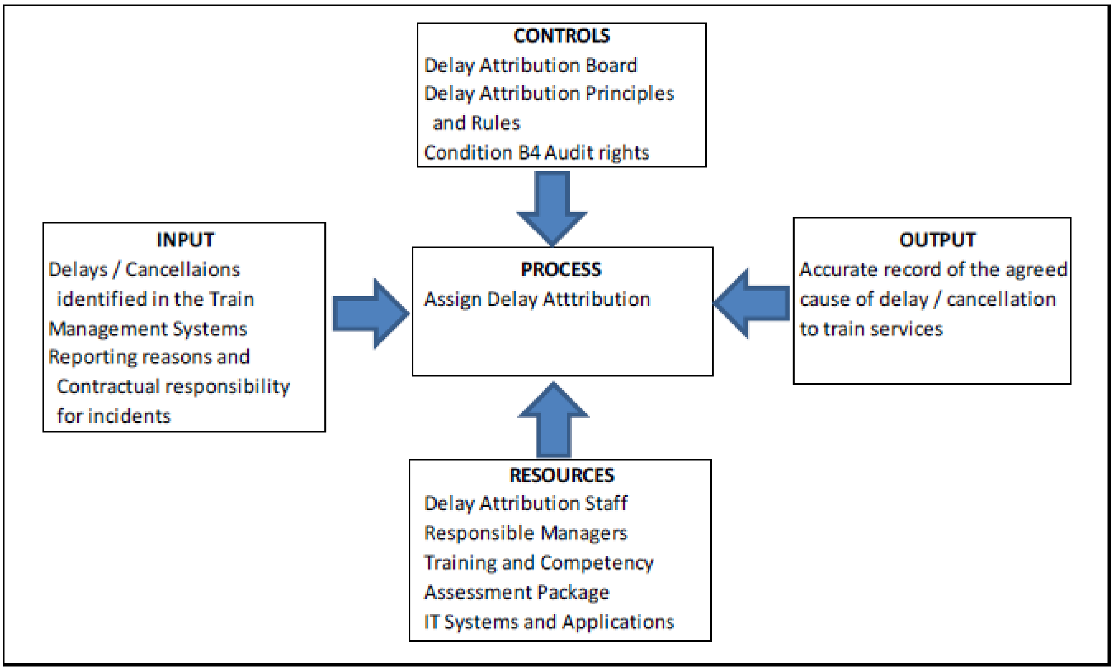


Figure 2-22: Delay Attribution Process

Punctuality of transport services has become a major issue during the last decade due to increased mobility of people, globalization of trade, competition with other transport modes, saturation of infrastructure capacities, and deregulation of the transport sector. Road congestion, and air and railway traffic delays are daily phenomena and seem to increase continuously (27).

Punctuality of train services, in general, is expressed as the percentage of trains passing, arriving or departing at given locations of the railway network no later than a certain time in minutes. Delays smaller than 5 minutes are usually not considered as delays by the European railway companies because of limited precision of the applied modes of measurement, tolerances of the timetable and insufficient means of control of operations in practice. As there are no standard definitions and the mode of measurement of delays is varying, the punctuality rates of the railways differ a lot (27).

As the time difference with regard to the scheduled time can be determined only on the basis of a timetable the latter's degree of precision determines the precision of the punctuality estimation. As the railway timetable for the public indicates only hours and minutes, the train delays could be defined as being 1 or more minutes behind schedule. A computerized timetable design enables, however, to determine the planned arrivals and departures by fractions of a minute, e.g. in steps of 5 or 10 sec. A high timetable precision of seconds is applied in Japanese Railways and even some European railway companies use this for internal purposes. But, so far, the punctuality levels published by most of the railway companies do not include a lot of trains with small delays and therefore create a much too positive image compared to reality (27).

In any case, the definition of delays should not be influenced by political or marketing aspects in order to assure a scientifically objective measurement and estimation. As delays may occur also during train stops, thus creating eventually differences, both arrival and departure delays should principally be considered. Whether it is suitable to publish arrival, as well as departure delays depends on the railway network. In first instance, departure delays are considered as being more important because they include dwell time delays. For reasons of practicability of control of operations and public perception, statistics of punctuality of train services do not need to include delays smaller than one minute. The setting of a larger minimal limit than one minute delay for the estimation of punctuality seems to be no longer justified for railways with state-of-the-art automatic train detection systems (27).

Trains are considered delayed if they arrive, pass or depart later than scheduled at the stopping position of the platform or stabling track. Early or late arrivals and departures are treated separately. Punctuality of train services is expressed as the percentage of trains that arrived, passed or departed no later than 60 sec compared to all train movements in the same time period at predefined representative network locations (27).

The presence of trains is detected automatically by means of axle counters, coils, induction loops, or track circuits. In general, the start and the end of the occupation of a signal block or a track The location of the devices, however, varies and depends on the track layout and the design of the section by a passing train is recorded and the data is saved a certain time for safety reasons. Signaling system. In most cases the last measurement point before a station is situated some hundred meters or even more than a 3 kilometer upstream of the platforms, whereas the first one after a station is located typically close to the departure signal. Moreover, the stop position of trains at a platform may vary if the length of trains is changing over time-of-day or day-of-week and the passenger access to the platform is not located at only one end. Therefore, the distances between the last (first) trains detection devices before (after) the station and the stop position of the different trains at the platform are to be determined in order to estimate the remaining deceleration (acceleration) time of the trains until (from) the stop (27).

Delay is often used as a metric of capacity; however, delay is a measure of level of service, not capacity and the relationship between delay and capacity is complicated. Delay can be defined as either the difference between the minimum, or unopposed, travel time and the actual travel time or the difference between the scheduled and actual travel time. Using either definition, delay increases as the level of service offered decreases. Trains can be delayed by both scheduled and unscheduled events. Scheduled delays are incorporated into the timetable as buffer time to allow for conflicts with other traffic. Unscheduled delays are stochastic and are a leading factor in unreliability and instability of a network (28).

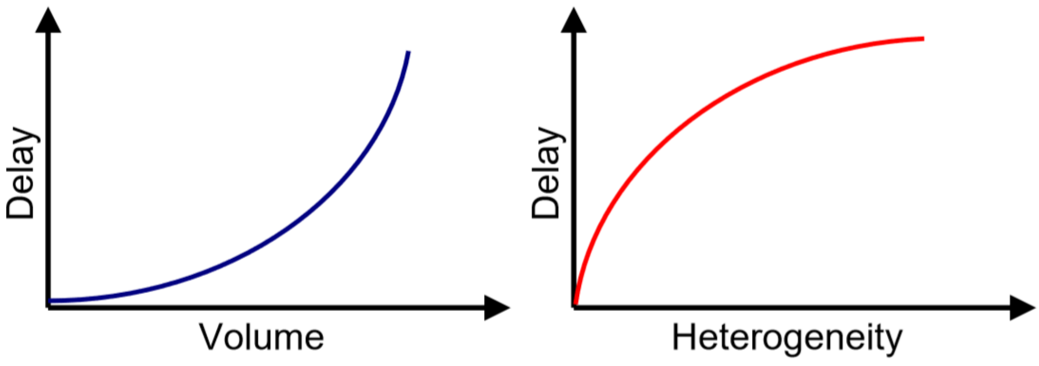
Unscheduled delays can be caused by numerous events including:

Mechanical failures, malfunctioning infrastructure, weather conditions, excessive boarding times of passengers, accidents at highway-railroad grade crossings and so on (28).

Delays to one train can lead to a cascading effect of delays to other trains. As a route nears its theoretical capacity the probability that a delay will lead to subsequent delays increases, while the ability to recover from these delays decreases (28).

The amount of delay is related to the volume and type of traffic on a route. With more traffic the number of meets and passes increases, and headways are reduced, increasing the probability of a delay causing additional delays to other traffic. It is generally agreed upon that delays increase exponentially with volume (Figure 2-23 a).

However, the specific delay volume relationship is dependent on the traffic mix on a route. Different train types have different operating characteristics influencing the amount of delay that a train experiences. Heterogeneity in these train characteristics causes additional conflicts increasing delays (Figure 2-23b) (28).



(a) (b)

Figure 2-23: The Delay-Volume (a) & Delay-Heterogeneity relationship (b)

Delay is the extra time it takes a train to operate on a route due to conflicts with other traffic. Reduction in delay is often used by the railroads to calculate the benefit of a project or operational change. However, the specific factors that cause these delays are not well understood. According to previous studies by Dingler on intermodal (freight trains with the highest maximum speeds, power to ton ratios and dispatching priorities) and bulk trains (freight trains with the lowest speeds, power to ton ratios and dispatching priorities) in a typical Midwestern north American single-track mainline, the delays can be categorized by conflict and source. Conflicts can be considered in three categories including meets, passes and line restrictions. Meets can be classified as any delay due to conflicts with one or more trains traveling in the opposite direction. Passes can be classified as any delay due to conflicts with one or more trains traveling in the same direction that result in one train overtaking another. When a conflict involves multiple meets and passes, the acceleration and braking delay can be attributed to the first conflict while the extra dwell time required to accommodate the additional conflicts can be attributed to each conflict accordingly. Line delays can be classified as any delay due to one train being slowed down by a preceding train traveling in the same direction that does not result in an overtake. For each conflict the specific operational source can be identified. Sources of delay include the delays while a train is braking, accelerating, at a constant slower speed or stopped. By splitting the delay up into conflicts and sources, it is possible to see which type of conflict has more delay, why that delay is occurring, and how it changes with changes in traffic composition (28).

Conflicts that Cause Delays When sorted by type of conflict most of the delay is accumulated during meets (Figure 2-24). The delays from meets are much larger than delays from line or pass delays. Each type of delay changes differently with changing traffic. The delays due to passes are the greatest at the highest levels of heterogeneity while mainline delays are the same with all levels of heterogeneity. The delays from meets closely follow the trend of the average delays. Consequently, the increased delays due to heterogeneity are primarily from increased meet delays (28).

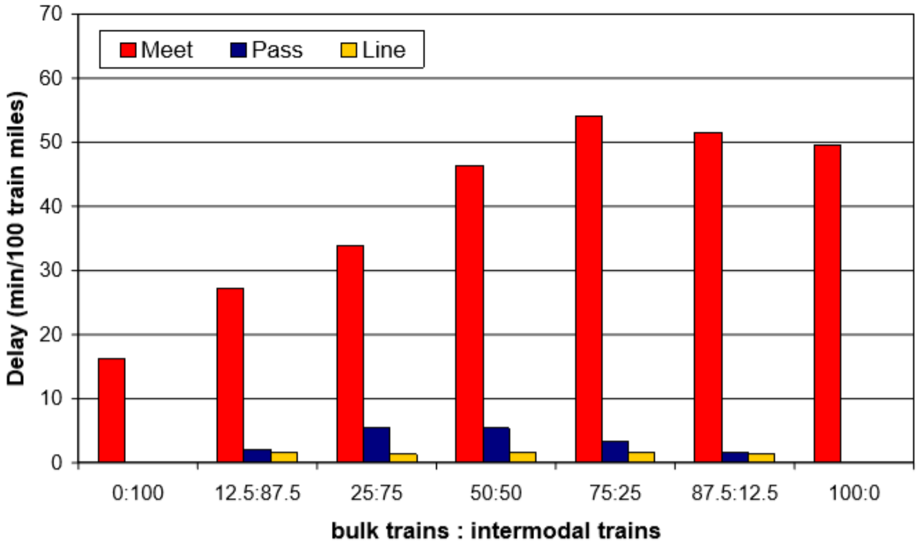


Figure 2-24: Average Delay by conflict and Ratio of Bulk to Intermodal Trains

Each source of delay has a different trend with regard to traffic mix (Figure 2-25). The delays while a train was traveling at a reduced speed were minor and relatively constant over all traffic mixes. The delays while a train is braking and accelerating increased with larger percentages of bulk trains. These delays are therefore due to changes in traffic and not increased heterogeneity. As the percentage of bulk trains increases the acceleration and braking delays increase accordingly (28).

The stopped delay is the only delay that increased with heterogeneity. Therefore, the increased delays with heterogeneity are due to a greater amount of time trains are stopped waiting in a siding. There are two possible explanations for this. First, at the higher levels of heterogeneity there is a greater likelihood two trains of different priorities will meet resulting in less efficient meets. These inefficient meets result in longer dwell times because a train will enter a siding earlier than it otherwise might. Secondly, higher heterogeneity results in more complex conflicts in which a train is met or passed by more than one train resulting in more time stopped (28).

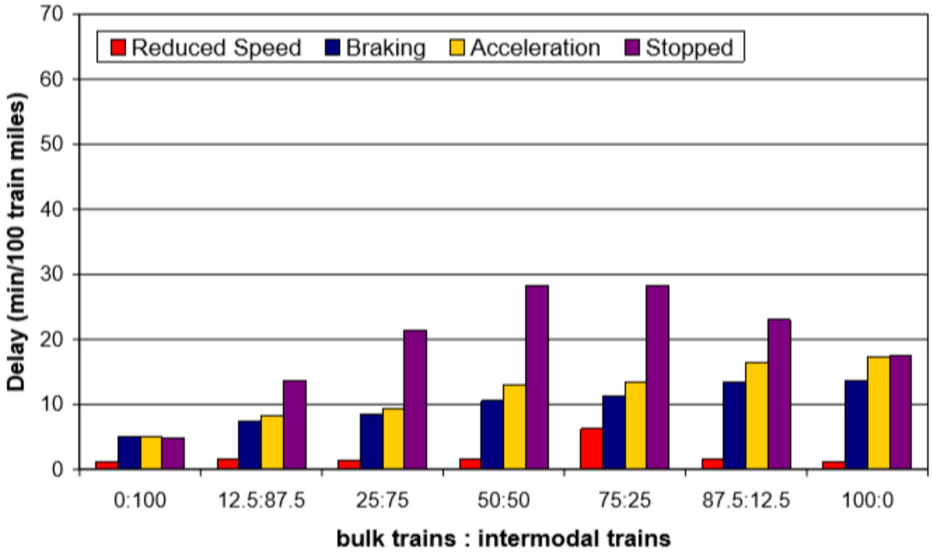


Figure 2-25: Average Delay by Source and Ratio of Bulk to Intermodal Trains

Three methods were found in the literature for estimating congested related train delay: Optimization-based, simulation-based, and parametric.

Optimization-based methods find a ''best'' route through the train network, and prescribe optimal train staging. ''Best'' is usually defined as minimizing total train time in the network or minimizing deviation from planned schedules, including applied penalties based on the perceived priority of various trains (passenger, intermodal, general merchandise). Optimization-based methods force researchers to abstract significantly from the physical network, and require an assignment of priority of trains which may not accurately mirror actual dispatching priorities. Thus, reported optimization-based congestion estimates are subject to the context of these stylized modeling environments (29).

Simulation-based methods forego seeking an optimum. They estimate likely delay given relatively simple decision rules often employed by trained is patchers. Simulation models can include stochastic elements of train running times. One of the primary challenges of simulation is to model the decision-making ability and rules of the train dispatcher. On one hand, decision rules can be simplistic, resulting in simulation system gridlock at lower traffic levels than the physical system is able to support. On the other hand, overstating dispatcher's look-ahead capability can overstate the throughput capacity of the track network or understate run times. In either case, benchmarking can be a challenge; the estimated delay impacts from a simulated system are subject to the modeling methodology and assumptions. As such, simulated environments may not reflect the impacts on the actual system accurately. Simulation and optimization systems can be costly to develop and maintain. Each track configuration and train mix is essentially unique; simulation and optimization models must be created or configured to match rail network configuration and operating conditions (29).

Railroads establish train classifications which receive varying horse power ratios (HPT) in order to achieve expected running times. The higher HPT is correlated with generally higher dispatching priorities for faster trains (30).

Figure 2-26 provides a schematic of the causal model. The most easily measured train performance statistic is train running time (TRT). TRT is a function of the trains free running time (FRT), and congestion-related delays (CRD). Total running time (TRT) is predicted by isolating FRT and CRD determinants, where TRT= FRT+ CRD. By definition, causal factors for FRT and CRD are orthogonal to each other (30).

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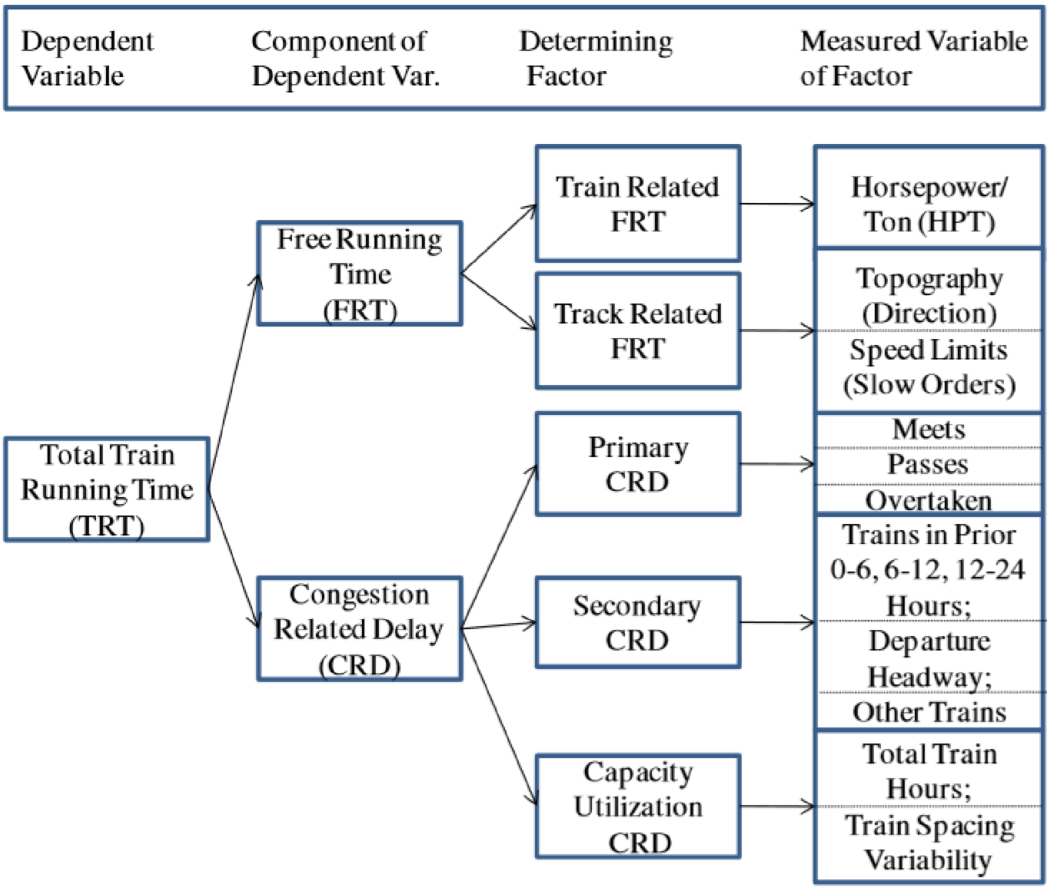


Figure 2-26: Schematic of casual total running time model

FRT is the theoretical minimum run time for a train on a track segment from the physics of the train operations with no impedance from other trains from contention for track resources. Free running time (FRT) is governed by two determining factors: Train factors (HPT) and rail factors (topography and speed limits). FRT factors are estimated only to specify the base component of TRT; additional time is CRD (30).

The dependability or RAM (Reliability, Availability and Maintainability) parameters are the most important elements that allow to estimate the Life Cycle Cost (LCC) of a system and to forecast performances during operating conditions. In the field of railway transportation, conventional measures, such as the mean delay of the train, or the Service Dependability (SD), can be profitably used to estimate the overall system behavior taking into account the presence of failures (30).

In railway systems short and rare train delays are usually acceptable for frequent passengers. For this reason, some conventional measures can be defined and utilized to estimate quantitatively the quality of service, strictly related to the schedule fulfillment. In particular, the mean delay a generic train collects to reach the destination, and the Service Dependability, that is the probability that a passenger, during a generic travel, collects a delay d not greater than an allowable quantity d, can be assumed as indicators of the railway service quality Within a railway system, signaling and automation play a key role for safety and service quality aspects. Different signaling and Automatic Train Control (ATC) systems operate today in Europe and this fact represents a technical and operational barrier against railway interoperability. Until today, to allow trains crossing the borders of the European countries, it was necessary to equip the rolling stocks with different on-board signaling and ATC systems and to have driving personnel specifically trained to properly use them. For this reason, in order to come to an international standardization of the European signaling systems, with particular reference to ATC systems, allowing the European railways to pursue technical and operational interoperability, the European Rail Traffic Management System (ERTMS) was born in 1995. The ERTMS system is composed of two fundamental subsystems (the on-board system and the track-side system) and three different application levels have been foreseen. In particular, the application level identifies both the operating relationships between track and train and the functional/physical structure of each subsystem. The ERTMS level 1 is a train control system based on spot transmission by means of balises and is used as an overlay to an underlying signaling system. In this case the train detection and integrity supervision, as well as the train separation and protection functions, are performed by the existing signaling system (interlocking, track circuits, etc.) and the relevant information is sent to the trains by means of the information points displaced along the track. The ERTMS level 2 is a train control system based on radio transmission that can be used as an overlay to an underlying signaling system. The information needed by the on-board system to properly drive the train in safe conditions, is generated track-side by a Radio Block Center (RBC) and is transmitted to the train via the GSM-R media. The Radio Block Center can perform by itself all the signaling functions, including train spacing and protection. Spot transmissions are necessary only to send fixed information to the trains as location references, entry/exit points marking, power supply changes and so on. Train integrity information is safely provided to the RBC by means of track-side systems external to ERTMS, as track circuits and axle counters. In this case the track-side signals can be suppressed, but only fixed block signaling logic can be implemented due to the discontinuity of the track-side train integrity detection systems (30).

The ERTMS level 3 is a radio based train control system. This case is fundamentally equal to level 2 except the train integrity information, which is evaluated by the RBC based on the continuous information directly provided by the trains thanks to specific on-board devices. Also in this case the track-side signals can be suppressed, and moving block signaling logic can be implemented thanks to the availability of continuous train integrity information (30).

From the functional point of view, within the architecture taken into account, a Traffic Management System (TMS) is interfaced with the Radio Block Center (RBC) providing this latter with traffic control and regulation information to be translated into orders dispatched to the trains. By means of the GSM-R system, structured in a Base Station Controller (BSC) and several Base Transceiver Stations (BTS), each one covering a given track length, the RBC communicates with the trains. Several Local Control Systems (LCS), connected to the RBC and to the TMS by means of a fiber-optics communication network, safely control, each one, a portion of the track and operate locally performing interlocking functions and collecting, from the field, the track occupancy information to be used by RBC in order to properly carry out the vital signaling functions. In Figure 2-27 the block diagram of the analyzed signaling and automation system is shown (31).

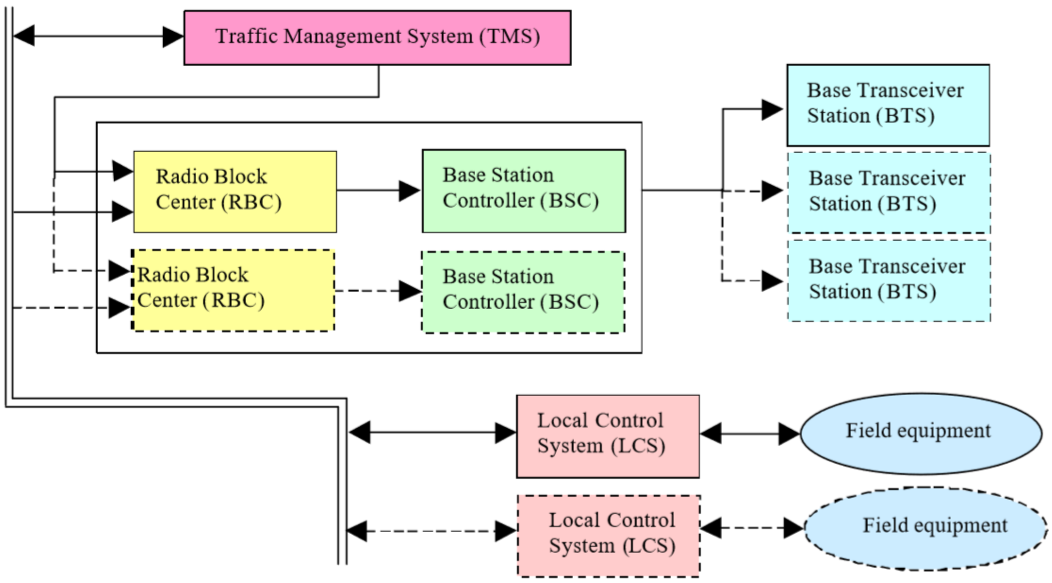


Figure 2-27: Signaling and automation system block diagram

The time for setting up and clearing the train routes might be reduced by changing to a (more modern) signaling system that works faster. The signal realizing time might be reduced by changing to driverless operation, as the realization and the reaction time of the driver can then be eliminated, or at least reduced. However, these topics represent only a small part of the block occupation time. Most of the block occupation time is actually used for the train to approach and pass the block section and for releasing the train route. Reducing the length of the block sections reduces the time it takes the trains to pass through the block sections, which will gain capacity. Alternatively, the block sections can be passed faster by running faster. However, by running faster the braking distance, and thereby the approach time increases, which results in a limit of the capacity gain of increasing the speed.

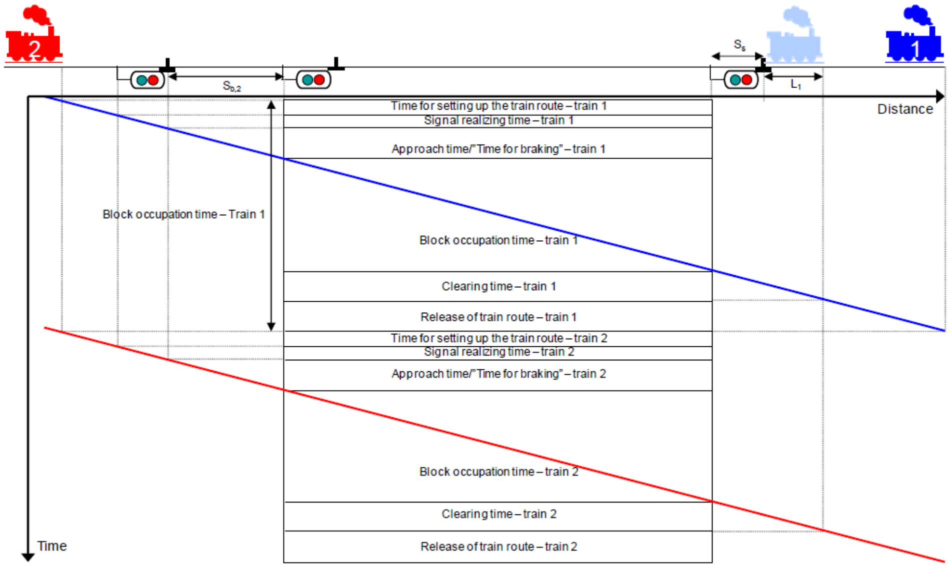


Figure 2-28: Elements of the block occupation time

To have parallel movement facilities, it is necessary to create a sufficient safety distance (SS) behind the exit signal. This can be achieved in two ways. Either by means of a dead-end track (the left side of the crossing station in figure 2-29) or by placing the exit signal at the necessary safety distance (SS) from the fouling point (the right side of the crossing station in figure 2-29) (31).

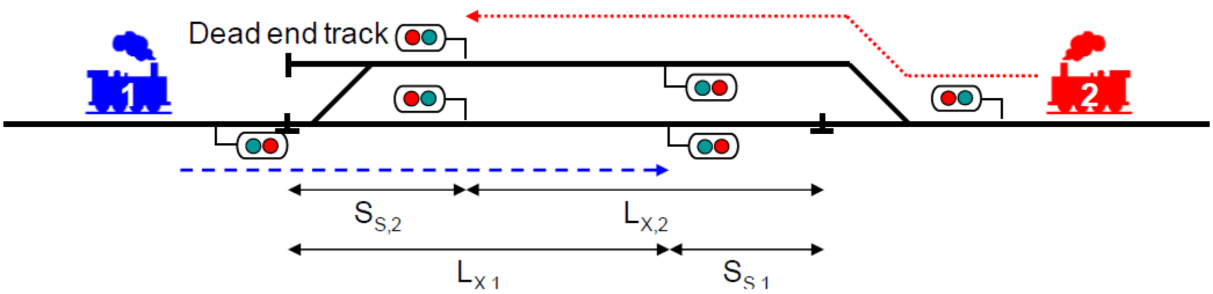


Figure 2-29: Station with parallel movement facilit. (31)

If a crossing station is unable to handle parallel movement, one of the trains must stop at the crossing station for a longer time while the other train enters the station, figure 2-30.

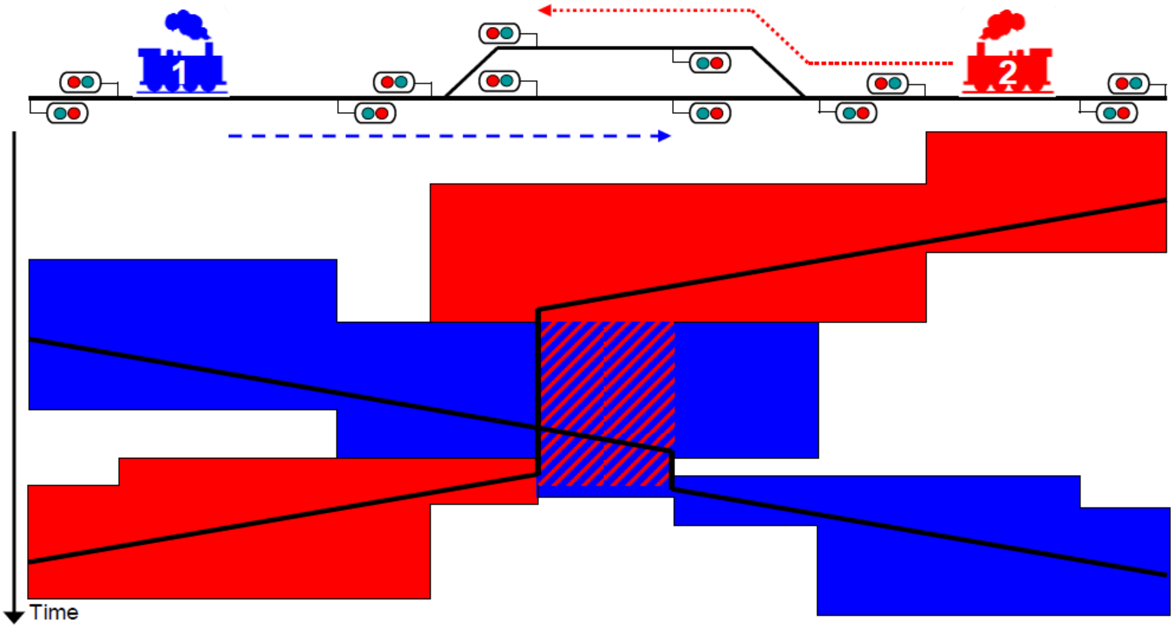


Figure 2-30: Crossing station without parallel movement facility (31)

The detailed blocking times in figure 2-31 indicate the capacity consumption of the crossing station. Here, the dwell time of train 2 is considerably longer than that of train 1 because the route of train 2 has to be released before train 1 may enter the crossing station. After train 1 has entered the crossing station its route has to be released to set up the departure route of train 2 from the station.

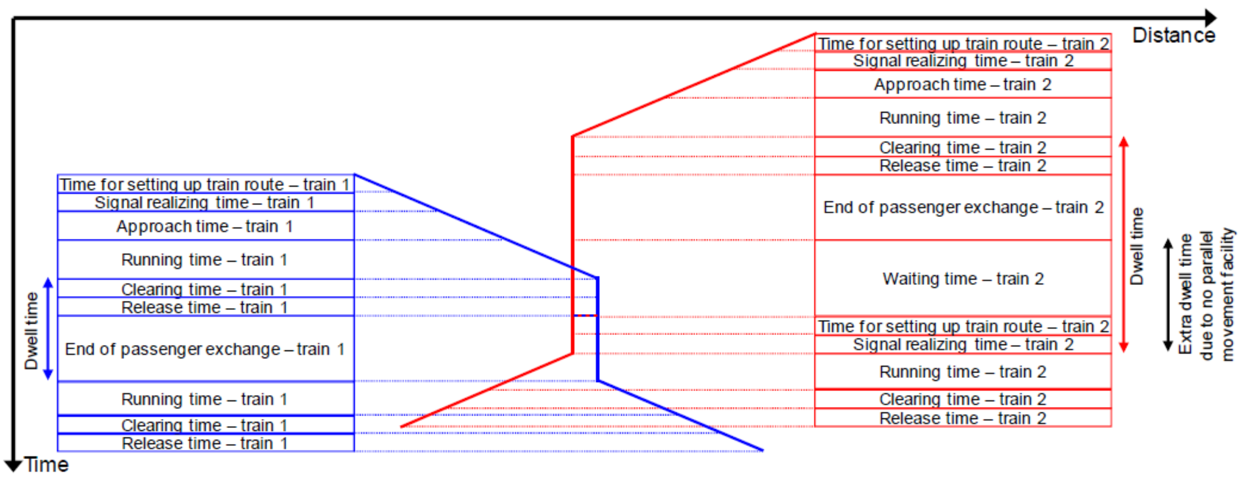


Figure 2-31: Detailed block occupation time for platform tracks of a crossing station (31)

Train service is highly affected by unavoidable disruptions representing the operational difficulties, such as traffic, load, accidents, maintenance problems or other operational difficulties. These factors are regarded as the common drivers affecting the punctuality of the service rendered. When disruptions occur, trains become oversaturated, bottlenecks are created, and travel times are extended thereby causing annoyance among the passengers. (32)

Railway service delay was done by Higgins et al. who grouped them into three types of delay. The first category is track related delays, which involve train slowing down or stop due to track problems. The second category is train dependent delays, which are caused by train car malfunctions. The final category is called terminal/schedule stop delays, which take place at the railway station or terminals. (32)

Nelson and O'Neil grouped the causes of delays as engineering and mechanical malfunctions, programmed track work, transportation crew failures, passenger-related issues, weather and cascades. The hierarchy of causes has recorded engineering failures as the most common incident whereby it recorded 25% of all reported delay minutes. It is followed by cascade delays that accounted 20% of the entire delay minutes. (32)

A report on research in UK during the year 1999-2000 revealed that train delay caused by rail operator contributes 50% of all delay minutes. This category of delay includes the train faults, crews as well as operation and station delays, among others. Poor rolling stocks are the main cause of the train faults which are mainly due to frequent breakdowns and low train speed. The other category of delays which comprised 35% of the delay minutes is due to the network or railway infrastructure causes. Besides the network operations, this category also includes the track and signaling faults. The final category of delays of 15% includes all external causes which are beyond the control of the railway operators. (32)

The delay propagation and the total delay can be calculated for a given initial delay provided that the timetable and the characteristics of the infrastructure are known. However, these calculations of delays are only possible for idealized situations. This is because only one railway line would be examined, no dispatching would be included, and it will be assumed that the timetable will regenerate before the next delay occurs. However, a delay on one railway line may influence other railway lines too, and the total amount of delay may be reduced through dispatching (e.g. changing the order of the trains). Furthermore, if two initial delays occur shortly after each other, the second delay might not have the same influence, as the train would have got a consecutive delay, also if the delay did not occur, Figure 2-32.

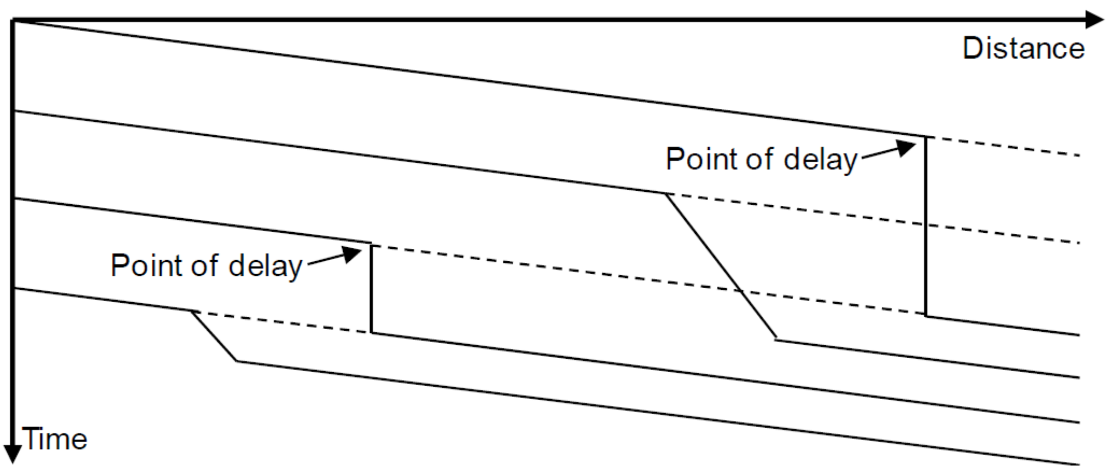


Figure 2-32: Two initial delays shortly after each other (broken lines are the planned timetable)

There are many simulation models that can be used for different analysis but in general, the models can be divided into three categories, Figure 2-33.

For analyzing delays and delay propagation, tactical (and/or operational) models can be used and OpenTrack. These types of simulation models are generally built up in several steps. First, the infrastructure must be built up before constructing the timetable. Then, the delay distribution of the initial delays must be entered together with the rules for dispatching. Finally, the simulation can be run and the results can be evaluated, Figure 2-33. To ensure a stable and reproducible result, 50–200 simulations should be conducted (33).

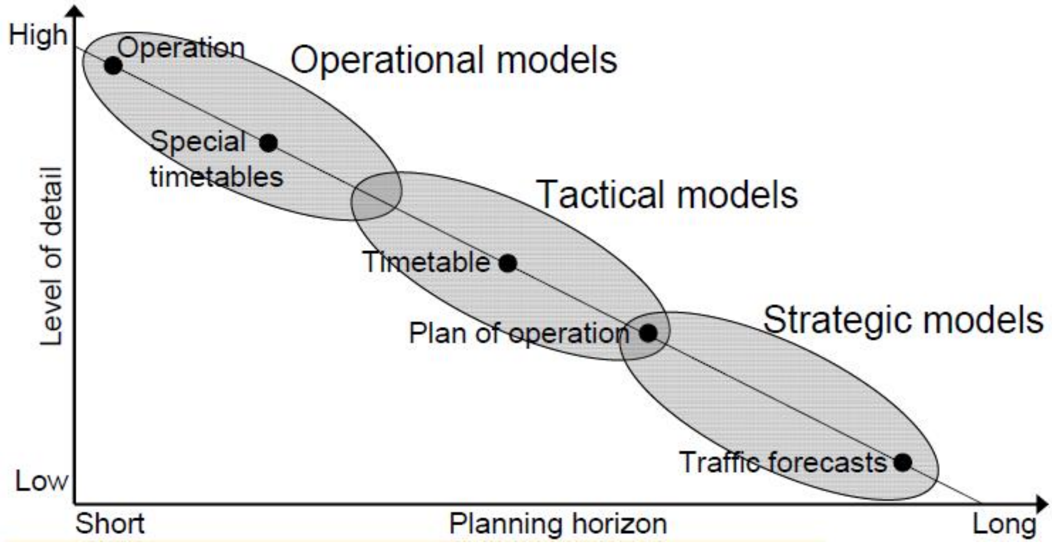


Figure 2-33: Different types of simulation models and their main types of analysis (33)

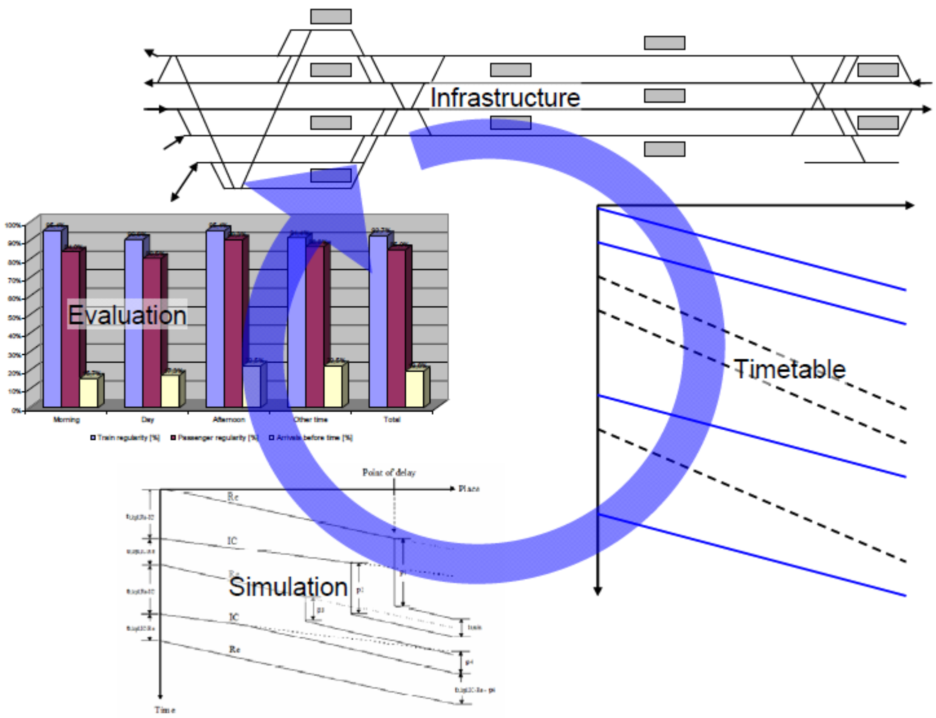


Figure 2-34: Typical steps when simulating delays in railway networks (33)

Knowing how to measure reliability and being able to simulate delays and passenger delays of future timetables, it is possible to analyze the future reliability. This is because delays can be taken into account in the planning process. Timetables can be simulated for expected delays – for both trains and passengers – and the best possible timetable can be chosen. This approach can also be used when planning timetables for contingency operation so the best timetable can be used in case of disturbed operation. (33)

Analyzing different future scenarios, it is also possible to decide whether a train should wait for a delayed connecting train. Not waiting will result in additional delays for the passengers in the delayed train transferring to the other train resulting in reduced reliability for the transferring passengers. However, the passengers in the train that does not wait will not become delayed, and hence experience improved reliability. In case the train has sufficient time supplement – and therefore can catch up the delay – before the next major station, most passengers in the waiting train will not experience reduced reliability although the train waits. In such a case, it may improve the overall reliability of the railway system that the train waits. (33)

When simulating future timetables and analyzing delays for trains and passengers, it is possible to optimize the transfer time based on the expected delay distributions. In this way, the transfer time can be adjusted so that the risk of missing the corresponding train is reduced without having a too high transfer time. This approach improves the reliability of the railway operation seen from the passengers' perspective. In the longer term, a decision support system can be used in the traffic control center to decide if a corresponding train should wait for a delayed train. (33)

If a timetable has a high amount of timetable supplement, it is easier to achieve high reliability in the operation. However, in the case of no disturbances in the operation, the passengers will spend longer time travelling than necessary: the passengers experience extended travel time. From the passengers' viewpoint, an extended travel time is better than a delay as it is possible to plan in relation to a scheduled delay. Therefore, socioeconomic calculations generally have a higher value for unplanned delays than for the travel time (including scheduled delays).

Being able to simulate passenger delays of future timetables, and knowing the socioeconomic values of time for scheduled and unscheduled delays, it is possible to estimate the best level of timetable supplement in the timetable. Figure 2-35 shows the idealized socioeconomic utility (with a given set of parameters) depending on the timetable supplement, and thereby implicitly the running time and (expected) delayed time.

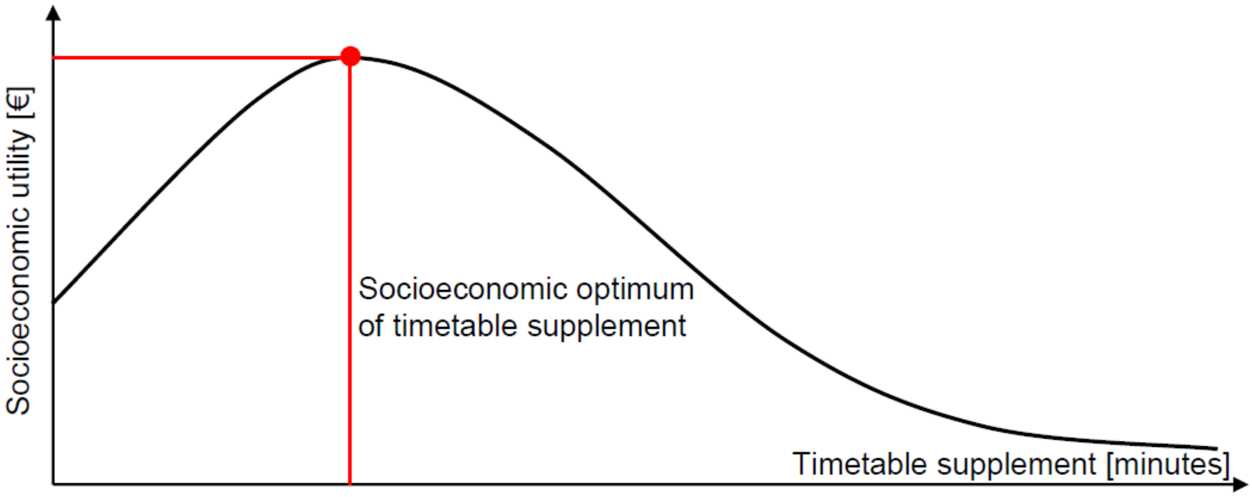


Figure 2-35: Socioeconomic utility of a given timetable (for an idealized situation) depending on the amount of timetable supplement (31)

Block and signaling system: The signals help extends the train driver's visibility, so it allows greater speeds. The role of signaling is to keep trains at a safe distance. In a moving block signaling system, which is a modern technology, the position of each train is known continuously, thus permitting better regulation of the relative distances

The European Rail Traffic Management System (ERTMS) is the initiative from the European Commission to create a unique signaling standard as a cornerstone for the achievement of the interoperability of the trans-European rail network and is likely to be adopted by the rest of the world as well.

To account for the diversity of functional/operational requirements, three system levels of reference have been identified. There are already ERTMS commercial projects in several countries, most of which have already established ERTMS level 2. In this level, ERTMS does not require trackside signals, and the train position is controlled with virtual signals and radio control messages.

To ensure the safe operation of the train and to enable the optimization of the line capacity, the specifications of ERTMS include the calculation method of the Headway Time between consecutive trains: Formula below. This theoretical method is the same in ERTMS level 1 and ERTMS level 2. Thus, the theoretical capacity is the same in both levels, although, in practice, ERTMS level 2 is more efficient. ERTMS determines the Headway Time by summing up the following four times (see Figure 2-36):

$$\text{Headway Time} = \text{Travel Time} + \text{Braking Time} + \text{Release Time} + \text{OT}$$

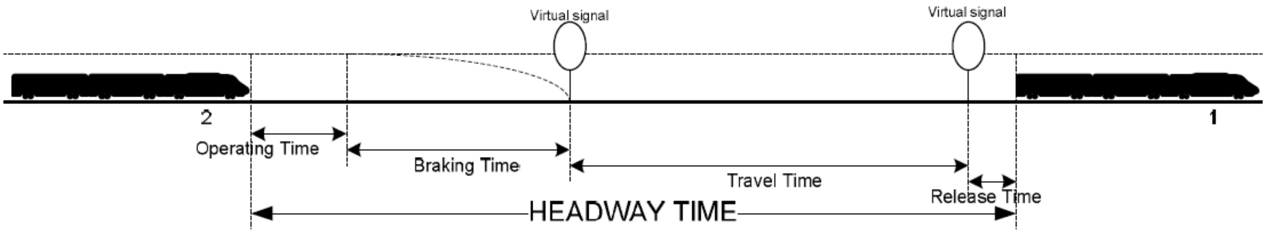


Figure 2-36: Headway Time

Travel Time is the time required to cover the distance between two consecutive virtual signals. Travel Time depends inversely on the train speed and directly on the distance between consecutive virtual signals.

Travel Time = F(Distance/Speed)

Braking Time is the time needed to cover the braking distance, that is, the distance required to stop a train before a virtual signal. Braking Time depends directly on the train speed and inversely on the maximum deceleration.

Braking Time = F'(Speed/Deceleration)

Release Time is the time required for the entire length of a train to cross a virtual signal. Release Time depends on the train speed and the train length.

Release Time = F''(Length/Speed)

Operating Time (OT) is a safety time. It is a constant, and it is set by the infrastructure managers.

In our tool, train speed is calculated for each meter of train path by means of an underlying dynamic model.

We assume a continuous Operating Time without interruptions (see Figure 2-37 a). However, with discontinuous Operating Times, the time period decreases due to the journey time of the first train (see Figure 2-37 b).

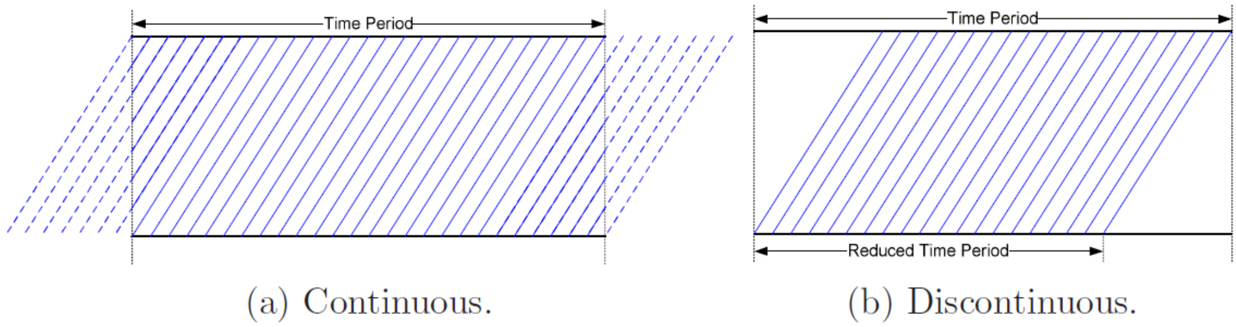


Figure 2-37: Continuous Operating Time (a) & Discontinuous Operating Time (b)

Chapter 3

3 Methodology Approach (case study)

3.1 Introduction

Railway will facilitate and expedite train movement to the best advantage to serve train service to the public and its industries with a reasonable expenditure. Many factors should be considering in railway transportation such as railway signaling systems and management. Railway signaling system is needed for ensuring the safe operation in rail traffic (34).

In this chapter of the study, information about case study is represented. Case study is Ghana Western Line Railway. Ghana is a country located along the Gulf of Guinea and Atlantic Ocean, in the subregion of West Africa.

3.2 Ghana Railway

The total Ghana rail network extends for 939 kilometers of routes (1,200 km of tracks, including double-track sections), all located in the southern regions; it is made up of the Western, Central and Eastern Lines. The country's railway operates through various cities, major and small towns.

The Western Line links Takoradi and Kumasi, serving Tarkwa, Huni Valley, Dunkwa and Obuasi.

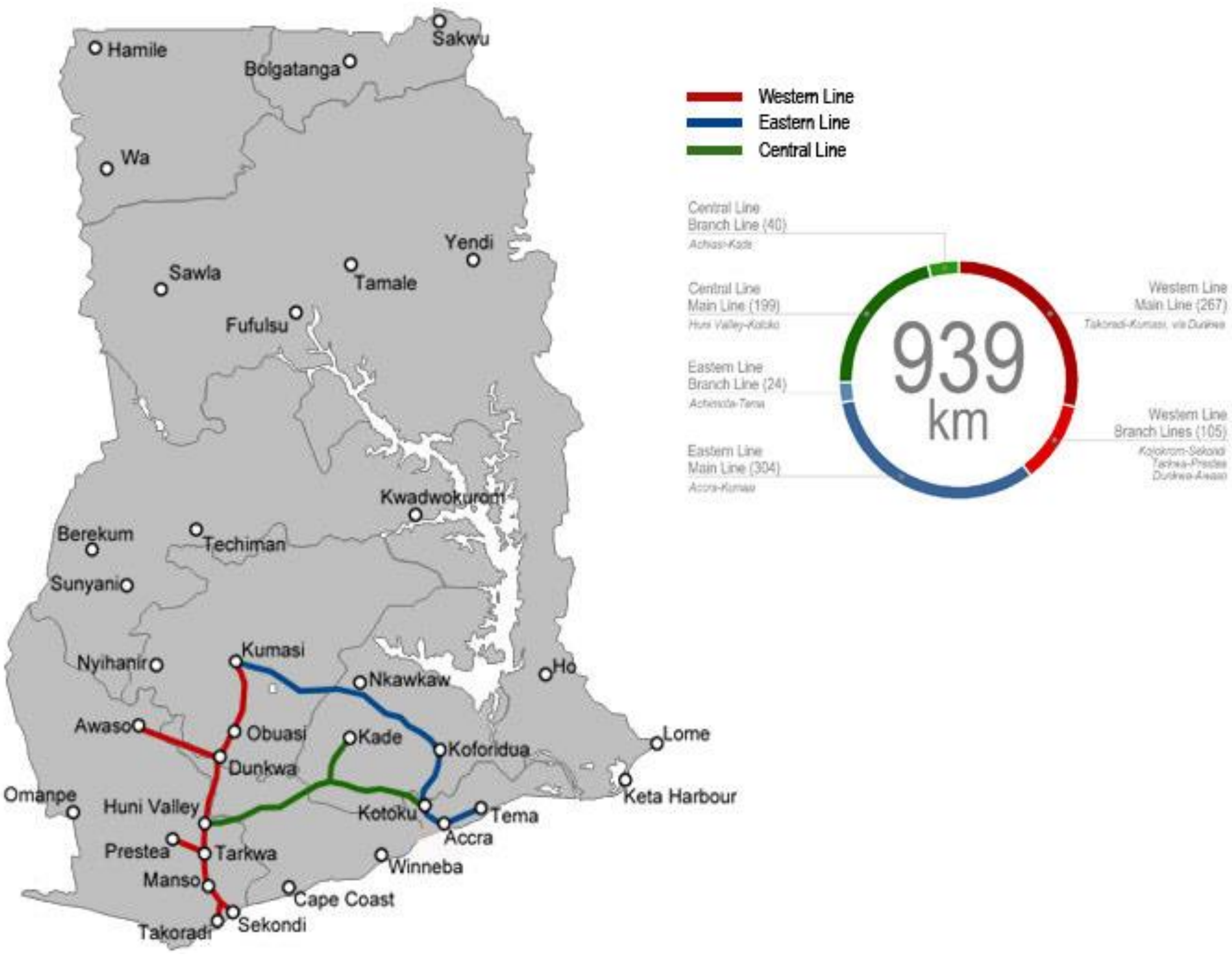


Figure 3-1: Ghana Existing Railway Network

3.3 Western Line Railway

The Western Railway Line as a whole (total length = 340km approx., see Figure 3-1) Consists of two lines:

Main line: from Takoradi to Kumasi, L=267km approx

Branch line: from Dunkwa to Awaso, L=73km approx.

The Line has a fundamental importance for the social and economic development of Ghana, mainly due to the following reasons:

- it connects the metropolitan areas of Takoradi-Sekondi and Kumasi, respectively the fourth and second most populated cities in Ghana
- it serves some important mineral deposits, like the bauxite mines near Awaso and the manganese mines near Tarkwa and Nsuta
- Takoradi Port is the second largest port in Ghana for goods traffic

- Kumasi is the connection point between the South and the North of Ghana, at the vertex of the Western and Eastern Lines of the existing railway network, and the starting point of the route for the goods traffic from or directed to Burkina Faso, which is a landlocked country.

Moreover, the Master Plan identified on the rehabilitated Line (Takoradi-Kumasi, 226km standard gauge double track):

- For freight mobility, a weighted average of about 2.28 million tons/year (at starting of analysis-2018); this volume will rise to 3.65million ton/year (2030) and 5.12 million tons/year (2047); the annual growth rate adopted varies between 2% and 4% during the whole period of analysis
- For passenger mobility, a weighted average of about 5,300 pass/day (at starting of analysis-2018); this volume will rise to 9,000 pass/day (2030) and 12,600 pass/day (2047); the annual growth rate adopted varies between 2% and 4.5%, highly correlated with the demographic trend of the country.

Figure 3-2: Western Railway Line Sections

The current transport system in Ghana depends mainly on the road network, made up of approximately 67,000km of main and secondary roads, of which approximately 12,800km are main arteries but of which only 3800km are paved. Another, more limited, contribution that has grown in recent years, is water transport that takes place along the Volta Lake between the ports of Akosombo in the South and Buipe and Yapei in the North.

The existing railway network Built during the colonial period, they are narrow (Cape) gauge, single track lines and were used for both freight and passenger traffic. Over the years this railway network has deteriorated, together with the rolling stock, due to lack of maintenance and is currently in a state of disrepair and is not able to guarantee reliable and safe transport.

3.4 Evolution of Transport Demand

The country covers an area of approximately 238,000sq.km, with a population of approximately 25 million inhabitants. The per capita gross income in 2010 was approximately 1300 US$. The annual development increase in the various sectors is between 6 and 8%.

The following table gives the global values of traffic demand in Ghana for a certain period of time that will then be assigned to the means of transport at the various timeframes.

Ghana Traffic Demand in Different years

Year	Scenario	Freight Traffic in mill.tons/year	Passenger Traffic in mill. pax/day
2008	Current	28.25	0.64
2015	Start of interventions	36.25	0.73
2030	During interventions	65.98	0.99
2047	End of interventions	128.57	1.38

The import-export traffic of goods from the ports of Tema and Takoradi completes the picture, having a total flow of respectively 14.0 and 4.0 mill.tons/year and a container traffic of 750,000 and 53,000 TEU.

3.5 Telecommunications

Wireless technology is the future of communication. Since 2005, throughout the world, wireless is exceeding wire line systems and the use of wireless communication is growing. This is due to the evolution of these technologies and the reduced prices due to the availability of components, large scale production and vendor competitiveness. Therefore, all over the world, any plans for the future must be based on wireless technology.

Of course, communication cannot be only radio, but an efficient network based on optic fibers must be used.

A railway network operation must rely on an efficient and complete range of information: voice, data services, ISDN services, video, signaling safe data, etc.: all the stations along the line must be connected with a central dispatcher and between stations signal data and block information shall be exchanged in an efficient and reliable system.

The long distance system used today and available from different vendors, is based on SDH technologies. This system uses optical fibers to transmit digital data at different speeds, so that there are different solutions available, based on the total traffic requirements for any specific network.

Once the backbone, that is the SDH communication network, is installed is the right time to choose the wireless system based on radio communication. Railways in the past have used their own radio in the range of 457-467 MHz, according to a special frequency plan that is exclusive for railways. For a developing country, the use of such band and proprietary networks could, at the moment, be competitive versus a more modern technology, such as GSM.

3.6 Signaling and Telecommunication Systems

3.6.1 Signaling

The proposed Signaling System for the Western Railway Line is based on the European Railway Traffic Management System Level 2 (ERTMS L2).

The ERTMS L2 signaling system is based on the continuous connection between the European Vital Computer (EVC) on-board the Trains circulating along the Railway Line and the Radio Block Centre (RBC), located at the Operation Control Centre (OCC), responsible of trains circulation management.

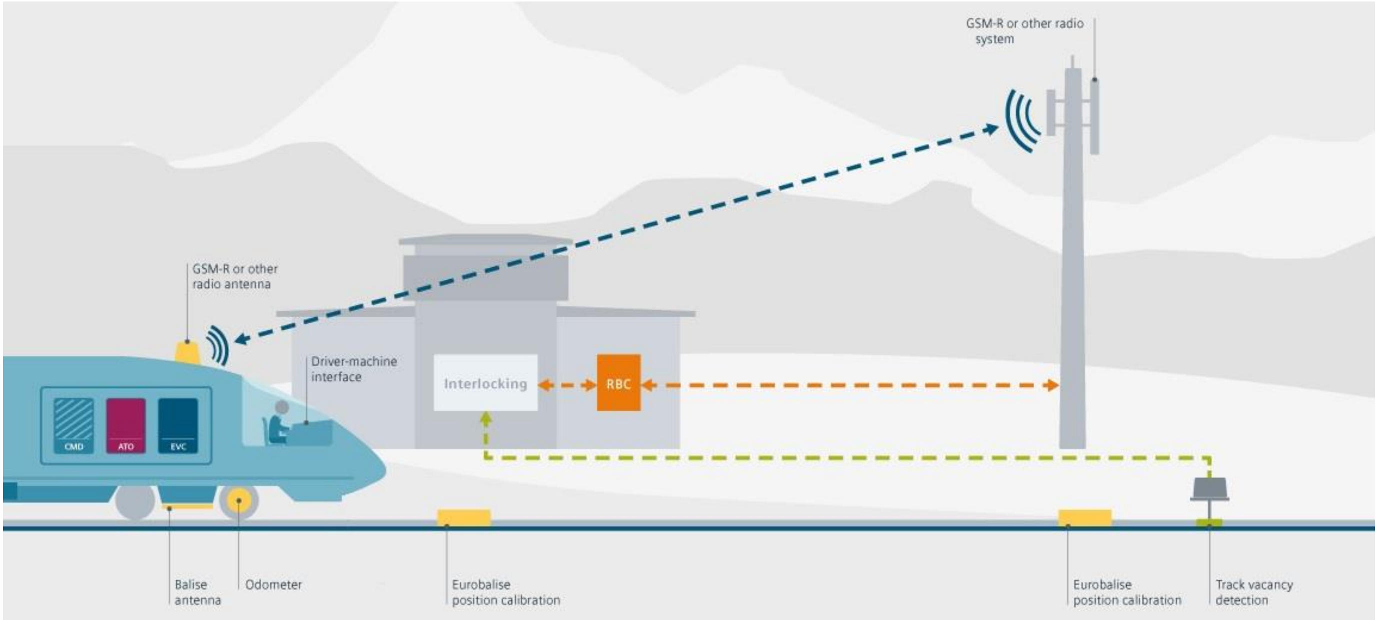


Figure 3-3: MS L2 system concept

At regular time intervals, the trains exchange the following main types of data with the Radio Block Centre:

- The Train calculates its position, by means of on-board odometric system, and send the Position Report to the RBC containing the information about the position of the train itself;
- The RBC, knowing the exact position of all the trains and the track conditions, sends the Movement Authority (MA) to the trains. The EVC, once received the MA, calculates the maximum allowed speed or the braking curve, and shows it to the train driver by means of a Driver Machine Interface (DMI).
- The EVC automatically applies the braking of the train if the driver overcomes the maximum allowed speed or the braking curve.

The exchange of the information between train and RBC takes place through a dedicated Telecommunication Radio Network, based on the European standard GSM-R.

The GSM-R Radio Network is achieved by means of Base Transceiver Stations (BTS), with antennas, located along the railway line and operating on radio frequencies dedicated to the railway system.

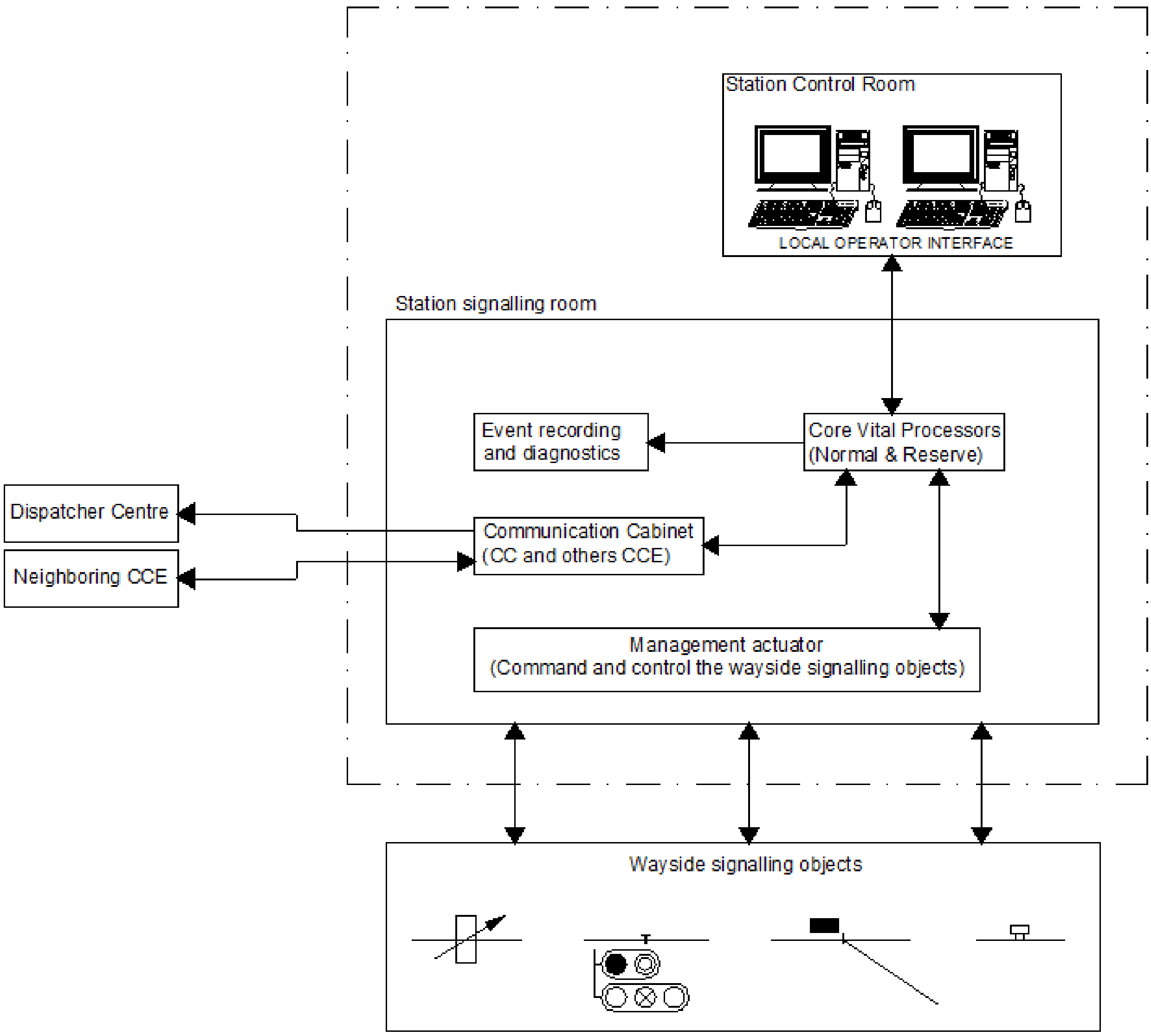


Figure 3-4: CCE Functional Diagram

For each station a dedicated CCE is foreseen, through which the Local Operator is able to manage the movement of trains inside the station (entrance route, exit route, shunting route, etc.).

Light signals are foreseen on the stations, even if they are an optional for ERTMS L2 Standard, in order to:

- Allow also the circulation of the trains not equipped with ERTMS L2 system (old trains or service trains);
- Allow partial activations of the railway Line, without waiting for the completion of its entire extension.

For the same reasons, the spacing between trains on the entire railway Line is managed by the Electric Axle Counting system (EAC).

The EAC system shall ensure the automatic spacing between trains by means of electric axels counters operated by the trains themselves, counting the axles of the trains outgoing and incoming in the stations. If the number of axles counted as outgoing from a station is equal to the number of axles counted in entrance to the next station, the section between the two stations can be considered free.

If the distance is less than 10 km, one block section is provided between the two stations and, therefore, it will be possible to send only one train at a time between two stations.

If the distance is greater than 10 km, one or more Intermediate Axle Counter Block Section (IACBS), are foreseen without light signals but with "ERTMS L2 virtual signals", practically identified by means of tin tables positioned in a particulars points of the railway line with the aim to identify a radio block section.

As far as the Train Circulation monitoring on the railway Line is concerned, the Dispatcher Centre of the Line is foreseen on the Operation Control Centre at Takoradi station, where the Dispatcher Centre Operator, knowing in real time the situation of the traffic circulation, in terms of position of the trains by means of ERTMS L2, and status of wayside signaling equipment (aspect of the light signals, state of point machines and track circuits, etc.) by means of links with each station CCE, can operate directly in order to reduce the negative effects of eventual train delays.

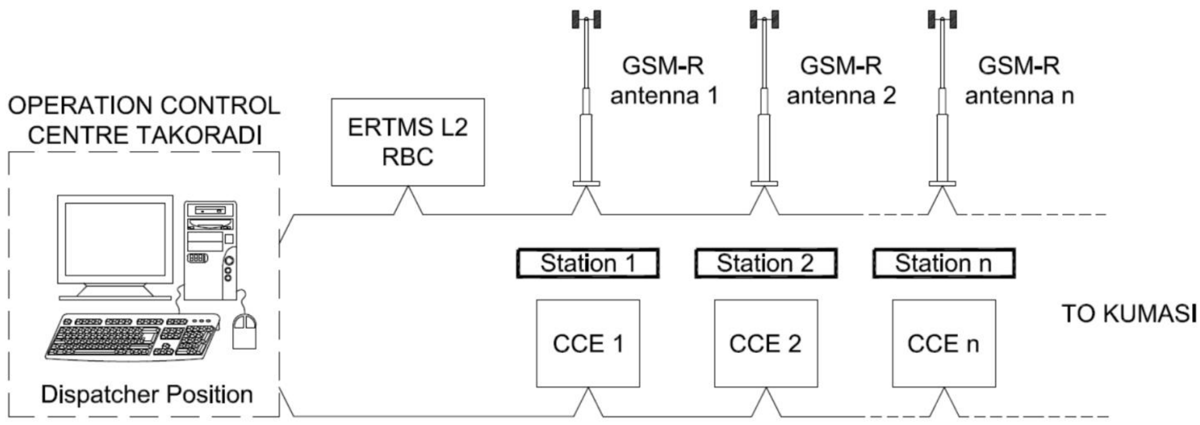


Figure 3-5: Line Signaling functional diagram

The light signals are observed and respected only by the drivers of the not ERTMS equipped trains. The aim of the Light Signals is to give information about the state of the track after the signal itself. The driver, looking at the aspect of the signals, has all the information needed to know the state of the track, and to regulate the speed of the train.

There are 4 principle signals and, in general, the information that they provide are:

- Distant signal: it informs if the entrance route is set; if no, the train has to stop behind the next signal (Home signal);
- Home signal: it informs if the train can enter in the station and the allowed speed;
- Exit signal: it informs if the train can leave the station;
- Shunting signal: it informs if the shunting route is set.

3.6.2 Telecommunications Systems

The following railway Telecommunication systems are proposed for the Western Railway Line:

- SDH Fiber Optic Network,
- GSM-R Radio System

3.6.2.1 SDH Fiber Optic Network

The backbone on which all data information will be transmitted between the elements of railway infrastructure to each other and to the OCC will be Synchronous Digital Hierarchy(SDH)fiber optic network.

The SDH system shall be functionally divided into:

- Access network;

- Transmission network

The Access network shall be constituted by flexible multiplexer (MUX-F) that may be considered a concentrator of low-speed services before they are brought into the local exchange for distribution.

Figure 3-6: Typical Solution for Fiber Optic Network Panel in Station Technical Room

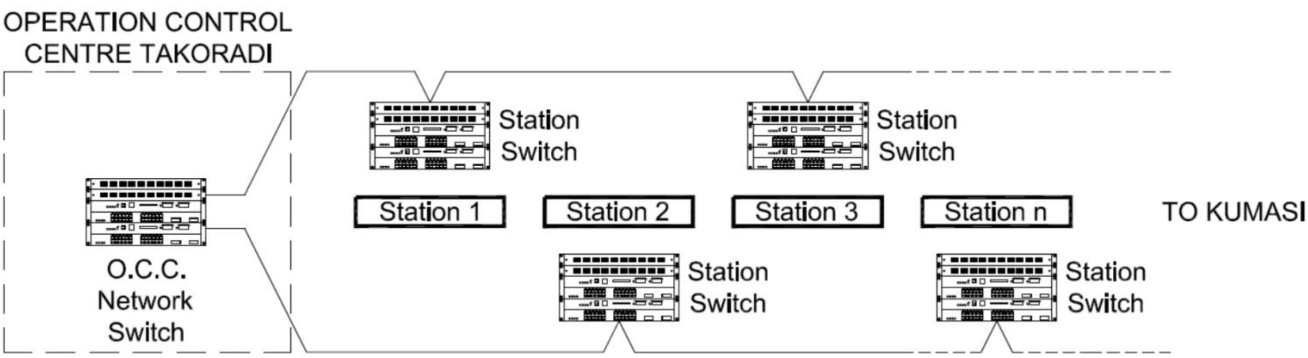


Figure 3-7: Line Fiber Optic Network Functional Diagram

3.6.2.2 GSM-R Radio System

The Radio System network will be based on the European standard GSM-Rand will be implemented using Base Transceiver Stations (BTS) and communication towers with antennas which are placed along the railway in order to provide radio coverage of the Line and Stations.

Figure 3-8: BTS and Communication Tower with Antenna

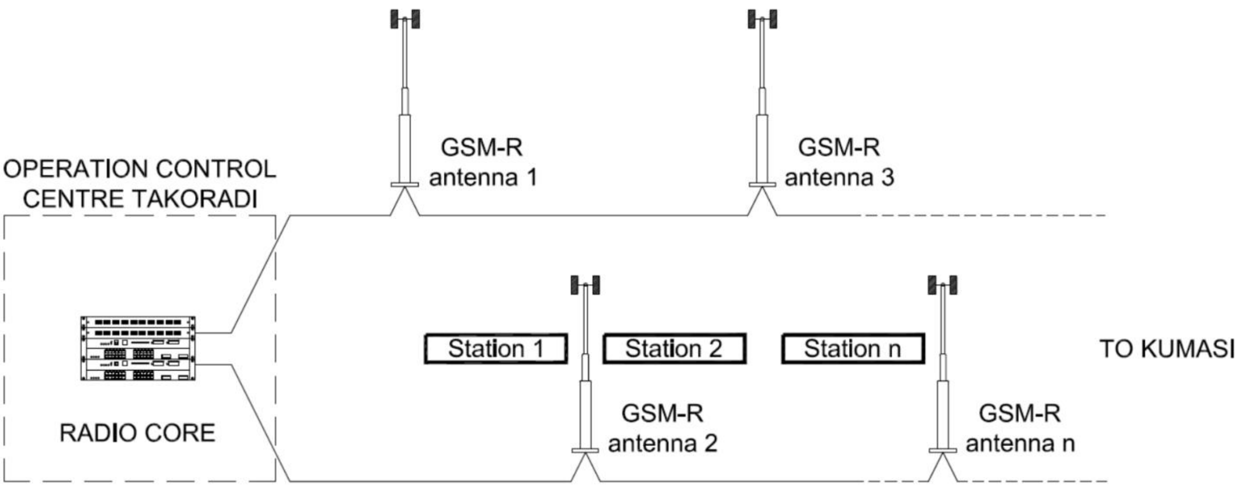


Figure 3-9: Line Radio Network Functional Diagram

3.6.2.3 Activation Scenarios for Signaling

Finally, when the Western Line will be completed from Takoradi to Kumasi, the Signaling and Telecommunication systems, including Operation Control Center, can be updated in order to put in operation the ERTMS L2 signaling system.

3.7 OpenTrack Simulator

OpenTrack began in the mid-1990s as a research project at the Swiss Federal Institute of Technology. The aim of the project Object-Oriented Modeling in Railways, was to develop a catalyst for practical economic solutions to complex railway technology problems.

Today, the railway simulation tool OpenTrack is a well-established railway planning software and it is used by railways, the railway supply industry, consultancies and universities in different countries.

OpenTrack describes a railway network in special graphs called double vertex graphs. A user can edit the network's topology graphically. Every element of the graph holds various attributes. An edge, for example, holds its length, the gradient, the maximum speed for different train categories and much more. A user can create and manage objects for edges and vertices, and also signals, switches, stations and routes. The following figure shows part of a topology.

The timetable database stores information for each train at each station, including arrival and departure times, minimal stop time, and connections to other trains.

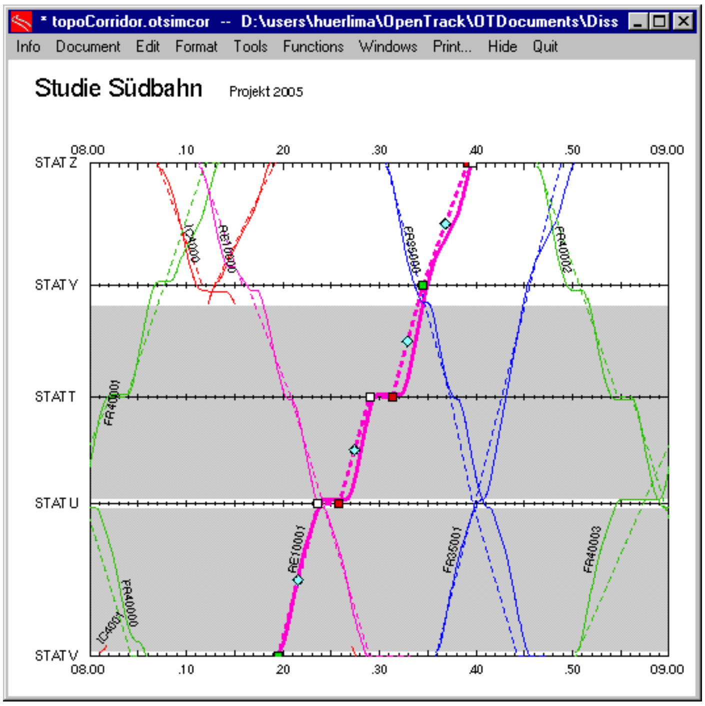


Figure 3-10: OpenTrack Simulator

The following figure shows how the simulation tool works. Predefined trains run according to the timetable on a railway network. During the simulation, OpenTrack calculates train movements under the constraints of the signaling system and timetable. After a simulation run, OpenTrack can analyze and display the resulting data in the form of diagrams, train graphs, occupation diagrams and statistics.

OpenTrack handles single simulation runs as well as multiple simulation runs where random generators produce different initial delays and station delays.

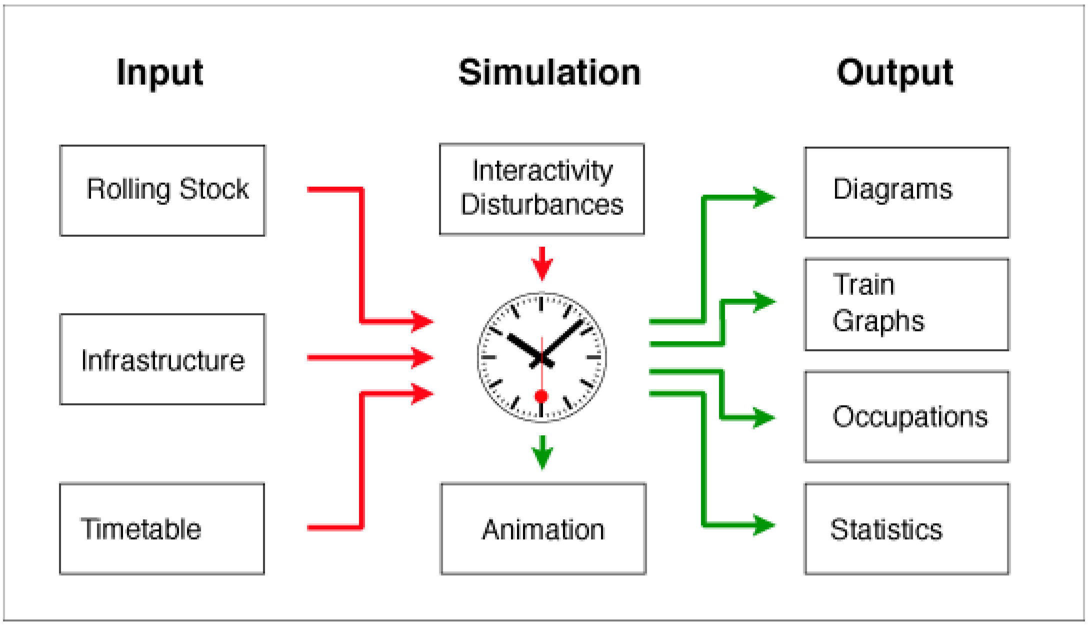


Figure 3-11: Input, Simulation, and Output in OpenTrack Simulator

Based on a number of input parameters, the headway calculator computes the minimum headway between two trains and is able to identify the critical block section. The two trains may vary in type (e.g. intercity, commuter, freight, etc.), route and stopping pattern. The headway calculation works for fixed block (discrete block), moving block and CBTC systems.

OpenTrack produces a number of outputs in text and/or graphic form.

In this study, OpenTrack simulation software is used for comparison delay between Fixed-block signaling system and Moving-block signaling system in case study Ghana Western Line.

Chapter 4

4 Data Collection and Analysis

4.1 OpenTrack Simulation Software

The objective of the OpenTrack simulation process is for the user-defined trains to fulfill the user-defined timetable on the user-defined layout. The motion of trains is modeled by the solution of the differential motion equation (continuous) combined with signal information (discrete).

OpenTrack can perform a variety of different evaluation using the simulation data. In this thesis delay will be evaluated according to the simulation.

OpenTrack uses two different types of signals: signals with changing information (light signals, beacons) and halt position indicators. The light signals are subdivided into main signals (signals that can show stop), distant signals (signals without stop aspect), combined signals (combination of main and distant signal) and shunting signals. Main signals (including combined signals) can be further subdivided into home, exit and block signals.

Virtual signals do not have a corresponding installation on the route, but are merely used to show the safety technology (for example discrete block division in case of the cab signaling).

The signal system Universal (Metric) is a general multi-aspect system, which represents speed relevant signal information in km/h. Speeds apply from the signal's Proceed-Indication or from the start of an optionally defined Slow Speed Zone, the Approach-Indication allows a brake application to the displayed speed, in case a train passes the signal with a higher speed.

Routes always begin and end at main signals (home signal, exit signal or block signal). In OpenTrack simulation software routes belong to the vertex at which the main signal of the route begin is located. Route attributes such as release time, signal indications, release groups and slow speed zone can be allocated to a route using the Route Inspector.

The top level of train operation infrastructure definition in OpenTrack is called an itinerary. An itinerary consists of one or several successive paths. Itineraries do not need to include paths that are all in the same direction; therefore itineraries are used to model setting backs.

OpenTrack manages locomotives in a database called Depot. Any number of locomotive types can be managed in each depot. Depot databases have filenames (name.depot), their extension name is always depot.

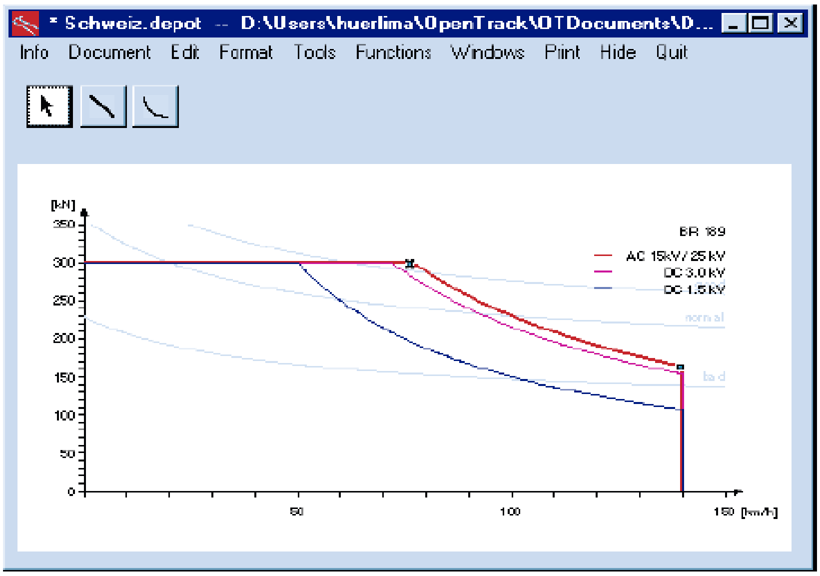


Figure 4-1: Z/V – Diagram Window

Figure 4-2: Document with Locomotive Image

Trains experience resistance while traveling. This resistance must be overcome by the locomotive's tractive strength as applied to the rails. The total resistance experienced by the train (R) is a sum of the traction resistance and acceleration resistance. This can be expressed in the following formula:

$$\boxed{R = R_F + R_a}$$

R:	Total Resistance	[R] = N
R_F:	Traction Resistance	$[R_F]$ = N
R_a:	Acceleration Resistance	$[R_a]$ = N

In order to realistically model trains that can be operated on both ETCS Level 3 and on conventional routes, OpenTrack enables users to define the braking characteristics (i.e. the Deceleration Function) of a train with a menu item, under which the properties are managed for both types of system (Function Table: non-ETCS / ETCS).

In the case of a train that operates under ETCS control, the deceleration function table consists of four columns rather than three for trains operating only in non-ETCS controlled track. The third column of the table in both cases lists deceleration values for the area outside of the ETCS control. In the case of the trains operating under ETCS, a fourth column is displayed which lists deceleration values for the area managed under ETCS.

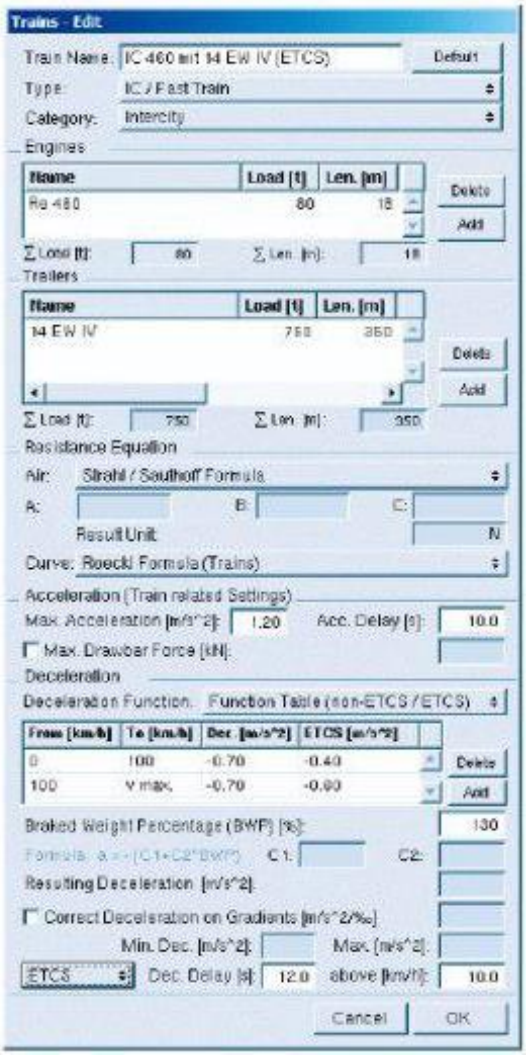


Figure 4-3: Train Inspector for Trains Running Under ETCS

The ETCS values in the fourth column are the starting point for calculating the individual ETCS braking curves. These values are used along with the values for the braking application delay curve (Dec. Delay [s]) and the speed above which the delay is applied when operating under ETCS release speed (above [km/h]).

The Dec. Delay [s] and above [km/h] values are shown at the bottom of the Deceleration Box when ETCS is indicated on the pulldown menu in the bottom left corner of the Train Inspector's Deceleration Box.

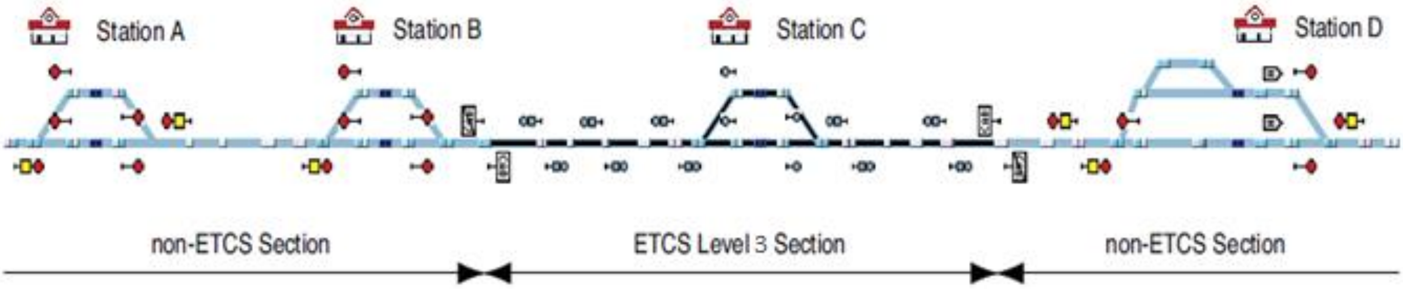


Figure 4-4: Line with non-ETCS / ETCS Level 3

Figure 4-4 shows a track section that contains one segment of ETCS Level 3 control.

The beginning and end of the ETCS Level 3 control is shown by the cab signaling start/end signals (CAB Start signal ETCS L3 or CAB End signal ETCS L3 in the signal inspector). The edges within the ETCS L3 controlled area have the property that signal information can be sent and received via radio (Loop / Radio ETCS in the Edge Inspector). These signals are marked as virtual signals (signal box is virtual in the Signal Inspector).

OpenTrack uses a protection system to ensure collision-free train operations during the simulation process.

The following two conditions guarantee safe operations:

- Each track section is reserved either for no trains or at most one train.
- Each train must be able to stop within the track section reserved for it.

The protection system and safety philosophy are used to define the effective distance ahead of and behind a train that lies in the train’s protected zone. The method currently used by railroads is to release track sections in discrete units, or routes. Each route is protected by a main signal, which prevents movement of trains on the route when it is set on stop.

The flowchart illustrated in Figure 4-5 outlines the conditions for a successful route reservation. A route can be reserved and its main signal display the appropriate signal for proceeding only if:

- All safety elements belonging to the route are free or reserved for the applying train.

- The applying train must have a free continuing way at the end of the route.
- The free blocking is ensured, i.e. prevent the situation where two trains have the same track section available for occupation (deadlock).

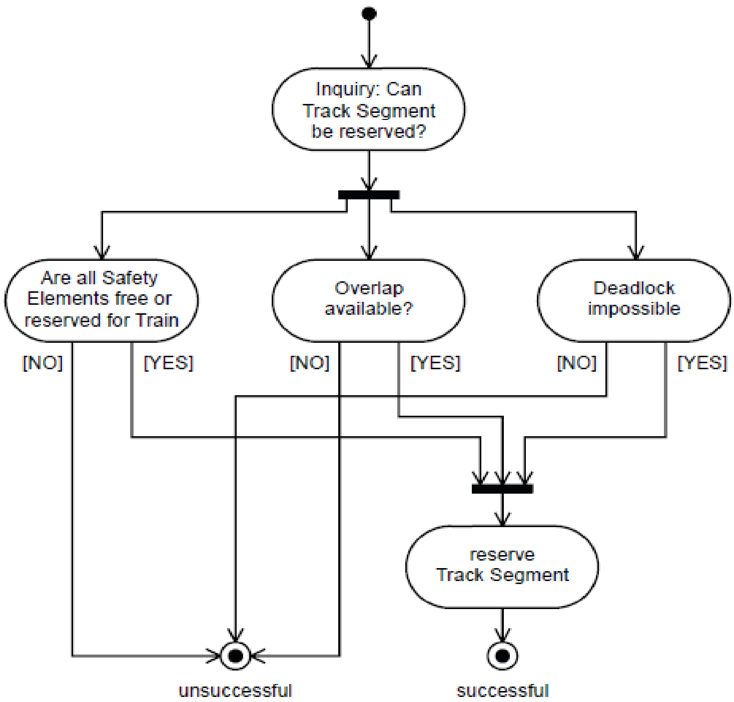


Figure 4-5: OpenTrack Flowchart: Track Segment Reservation

Figure 4-6 illustrates the case of a successful route reservation. In this example Train Z1 is approaching the point (AP1) of requesting the route from HS1 to HS2. As the figure shows, the train's brake curve has been precalculated for the possibility that Train Z1 will need to stop at Point HS1. In the example Train Z1 receives permission to proceed on the route HS1 to HS2 and so the figure shows the train continuing at speed V-Z1 until it the point where it is necessary to brake to stop at point HS2.

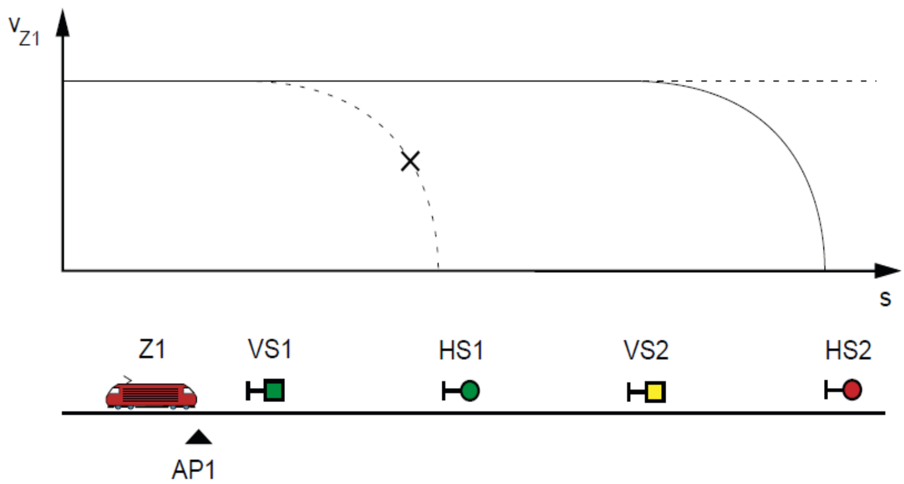


Figure 4-6: Successful Track Segment Reservation

In contrast, Figure 4-7 illustrates the case of an unsuccessful route reservation. In this example Train Z1's request to enter the section behind Signal HS1 fails despite free safety elements because a part (segment 'DRW' in the figure, overlap) of the through route is being used to accommodate Train Z2. Thus Train Z1 must assume that it will need to stop at the beginning of the requested route (at HS1) and can proceed past main signal HS1 only when Train Z2 moves into the siding and can release the section of the through route requested by Train Z1.

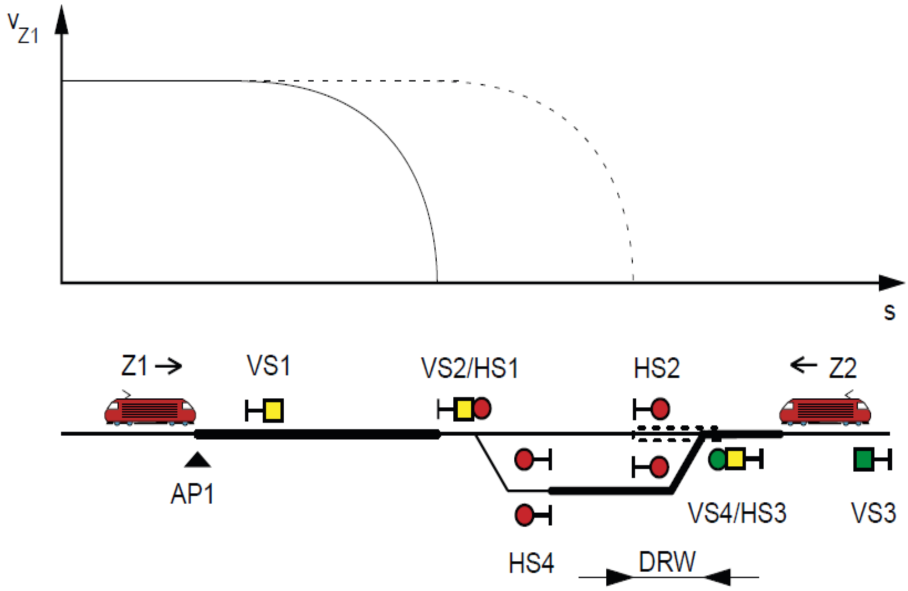


Figure 4-7: Unsuccessful Track Segment Reservation (Through Route Not Free)

The second major type of signaling system is a moving-block signal system. A moving-block signal system is characterized by flexible block lengths; the block length is calculated based on train braking characteristics, train speeds and track layout. In contrast to fixed-block systems, in a moving block system the flexible block (Moving block) is continuously examined to determine whether it is the appropriate length for the optimal progressive movement of the train while maintaining the necessary braking distance from other trains (i.e. track segments occupied or reserved for other trains). During acceleration or travel at constant speed the moving-block system constantly checks that the train remains within its safe current braking distance. If the system recognizes a point of conflict, it moves into the next more restrictive speed condition.

Figure 4-8 shows the process used by OpenTrack to reserve track sections in moving-block signal systems.

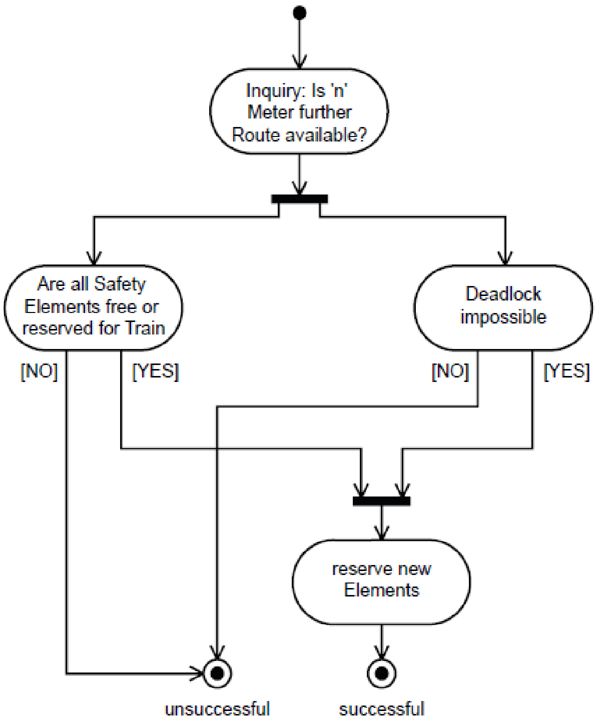


Figure 4-8: OpenTrack Flowchart: Route Reservation with Moving Block

Figure 4-9 illustrates the braking behavior of Train Z2 as it approaches a stopped train (Train Z1) in a moving block signal system. In the figure Train Z2 has been accelerating up its maximum speed, but at time (t-Δt) it receives a warning that further acceleration is impossible given the available braking distance. At the time t Train Z2 begins its effective brake applications, with the goal of stopping behind Train Z1. During each brake step the system examines whether Train Z2's speed can be increased, which would only be true if Train Z1 moved far enough to the right to shift Train Z2's danger point, thus permitting a termination of braking for Train Z2.

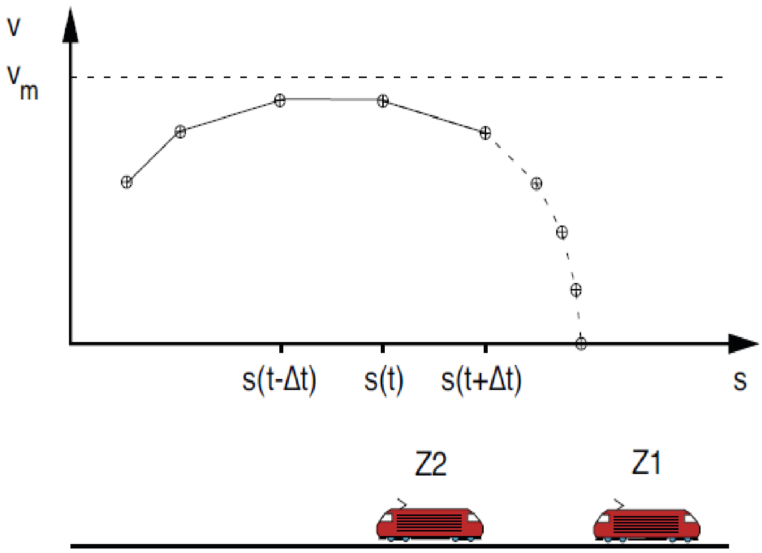


Figure 4-9: Moving Block: Braking Behavior

4.2 OpenTrack Simulation Results

In the case study project, there are nine stations. These stations are modeled in OpenTrack software, in two different signaling system: Fixed-block signaling system and Moving-block signaling system.

The following figure illustrates OpenTrack Model for this case study:

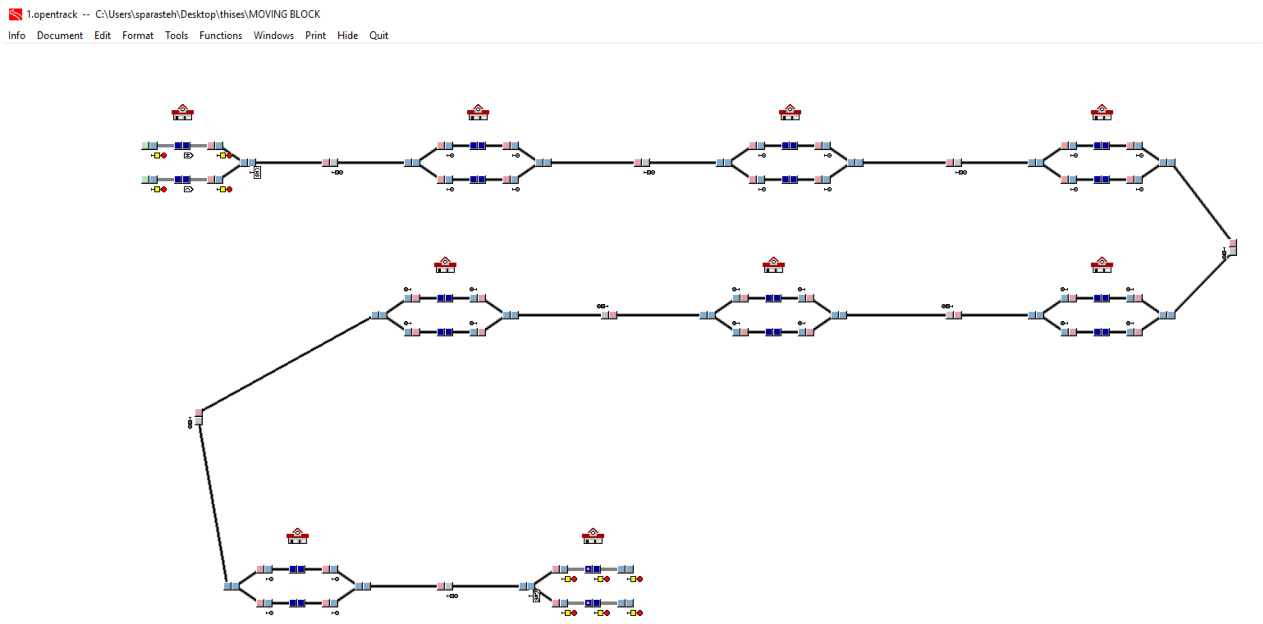


Figure 4-10: OpenTrack Model – Fixed-Block Signaling System

This case study includes two different signaling systems (Fixed-block signaling system and Moving-block signaling system) and two different transport system (Freight and Passenger transport). OpenTrack output is represented in different charts and figures, such as Space-Distance Diagram, Distance-Time Diagram, Timetable & Delay, Delay diagram and Timetable diagram in Freight Transport and Passenger Transport.

In this case study, speed of freight trains is 80 km/h and speed of passenger trains is 120 km/h.

According to the following results, delay in Moving-block signaling system is less than delay in Fixed-block signaling system.

The result of the simulation demonstrates in below figures:

4.2.1. Fixed-Block Signaling System Results (Freight Transport)

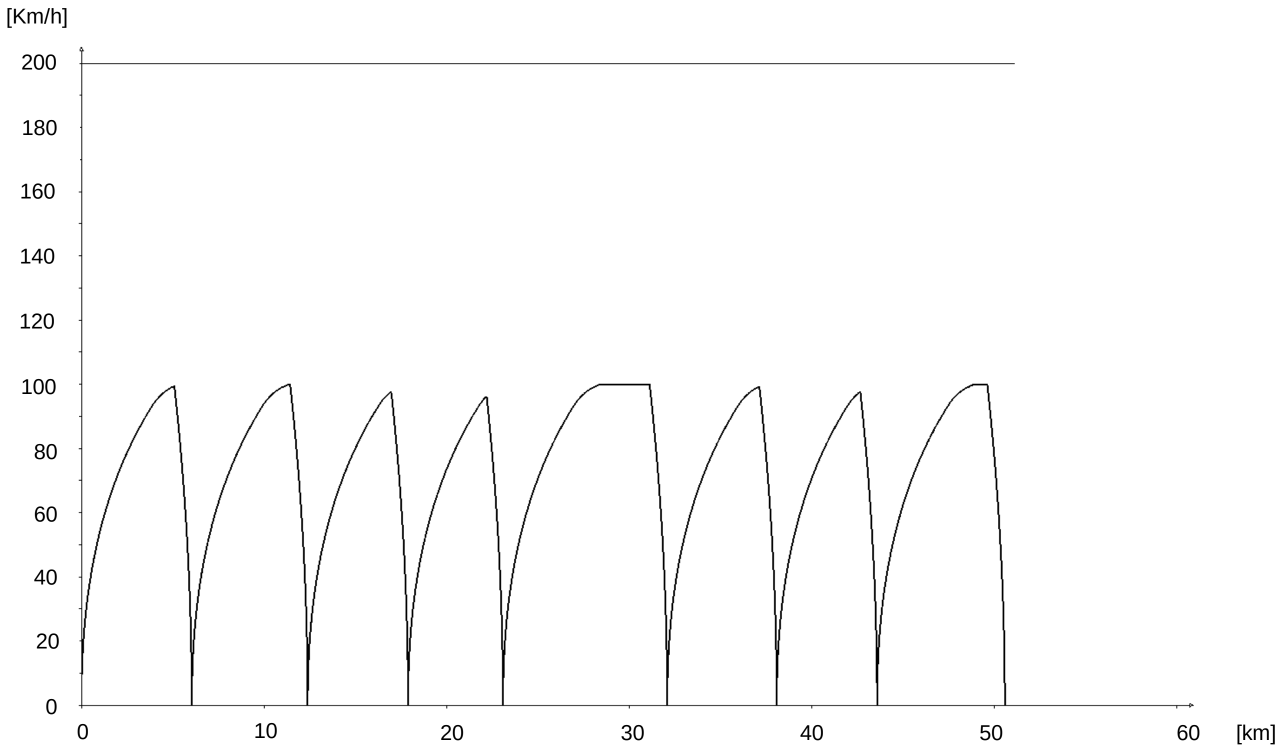


Figure 4-11: Speed-Distance Diagram - Freight Transport (Fixed-Block Signaling System)

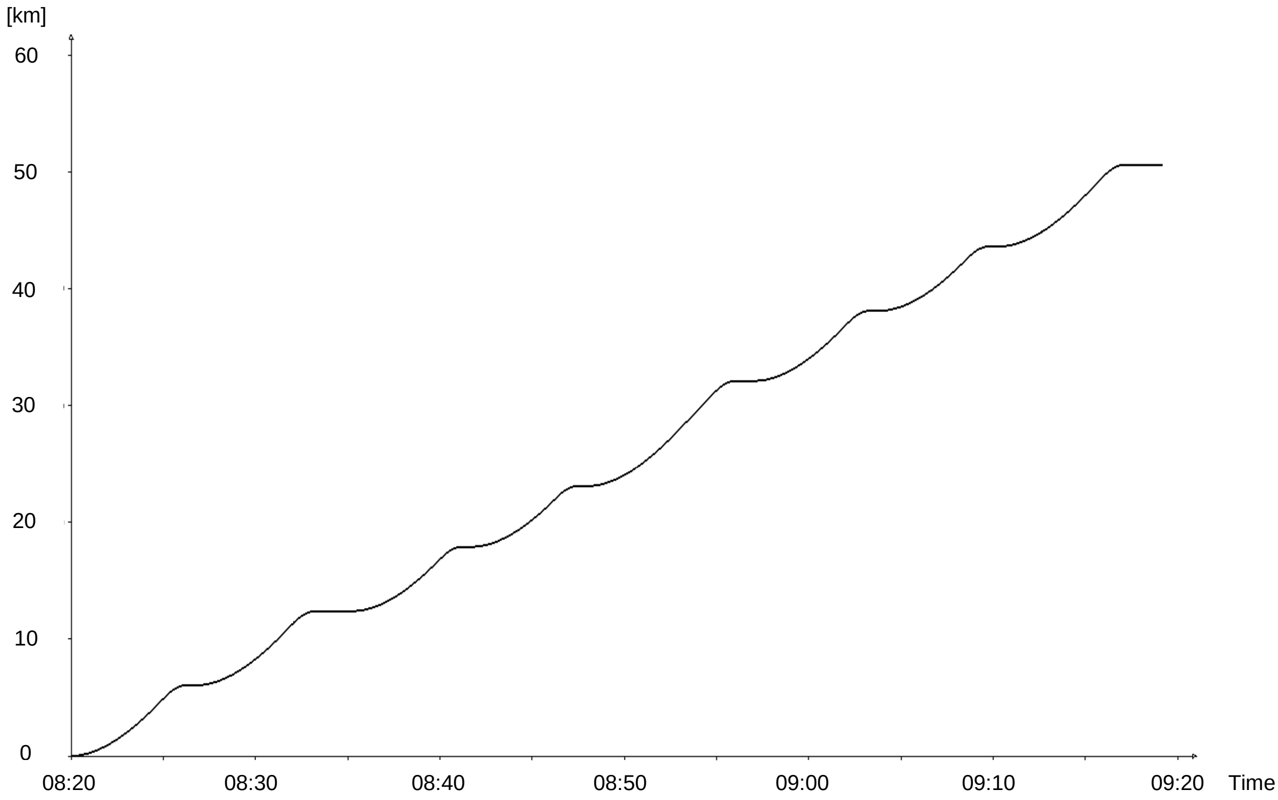


Figure 4-12: Distance-Time Diagram - Freight Transport (Fixed-Block Signaling System)

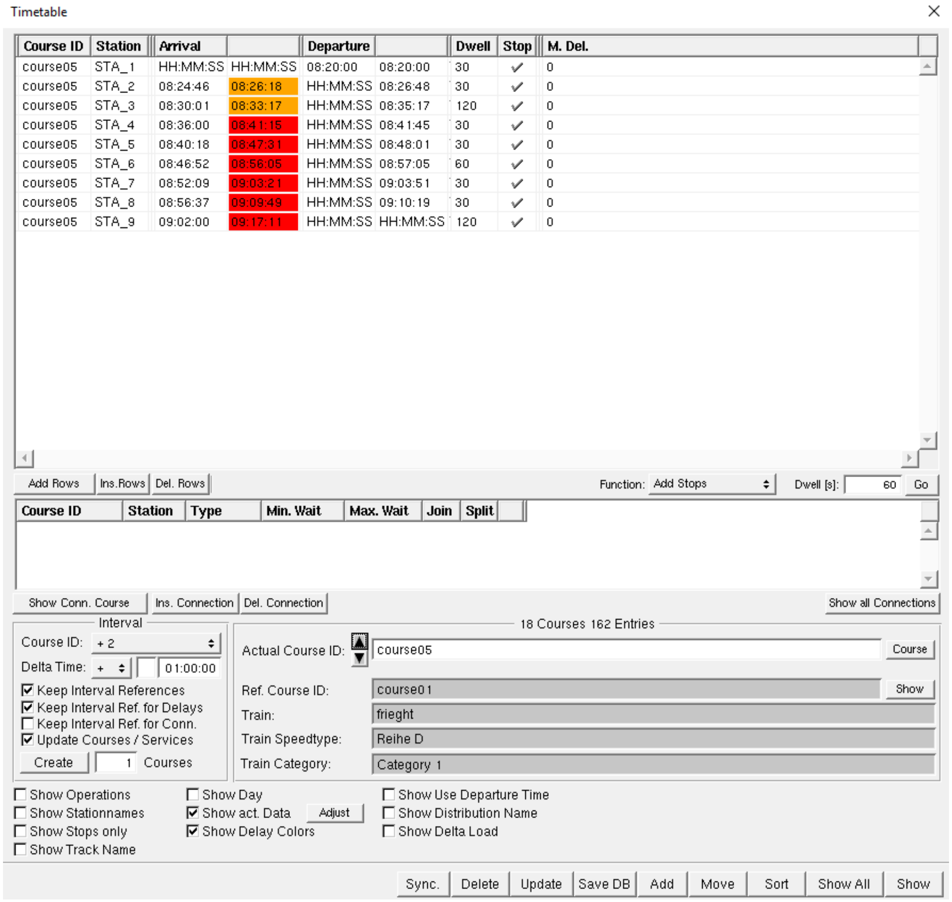


Figure 4-13: Timetable & Delay - Freight Transport (Fixed-Block Signaling System)

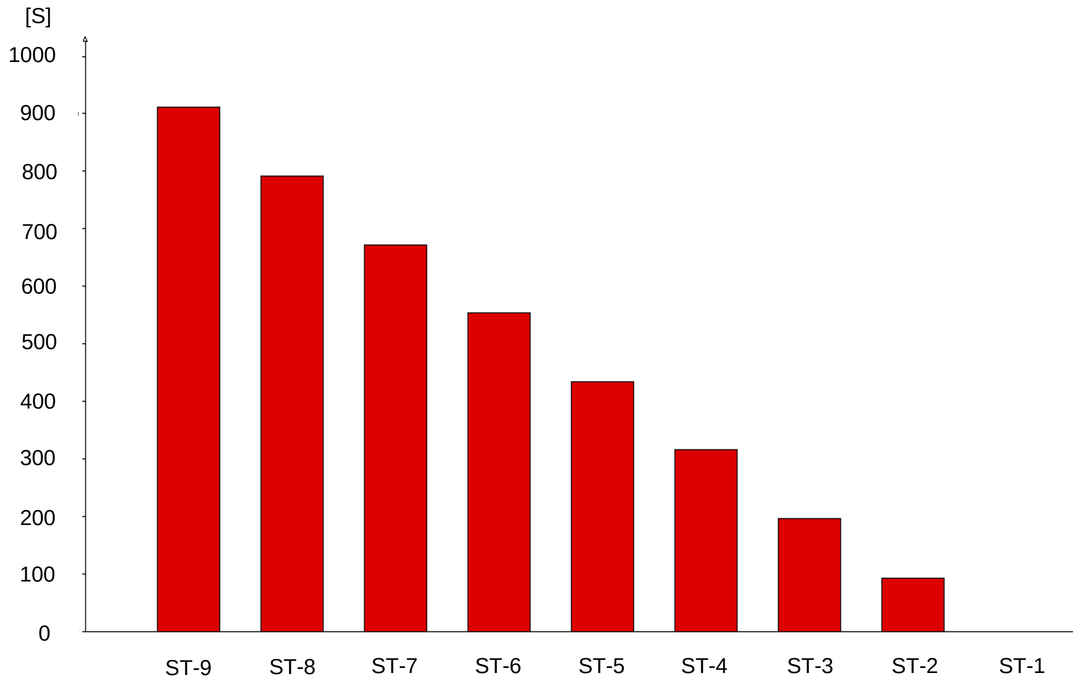


Figure 4-14: Delay - Freight Transport (Fixed-Block Signaling System)

4.2.2. Fixed-Block Signaling System Results (Passenger Transport)

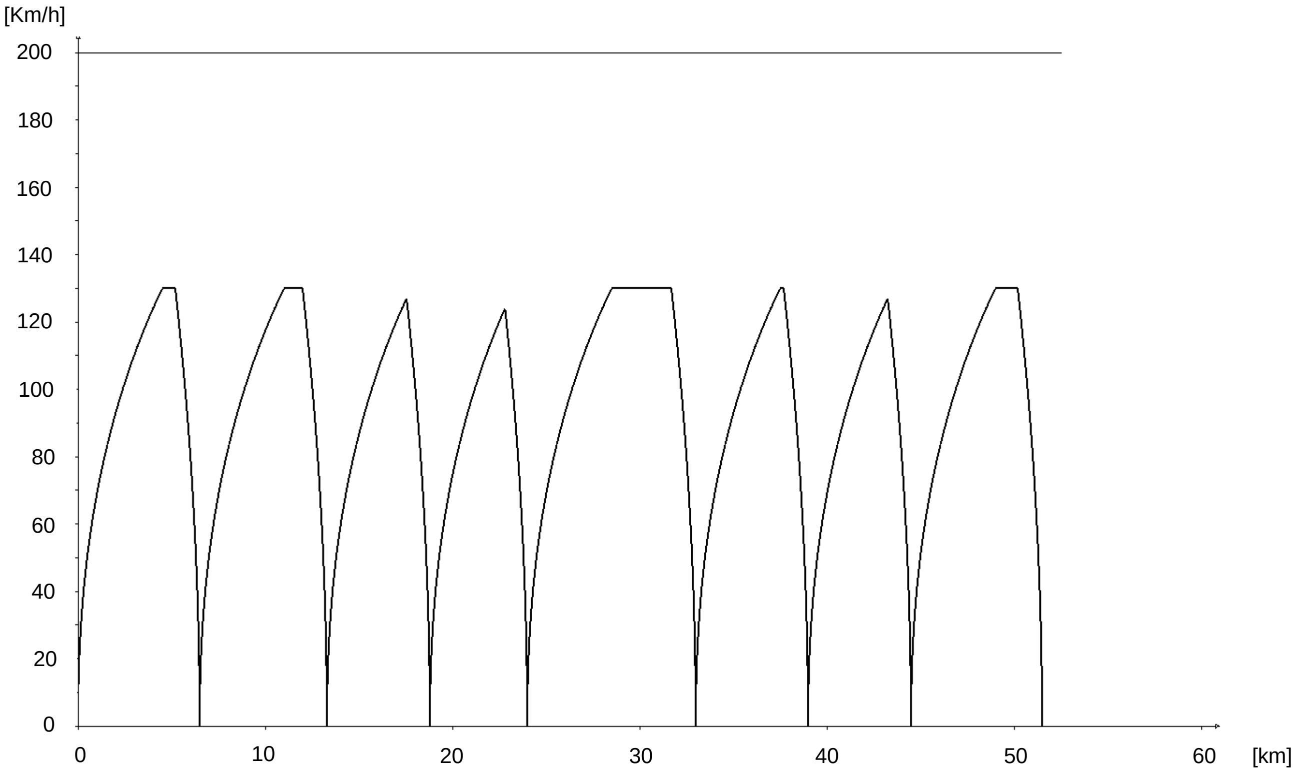


Figure 4-15: Speed-Distance Diagram - Passenger Transport (Fixed-Block Signaling System)

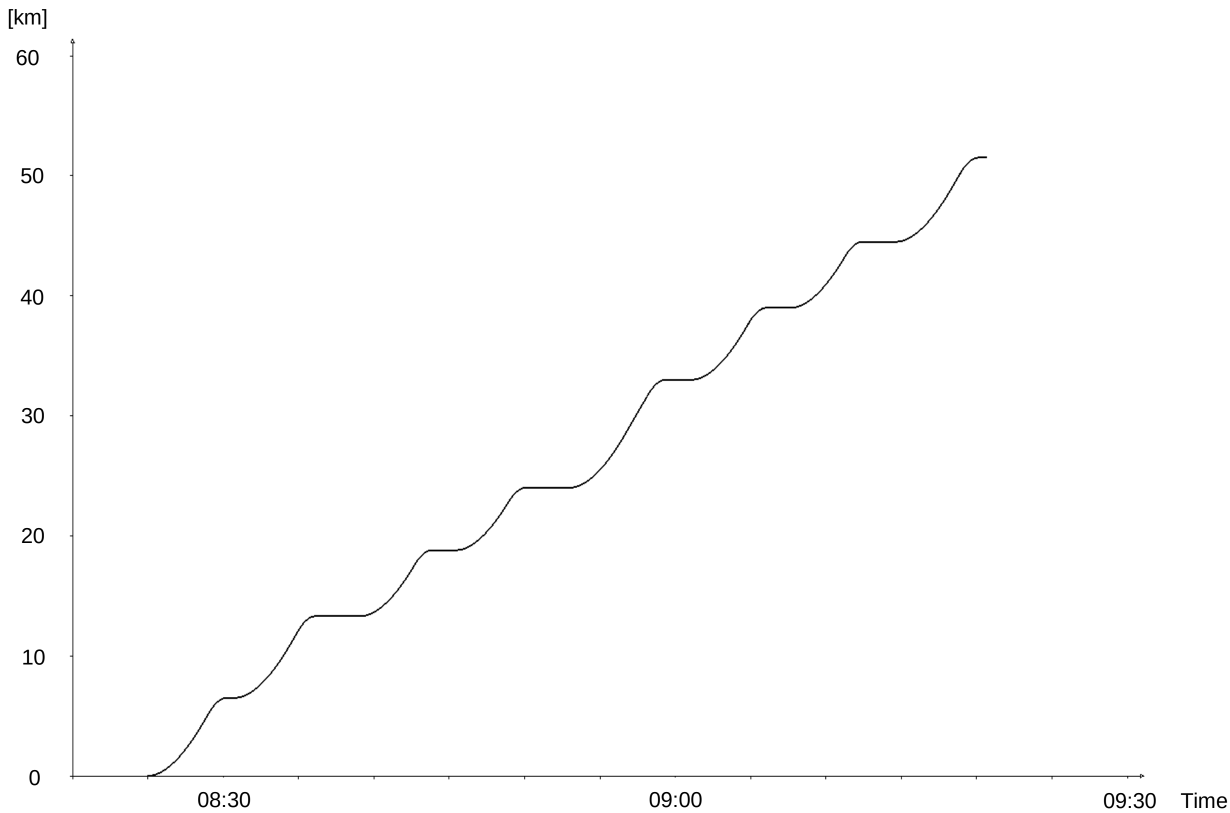
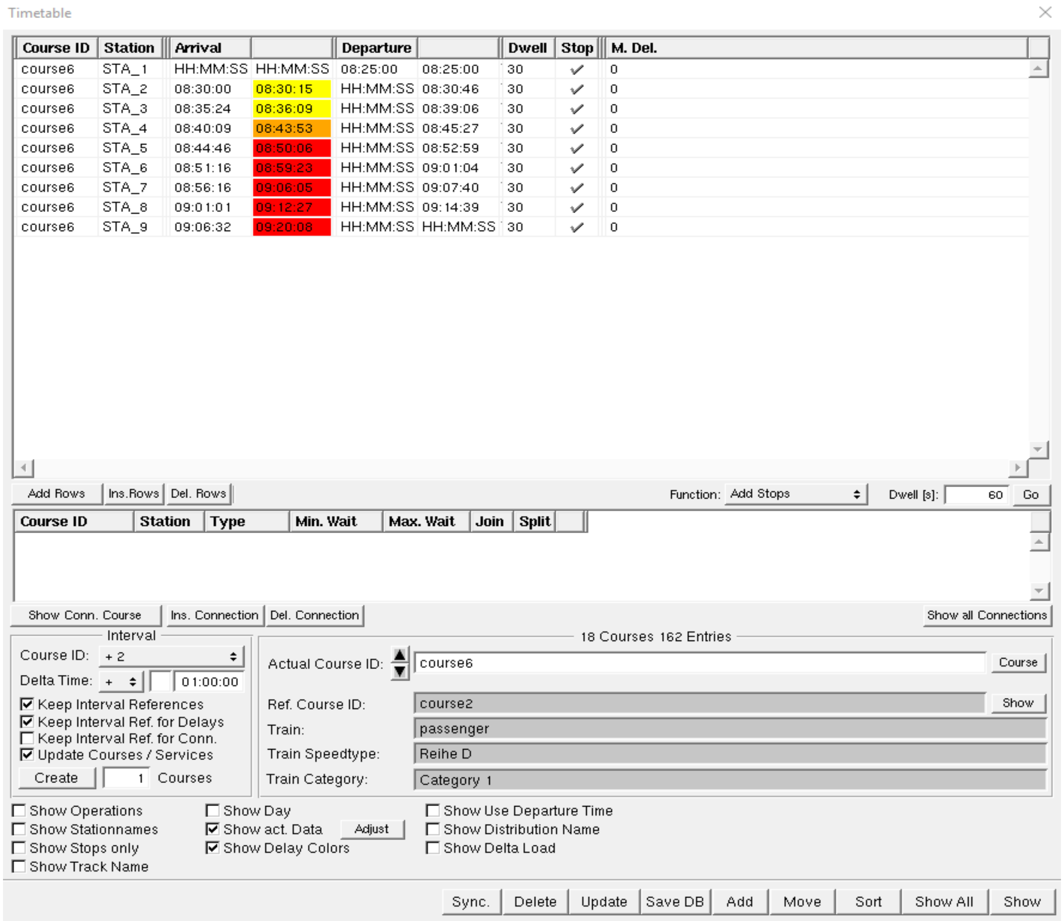


Figure 4-16: Distance-Time Diagram - Passenger Transport (Fixed-Block Signaling System)



Course ID	Station	Arrival		Departure		Dwell	Stop	M. Del.
course6	STA_1	HH:MM:SS	HH:MM:SS	08:25:00	08:25:00	30	✓	0
course6	STA_2	08:30:00	08:30:15	HH:MM:SS	08:30:46	30	✓	0
course6	STA_3	08:35:24	08:36:09	HH:MM:SS	08:39:06	30	✓	0
course6	STA_4	08:40:09	08:43:53	HH:MM:SS	08:45:27	30	✓	0
course6	STA_5	08:44:46	08:50:06	HH:MM:SS	08:52:59	30	✓	0
course6	STA_6	08:51:16	08:59:23	HH:MM:SS	09:01:04	30	✓	0
course6	STA_7	08:56:16	09:06:05	HH:MM:SS	09:07:40	30	✓	0
course6	STA_8	09:01:01	09:12:27	HH:MM:SS	09:14:39	30	✓	0
course6	STA_9	09:06:32	09:20:08	HH:MM:SS	HH:MM:SS	30	✓	0

Figure 4-17: Timetable & Delay - Passenger Transport (Fixed-Block Signaling System)

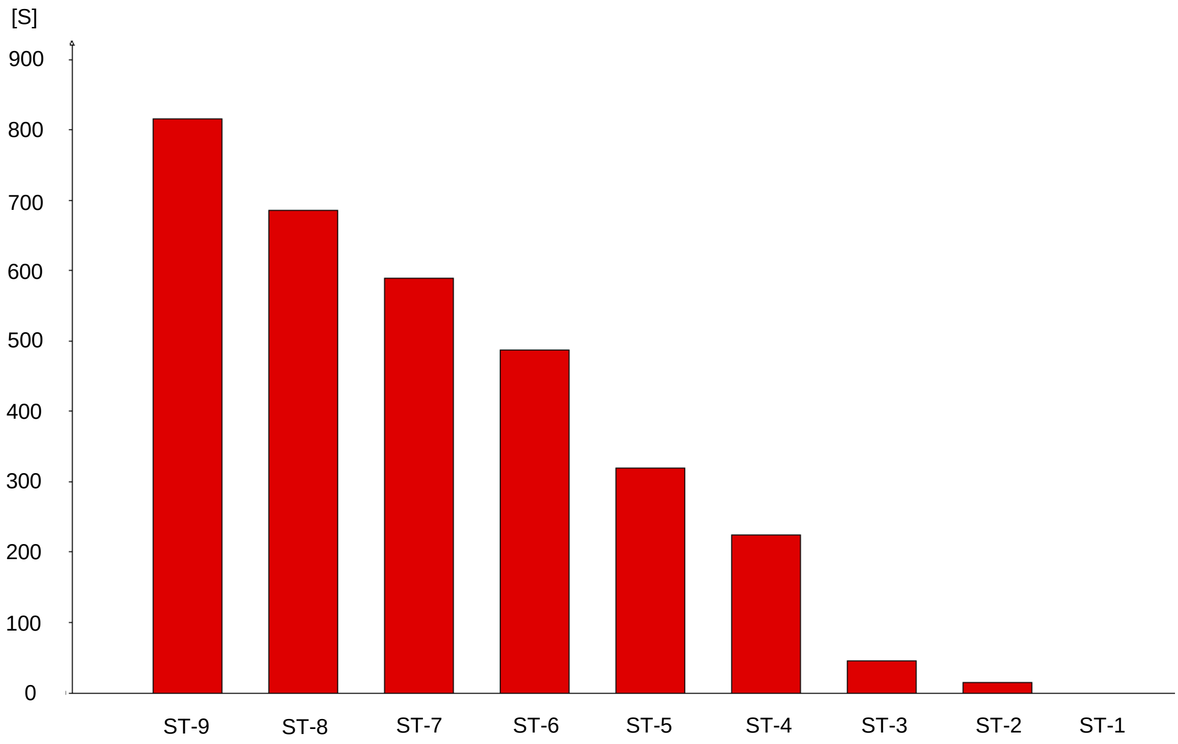


Figure 4-18: Delay - Passenger Transport (Fixed-Block Signaling System)

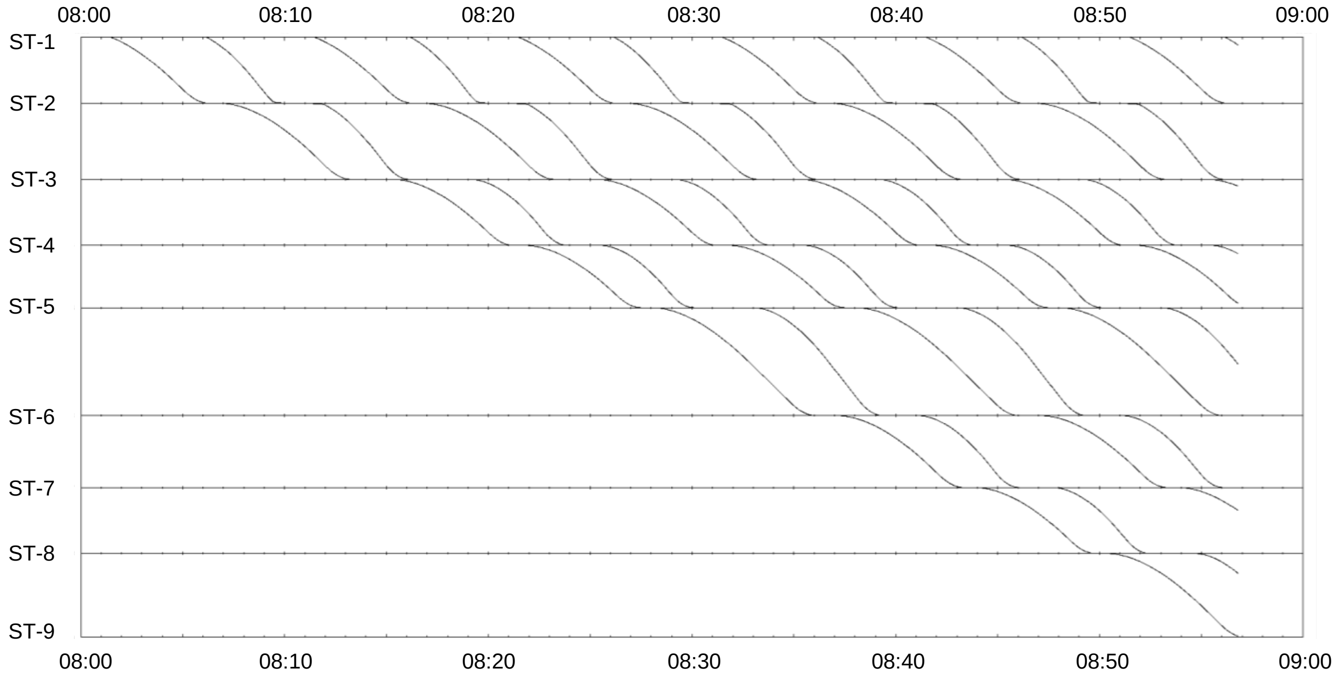


Figure 4-19: Timetable Diagram – Freight & Passenger Transport (Fixed-Block Signaling System)

4.2.3. Moving-Block Signaling System Results (Freight Transport)

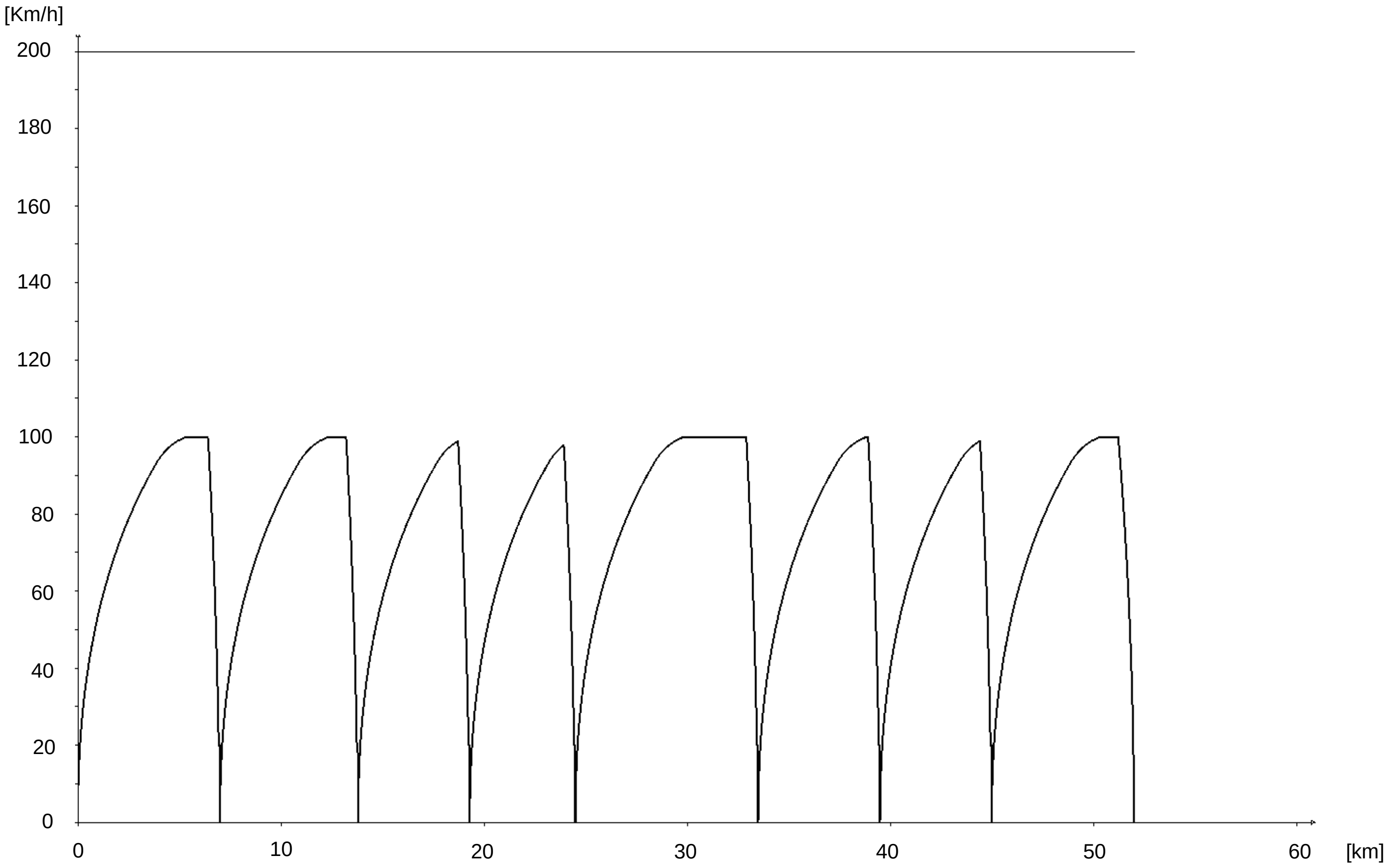


Figure 4-20: Speed-Distance Diagram - Freight Transport (Moving-Block Signaling System)

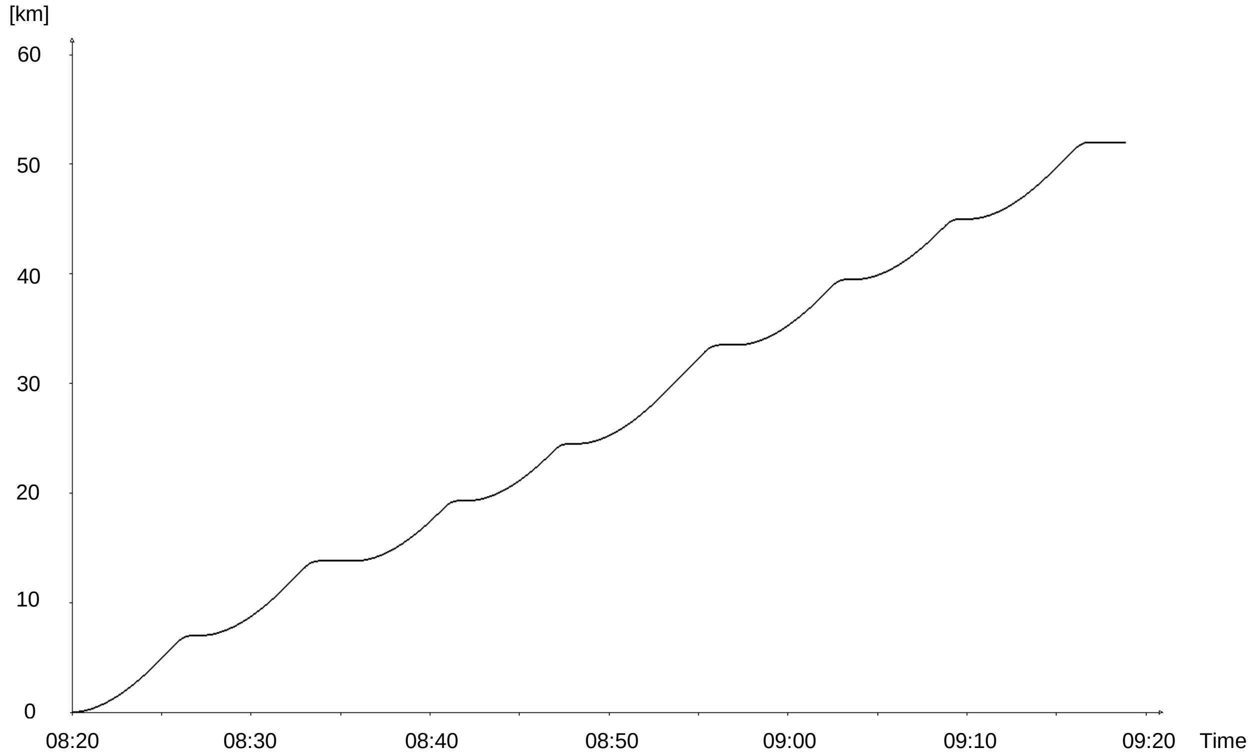
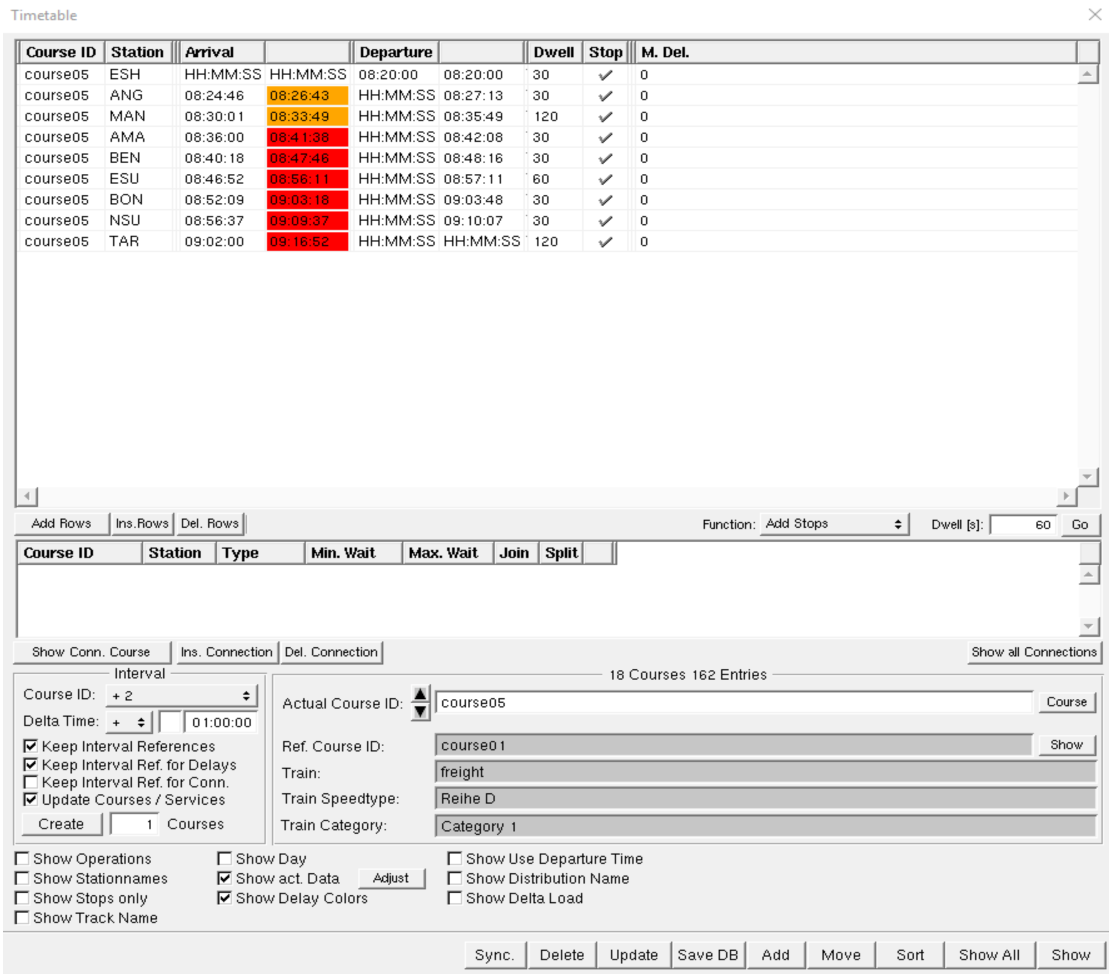


Figure 4-21: Distance-Time Diagram - Freight Transport (Moving-Block Signaling System)



Course ID	Station	Arrival		Departure		Dwell	Stop	M. Del.
course05	ESH	HH:MM:SS	HH:MM:SS	08:20:00	08:20:00	30	✓	0
course05	ANG	08:24:46	08:26:43	HH:MM:SS	08:27:13	30	✓	0
course05	MAN	08:30:01	08:33:49	HH:MM:SS	08:35:49	120	✓	0
course05	AMA	08:36:00	08:41:38	HH:MM:SS	08:42:08	30	✓	0
course05	BEN	08:40:18	08:47:46	HH:MM:SS	08:48:16	30	✓	0
course05	ESU	08:46:52	08:56:11	HH:MM:SS	08:57:11	60	✓	0
course05	BON	08:52:09	09:03:18	HH:MM:SS	09:03:48	30	✓	0
course05	NSU	08:56:37	09:09:37	HH:MM:SS	09:10:07	30	✓	0
course05	TAR	09:02:00	09:16:52	HH:MM:SS	HH:MM:SS	120	✓	0

Figure 4-22: Timetable & Delay - Freight Transport (Moving-Block Signaling System)

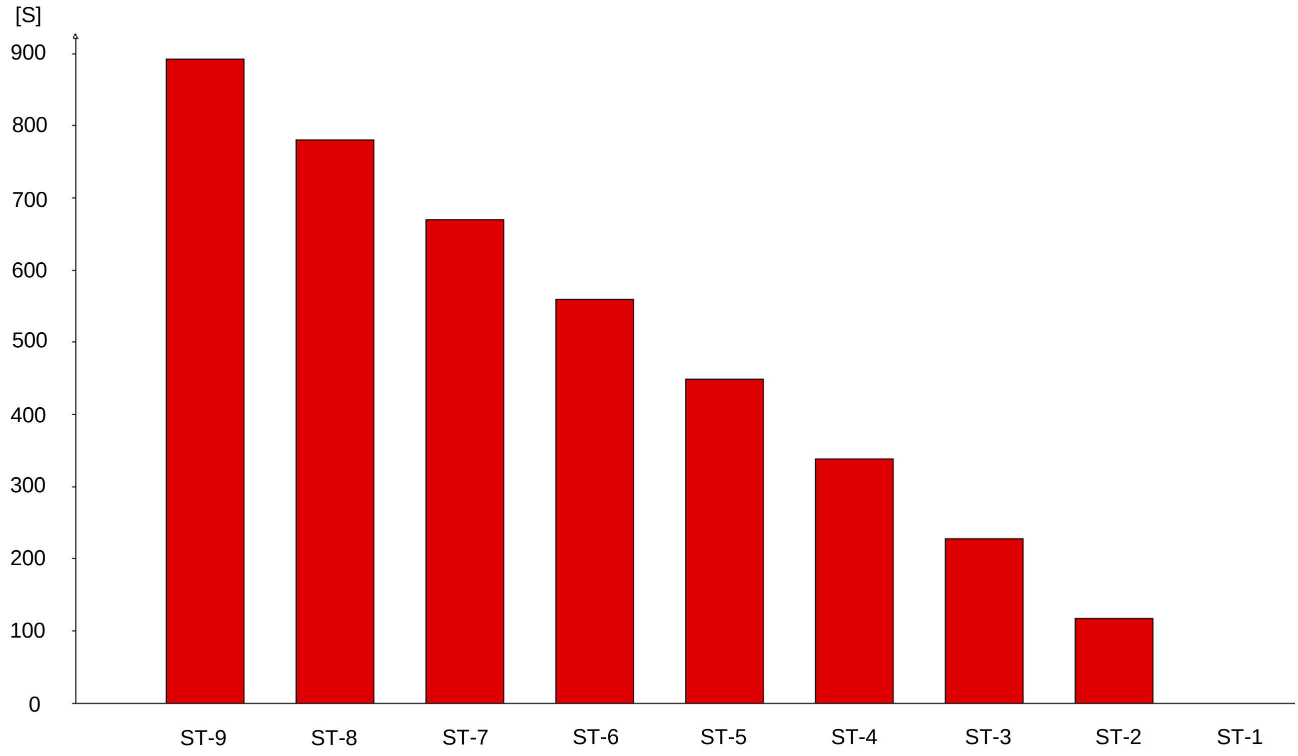


Figure 4-23: Delay - Freight Transport (Moving-Block Signaling System)

4.2.4. Moving-Block Signaling System Results (Passenger Transport)

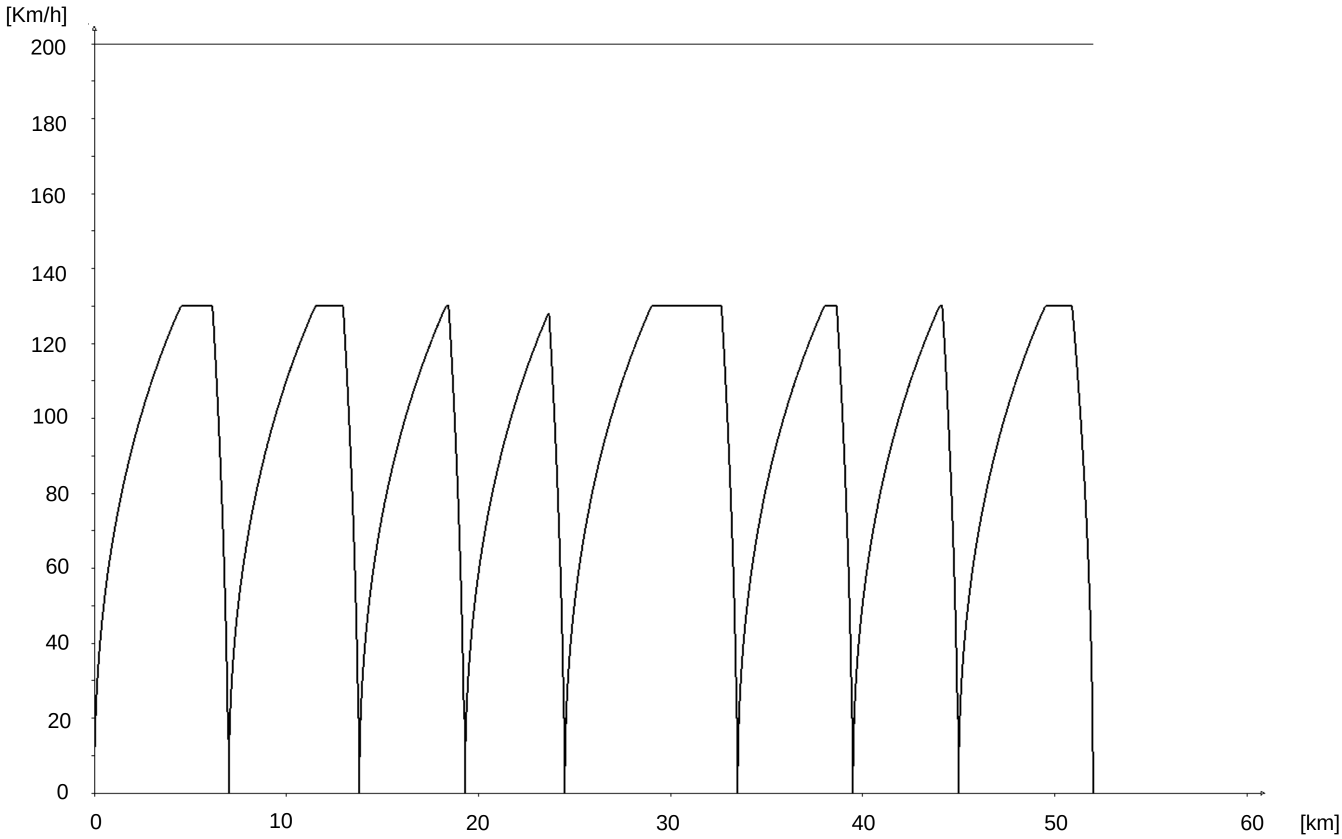


Figure 4-24: Speed-Distance Diagram - Passenger Transport (Moving-Block Signaling System)

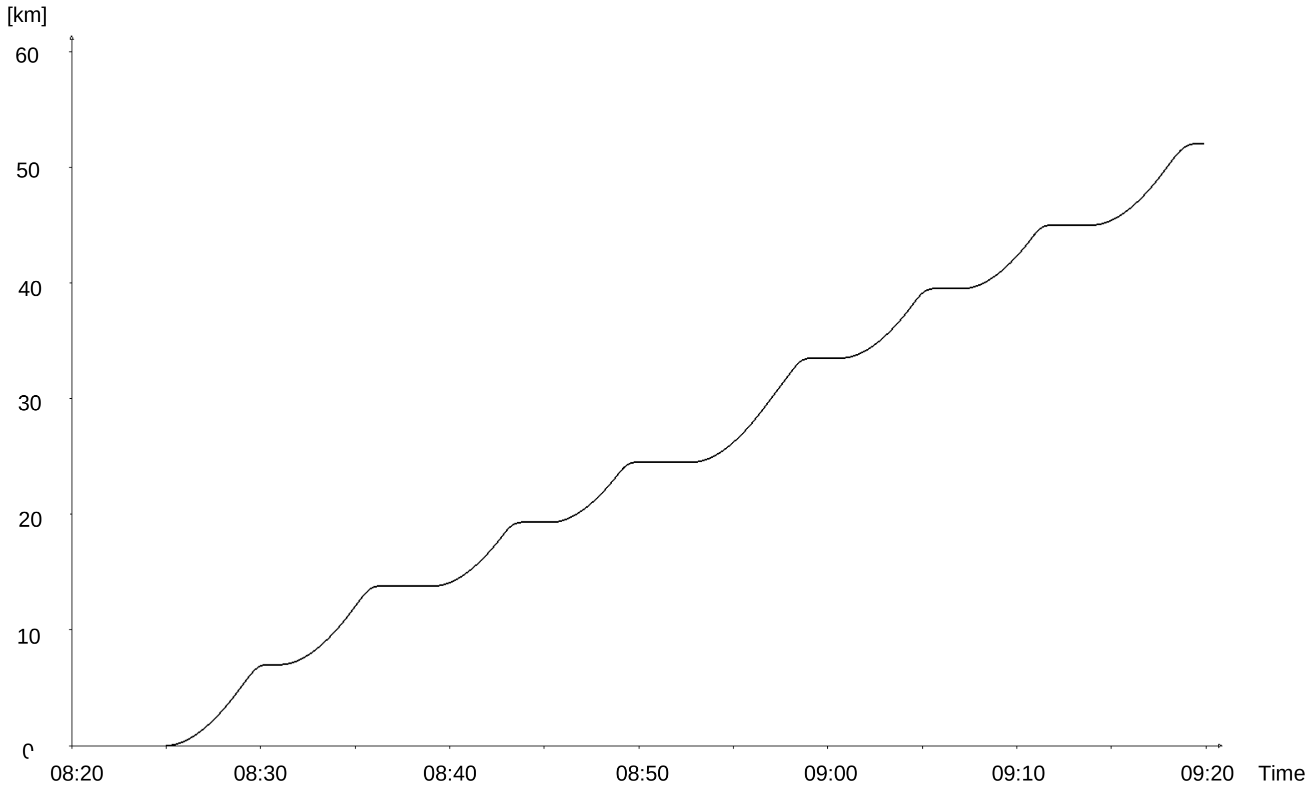


Figure 4-25: Distance-Time Diagram - Passenger Transport (Moving-Block Signaling System)

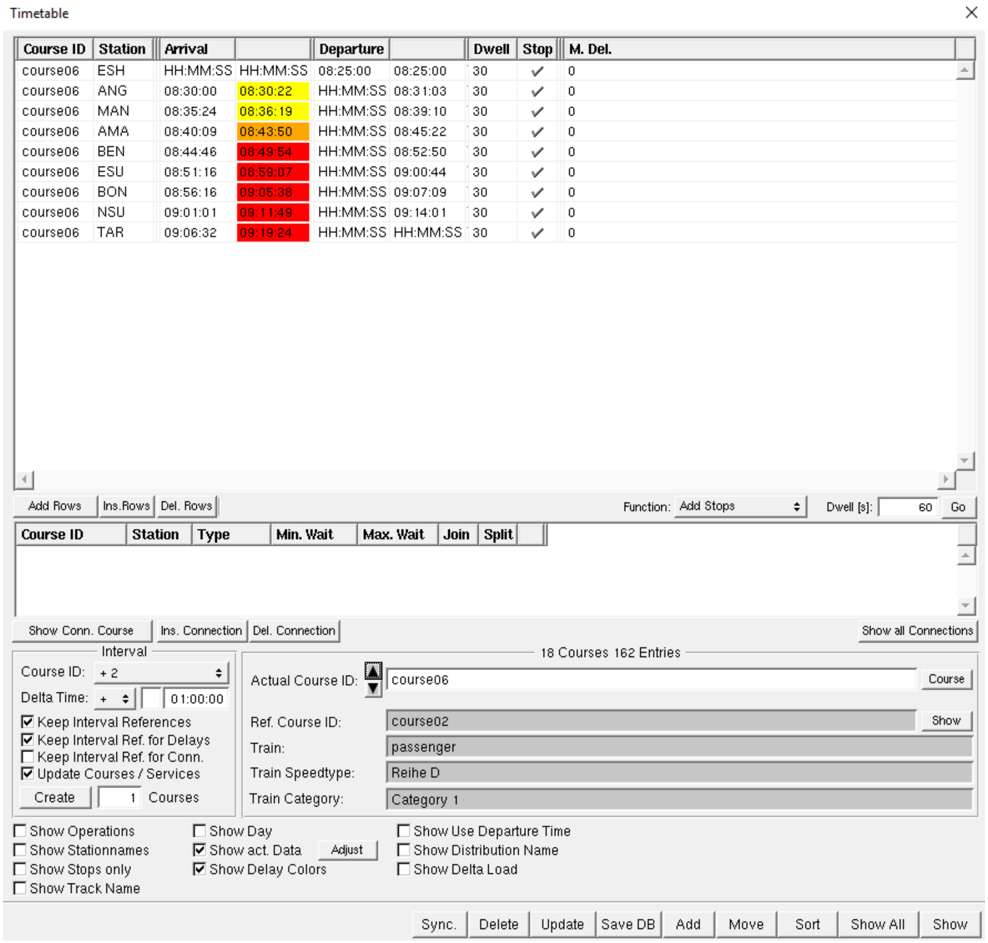


Figure 4-26: Timetable & Delay - Passenger Transport (Moving-Block Signaling System)

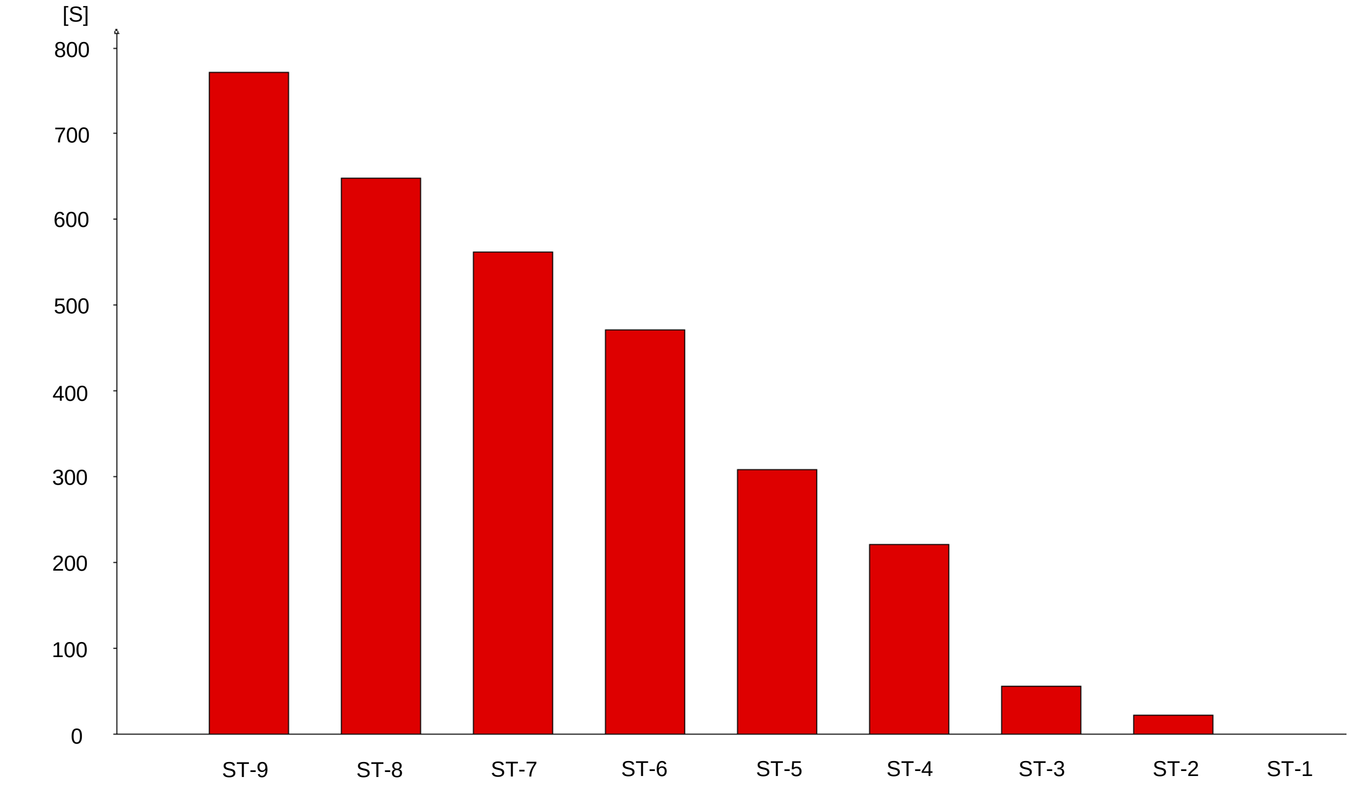


Figure 4-27: Delay - Passenger Transport (Moving-Block Signaling System)

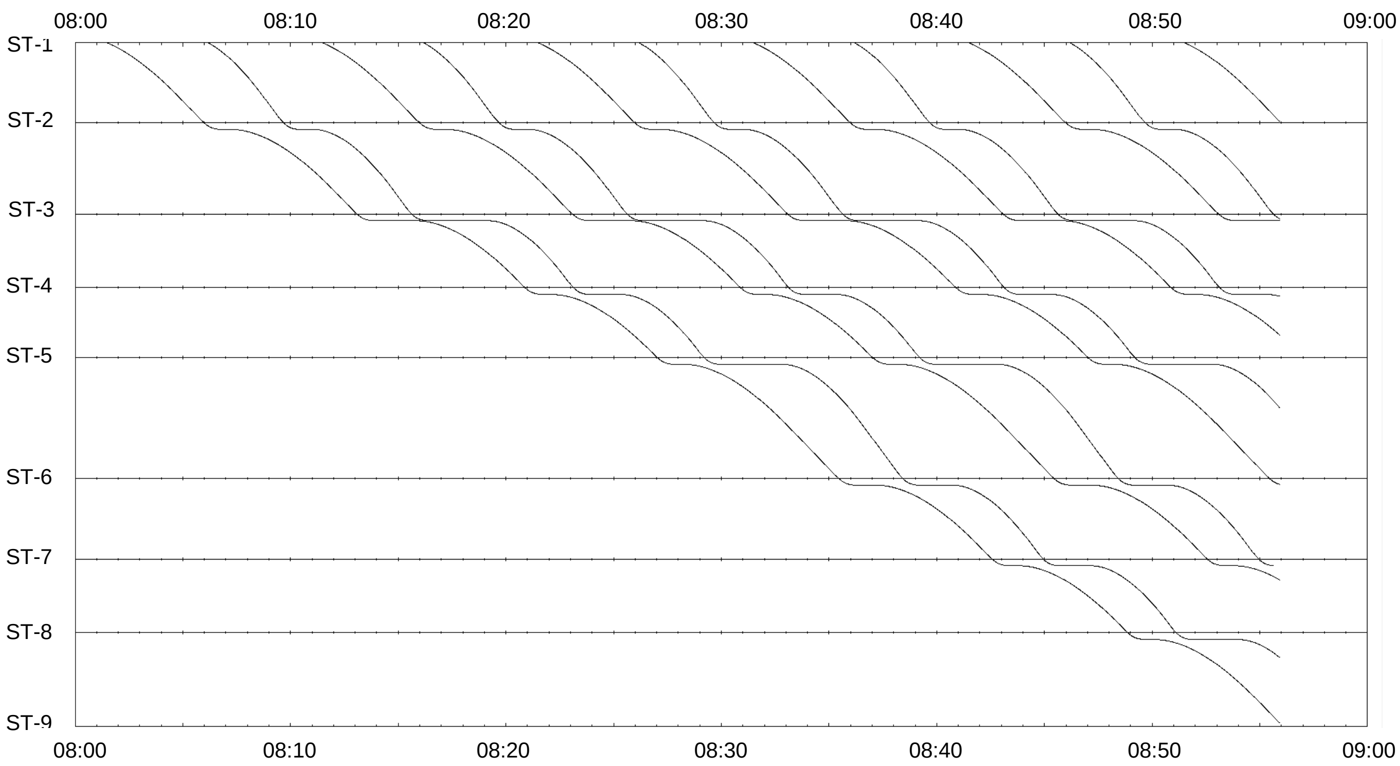


Figure 4-28: Timetable Diagram – Freight & Passenger Transport (moving-Block Signaling System)

4.3 Cost Analysis

According to previous studies and projects in all over the world, the cost of installation of ETCS Level 3 is about $1.5 million per route-km.

On the other hand, the cost of installation of Fixed-block signaling system is about $0.5 million per route-km according to survey in Team engineering.

Consequently, following results for cost of using signaling system are calculated:

- The Cost of the using Moving-block signaling system is $1.5 x 57km = $85.8
- The Cost of the using Fixed-block signaling system is $0.5 x 57km = $28.5

Furthermore, following results for annual delay reduction of using Moving-block signaling system are calculated according to:

- Freight Traffic in 2047 is 128.57 mill.tons/year
- Passenger Traffic in 2047 is 1.38 mill.pax/day

So,

- Annual delay reduction per freight transport for Moving-block signaling system is 128.57 x 10^6 x 19s = 244 x 10^6 (second) = 678564 (hour)
  If the cost of time for every person per hour consider $2, the total cost of one year by changing signaling system from Fixed-block signaling system to Moving-block signaling system will be $1.35 million.
- Annual delay reduction per passenger transport for Moving-block signaling system is 1.38 x 10^6 x 365 x 44s = 22163 x 10^6 (second) = 6156388 (hour)
  If the cost of time for every person per hour consider $5, the total cost of one year by changing signaling system from Fixed-block signaling system to Moving-block signaling system will be $30.78 million.

As a result, by changing signaling system from Fixed-block signaling system to Moving-block signaling system, $214.2 million will save in this project in 20 years (equal to technical life of the project).

In the following figures, the Cost comparison in Moving-block signaling system and Fixed-block signaling system according to following table demonstrates:

Cost ($million) per km		
Parameters	**Fixed-block signaling System**	**Moving-block signaling System**
Design	0.3	0.3
Infrastructure	2.9	2.9
Signaling	0.3	1.5
Structure	1	1

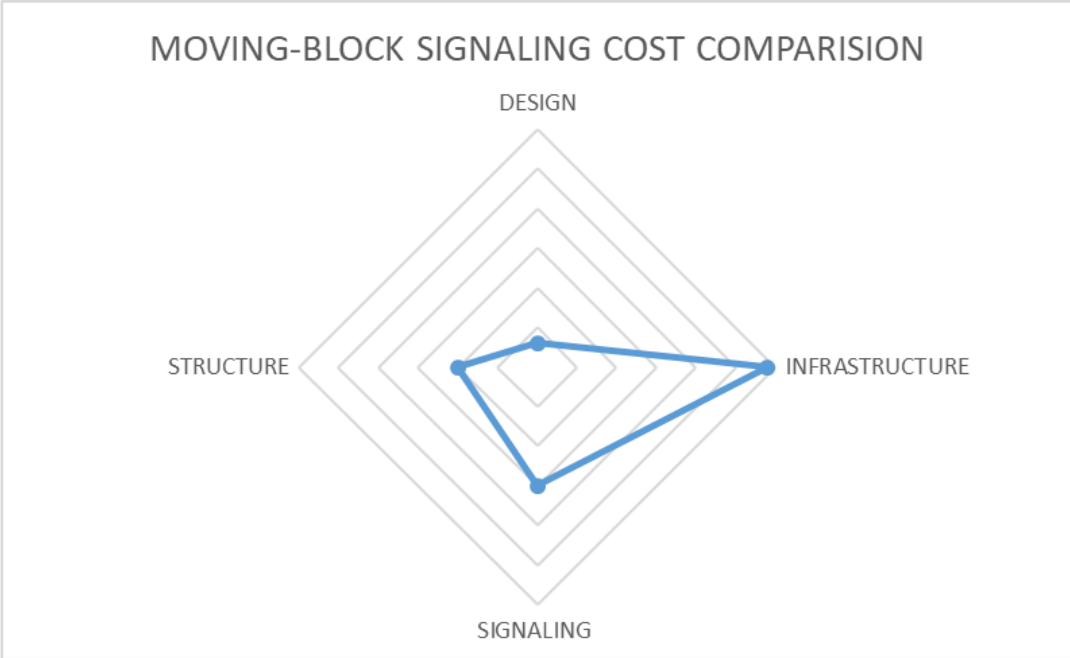


Figure 4-29: Moving-Block Signaling System Cost Comparison

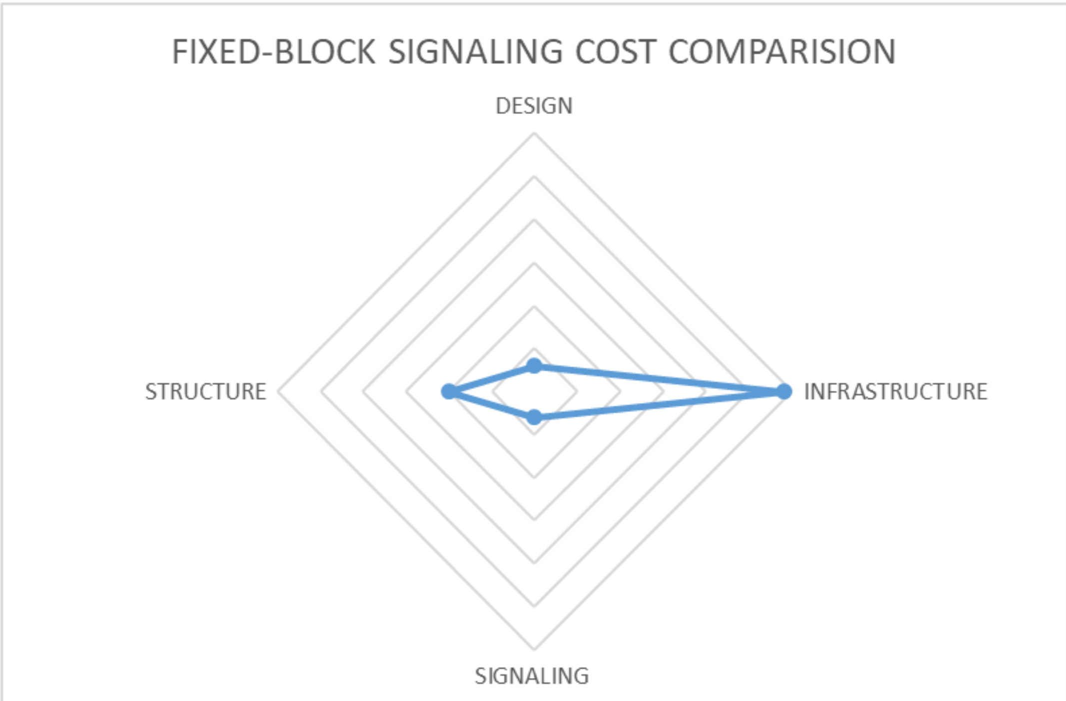


Figure 4-30: Fixed-Block Signaling System Cost Comparison

Chapter 5

5 Conclusion

Today, rail transportation, as the lowest CO2-emmission mode of transport, emerges as a key alternative to road and air transport, both in terms of passenger and freight.

Train control is an important part of the railway operations management system. The railway signaling is a complex and fascinating subject and it is the key system to ensure the safe operation of railway traffic and it used to direct railway traffic and keep trains clear of each other at all times. Therefore, it is important to have a safe and reliable railway signaling system.

Fixed-block signaling system is a solution based on a technology invented in the 1860's. In moving-block signaling system, there is an adjustable distance based on a real time calculation of the train speed. So the immediate benefit of moving-block signaling system is the headway between trains is reduced. Another aspect of moving block is the safety distance moves with the train, as its name is moving block. So instead of using static entity defined by the location of signals and trip stops, it uses moving block for providing safety distance. Consequently, there is no wasted space, the train is not left waiting for a block to clear (as it is in fixed block) and the most important, and the headway is kept as short as possible.

On the other hand, according to results of case study in this thesis, delay also decreased by using Moving-block signaling system instead of Fixed-block signaling system.

Consequently, by changing signaling system from Fixed-block signaling system to Moving-block signaling system, $214.2 million will save in this project in 20 years (equal to technical life of the project).

Moreover, according to my study, using moving-block signaling system is more reasonable when the distance between station is high, speed of the trains is equal, and without mixed traffic. In this case study, because of the mixed traffic situation in freight and passenger transport and distance between stations (6-9 km), using moving-block signaling system is complicated from the safety point of view.

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