Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Zhijin Liu

Availability Estimation and Allocation for ERTMS

Master's thesis in Reliability, Availability, Maintainability and Safety (RAMS)
Supervisor: Associate Professor Yiliu Liu
June 2019

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Preface

This is a Master's thesis, as partial fulfillment of the requirements to the master of science (MSc) degree in Reliability, Availability, Maintainability and Safety (RAMS), in the Department of Mechanical and Industrial Engineering (MTP) at Norwegian University of Science and Technology (NTNU). It was carried out during the spring semester of 2019, from January to June, as a continuation of the Reliability, Availability, Maintainability and Safety, Specialization Project.

The primary targets of this thesis are to estimate the overall availability for railway systems by simulation, which is done by MATLAB (Version R2018b), considering ERTMS failures and unplanned dwell time, to allocate the failure or repair rates to reach expected availability and to assess the system resilience upon shocks. The readers shall ideally have a basic understanding of RAMS engineering, railway systems, and MATLAB coding.

Trondheim, 2019-06-11

刘志谨 Zhijin Liu

Zhijin Liu

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Finally, my special thanks would go to my beloved family in China, for their continuous support and encouragement throughout past years.

Z.L.

Summary

This thesis focuses on the availability estimation by simulation, availability allocation and resilience assessment for railway systems.

Firstly, a brief background of the railway has been given including history, infrastructure and operation, as well as its relation with RAMS engineering. Also, the concepts of availability and punctuality are introduced with formulas and requirements. Besides, a classic definition of resilience is presented and a definite integral method for resilience assessment is proposed. The main approach to determine availability in this thesis, simulation, is described exhaustively in the following chapter.

Then, the overall availability of railway systems in different scenarios is estimated by MATLAB (Version R2018b) simulation. It is proven that the availability performance can fulfill the requirements, under certain assumptions and omission. The discussion of results reveals the proportion of delay reasons including signaling system failures, unexpected dwell time and cascades. Also, the average availability-time diagram of the whole journey is estimated to determine the critical time.

Later, availability allocation is done for the signaling system to reach expected availability. Two allocation methods are chosen. The management implication is discussed based on the results. Meanwhile, a new average availability-time diagram is generated with allocated overall repair rate is generated to present the influences of repair rate upon availability performance and critical time.

In the last part, the proposed definite integral method is applied to prove its applicability for resilience assessment. Several scenarios are simulated and the reasons regarding the differences in resilience performance are discussed as well as the impact of repair rate.

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Chapter 1

Introduction

Recently rail transportation has become the major form for both passengers and freight in many countries. It has some significant advantages, such as higher energy efficiency, higher safety, and heavier load when compared with other types of transport like trucks or aircraft. Availability is one of the most important indicators in the rail industry since it can directly influence the economy of railway operators. This thesis includes mainly three parts, availability estimation by simulation for railway systems, availability allocation and resilience assessment for the signaling system. Several scenarios will be simulated by MATLAB.

1.1 Background

As rail transportation grows rapidly because of the rising amount of both freight and passengers, the demand for availability and punctuality is becoming more and more important. Several causes such as hardware failures, incidents or unexpected dwell time could lead to delays in the rail industry. Availability estimation by simulation can determine the overall availability based on those delay reasons. When the availability performance is not satisfactory, it's still possible to increase the availability by tuning failure or repair rates. This process is of great value since it can verify if the railway systems can fulfill the requirements and if further improvement is applicable in the early phase so that the challenges in the operational phase to reach the expected availability will be eased.

The standard EN 13306: Maintenance Terminology [2] has defined availability as the ability of an item to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided. Existing studies have proposed several methods for availability estimation. For example, Qiu, etc have built a state-chart model in Stateflow for availability assessment of railway signaling systems with uncertainty analysis [3]. Song and Schnieder have applied the Colored Petri nets approach for modeling of railway systems and maintenance [4]. But so far little attention has been paid on the further work, availability allocation, after availability estimation.

Besides, Bane NOR (Norwegian National Rail Administration) has defined it as a requirement: no later than 4 minutes in each station [5]. This definition is from the perspective of customers and allows a certain degree of delay. The researching gap here is that most proposed methods have zero tolerance against failures or other delay causes.

Resilience, which is defined as the capability of an entity to recover from an external disruptive event [6], is of interest by many researchers. Availability also can be observed with a resilience behavior since it will fall after failures and rise with repairs. Few existing studies have assessed the resilience of railway availability, so this topic has come into scope.

Generally, challenges are:

- No availability estimation based on Bane NOR's requirement;
- Lack of allocation work after availability estimation;
- No relevant research on the resilience assessment of railway availability.

1.2 Objectives

The main objectives of this Master's thesis are:

- Propose a detailed simulation process to estimate the system overall availability and carry out availability allocation.
- Find an appropriate approach to assess railway availability resilience.

To be more specific:

1. Introduce the background of rail transport and availability concepts in railway systems.
2. Find an applicable resilience assessment method.
3. Estimate the availability of different scenarios and evaluate the influences of various delay reasons.
4. Generate the average availability-time diagram to determine the critical time.
5. Allocate failure or repair rate for a higher availability target and discuss the management implication.
6. Evaluate the impact of allocated repair rate upon the average availability-time diagram.
7. Assess resilience and discuss the effect of repair rate by comparison.
8. Discuss the results and recommend further work.

1.3 Limitations

It's not a viable option to construct scenarios perfectly owing to the complexity or lack of relevant data. Hence, delay models have to be simplified, which means some activities will be omitted and some parameters will be approximated, and some situations will not be considered when modeling. So, the final quantitative results might be inaccurate when compared with the data in real practice. It is here just a presentation of the model-based simulation process. Some limitations are listed below while other assumptions are mentioned in respective chapters.

- It's difficult to consider all of the numerous delay reasons. Hence, some of them are omitted.
- In actual operation, components may have different degradation levels and the performance will vary, so as the trains. But in this thesis, trains are simplified to have only two states, working and repairing (before and after failure).
- Total failure rates and overall repair rates will be used instead of individual parameters of components to simplify the simulation process.

- Some data is missing because it's secret in the industry (failure rates of some components) or it's never been collected (dwell time distribution at stations). As a result, some items have to be out of scope.
- Common cause failures are ignored due to complexity.
- The average availability-time diagram for multiple vehicles is out of scope due to complexity.
- The number of simulation runs shall be the larger the better but is actually limited due to the computer hardware performance. Less runs bring great randomness.
- The quantitative results could vary from those observed in actual operation since the models cannot be as same as the real structure. Differences and deviations will exist.

1.4 Approach

This report begins with the introduction of railway systems and availability-related concepts. Then a literature review reveals the existing research levels and deficiencies. Objects are proposed based on the review.

To fulfill the objects, one section of train journey will be chosen as a case study to run the simulation for availability estimation and resilience assessment, while availability allocation will be done through quantitative calculation and the results obtained will be discussed for management implication.

1.5 Structure of the Report

The rest of the report is structured as follows.

- Chapter 2 gives an introduction to rail transport and its traffic control system and availability-related concepts. One resilience assessment method is also selected in this chapter.
- Chapter 3 introduces the background and steps for availability estimation by simulation.

- Chapter 4 describes the chosen scenario, presented input parameters for simulation and demonstrates the simulation of a single-vehicle system.
- Chapter 5 demonstrates the simulation of a multiple-vehicle system.
- Chapter 6 presents the detail process of availability allocation by two methods as well as its significance in management.
- Chapter 7 assesses the resilience by the chosen method and verifies the applicability.
- Chapter 8 lists the achievements and results of this thesis.
- Chapter 9 recommends some further work.

Chapter 2

Railway System and Availability

The railway is a mass transport system. Vehicles powered by diesel traction or electrification systems move on a dedicated steel guideway defined by two parallel rails. From the perspective of transportation systems, a railway system shall comprise three constituents: infrastructure, rolling stock and operation[7].

2.1 General History

2.1.1 Origin

Evidence shows that a rudimentary form of rail transport was operated from around 600 BC in ancient Greece. That paved trackway, Diolkos, enabled transporting boats across the Isthmus of Corinth and stayed in use for 650 years. Wheeled vehicles pulled by livestock or men ran in the grooves of limestone [8].

2.1.2 Revolution of Materials and Power Sources

Technical and productivity development was made through centuries. An important revolution in rail transport was the change in rail materials. When rails were introduced, the original material was wood. In the late 1760s, metal was introduced by the Coalbrookdale Company, with fixed plates of cast iron to the upper surface of wooden rails [9]. In 1803, Surrey Iron Railway was opened in south London with unflanged wheels running on L-shaped iron plates [10].

It was a milestone to replace iron with steel since steel rails could last several times than iron, which allowed heavier longer trains and longer lengths of rails to be rolled. The first steel rails were produced at Derby station in England in 1857 [11], which was the pioneer of modern hot-rolled steel rails.

The most significant change in the rail industry was the application of various power sources. Livestock, especially horses, remained the prior power for rail transport even after the invention of steam engines until the end of the 19th century. The reason was mainly that the animal-powered cars caused less pollution compared to smoke from steam engines. The first full-scale steam-powered railway locomotive was created in the UK in 1804 [12]. While the first locomotive powered by electricity was invented in 1837, using galvanic batteries and then in the 1890s, alternating current electric locomotives were designed. Meanwhile, the earliest prototype of an internal combustion engine in a railway locomotive was designed in 1888.

2.1.3 High-speed Rail

High-speed rail refers to a type of rail transport which can operate faster than traditional rail traffic. Although there is no commonly applied standard, it's widely considered that existing lines in excess of 200 km/h and a new line in excess of 250 km/h are high-speed.

In the late 19th century, the average speed of many regularly operated trains could reach around 100 km/h. At that time, a major challenge was to increase velocity. The first experiment of high-speed rail development began in 1899 in Germany. Two railcars were built with electrical equipment from different companies. The highest speed of each railcar achieved 206.7 km/h and 210.2 km/h in 1903 respectively. Given the cost and disasters such as derailments and head-on collisions, the introduction of high-speed rail service was not successful. But the speed of train service continued rising. In 1905, railcars could run at an average speed of 130 km/h between Los Angeles and Long Beach. Then in 1931, the trains built for Philadelphia and Western Railroad were able to reach 148 km/h. On 15 May 1933, a new top speed record for regular was made between Hamburg and Berlin at 160 km/h.

With the development of reliability and safety of high-speed rail, the construction of world's first high-speed rail system, Tōkaidō Shinkansen, finally finished in 1964. The original operation was designed between Osaka and Tokyo in Japan and reached a top speed of 210 km/h and an average speed of 162.8 km/h in the first traveling. This marked a new era of rail transport, and high-speed rail service has been built in Japan, Spain, France, Germany, Italy, China, the UK, South Korea, Scandinavia, Belgium, and the Netherlands, with the increasing speed up to and above 300 km/h [13].

2.2 Railway Infrastructure

On the hardware level, a railway system has two main components, the infrastructure and the trains. Railway infrastructure includes the railway tracks and all civil engineering structures (stations, tunnels, etc) and systems/premises which ensure the railway traffic [7]:

- Tracks: Tracks provide the path for wheels to roll on and enable the trains running without turning. Railway tracks consist of a series of components that transfer the static and dynamic traffic loads to the foundation, such as rails, sleepers, elastic pads, switches, fastening, ballast, concrete slab, etc.
- Civil engineering structures: Civil engineering structures include tunnels, bridges, over/underpasses, noise barriers, fencing, drainage systems, etc.
- Systems/premises: The systems include signaling, electrification, telecommunication systems, and level crossing. While the premises comprise stations, depots, and other building facilities.

2.3 Railway Operation

The term railway operation refers to all activities through which a railway company secures revenue service. Activities include [7]:

- Technical: Including scheduling/tracing of routes, production/implementation of rules and manuals, capacity allocation, traffic safety, staffing of station/trains, and regulation/-traffic control.

- Commercial: The activities regarding fares policy, market, and organization and management of traffic.
- Maintenance: To ensure efficient operation of the railway system, a proper maintenance plan is indispensable. The maintenance in railway operation covers railway infrastructure, rolling stock and other relevant equipment.

The technical (especially scheduling, capacity allocation and traffic safety) and maintenance part could be interesting topics in RAMS engineering. The following paragraphs will introduce those activities in detail.

2.3.1 Technical Activities

Railway Scheduling

Railway scheduling is the process by which the 'demand' for both passenger and freight transport is brought together with 'supply side' constraints (such as limited infrastructure capacity, rolling stock, and staff) to generate timetables and resource plans that fulfill the demand at a reasonable level of cost. This activity is also known as 'train planning'[14]. Figure 2.1 describes the process.

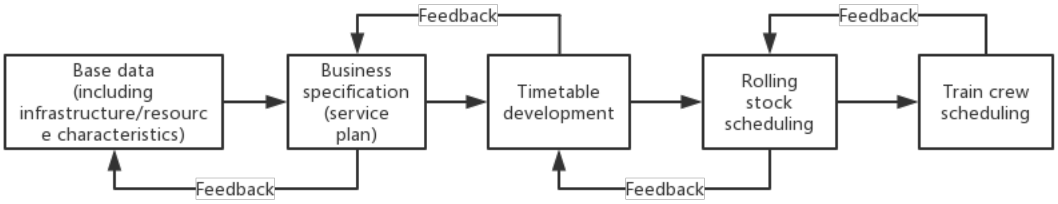

Figure 2.1: Railway Scheduling Process

The whole process consists of five phases and starts with collecting base data (infrastructure and resource characteristics and availability). Then conflicting business specifications (also known as 'service plans'), which come from the different requirements of the customers of the railway, will be produced. The plans will be delivered to the timetable planners for timetable development when finished. In this phase, the times provided in the services plans will be transferred into detailed schedules, accurate to fractions of a minute, based on the details of the infrastructure and the vehicles. The next step is to allocate the rolling stock. A rolling stock diagram, which is a listing of the services which a notional item of the rolling stock shall undertake during the working period, will be generated in this phase. The last stage is train crew scheduling, which includes allocating train crew to all the rolling stock taking into account the proper number of crew, publishing rules and regulations regarding train crew working hours, required knowledge and various compulsory ancillary tasks (such as reporting for duty, signing on, training, etc.) as well as producing rosters. Each phase can provide feedback to the previous one in order to improve the performance [14].

When timetables are generated, it's necessary to verify the punctuality. This thesis will demonstrate a detailed process to estimate the influence of delays against punctuality in the following chapter 4 and 5.

Capacity Allocation

The definition of capacity can be the capability of the infrastructure to handle one or several timetables [15]. Capacity is generally measured as the form of access rights, which are the contractual rights in the track access agreements between rail track and operation companies to run a specific number of vehicles on specific parts of the railway net during specific periods. Rail capacity has some key characteristics: non-homogeneous, interdependency and contingent valuation, network effects and complexity, franchise commitments and high transaction costs [16]. Together those characteristics have made capacity allocation an activity to seize the balance between restrictions and costs by tuning access rights.

Track capacity allocation concerns multiple users facing demand indivisibilities, running trains over an inelastic supply of railway tracks. Some features can influence the allocation problem, such as the number of blocks (the shortest segment of a line that can hold one train at a time) of each line [17], network effects and complexity (major re-scheduling on busy routes needs the simultaneous involvement of both infrastructure managers and operation companies), high transaction costs and franchise commitments. Some mechanisms for allocating capacity have been introduced, such as market-based mechanisms, cost-based mechanisms, and administered mechanism [16].

Traffic Safety

It's unavoidable to face risk when conducting transport activities, which is associated with fatalities, injuries as well as damage to the asset. Death due to railway accidents occur rarely and potential accident precursors can be revealed to identify risks. The accident precursor and the mitigation actions [18]:

1. Human performance: A better safety culture shall be established. On top of that, better operation procedures and training can be of more significance than changes in attitude.
2. Technical failures: Satisfying system engineering, sufficient root cause analysis and a commitment to continuous reliability improvement can reduce the risk regarding technical failures. Due to the consistent management attention, the importance of this category decreases progressively.
3. Passenger actions: Basically passenger actions are the main contributor towards injuries and fatalities, often due to unconscious or careless behaviors. The most significant improvement in the solution is better communication between passengers and crew. Also, better design and control of passenger flows can reduce risks dramatically.
4. Malicious and illegal action: This is a cause of relatively few incidents. A proper ticketing system shall be introduced to reduce crime. Also, high-quality close circuit television (CCTV) system shall be implemented for monitoring vandalism and antisocial behavior. Besides, station personnel, especially security crew and police, shall get trained well to support security.
5. Fire: It shall be forbidden to use all ignition sources on the train. Also, smoke and fire detectors should be installed.
6. Management action: The awareness of managers to purchase equipment, apply safety procedures and other methods to reduce risk shall be strengthened.

2.3.2 Railway Maintenance

Railway maintenance plays a significant role in availability improvement and reducing the cost of railway incidents. The rolling stock will be taken out of operation for maintenance regularly. The periodic preventive maintenance brings planned maintenance cost, which is mainly the cost of component replacement. But occasionally a failure may occur, which leads to unplanned maintenance cost, including corrective maintenance cost, safety cost and cost related to delays and damage to the asset [19]. In addition, the rail also needs both preventive maintenance (to improve the overall conditions of rail) and corrective maintenance (upon failures) [20].

The maintenance strategy is the optimization for the balance between preventive maintenance and corrective maintenance, as well as the quality of maintenance (as good as new or imperfect maintenance). Besides all types of costs, parameters such as failure rates will be determined to calculate the total cost per unit time, which shall be as low as possible theoretically. The clock-based maintenance plan will be produced based on the input of the corresponding preventive interval. But even though the plan exists, it can be changed as new information becomes available, such as new estimated reliability parameters and unforeseen failures, and the clock-based maintenance can be updated to opportunity based maintenance [19].

2.4 European Rail Traffic Management System

Due to the rapid development of rail transportation, a standardized railway control system has become necessary, since now different national legacy railway signaling systems still exist in Europe, which could be the barricades against seamless cross-border transportation between European countries. European Rail Traffic Management System (ERTMS) is the solution for this barrier [1].

ERTMS is a standardized system in order to replace different national railway control systems in Europe [21]. ERTMS mainly has two basic components, GSM-R and ETCS. GSM-R (Global System for Mobile Communications – Railway) is a radio system extended from the standard GSM (Global System for Mobile Communications) system, allocated with specific frequencies for railway operation. It authorizes the data transmission between trackside and the trains

[22]. ETCS (European Train Control System) is an ATP (Automatic Train Protection) system for both low and high-speed railway systems. It can bring a standard for a uniform signaling system on a Man-Machine interface [23]. ETCS has different functional levels based on the differences of railway equipment and information transmission methods[24]. Level 2 is the currently highest level of deployment and ERTMS in this thesis will be equipped with this level.

2.4.1 ERTMS History

Transport traffic control has been one of the top requirements since the birth of the modern railway industry, which brought the emergence of signaling systems. As the demand for international transportation grew, the existence of different traffic control methods in different countries became a significant drawback [24].

By the end of the 1980s, more than 20 local train control standards were applied in Europe. Meanwhile, existed lineside signaling systems failed to follow the evolution of high-speed railway. Hence, the European Transport minister decided to begin a new industrial project to solve those problems in 1989. Later in 1990, a group of railway specialists gathered to determine the requirements of ETCS. In 1995, the European Commission published a global strategy for the further development of ERTMS, including the development and validation phase. Full-scale experiments were planned in France, Germany, and Italy during the validation phase. In the summer of 1998, UNISIG (the Union of Signaling Industry), an industrial consortium which was created to develop the ERTMS/ETCS technical specifications, was formed to finalize the specifications. On 25th April 2000, the final signature on ERTMS specification (Class 1) marked the arrival of ERTMS.[25]

2.4.2 ERTMS Structure

It has been discussed in the report of Reliability, Availability, Maintainability and Safety, Specialization Project(TPK4550) that the ERTMS can be divided into two systems and several subsystems[1]. Based on this conclusion and the RAM analysis of ERTMS trackside and lineside [26], a structural model is built and shown in figure 2.2 (including ERTMS, two systems, and multiple subsystems).

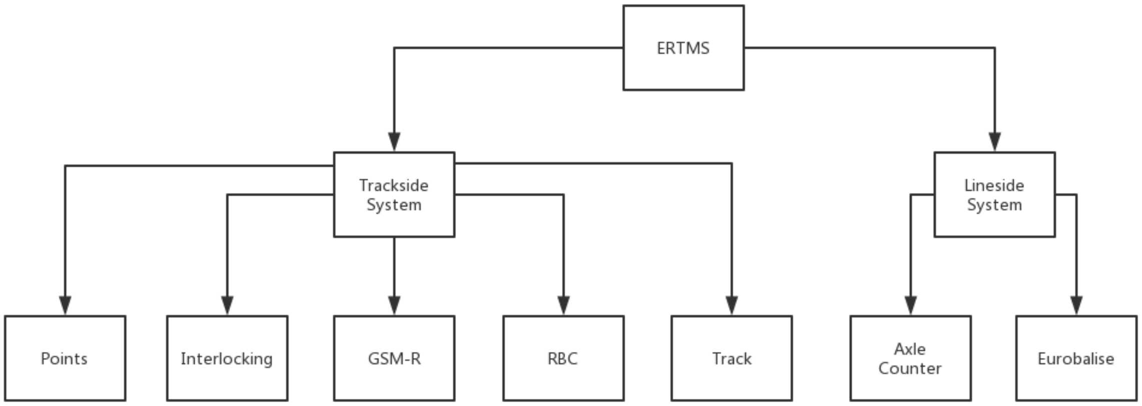

Figure 2.2: ERTMS Structure

Brief descriptions of some subsystems: [26] [27] [28]:

- Eurobalise: A Eurobalise can send position data to a train when it is passing through.
- RBC (Radio Block Center): RBC is a computer-based system that processes the trackside data and provides information such as movement authorities and possible emergency to the train.
- Interlocking: Interlocking is responsible for train routing and the acquisition of the track occupancy status.
- Axle counters: An axle counter basically counts the number of axles entering at a section and number of axles leaving that section.

The subsystems RBC and GSM-R can be decomposed more deeply into components. The following table 2.1 describes the detailed decomposition [1].

Table 2.1: Composition of RBC and GSM-R

subsystem	component	component description
RBC	VC	the vital computer of RBC
	BUS	the communication bus unit
	GSM interface	the communication interface to GSM-R
	WAN interface	the communication interface to Interlocking
GSM-R	MSC	the mobile switching center
	TRAU	the transcoder and rate adaptation unit
	BSC	the base station controller
	BTS	the base transceiver station
	PRI interface	the interface between RBC and MSC
	A interface	the interface between MSC and TRAU
	Ater interface	the interface between TRAU and BSC
	Abis interface	the interface between BSC and BTS

2.5 Availability, Punctuality and Resilience

2.5.1 Availability and Punctuality

Availability is defined as the ability of an item to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided[2]. For quantitative calculation, the mean availability (A) is:

$$A = \frac{Uptime}{Total\ time} = \frac{Uptime}{Uptime + Downtime} \tag{2.1}$$

The uptime and downtime are the time interval throughout which an item is in an up and down state respectively[2]. The uptime can also refer to the mean time to failure (MTTF) and the downtime is the mean time to repair (MTTR) plus the mean logistic delay (MLD). When the components are exponentially distributed, the failure rate λ and repair rate μ are:

$$\lambda = \frac{1}{MTTF} \tag{2.2}$$

$$\mu = \frac{1}{MTTR + MLD} \tag{2.3}$$

So the availability formula can also be written as:

$$A = \frac{uptime}{uptime + downtime} = \frac{MTTF}{MTTF + (MTTR + MLD)} = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda} + \frac{1}{\mu}} = \frac{\mu}{\mu + \lambda} \tag{2.4}$$

Availability is one of the most significant indicators in the railway industry because it's the key performance that can affect the economy of railway organizations. More passengers will intend to choose rail transport when the trains can arrive punctually, or they would switch to another way of transportation [26].

The availability estimation in this thesis focuses more on the actual experience of passengers. For instance, the train may face a hardware failure on the track but still arrives at the final station 'on time' (within a margin of time) due to a quick response and efficient maintenance. From the perspective of passengers, the failure can be omitted. The availability defined by the requirement from Bane NOR (Norwegian National Rail Administration) is that the train must arrive at the stations within four minutes after scheduled arrival time [26].

The term punctuality is defined differently across the world [29]. The definition by Bane Nor is that a train is considered to be on time if it reaches its final station within a margin of four minutes. For long-distance trains, this margin is six minutes [5], which is the selected standard in this thesis. The requirements by the Bane NOR for punctuality and availability are 90% and 99.3% respectively [26].

Train delays have mainly four categories of reasons, which are station-related (passengers and rapid transit operation), train-related (mechanical malfunction, etc), operation-related (construction, accidents, track assignment, etc) and timetable-related (precision of parameters and design issues) [30]. The model in this thesis will mainly focus on the delay caused by the failures of the signaling system, ERTMS, as well as the unexpected dwell time on stations.

After the availability estimation, the original definition (formula 2.1) will be used to evaluate the performance of the hardware system (ERTMS).

2.5.2 Resilience

Availability will fall or rise with failures or repairs. This behavior has motivated the resilience assessment of availability, which can be seen as an extension of availability estimation and allocation works.

Resilience is defined as the capability of an entity to recover from an external disruptive event [6]. The term resilience has different concepts in various fields, such as rebound, robustness, graceful extensibility or sustained adaptability [31]. In this thesis, the label resilience mainly refers to how the system availability rebounds from shock and returns to a normal state. The system robustness will also be considered when assessing resilience.

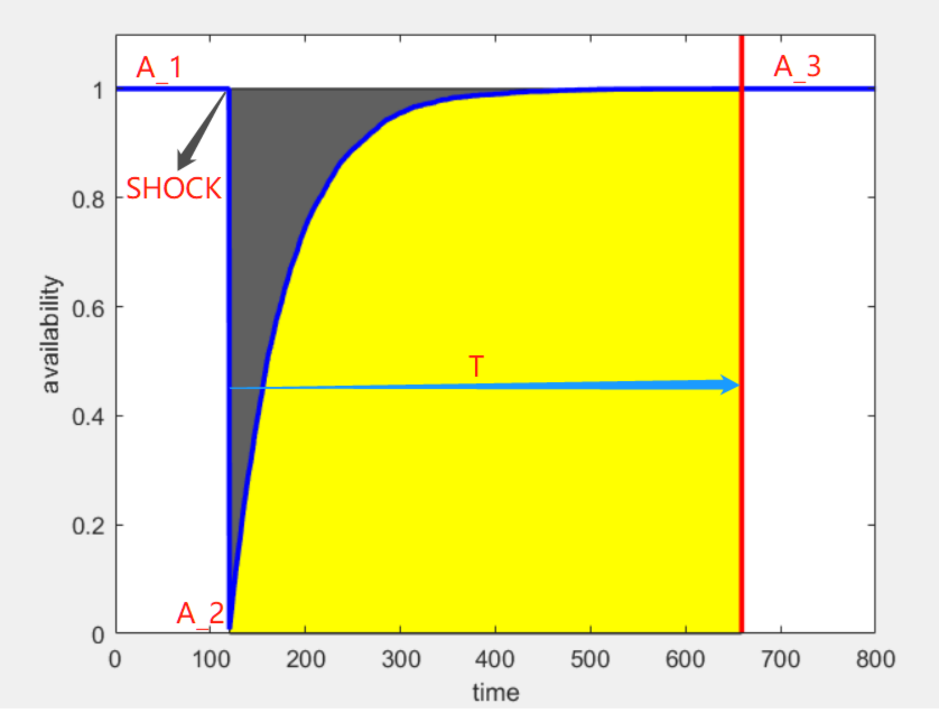

Figure 2.3: Availability-Time Diagram

The availability-time diagram (figure 2.3) describes the resilience activity after suffering from shock. In this example, the initial availability A_1 is equal to 1 and decreases suddenly to a post-shock transient-state availability A_2 ($A\_2 = 0$) due to the shock. After a continuous growth during the post-shock steady-state time T, the availability returns to A_3, which is the post-shock steady-state availability and equal to A_1 in this case.

Resilience metric has been proposed based on those parameters for multiple shocks [6]. Considering that the initial availability is equal to the availability before shock and only one shock will happen in this case, the metric can be simplified as:

$$\rho = \frac{A\_2 \times A\_3}{lnT} \tag{2.5}$$

Higher A_2,A_3 and lower T will result in a better result but the meanings are different. A_2 shows better robustness against shocks, while A_3 represents the ability how well (as good as new or imperfect) the availability will rebound from external disruptive events. T is the indicator of rebounding time.

This formula has a significant drawback. If A_2 is zero, which is likely to happen when the whole system shuts down, the result is always zero. Besides, when simulation, T is the maximum time to repair among the simulation series, which means that it can be easily influenced by extreme value so that the calculation based on the metric 2.5 will be affected further. So, another method to evaluate resilience is necessary.

It's also possible to assess resilience by calculating the yellow-colored area (definite integral). Similar to that the area in velocity-time diagram means path length, the area with yellow means the spent 'path length' of availability and time during the process from the shock to a post-shock steady-state. Then the meaning of the gray area is the 'path length' loss during that period.

Similar to the result based on metric 2.5, T, which is also the span of the yellow area, can be influenced by the extreme value of random time to repair. As a result, the definite integral result of the yellow part is unstable. While the influence upon the gray area will be relatively much lower since the gap between A_3 and the real-time availability (blue curve) is close to zero when reaching time T. Hence, the gray area is considered as an optimal indicator to assess resilience in this thesis and the lower value represents better performance. The shape of the gray area is mainly determined by the post-shock transient-state availability A_2 and the curve with continuous growth, which represent system robustness and the ability to rebound respectively.

2.6 Summary of the Chapter

This chapter has briefly introduced the development of the rail industry, the infrastructure and some operation activities. Besides, the concepts which shall be studied in this thesis, availability, punctuality and resilience, have been presented with definitions and calculating methods. The next chapter will show the detailed background of simulation, which is the main approach to estimate availability in this thesis.

Chapter 3

Approach of Simulation

Availability estimation is one of the main objectives in this thesis but conducting real-scale industrial experiments is not a viable option. Hence, the main approach to determine availability is to run simulations based on simplified models.

A simulation is an approximate imitation of the operation of a process or a system [32]. Usually, direct observation can provide more accurate results but experiments sometimes have drawbacks such as danger, high costs and inconvenience. Modeling is the initial phase of the simulation process. Once the models are built, the next phase, simulation experiments, can begin. In the last phase, the results need to be analyzed.

3.1 Modeling

Modeling is the first phase of simulation. The term model means a representation of the construction and working of some systems of interest, in order to determine its behavior and variation of output parameters to the input parameters[33][34]. Model-based study of the behavior of a system has some advantages, such as lower costs and time of implementation, testing and experimentation and ease of changing conditions[34].

While modeling is the activity to develop a model based on an original system, the basic steps are [33]:

- Identify and formulate the problem with an existing system.

- Collect and process data on system specifications.
- Develop an initial model.
- Compare the model's performance with the real performance of the existing system to assess confidence.
- Document objectives, hypothesis and input variables.

3.2 Simulation Experiments

In this phase, the main steps are to design proper experiments (select performance measures and input variables) under appropriate conditions and then perform simulation runs. The target is to obtain data on the selected performance measures[33].

3.3 Simulation Analysis

Since the experiment data is now obtained, the target during this phase is to identify the reasons for changes in the performance measures and to solve the initial problem formulated in the modeling phase. In addition, further work could be recommended such as increasing the precision or sensitivity analysis [33].

3.4 Monte Carlo Methods

Monte Carlo Methods are applied in a great variety of areas. The principle of Monte Carlo methods is the approximation of an expectation of a random variable X by the arithmetic mean of independent and identically distributed realization of X [35]. The relation is:

$$E[X] \approx \frac{1}{n} \sum_{n}^{i=1} X_i \tag{3.1}$$

The typical steps of Monte Carlo methods are:

- Define a range of possible input variables;
- Generate input variables randomly from a probability distribution within the range;
- Calculate the output variables based on the input variables;
- Aggregate the results.

3.5 Availability Estimation by Simulation

The initial target of this thesis is to determine the availability and punctuality of railway systems by simulation. Monte Carlo methods will be applied to run the simulation and the basic algorithm is to generate a set of traveling time which follows specific distributions, to compare with the requirement proposed by Bane NOR and then aggregate the results.

3.6 Summary of the Chapter

This chapter has introduced the brief background of availability estimation by simulation. The following chapter 4 and 5 will demonstrate the complete steps.

Chapter 4

Availability Estimation of Single Rolling Stock

Regarding the availability allocation, the initial step of this thesis is to determine the overall availability and then to evaluate if it satisfies the requirement. This chapter will introduce a detailed simulation-based solution to assess the availability loss caused by hardware failure and unexpected dwell time.

This chapter will focus on a single-vehicle system, which is not practicable in the industry. The reasons are twofold:

- Present and validate the basic simulation algorithm.
- Estimate the unavailability caused by the train itself, which will be compared with the unavailability triggered by interaction next chapter.

4.1 Scenario Description

Railway transports passenger and freight. This thesis will focus on passenger train service. Normally passenger trains are divided into four products: long-distance trains (i.e. intercity trains, international trains), regional trains, peak hour trains and suburban lines [15]. In this chapter, the rail section from Oslo S to Bergen, which is regional service, will be selected as a case study because of its sufficient length and more strict availability target than that of long-distance service. The train departs from Oslo S and reaches Bergen after 19 stops and the whole journey costs around 7 hours [36]. To simplify the simulation, five stations will be chosen as the assessed points (Oslo S, Hønefoss, Ål, Voss, Bergen). All the planned dwell periods at stations will be set to 0.1 hours. The time that is actually spent can take the place of the time in the timetable. The table 4.1 describes the simplified timetable.

Table 4.1: Simplified Timetable

Station	Activity	Time (timetable)	Time (actully spent)
Oslo S	Boarding	11:57	0:00
	Departure	12:03	0:06
Hønefoss	Boarding	13:25	1:28
	Departure	13:31	1:34
Ål	Boarding	15:12	3:15
	Departure	15:18	3:21
Voss	Boarding	17:30	5:33
	Departure	17:36	5:39
Bergen	Arriving	18:55	6:58

The following figure 4.1 shows the planned time and intervals between stations.

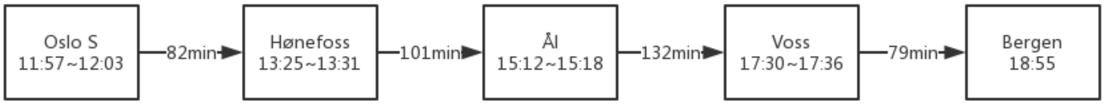

Figure 4.1: Planned Time and Intervals

4.2 ERTMS Performance Parameters

In order to assess the overall availability, necessary data shall be collected, such as failure rates and repair rates, which can be calculated by the MTTF, MTTR and MLD, if the components follow exponential distributions. Bane NOR has classified several typical failure modes for the ERTMS components as well as the required time-related indicators, such as MTTF and MTTR [26]. Based on that, the ERTMS failure rates and repair rates can be calculated. The results are shown in the table 4.2 below.

Table 4.2: Components Failure Parameters

Failure Components	Failure Mode	Failure Rate (per hour)	Repair Rate (per hour)
Points Failure	Control over straight track but not on switching	8.33333E-06	0.363636
	Control over switching but not on straight track	8.33333E-06	0.363636
	No control	8.33333E-06	0.363636
Interlocking	Processors down	2.27273E-06	0.571429
GSM-R	Decentral failures influencing several base stations	5.70776E-06	0.173913
	Central failure influencing all base stations	5.70776E-06	0.307692
RBC	Component down	2.27273E-06	0.117647
Track	Rupture	2.73973E-06	0.307692
Maintenance	Delayed for whole track segment	0.000114155	1
Axle Counter	Reset request	4.54545E-06	0.210526
	Failure per location	1.14943E-05	4
Eurobalise	Component down	2.27273E-06	0.571429

In order to simplify the simulation process, total failure rates and overall repair rates will be used. The total failure rate of ERTMS is the sum of the rates for all the failure modes, which is $\lambda_{total} = 0.000176168\ per\ hour.$

Since the components are in the series structure and the failure and repair rates are known, the theoretical system availability can be calculated. The first step is to calculate the availability due to each failure mode by using the formula 2.4. Then the system overall availability is the multiplication of each availability. The calculation is done by Excel and the result ($A_{Overall} = 0.9997051$) is shown in table 4.3 below.

The theoretical overall availability also follows the formula 2.4, which means:

$$A_{Overall} = \frac{\mu_{Overall}}{\mu_{Overall} + \lambda_{Total}} = 0.9997051 \tag{4.1}$$

The overall repair rate can be determined:

Table 4.3: Overall Availability Calculation by Excel

Failure mode	Failure rate	Repair rate	Availability	System availability
1	8.333E-06	0.36363636	0.9999771	0.9997051
2	8.333E-06	0.36363636	0.9999771	
3	8.333E-06	0.36363636	0.9999771	
4	2.273E-06	0.57142857	0.999996	
5	5.708E-06	0.17391304	0.9999672	
6	5.708E-06	0.30769231	0.9999815	
7	2.273E-06	0.11764706	0.9999807	
8	2.74E-06	0.30769231	0.9999911	
9	0.0001142	1	0.9998859	
10	4.545E-06	0.21052632	0.9999784	
11	1.149E-05	4	0.9999971	
12	2.273E-06	0.57142857	0.999996	

$$\mu_{Overall} = \frac{\lambda_{Total}}{\frac{1}{A_{Overall}} - 1} = \frac{0.000176168}{\frac{1}{0.9997051} - 1} = 0.598854667\ per\ hour \tag{4.2}$$

It's notable that the overall repair rate is a weighted average value of the repair rates of each component and the weights are decided based on the failure rates. The higher the failure rate is, the more likely that kind of failure is going to occur, and the higher the weight shall be.

4.3 Dwell Time at Stations

Unexpected delays can also be caused by station-related issues. To improve the performance of transportation systems, many researchers study the operation and control of the traffic system, including the dwell time model at stations. It has been revealed that in some situations, for example, the bus rapid transit lines in Changzhou, China, of which the stations are enclosed like light rails, the dwell time follows a logarithmic normal distribution based on statistical analysis [37].

To run the simulation, this model has been chosen in this thesis. The actual time distribution in Norway has never been studied, so one assumption is made for the expected value and variance. The expected value of the dwell time is 5 minutes with a variance of 1. Since the dwell time follows a logarithmic normal distribution, the two parameters are determined: $\mu = 1.591$, $\sigma = 0.198$. The probability density function is shown below in figure 4.2.

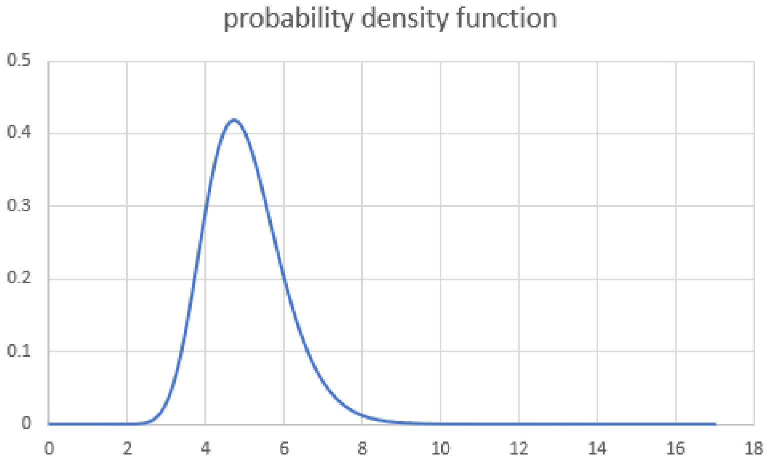

Figure 4.2: Probability Density Function

4.4 Simulation of the Scenario

4.4.1 Simulation Assumptions

Several assumptions have been made before the simulation.

- The failure rates and repair rates stay constant.
- The actual departure time shall always be no earlier than the planned time, which means that if all passengers finish boarding or alighting before the planned departure time, the train shall still wait.

The basic algorithm:

- Generate a series of time to failure (exponential distributed) and compare it with the planned time in each section to determine if a failure will happen. The actual duration in each section is the planned time (without failures), or planned time plus a random time to repair (also exponential distributed) when failures happen.
- Generate a series of time intervals at stations (follow a logarithmic normal distribution).

- Compare the time when boarding is ready with the planned time to ensure no early departures. The total time is the sum of actual duration in each section and the larger one between the planned time and boarding time at stations.
- Compare the total time with the timetable to determine if delays happen.

The simulation is done by MATLAB (Version R2018b) and the code with a brief explanation of the algorithm can be found in the appendix B.1.

4.4.2 Results and Analysis

After simulating one million times, the average punctuality is 0.998028 and the average availability is 0.998802. Both fulfill the requirements by Bane NOR. Since some causes, such as accidents or train mechanical malfunction, are omitted, the results could be overestimated compared with the actual practice. On the other hand, it's notable that the availability is underrated as most stations are removed in the simulated scenario. The availability will be higher when taking into account all the stations but the model will be too complicated then.

Calculating the proportion of delays caused by the failure of ERTMS and the unexpected dwell time is useful to improve the availability performance. Two approximations are made that the number of delays caused by multiple failures in one trip is omitted (not likely to happen) and when failures occur, the train will be delayed (MTTR is much larger than the permitted four minutes), which means the number of ERTMS failures is equal to that of the ERTMS-related delays. The code is attached in the appendix B.2. The result reveals that 57.69% of the delays are caused by ERTMS malfunction, while deferred boarding and alighting leads to the rest (42.31%).

4.5 Average Availability

Hardware failures occur randomly through the journey. It is of help to find the time with the lowest average availability, which is the critical time, to optimize the maintenance schedule. This part will focus on hardware, so the dwell time influence will be removed. The scenario can be simplified that one train normally spends 394 minutes (the total time minus the dwell time) to run from Oslo to Bergen and the maximum number of failure each journey is 1. The algorithm is:

- Firstly, the time to failure and repair (both exponentially distributed) will be generated respectively. If the time to failure is lower than the planned time (394 minutes), one failure will happen.
- Then the total time will be calculated by adding the time to failure and repair together if failure exists, or only the planned time. Find the maximum total time.
- An availability matrix will be generated and each row vector is the time-varying availability of one simulation. It's notable that in order to calculate the average availability, all row vectors shall share the same length. The solution is that the availability will stay 1 when the train finishes the operation until the maximum total time.
- Based on the availability matrix, the average availability vector can be determined by calculating the average value of each column.
- The final step is to generate a time vector and plot the average availability-time diagram.

The code is attached in the appendix B.3 with some explanatory notes. The following figure 4.3 shows the result.

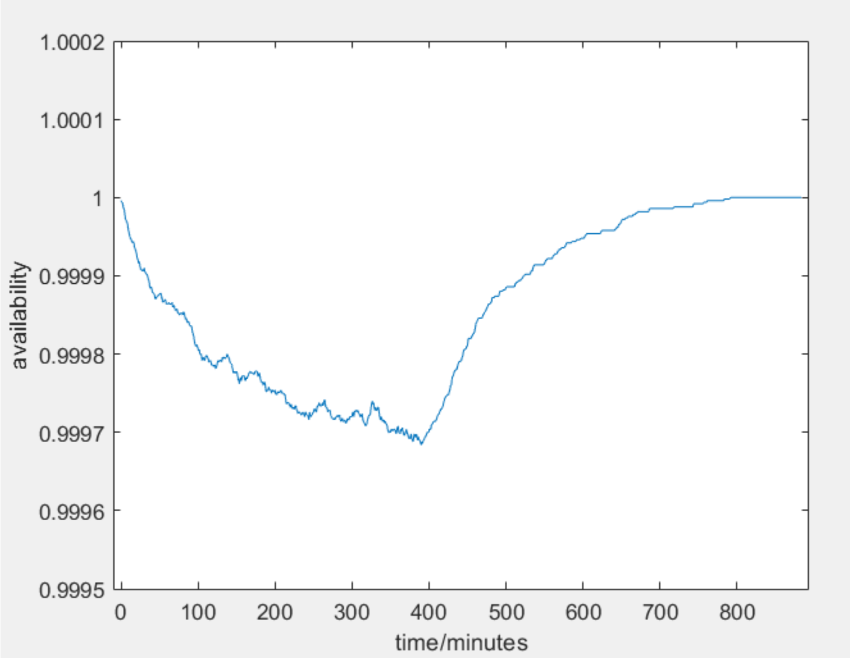

Figure 4.3: Average Availability

The availability keeps a dropping trend until the critical time, which is around 390 minutes according to the simulation and close to the planned time, and then returns to 1 at 880 minutes, which means the maximum delay is approximately 8 hours. The result of critical time is reasonable since the probability of failure increases as the train operates. The randomness of both time to failure and to repair results in the serrated waves of the diagram.

4.6 Summary of the Chapter

The availability and punctuality of one single train have been assessed by simulation and both fulfill the required target. The contributions of delay reasons shared by hardware and dwell duration have also been revealed. In the last part, the average availability diagram shows the trend of the time-varied availability as well as the critical time with the lowest average availability.

Since only one train is considered, the influence caused interaction among vehicles on availability remains unrevealed. Hence, the simulation will be expanded to multiple vehicles to study the effect of earlier delays upon later trains.

Chapter 5

Availability Estimation of Multiple Vehicles

5.1 Scenario Description

It's not likely to keep only one train on the rail line all the time in operation. The vehicles which share the same line may interact with each other when a failure occurs. The cascades are delays to trains caused by earlier delays of other trains [38]. In order to assess the influence caused by cascades, the simulation of multiple vehicles shall be done.

In this situation, three identical trains will run on the same rail line and the time interval between two trains is set to half an hour. The distribution of the dwell time at stations and the performance parameters of the ERTMS remain the same. The new planned time is shown in figure 5.1 below.

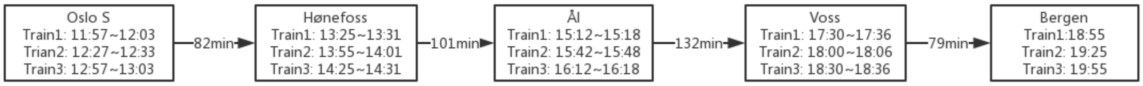

Figure 5.1: Planned Time and Intervals for Multiple Trains

5.2 Simulation of the Scenario

Besides the assumptions which have been made for the simulation in the previous chapter, it's necessary to add more preconditions.

- When the earlier train stops due to failure and cannot get repaired in time so that the later train also comes to the address, cascades will happen (no overtaking allowed).
- After the earlier train gets fixed, it's essential to keep a distance between two vehicles to ensure safety. The later train will depart 6 minutes after the earlier train's departure.

The code is attached in the appendix B.4. The basic algorithm in chapter 4 is now extended with a comparison between trains to find cascades. The results show that the overall punctuality is 0.997202 and the overall availability is 0.998248 after simulating for one million times.

5.3 Results Analysis

Firstly, it's necessary to classify the delays into three categories, ERTMS-related delays without cascades, dwell delays and cascades. The first train cannot experience cascades. Since the MTTR is much higher than the interval between two trains, and dwells are not likely to result in delays which exceed that interval, it's reasonable to consider that the necessary and sufficient condition of cascades is the ERTMS delays of earlier trains. So, the cascades of the second train are equal to the ERTMS failures of the first train, and similarly, the cascades of the third train can be determined as the total number of ERTMS malfunction of the two previous trains, which means:

$$D_{Train\ 2,cascades} = D_{Train\ 1,ERTMS\ delays} \tag{5.1}$$

$$D_{Train\ 3,cascades} = D_{Train\ 1,ERTMS\ delays} + D_{Train\ 2,ERTMS\ delays} \tag{5.2}$$

The code for simulating the proportion is shown in the appendix B.5. The simulation shows that the proportions of ERTMS delays (without cascades), dwell time delays and cascades are 0.4137, 0.1628 and 0.4235 respectively. Cascades have become the leading cause, followed by ERTMS delays.

The next step is to evaluate the influence of cascades. The following table 5.1 compares the performance of two scenarios and shows the increased percentage of unavailability and unpunctuality. When cascades are taken into account, the unavailability is increased by 46.2437%, while the unpunctuality is 41.8864% higher.

Table 5.1: Comparison between Two Scenarios

	Single	Multiple	Increased
Availability	0.998802	0.998248	NA
Unavailability	0.001198	0.001752	46.2437%
Punctuality	0.998028	0.997202	NA
Unpunctuality	0.001972	0.002798	41.8864%

It's notable that the influence of cascades upon unpunctuality is approximately equal to the proportion of cascades. Considering the results are generated from two series of simulation, the very limited difference should be acceptable. This verifies the rationality of the hypothesis that the number of cascades is equal to that of the ERTMS failures of the previous trains (equation 5.1 and 5.2).

5.4 Summary of the Chapter

The availability and punctuality of the three-train scenario are simulated and can still meet the requirement. The percentage of delays led by ERTMS, dwell time and cascades has also been calculated. The result shows that cascades are the main reason for total delays, followed by ERTMS delays while dwell time is the least influential cause. Besides, the increasing proportion of unavailability and unpunctuality after adding two more vehicles, which is caused by cascades, has been assessed.

Chapter 6

Availability Allocation for ERTMS

The availability estimated by simulation has been proved that it can achieve the target, but it's still possible to improve the overall availability by allocation. This chapter will present the full allocating process. Two methods will be applied for allocation, the equal allocation and the ARINC method (also known as weighted allocation)[39].

6.1 Availability Allocation

Allocation usually refers to the assignment of available resources to various uses. In RAMS engineering, when availability does not fulfill the target, it's possible to allocate the availability for each component by tuning repair or failure rate based on the requirement [40]. This process is called availability allocation.

In many cases, the problem of availability allocation can be formulated as an optimization problem for multiple parameters: minimize the cost and maximize the overall availability [41]. A general model of the system shall be built to determine the relationship between overall availability and the failure/repair rate of each component. Meanwhile, a cost model is also necessary to calculate the cost when failure/repair rate is allocated.

Several methods are proposed such as equal appointment, AGREE (Advisory Group of Reliability of Electronic Equipment) and ARINC (Aeronautical Radio, Inc) methods[39]. Allocation in this thesis will apply equal appointment and ARINC methods while the cost model will be omitted due to lack of data.

6.2 Availability in RAMS Engineering

In this chapter, since the allocation task is to determine the maximum failure rate and minimum repair rate of each component, the original definition (formula 2.1) of availability will be selected, instead of the requirement from Bane NOR.

The theoretical availability has been calculated in chapter 3, which is $A_{overall} = 0.9997051$. To verify this parameter, simulation has been carried out. The code is attached in the appendix B.6. The estimated result after one million times is $A_{estimated\ overall} = 0.99971971$, which is highly close to the theoretical value.

6.3 Allocation for ERTMS

The ERTMS structure is shown in figure 2.2. The order of availability allocation is from top to bottom: systems, subsystems and then, components.

6.3.1 Allocation (System and Subsystem Levels)

It has been proved that the availability performance is satisfactory after the simulation, but the result is overrated due to the existence of ignored potential failure modes and incidents. In order to meet the requirement, and to show the process of availability allocation, a higher target is required. Since the estimated overall availability $A_{estimated\ overall}$ is 0.99971971, it's suitable to select 0.9998 (A_S^*) as the availability target in steady state. All data can be found in previous chapters. Since the failure rates and repair rates of all the subsystems are known, it's suitable to apply the weighted method. The detailed process is:

1. The first step is to eliminate the impact of the planned yearly maintenance on availability. A_m is the availability of preventive maintenance and A_{wm}^* is the overall availability target without the yearly maintenance.

$$A_m = \frac{\mu_m}{\mu_m + \lambda_m} = \frac{1}{1 + 0.000114943} = 0.99988586 \tag{6.1}$$

$$A_{wm}^* = \frac{A_S^*}{A_m} = \frac{0.9998}{0.99988586} = 0.99991413 \tag{6.2}$$

2. The next step is to calculate the ratio of failure rate and repair rate, θ_i. Some subsystems have multiple failures and shall be considered respectively.

$$\theta_{points,1} = \frac{\lambda_{points,1}}{\mu_{points,1}} = \frac{8.3333 \times 10^{-6}}{0.363636} = 2.29167 \times 10^{-5} \tag{6.3}$$

Similarly, we can obtain all the ratios (table 6.1).

Table 6.1: Ratios of Failure and Repair Rates

Subsystem	Ratio	Subsystem	Ratio
Points, 1	2.29167E-05	RBC	1.93182E-05
Points, 2	2.29167E-05	Track	8.90411E-06
Points, 3	2.29167E-05	Axle Counter, 1	2.15909E-05
Interlocking	3.97727E-06	Axle Counter, 2	2.87356E-06
GSM-R,1	3.28196E-05	Eurobalise	3.97727E-06
GSM-R, 2	1.85502E-05		

3. The following step is to calculate the weight of each subsystem, $\omega_i = \frac{\theta_i}{\sum_{i=1}^{n}\theta_i}$, which keeps unchanged.

$$\omega_{points,1} = \frac{\theta_{points,1}}{\sum_{i=1}^{n}\theta_i} = \frac{2.29167 \times 10^{-5}}{1.80761 \times 10^{-4}} = 0.126779 \tag{6.4}$$

Similarly, all weights (table 6.2):

Table 6.2: Weights of Failure and Repair Rates

Subsystem	Ratio	Subsystem	Ratio
Points, 1	0.126779	RBC	0.106871
Points, 2	0.126779	Track	0.049259
Points, 3	0.126779	Axle Counter, 1	0.119444
Interlocking	0.022003	Axle Counter, 2	0.015897
GSM-R,1	0.181564	Eurobalise	0.022003
GSM-R, 2	0.102623		

4. Then, the target failure rate for each subsystem (the repair rates stay unchanged):

$$\begin{aligned}\lambda^*_{points,1} &= \mu_{points,1}\omega_{points,1}(\frac{1}{A^*_{wm}} - 1) = 0.3636363 \times 0.126779 \times (\frac{1}{0.99991413} - 1) \\ &= 3.95895 \times 10^{-6}\end{aligned} \tag{6.5}$$

Similarly, all the allocated failure rates can be obtained (table 6.3).

Table 6.3: Allocated Failure Rates

Subsystem	Failure Rate	Subsystem	Failure Rate
Points, 1	3.95895E-06	RBC	1.07971E-06
Points, 2	3.95895E-06	Track	1.30157E-06
Points, 3	3.95895E-06	Axle Counter, 1	2.15943E-06
Interlocking	1.07971E-06	Axle Counter, 2	5.46062E-06
GSM-R,1	2.71161E-06	Eurobalise	1.07971E-06
GSM-R, 2	2.71161E-06		

The purpose of this step is to improve availability by increasing reliability.

5. Also, it's possible to tune the repair rate while the failure rates keep unmodified. The purpose is to improve availability by increasing maintainability.

$$\mu^*_{points,1} = \frac{\lambda_{points,1}}{\omega_{points,1}(\frac{1}{A^*_{wm}} - 1)} = \frac{8.33333 \times 10^{-6}}{0.126779 \times (\frac{1}{0.99991413} - 1)} \\ = 0.765431 \tag{6.6}$$

Similarly, the allocated repair rates are shown below in table 6.4.

Table 6.4: Allocated Repair Rates

Subsystem	Repair Rate	Subsystem	Repair Rate
Points, 1	0.765431	RBC	0.247639
Points, 2	0.765431	Track	0.647672
Points, 3	0.765431	Axle Counter, 1	0.443144
Interlocking	1.202820	Axle Counter, 2	8.419739
GSM-R,1	0.366076	Eurobalise	1.202820
GSM-R, 2	0.647672		

The allocated overall repair rate $\mu^*_{overall} = 0.722105775$ can be determined (similar to the process in figure 4.3 and equation 4.1, 4.2).

After the allocation, new availability can be calculated based on the modified repair rates, or the modified failure rates, and the results shall be the same.

For example, calculate the new availability for points failure (three failure modes):

$$A^*_{points,1} = \frac{\mu_{points,1}}{\mu_{points,1} + \lambda^*_{points,1}} = \frac{0.363636}{0.363636 + 3.95895 \times 10^{-6}} = 0.99998911 \tag{6.7}$$

$$A^*_{points,2} = \frac{\mu_{points,2}}{\mu_{points,2} + \lambda^*_{points,2}} = \frac{0.363636}{0.363636 + 3.95895 \times 10^{-6}} = 0.99998911 \tag{6.8}$$

$$A^*_{points,3} = \frac{\mu_{points,3}}{\mu_{points,3} + \lambda^*_{points,1}} = \frac{0.363636}{0.363636 + 3.95895 \times 10^{-6}} = 0.99998911 \tag{6.9}$$

The new availability for the points subsystem:

$$A^*_{points} = A^*_{points,1} \times A^*_{points,1} \times A^*_{points,1} = 0.99998911 \times 0.99998911 \times 0.99998911 \\ = 0.99996734 \tag{6.10}$$

The new availability for all subsystems (table 6.5):

Table 6.5: Allocated Availability for Subsystems

Subsystem	New Availability	Subsystem	New availability
Points	0.99996734	Track	0.99999577
Interlocking	0.99999811	Axle Counter	0.99998838
GSM-R	0.99997560	Eurobalise	0.99999811
RBC	0.99999082		

For the system level, the allocated availability for the lineside system:

$$A^*_{lineside} = A^*_{axlecounter} \times A^*_{Eurobalise} = 0.99998838 * 0.99999811 = 0.99998649 \tag{6.11}$$

Similarly, the availability for the trackside system: $A^*_{trackside} = 0.99992764$.

The new availability for the whole ERTMS:

$$A^*_{ERTMS} = A^*_{lineside} \times A^*_{trackside} = 0.99998649 \times 0.99992764 = 0.99991413 \tag{6.12}$$

When taking into account the impact of the yearly maintenance:

$$\begin{aligned} A^*_{overall} &= A^*_{ERTMS} \times A_m = 0.99991413 * 0.99988585 = 0.9998 \\ &= A^*_S \end{aligned} \tag{6.13}$$

This has proved that the allocation reaches the target.

6.3.2 Allocation (Component Level)

It's been mentioned before that the RBC and GSM-R subsystems consist of several components. The failure rates of those components are known, so the equal allocation method can be applied here to determine the minimal repair rates to achieve the allocated availability of subsystems.

The failure rates of the components are shown in table 6.6.

Table 6.6: Component Failure Rates [1]

item	failure rate (per hour)	item	failure rate (per hour)	item	failure rate (per hour)
VC	1.48E-05	MSC	1.50E-06	PRI interface	4.51E-06
BUS	4.44E-06	TRAU	1.20E-05	A interface	1.50E-06
GSM interface	5.80E-06	BSC	6.01E-06	Ater interface	1.00E-06
WAN interface	2.50E-06	BTS	4.62E-06	Abis interface	6.01E-06

The required availability for each component in RBC:

$$A^*_{i,RBC} = {A^*_{RBC}}^{\frac{1}{4}} = 0.99999082^{\frac{1}{4}} = 0.99999771 \tag{6.14}$$

The required availability for each component in GSM-R:

$$A^*_{i,GSM-R} = {A^*_{GSM-R}}^{\frac{1}{8}} = 0.99997560^{\frac{1}{8}} = 0.99999695 \tag{6.15}$$

The allocated repair rate for VC:

$$\mu^*_{VC} = \frac{\lambda_{VC} A^*_{i,RBC}}{1 - A^*_{i,RBC}} = \frac{1.48 \times 10^{-5} \times 0.99999771}{1 - 0.99999771} = 6.450533 \tag{6.16}$$

The step to calculate the modified repair rates for all components is the same, and the results (table 6.7):

Table 6.7: Allocated Repair Rates (Components)

item	allocated repair rate (per hour)	item	allocated repair rate (per hour)
VC	6.450533	BSC	1.970139
BUS	1.935160	BTS	1.514483
GSM interface	2.527911	PRI interface	1.478424
WAN interface	1.089617	A interface	0.491715
MSC	0.491715	Ater interface	0.327810
TRAU	3.933722	Abis interface	1.970139

6.3.3 Management Implication

Availability allocation reveals the possibilities to improve availability by better reliability (decreased failure rate) or better maintainability (increased repair rate). For railway systems, operation companies can always purchase more reliable equipment to reach better availability. Even if the equipment is fixed, it's still possible to ameliorate the availability by introducing more advanced maintenance technologies to enhance maintainability. Besides, availability allocation provides an idea to determine repair rate targets when only failure rates are known, and vice versa.

Besides, the comparison between table 4.2 and table 6.3/6.4 shows the difficulty to increase availability when the demand is high. When the availability is increased by $\frac{A_S^* - A_{estimated\ overall}}{A_{estimated\ overall}} = \frac{0.9998 - 0.99971971}{0.99971971} = 0.008\%$, the failure rate needs to be decreased by around 50% (table 6.3), or the repair rate needs to approximately double (table 6.4).

6.4 Average Availability with Allocated Overall Repair Rate

Since the overall repair rate has increased after the allocation, it's of value to re-run the simulation to assess the influence of repair rate upon the average availability. The repair rate in the appendix B.3 shall be replaced with $\mu^*_{overall} = 0.722105775$. The following figure 6.1 shows the new availability-time diagram.

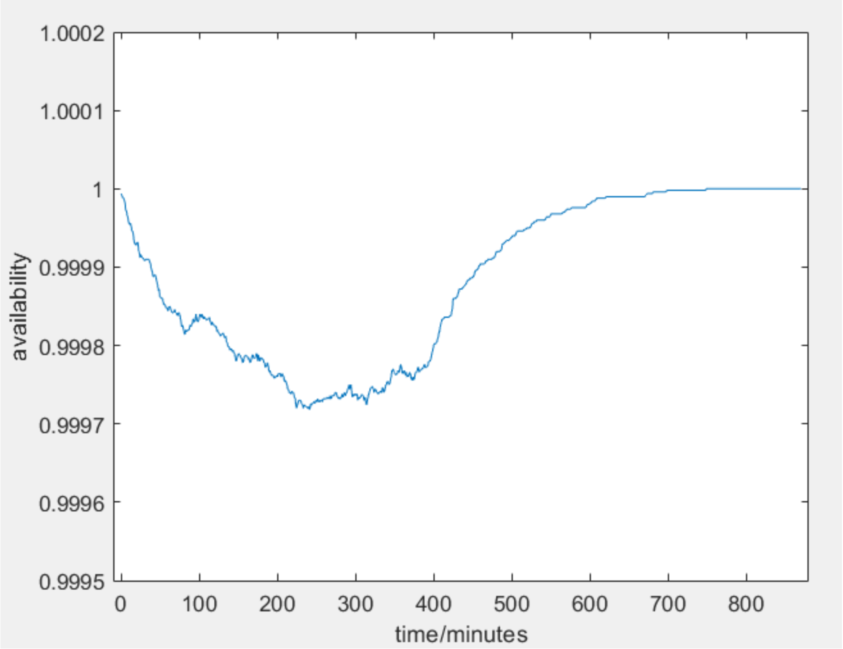

Figure 6.1: Average Availability with Allocated Overall Repair Rate

The new critical time has moved forward to around 240 minutes and the maximum time decreases slightly. Also, the least average availability is higher. It's reasonable to believe that higher repair rates can result in better availability performance and relatively earlier critical time.

6.5 Summary of the Chapter

This chapter provides complete steps of availability allocation based on equal and weighted methods and both failure and repair rates have been tuned to meet the target as well as the discussion of management implication. In addition, the allocated repair rate has been applied in simulation to generate a new availability-time diagram. It can be seen that availability performance has turned better and the critical time is earlier.

Chapter 7

Discussion on Resilience of ERTMS

7.1 Resilience Assessment of the Single-train System

Resilience assessment is motivated by availability estimation and allocation works since it can be seen as an extension of previous models. One definite integral method to assess resilience has been introduced in section 2.5.2. In order to verify the applicability of the method, the algorithm in section 4.5 is chosen. Shocks shall appear at the same time in each simulation, so the random time to failure has been replaced by a fixed value (100 minutes is selected). In this section, only one train runs on the track and the original overall repair rate is used (equation 4.2).

The code can be found in the appendix B.7. The result can be seen in figure 7.1. The average availability decreases to 0 due to the shocks appearing in every simulation at the same time and then returns to 1 with a declining speed. The gray-colored area is 99.89 while the post-shock steady-state time is 1000 minutes. The rebounding curve is similar to the theoretical exponential distribution diagram but differences do exist since theoretically, the availability will never return to 1 again.

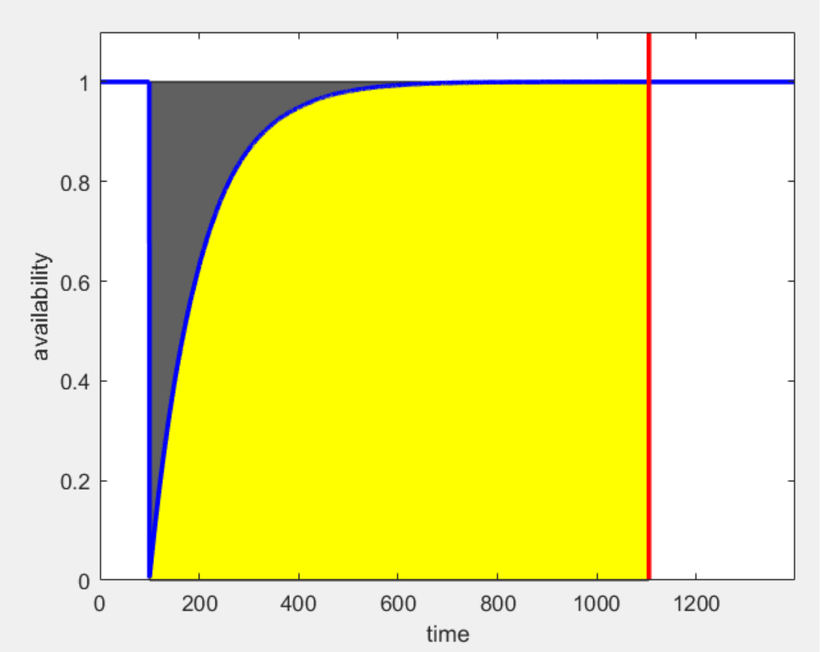

Figure 7.1: Availability-Time Diagram of Single Train System

7.2 Resilience Assessment of the Triple-train System

Similar to the scenario in chapter 5, two extra trains are included now to study the influence of cascades on the overall resilience while the dwell time is omitted. In this case, train 1 will fail at 100 minutes if it's not repaired in time, cascades will appear. The repair duration is still exponentially distributed with original parameters. No hardware failure will occur for train 2 and 3. The interval between trains as planned is 30 minutes and to ensure safety, the new interval after cascades is 5 minutes. The code is in the appendix B.8 with explanations. Figure 7.2 shows the availability of each train during the operation period while figure 7.3 represents the overall average availability of three trains.

The explanation and discussion for figure 7.2:

- The blue, green and red curves are representing the average real-time availability of train 1, 2 and 3 respectively.
- It's possible that when train 2 arrives in the failure location of train 1, train 1 has been repaired and departs more than 5 minutes (the new interval to ensure safety) ago. Then

no cascades will happen, and this can explain why the lowest availability of train 2 is not zero. The lowest availability of train 3 is higher than that of train 2 for the same reason.

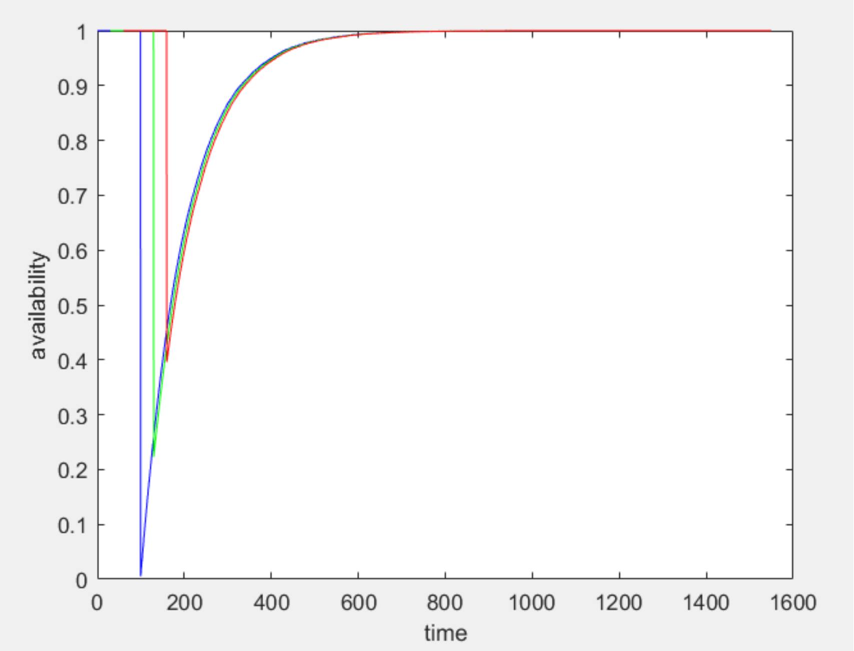

Figure 7.2: Availability of Each Train

The explanation and discussion for figure 7.3:

- The blue diagram drops 3 times due to shock (train 1), cascades (train 2) and cascades (train 3) respectively.
- It's notable that the main reason why the availability performance is better than that of the single-train system is that hardware failures of train 2 and 3 have been ignored.
- The gray area is 79.37, which is smaller than that in figure 7.1. The reason is that the triple-train system is better in robustness so that the availability diagram does not contact the time axle.
- The post-shock steady-state time T is even higher than that in figure 7.1, which has again proven the randomness of T and its inadequacies to be an indicator of resilience in simulation.

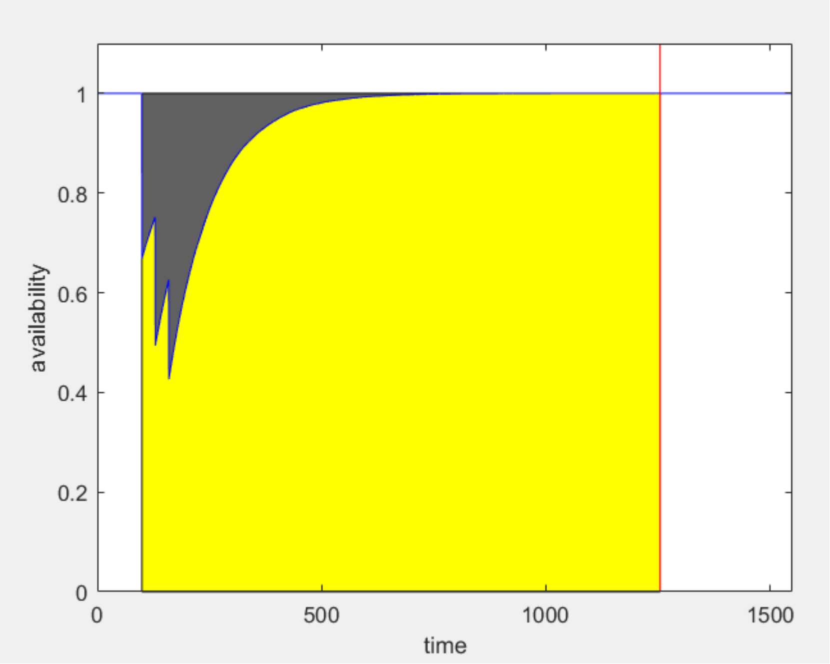

Figure 7.3: Overall Average Availability of Three Trains

7.3 Impact of Repair Rate

Obviously, allocated repair rate will result in better availability. This section will discuss the impact of tuned repair rate on availability resilience. The repair rate in appendix B.7 and B.8 will be replaced by the allocated value $\mu^*_{overall} = 0.722105775$.

Table 7.1: Comparison between Results With/Without Allocation

Scenario	Gray Area	Decreased after allocation
single-train, original repair rate	99.89	16.97%
single-train, allocated repair rate	82.94	
triple-train, original repair rate	79.37	20.20%
triple-train, allocated repair rate	63.34	

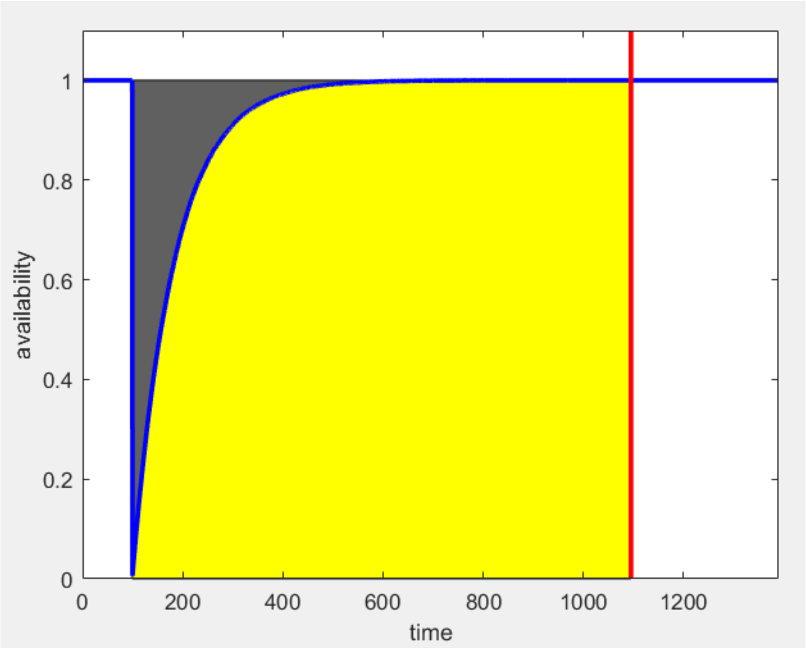

Figure 7.4: Availability-Time Diagram of Single Train System (Allocated Repair Rate)

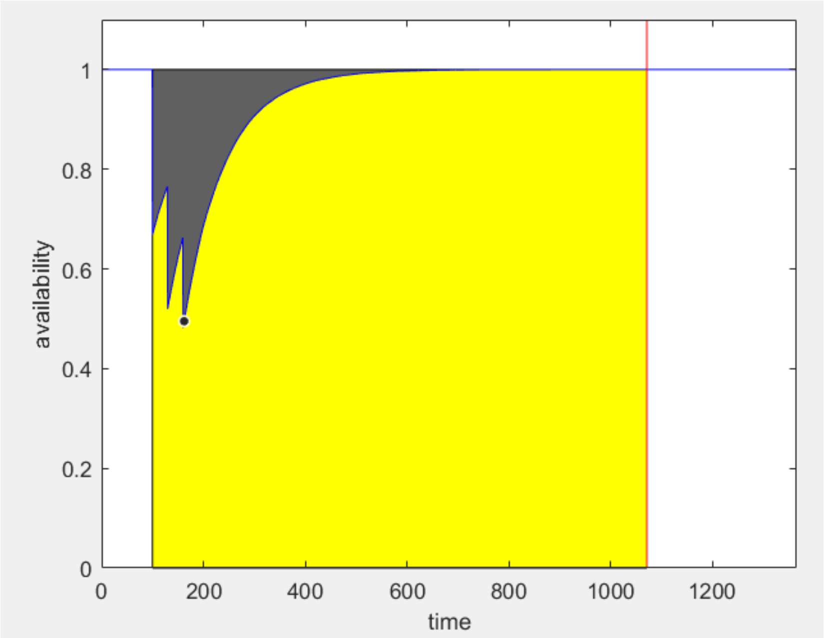

Figure 7.5: Overall Average Availability of Three Train (Allocated Repair Rate)

The figures above present the diagrams and the gray area is 82.94 in figure 7.4 while 63.34 in figure 7.5. Table 7.1 shows decreased proportions of the chosen indicator.

Figure 7.6 is generated as the comparison between figures 7.1 (the lower line chart) and 7.4 (the upper line chart), while figure 7.7 is the comparison between figures 7.3 (the lower line chart) and 7.5 (the upper line chart).

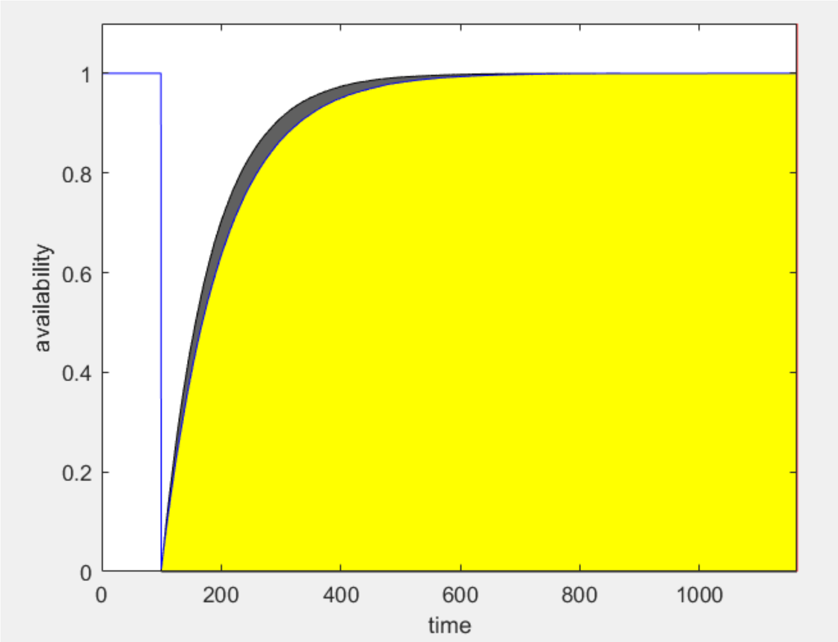

Figure 7.6: Comparison between Figures 7.1 and 7.4

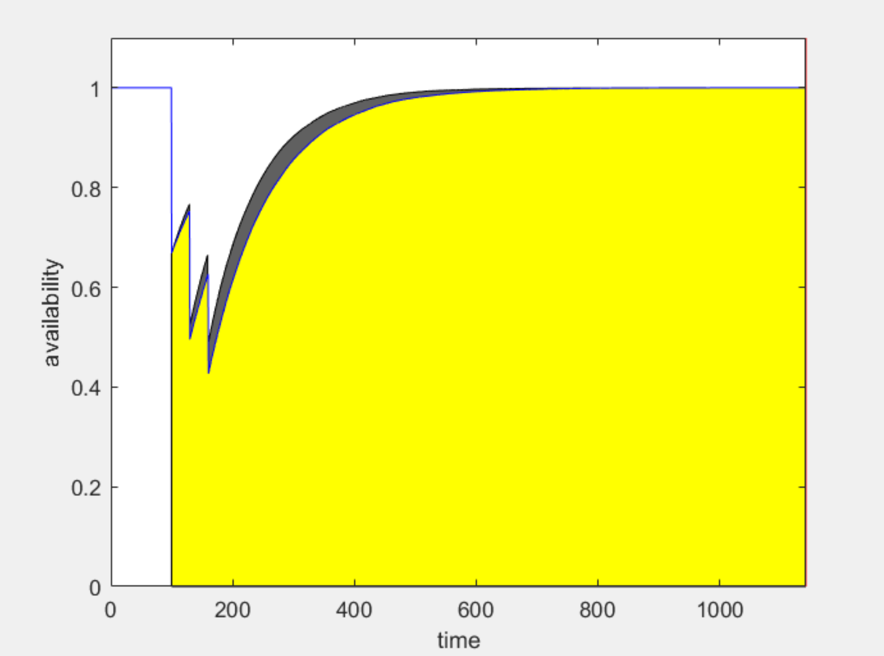

Figure 7.7: Comparison between Figures 7.3 and 7.5

Figures 7.6 and 7.7 explain how tuned repair rate can improve resilience in two ways:

- In figure 7.6, it's obvious that the slope of the recovery section of the upper curve is higher, which means higher repair rate can result in quicker rebounding so that resilience performance can be improved.
- In figure 7.7, it can be found that in this situation, a higher repair rate leads to higher lowest availability, which brings stronger robustness. This contributes to better resilience performance, too.

7.4 Summary of the Chapter

The definite integral method proposed in section 2.5.2 has been applied and a series of figures have been generated. The simulation of this chapter proves the feasibility of the method. Results present the features of improved resilience behavior, which are higher post-shock transient-state availability (better robustness) and a higher slope of the rebounding section (quick rebounding).

Chapter 8

Conclusion

This thesis presents a detailed process of availability estimation by simulation, availability allocation and resilience assessment for railway systems. The main achievements can be summarized as follow:

- For both single-vehicle and multiple-vehicle systems, the estimated availability and punctuality can fulfill the requirements by Bane NOR.
- The contribution towards delays by ERTMS failure, unexpected dwell time and cascades has been estimated and cascades are the leading reason in the multiple-vehicle system based on simulation.
- Complete steps of availability allocation (equal and weighted method) have been demonstrated. The significance of availability allocation has been discussed.
- The comparison between two time-varied average availability diagram based on original and allocated repair rate respectively shows that the higher repair rate will lead to better availability performance and earlier critical time with the lowest point in the diagram.
- A definite integral method for resilience assessment has been proposed and validated. The comparison between single-vehicle and multiple-vehicle systems reveal that higher post-shock transient-state availability (better robustness) could result in better resilience performance while the comparison between original and allocated repair rate reveals the impact upon the slope of the rebounding curve.

Chapter 9

Recommended Further Work

The scenarios and models for assessment are simplified owing to limitations. It's possible to improve the precision of results when introducing more activities such as common cause failures or more delay causes by extended the existing models. Besides, it's recommended to obtain data which can improve the accuracy and value of results but now remains hidden.

- More delay causes could be considered when estimating the availability.
- It's of value to collect dwell time distribution data for railway operators for more accurate results.
- In order to assess the influence of cascades upon average availability, the time-varied overall average availability estimation could be done.
- Due to the computer hardware limitation, the number of simulation runs in some scenarios is only 50000 (such as the codes in the appendix B.8), which would bring great randomness. This could be solved by better computers.
- The impact of common cause failure can be evaluated as an extension of availability estimation of multiple vehicles.
- If the data of cost models in availability allocation is sufficient, it's recommended to consider keeping the balance between minimizing the cost and maximizing the overall availability.

Appendix A

Acronyms

AGREE Advisory Group of Reliability of Electronic Equipment

ARINC Aeronautical Radio, Inc

Bane NOR Norwegian National Rail Administration

BSC Base station controller

BTS Base transceiver station

CCTV Close circuit television

ERTMS European Railway Traffic Management System

ETCS European Train Control System

GSM Global System for Mobile Communications

GSM-R Global System for Mobile Communications – Railway

MLD Mean logistic delay

MSC Mobile Switching Center

MTTF Mean time to failure

MTTR Mean time to repair

RAMS	Reliability, availability, maintainability, and safety
RBC	Radio Block Center
TRAU	Transcoder and rate adaptation unit
UNISIG	the Union of Signaling Industry
VC	Vital Computer

Appendix B

MATLAB Code

B.1 Simulation of Single Rolling Stock

```
%basic parameters
n=1000000
lambda=(0.000176168/60);
mu=(0.598854667/60);

%planned duration
T_P1=linspace(6,6,n);
T_P2=linspace(82,82,n);
T_P3=linspace(6,6,n);
T_P4=linspace(101,101,n);
T_P5=linspace(6,6,n);
T_P6=linspace(132,132,n);
T_P7=linspace(6,6,n);
T_P8=linspace(79,79,n);

%planed time
T_S1=linspace(6,6,n);
T_S2=linspace(88,88,n);
T_S3=linspace(94,94,n);
T_S4=linspace(195,195,n);
```

```
T_S5=linspace(201,201,n);
T_S6=linspace(333,333,n);
T_S7=linspace(339,339,n);
T_S8=linspace(418,418,n);

%simulated dwell duration
T_1=lognrnd(1.591,0.198,1,n);
T_3=lognrnd(1.591,0.198,1,n);
T_5=lognrnd(1.591,0.198,1,n);
T_7=lognrnd(1.591,0.198,1,n);

%simulated duration between stations
T_2=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 82
       T_2(1,i_n) = 82;%as planned
   else
       T_2(1,i_n) = 82+exprnd(1/mu);%planned time+repairing
   end

end

T_4=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 101
       T_4(1,i_n) = 101;
   else
       T_4(1,i_n) = 101+exprnd(1/mu);
   end

end

T_6=zeros(1,n);

```

```
for i_n = 1: n
   if exprnd(1/lambda) > 132
       T_6(1,i_n) = 132;
   else
       T_6(1,i_n) = 132+exprnd(1/mu);
   end

end

T_8=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 79
       T_8(1,i_n) = 79;
   else
       T_8(1,i_n) = 79+exprnd(1/mu);
   end

end

%actual time
T_A1=zeros(1,n);
for i_n=1:n
    if T_1(1,i_n)>T_P1(1,i_n)
        T_A1(1,i_n) = T_1(1,i_n);%delayed
    else
        T_A1(1,i_n) = T_P1(1,i_n);%as planned
    end
end

T_A2=zeros(1,n);
for i_n=1:n
    T_A2(1,i_n) = T_A1(1,i_n)+T_2(1,i_n);%the actual arriving time
end

T_A3=zeros(1,n);
```

```
for i_n=1:n
    if T_3(1,i_n)+T_A2(1,i_n)>T_S3(1,i_n)
        T_A3(1,i_n) = T_A2(1,i_n)+T_3(1,i_n);%delayed
    else
        T_A3(1,i_n) = T_S3(1,i_n);%as planned
    end
end

T_A4=zeros(1,n);
for i_n=1:n
    T_A4(1,i_n) = T_A3(1,i_n)+T_4(1,i_n);
end

T_A5=zeros(1,n);
for i_n=1:n
    if T_5(1,i_n)+T_A4(1,i_n)>T_S5(1,i_n)
        T_A5(1,i_n) = T_A4(1,i_n)+T_5(1,i_n);
    else
        T_A5(1,i_n) = T_S5(1,i_n);
    end
end

T_A6=zeros(1,n);
for i_n=1:n
    T_A6(1,i_n) = T_A5(1,i_n)+T_6(1,i_n);
end

T_A7=zeros(1,n);
for i_n=1:n
    if T_7(1,i_n)+T_A6(1,i_n)>T_S7(1,i_n)
        T_A7(1,i_n) = T_A6(1,i_n)+T_7(1,i_n);
    else
        T_A7(1,i_n) = T_S7(1,i_n);
    end
end

```

```
T_A8=zeros(1,n);
for i_n=1:n
    T_A8(1,i_n) = T_A7(1,i_n)+T_8(1,i_n);
end

%punctality
X=zeros(1,n);
for i_n=1:n
    if T_A8(1,i_n)≥T_S8(1,i_n)+4
        X(1,i_n)=0; %not punctual
    else
        X(1,i_n)=1; %punctual
    end
end

digits(6)
P=vpa(mean(X))

%availability
Y_2=zeros(1,n);
Y_3=zeros(1,n);
Y_4=zeros(1,n);
Y_5=zeros(1,n);

for i_n=1:n
    if T_A2(1,i_n)≥T_S2(1,i_n)+4
        Y_2(1,i_n)=0; %delayed
    else
        Y_2(1,i_n)=1; %on time
    end
end

for i_n=1:n
    if T_A4(1,i_n)≥T_S4(1,i_n)+4
        Y_3(1,i_n)=0;
    else
```

```
        Y_3(1,i_n)=1;
    end
 end

for i_n=1:n
    if T_A6(1,i_n)≥T_S6(1,i_n)+4
        Y_4(1,i_n)=0;
    else
        Y_4(1,i_n)=1;
    end
end

for i_n=1:n
    if T_A8(1,i_n)≥T_S8(1,i_n)+4
        Y_5(1,i_n)=0;
    else
        Y_5(1,i_n)=1;
    end
end

digits(6)
A=vpa((mean(Y_2)+mean(Y_3)+mean(Y_4)+mean(Y_5))/4)
```

B.2 Results Analysis for Simulation of Single Rolling Stock

(shall follow B.1)

```
%delay due to ERTMS in each section
C_1=zeros(1,n);
for i_n=1:n
   if T_2(1,i_n)>82
       C_1(1,i_n)=1; %delay
   else
       C_1(1,i_n)=0; %working normally
```

```
    end
end
D_1=sum(C_1);

C_2=zeros(1,n);
for i_n=1:n
    if T_4(1,i_n)>101
        C_2(1,i_n)=1;
    else
        C_2(1,i_n)=0;
    end
end
D_2=sum(C_2);

C_3=zeros(1,n);
for i_n=1:n
    if T_6(1,i_n)>132
        C_3(1,i_n)=1;
    else
        C_3(1,i_n)=0;
    end
end
D_3=sum(C_3);

C_4=zeros(1,n);
for i_n=1:n
    if T_8(1,i_n)>79
        C_4(1,i_n)=1;
    else
        C_4(1,i_n)=0;
    end
end
D_4=sum(C_4);

%total delay
D_total=n-sum(X);
```

```

%delay due to ERTMS
D_ERTMS=D_1+D_2+D_3+D_4;

%delay due to dwell time
D_dwell=D_total-D_ERTMS;

%proportion
P_ERTMS=D_ERTMS/D_total
P_dwell=D_dwell/D_total
```

B.3 Average Availability

```
%basic parameters
n=500000;
m=1000;%for plotting figures
lambda=(0.000176168/60);
mu=(0.598854667/60);

%time to failure and repair
T=zeros(1,n);
for i_n=1:n
    T(1,i_n)=exprnd(1/lambda); %ramdom time to failure
end

M=zeros(1,n);
for i_n=1:n
    M(1,i_n)=exprnd(1/mu); %ramdom time to repair
end

%total time
t=zeros(1,n);
for i_n=1:n
```

```
    if T(1,i_n)>394
        t(1,i_n)=394;
     else
        t(1,i_n)=394+M(1,i_n);
    end
end


X=zeros(n,m);
T_max=max(t);

for i_n=1:n
    if T(1,i_n)<394
        X(i_n,:)=[ones(1,fix(m*T(1,i_n)/T_max)) zeros(1,fix(m*M(1,i_n)/T_max)) ones(1,m-fix(m*T(1,i_n)/T_max)-fix(m*M(1,i_n)/T_max))];%availability performance for each time with failure
    else
        X(i_n,:)=ones(1,m);%without failure
    end
end


A=mean(X',2)';%average time
T_x=linspace(0,T_max,m);%time
figure(1)
plot(T_x,A),xlabel('time/minutes'), ylabel('availability')
xlim([-10, T_max+10]);
ylim([0.9995, 1.0002]);

[a,b]=find(A==min(A));%find lowest average availability
T_critical=T_x(min(a),min(b))%the critical time
```

B.4 Simulation of Multiple Vehicles

```
%basic simulation parameters
n=1000000
lambda=(0.000176168/60);
mu=(0.5988547/60);

%planned duration
T_P1=linspace(6,6,n);
T_P2=linspace(82,82,n);
T_P3=linspace(6,6,n);
T_P4=linspace(101,101,n);
T_P5=linspace(6,6,n);
T_P6=linspace(132,132,n);
T_P7=linspace(6,6,n);
T_P8=linspace(79,79,n);

%planned interval
I=linspace(30,30,n);

%planned interval when failure
I_1=linspace(6,6,n);
I_2=linspace(12,12,n);

%planned time
T_S1=linspace(6,6,n);
T_S2=linspace(88,88,n);
T_S3=linspace(94,94,n);
T_S4=linspace(195,195,n);
T_S5=linspace(201,201,n);
T_S6=linspace(333,333,n);
T_S7=linspace(339,339,n);
T_S8=linspace(418,418,n);

T2_S1=linspace(36,36,n);
T2_S2=linspace(118,118,n);
T2_S3=linspace(124,124,n);
```

```
T2_S4=linspace(225,225,n);
T2_S5=linspace(231,231,n);
T2_S6=linspace(363,363,n);
T2_S7=linspace(369,369,n);
T2_S8=linspace(448,448,n);

T3_S1=linspace(66,66,n);
T3_S2=linspace(148,148,n);
T3_S3=linspace(154,154,n);
T3_S4=linspace(255,255,n);
T3_S5=linspace(261,261,n);
T3_S6=linspace(393,393,n);
T3_S7=linspace(399,399,n);
T3_S8=linspace(478,478,n);

%simulated dwell duration
T_1=lognrnd(1.591,0.198,1,n);
T_3=lognrnd(1.591,0.198,1,n);
T_5=lognrnd(1.591,0.198,1,n);
T_7=lognrnd(1.591,0.198,1,n);

T2_1=lognrnd(1.591,0.198,1,n);
T2_3=lognrnd(1.591,0.198,1,n);
T2_5=lognrnd(1.591,0.198,1,n);
T2_7=lognrnd(1.591,0.198,1,n);

T3_1=lognrnd(1.591,0.198,1,n);
T3_3=lognrnd(1.591,0.198,1,n);
T3_5=lognrnd(1.591,0.198,1,n);
T3_7=lognrnd(1.591,0.198,1,n);

%simulated duration between stations
T_2=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 82
```

```
        T_2(1,i_n) = 82;%as planned
    else
        T_2(1,i_n) = 82+exprnd(1/mu);%planned time+repairing
    end

end

T_4=zeros(1,n);

for i_n = 1: n
    if exprnd(1/lambda) > 101
        T_4(1,i_n) = 101;
    else
        T_4(1,i_n) = 101+exprnd(1/mu);
    end

end

T_6=zeros(1,n);

for i_n = 1: n
    if exprnd(1/lambda) > 132
        T_6(1,i_n) = 132;
    else
        T_6(1,i_n) = 132+exprnd(1/mu);
    end

end

T_8=zeros(1,n);

for i_n = 1: n
    if exprnd(1/lambda) > 79
        T_8(1,i_n) = 79;
    else
        T_8(1,i_n) = 79+exprnd(1/mu);
```

```
    end

end

T2_2=zeros(1,n);

for i_n = 1: n
    if exprnd(1/lambda) > 82
        T2_2(1,i_n) = 82;
    else
        T2_2(1,i_n) = 82+exprnd(1/mu);
    end

end

T2_4=zeros(1,n);

for i_n = 1: n
    if exprnd(1/lambda) > 101
        T2_4(1,i_n) = 101;
    else
        T2_4(1,i_n) = 101+exprnd(1/mu);
    end

end

T2_6=zeros(1,n);

for i_n = 1: n
    if exprnd(1/lambda) > 132
        T2_6(1,i_n) = 132;
    else
        T2_6(1,i_n) = 132+exprnd(1/mu);
    end

end
```

```

T2_8=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 79
       T2_8(1,i_n) = 79;
   else
       T2_8(1,i_n) = 79+exprnd(1/mu);
   end

end

T3_2=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 82
       T3_2(1,i_n) = 82;
   else
       T3_2(1,i_n) = 82+exprnd(1/mu);
   end

end

T3_4=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 101
       T3_4(1,i_n) = 101;
   else
       T3_4(1,i_n) = 101+exprnd(1/mu);
   end

end

T3_6=zeros(1,n);

```

```
for i_n = 1: n
   if exprnd(1/lambda) > 132
       T3_6(1,i_n) = 132;
   else
       T3_6(1,i_n) = 132+exprnd(1/mu);
   end

end

T3_8=zeros(1,n);

for i_n = 1: n
   if exprnd(1/lambda) > 79
       T3_8(1,i_n) = 79;
   else
       T3_8(1,i_n) = 79+exprnd(1/mu);
   end

end

%actual time (1)
T_A1=zeros(1,n);
for i_n=1:n
    if T_1(1,i_n)>T_P1(1,i_n)
        T_A1(1,i_n) = T_1(1,i_n);%delayed
    else
        T_A1(1,i_n) = T_P1(1,i_n);%as planned
    end
end

T_A2=zeros(1,n);
for i_n=1:n
    T_A2(1,i_n) = T_A1(1,i_n)+T_2(1,i_n);%actual arriving time
end

T_A3=zeros(1,n);
```

```
for i_n=1:n
    if T_3(1,i_n)+T_A2(1,i_n)>T_S3(1,i_n)
        T_A3(1,i_n) = T_A2(1,i_n)+T_3(1,i_n);%delayed
    else
        T_A3(1,i_n) = T_S3(1,i_n);%as planned
    end
end

T_A4=zeros(1,n);
for i_n=1:n
    T_A4(1,i_n) = T_A3(1,i_n)+T_4(1,i_n);
end

T_A5=zeros(1,n);
for i_n=1:n
    if T_5(1,i_n)+T_A4(1,i_n)>T_S5(1,i_n)
        T_A5(1,i_n) = T_A4(1,i_n)+T_5(1,i_n);
    else
        T_A5(1,i_n) = T_S5(1,i_n);
    end
end

T_A6=zeros(1,n);
for i_n=1:n
    T_A6(1,i_n) = T_A5(1,i_n)+T_6(1,i_n);
end

T_A7=zeros(1,n);
for i_n=1:n
    if T_7(1,i_n)+T_A6(1,i_n)>T_S7(1,i_n)
        T_A7(1,i_n) = T_A6(1,i_n)+T_7(1,i_n);
    else
        T_A7(1,i_n) = T_S7(1,i_n);
    end
end

```

```
T_A8=zeros(1,n);
for i_n=1:n
    T_A8(1,i_n) = T_A7(1,i_n)+T_8(1,i_n);
end
%punctuality (1)
X=zeros(1,n);
for i_n=1:n
    if T_A8(1,i_n)≥T_S8(1,i_n)+4
        X(1,i_n)=0;
    else
        X(1,i_n)=1;
    end
end

digits(6)
P_1=vpa(mean(X));
%actual time (2)
T2_A1=zeros(1,n);
for i_n=1:n
    T2_A1(1,i_n)=max(max(T_A1(1,i_n)+I_1(1,i_n),T2_1(1,i_n)+I(1,i_n)),T2_S1(1,i_n));%cascades, delayed or as planned
end

T2_A2=zeros(1,n);
for i_n=1:n
    T2_A2(1,i_n)=max(T2_2(1,i_n)+T2_A1(1,i_n),T_A2(1,i_n)+I_1(1,i_n));%actual arriving time (with or without cascades)
end

T2_A3=zeros(1,n);
for i_n=1:n
    T2_A3(1,i_n)=max(max(T2_A2(1,i_n)+T2_3(1,i_n),T2_S3(1,i_n)),T_A3(1,i_n)+I_1(1,i_n));%delayed, as planned or cascades
end

T2_A4=zeros(1,n);
```

```
for i_n=1:n
    T2_A4(1,i_n)=max(T2_4(1,i_n)+T2_A3(1,i_n),T_A4(1,i_n)+I_1(1,i_n));
end

T2_A5=zeros(1,n);
for i_n=1:n
    T2_A5(1,i_n)=max(max(T2_A4(1,i_n)+T2_5(1,i_n),T2_S5(1,i_n)),T_A5(1,i_n)+I_1(1,i_n));
end

T2_A6=zeros(1,n);
for i_n=1:n
    T2_A6(1,i_n)=max(T2_6(1,i_n)+T2_A5(1,i_n),T_A6(1,i_n)+I_1(1,i_n));
end

T2_A7=zeros(1,n);
for i_n=1:n
    T2_A7(1,i_n)=max(max(T2_A6(1,i_n)+T2_7(1,i_n),T2_S7(1,i_n)),T_A7(1,i_n)+I_1(1,i_n));
end

T2_A8=zeros(1,n);
for i_n=1:n
    T2_A8(1,i_n)=max(T2_8(1,i_n)+T2_A7(1,i_n),T_A8(1,i_n)+I_1(1,i_n));
end

%punctuality (2)
X_2=zeros(1,n);
for i_n=1:n
    if T2_A8(1,i_n)≥T2_S8(1,i_n)+4
        X_2(1,i_n)=0;
    else
        X_2(1,i_n)=1;
    end
end

```

```
digits(6)
P_2=vpa(mean(X_2));

%actual time (3)
T3_A1=zeros(1,n);
for i_n=1:n
    T3_A1(1,i_n)=max(max(T3_1(1,i_n)+I(1,i_n)+I(1,i_n),T3_S1(1,i_n)),max(T_A1(1,i_n)+I_2(1,i_n),T2_A1(1,i_n)+I_1(1,i_n)));%delayed, as planned, cascades due to train 1 or cascades due to train 2
end

T3_A2=zeros(1,n);
for i_n=1:n
    T3_A2(1,i_n)=max(max(T3_2(1,i_n)+T3_A1(1,i_n),T_A2(1,i_n)+I_2(1,i_n)),T2_A2(1,i_n)+I_1(1,i_n));%actual arriving time (without cascades, with cascades from train 1 or train 2)
end

T3_A3=zeros(1,n);
for i_n=1:n
    T3_A3(1,i_n)=max(max(T3_A2(1,i_n)+T3_3(1,i_n),T3_S3(1,i_n)),max(T_A3(1,i_n)+I_2(1,i_n),T2_A3(1,i_n)+I_1(1,i_n)));%delayed, as planned, cascades due to train 1 or cascades due to train 2
end

T3_A4=zeros(1,n);
for i_n=1:n
    T3_A4(1,i_n)=max(max(T3_4(1,i_n)+T3_A3(1,i_n),T_A4(1,i_n)+I_2(1,i_n)),T2_A4(1,i_n)+I_1(1,i_n));
end

T3_A5=zeros(1,n);
for i_n=1:n
    T3_A5(1,i_n)=max(max(T3_A4(1,i_n)+T3_5(1,i_n),T3_S5(1,i_n)),max(T_A5(1,i_n)+I_2(1,i_n),T2_A5(1,i_n)+I_1(1,i_n)));
end
```

```

T3_A6=zeros(1,n);
for i_n=1:n
    T3_A6(1,i_n)=max(max(T3_6(1,i_n)+T3_A5(1,i_n),T_A6(1,i_n)+I_2(1,i_n)),
       T2_A6(1,i_n)+I_1(1,i_n));
end

T3_A7=zeros(1,n);
for i_n=1:n
    T3_A7(1,i_n)=max(max(T3_A6(1,i_n)+T3_7(1,i_n),T3_S7(1,i_n)),max(T_A7(1,
       i_n)+I_2(1,i_n),T2_A7(1,i_n)+I_1(1,i_n)));
end

T3_A8=zeros(1,n);
for i_n=1:n
    T3_A8(1,i_n)=max(max(T3_8(1,i_n)+T3_A7(1,i_n),T_A8(1,i_n)+I_2(1,i_n)),
       T2_A8(1,i_n)+I_1(1,i_n));
end

%punctuality (3)
X_3=zeros(1,n);
for i_n=1:n
    if T3_A8(1,i_n)≥T3_S8(1,i_n)+4
        X_3(1,i_n)=0;
    else
        X_3(1,i_n)=1;
    end
end
digits(6)
P_3=vpa(mean(X_3));

%overall punctuality
P=(P_1+P_2+P_3)/3

%availability (1)
Y_2=zeros(1,n);
```

```
Y_3=zeros(1,n);
Y_4=zeros(1,n);
Y_5=zeros(1,n);

for i_n=1:n
    if T_A2(1,i_n)≥T_S2(1,i_n)+4
        Y_2(1,i_n)=0;
    else
        Y_2(1,i_n)=1;
    end
end

for i_n=1:n
    if T_A4(1,i_n)≥T_S4(1,i_n)+4
        Y_3(1,i_n)=0;
    else
        Y_3(1,i_n)=1;
    end
end

for i_n=1:n
    if T_A6(1,i_n)≥T_S6(1,i_n)+4
        Y_4(1,i_n)=0;
    else
        Y_4(1,i_n)=1;
    end
 end

for i_n=1:n
    if T_A8(1,i_n)≥T_S8(1,i_n)+4
        Y_5(1,i_n)=0;
    else
        Y_5(1,i_n)=1;
    end
end

```

```
digits(6)
A_1=vpa((mean(Y_2)+mean(Y_3)+mean(Y_4)+mean(Y_5))/4);

%availability (2)
Y2_2=zeros(1,n);
Y2_3=zeros(1,n);
Y2_4=zeros(1,n);
Y2_5=zeros(1,n);

for i_n=1:n
    if T2_A2(1,i_n)≥T2_S2(1,i_n)+4
        Y2_2(1,i_n)=0;
    else
        Y2_2(1,i_n)=1;
    end
end

for i_n=1:n
    if T2_A4(1,i_n)≥T2_S4(1,i_n)+4
        Y2_3(1,i_n)=0;
    else
        Y2_3(1,i_n)=1;
    end
end

for i_n=1:n
    if T2_A6(1,i_n)≥T2_S6(1,i_n)+4
        Y2_4(1,i_n)=0;
    else
        Y2_4(1,i_n)=1;
    end
end

for i_n=1:n
    if T2_A8(1,i_n)≥T2_S8(1,i_n)+4
        Y2_5(1,i_n)=0;
```

```
    else
        Y2_5(1,i_n)=1;
    end
end

digits(6)
A_2=vpa((mean(Y2_2)+mean(Y2_3)+mean(Y2_4)+mean(Y2_5))/4);

%availability (3)
Y3_2=zeros(1,n);
Y3_3=zeros(1,n);
Y3_4=zeros(1,n);
Y3_5=zeros(1,n);

for i_n=1:n
    if T3_A2(1,i_n)≥T3_S2(1,i_n)+4
        Y3_2(1,i_n)=0;
    else
        Y3_2(1,i_n)=1;
    end
end

for i_n=1:n
    if T3_A4(1,i_n)≥T3_S4(1,i_n)+4
        Y3_3(1,i_n)=0;
    else
        Y3_3(1,i_n)=1;
    end
end

for i_n=1:n
    if T3_A6(1,i_n)≥T3_S6(1,i_n)+4
        Y3_4(1,i_n)=0;
    else
        Y3_4(1,i_n)=1;
    end
```

```
end

for i_n=1:n
    if T3_A8(1,i_n)≥T3_S8(1,i_n)+4
        Y3_5(1,i_n)=0;
    else
        Y3_5(1,i_n)=1;
    end
end

digits(6)
A_3=vpa((mean(Y3_2)+mean(Y3_3)+mean(Y3_4)+mean(Y3_5))/4);

%overall availability
digits(6)
A=(A_1+A_2+A_3)/3
```

B.5 Results Analysis for Simulation of Multiple Vehicles

(shall follow B.4)

```
%delay due to ERTMS in each section (1)
C_1=zeros(1,n);
for i_n=1:n
       if T_2(1,i_n)>82
           C_1(1,i_n)=1; %delay
       else
           C_1(1,i_n)=0; %working normally
       end
end
D_1=sum(C_1);

C_2=zeros(1,n);
for i_n=1:n
```

```
       if T_4(1,i_n)>101
           C_2(1,i_n)=1;
       else
           C_2(1,i_n)=0;
       end
end
D_2=sum(C_2);

C_3=zeros(1,n);
for i_n=1:n
       if T_6(1,i_n)>132
           C_3(1,i_n)=1;
       else
           C_3(1,i_n)=0;
       end
end
D_3=sum(C_3);

C_4=zeros(1,n);
for i_n=1:n
       if T_8(1,i_n)>79
           C_4(1,i_n)=1;
       else
           C_4(1,i_n)=0;
       end
end
D_4=sum(C_4);

%delay due to ERTMS in each section (2)
C2_1=zeros(1,n);
for i_n=1:n
       if T2_2(1,i_n)>82
           C2_1(1,i_n)=1;
       else
           C2_1(1,i_n)=0;
       end
```

```
end
D2_1=sum(C2_1);

C2_2=zeros(1,n);
for i_n=1:n
       if T2_4(1,i_n)>101
           C2_2(1,i_n)=1;
       else
           C2_2(1,i_n)=0;
       end
end
D2_2=sum(C2_2);

C2_3=zeros(1,n);
for i_n=1:n
       if T2_6(1,i_n)>132
           C2_3(1,i_n)=1;
       else
           C2_3(1,i_n)=0;
       end
end
D2_3=sum(C2_3);

C2_4=zeros(1,n);
for i_n=1:n
       if T2_8(1,i_n)>79
           C2_4(1,i_n)=1;
       else
           C2_4(1,i_n)=0;
       end
end
D2_4=sum(C2_4);

%delay due to ERTMS in each section (3)
C3_1=zeros(1,n);
   for i_n=1:n
```

```
       if T3_2(1,i_n)>82
           C3_1(1,i_n)=1;
       else
           C3_1(1,i_n)=0;
       end
end
D3_1=sum(C3_1);

C3_2=zeros(1,n);
for i_n=1:n
       if T3_4(1,i_n)>101
           C3_2(1,i_n)=1;
       else
           C3_2(1,i_n)=0;
       end
end
D3_2=sum(C3_2);

C3_3=zeros(1,n);
for i_n=1:n
       if T3_6(1,i_n)>132
           C3_3(1,i_n)=1;
       else
           C3_3(1,i_n)=0;
       end
end
D3_3=sum(C3_3);

C3_4=zeros(1,n);
for i_n=1:n
       if T3_8(1,i_n)>79
           C3_4(1,i_n)=1;
       else
           C3_4(1,i_n)=0;
       end
end
```

```
D3_4=sum(C3_4);

%total delay
D_total=3*n-sum(X)-sum(X_2)-sum(X_3);

%delay due to ERTMS without cascades
D_ERTMS1=D_1+D_2+D_3+D_4;
D_ERTMS2=D2_1+D2_2+D2_3+D2_4;
D_ERTMS3=D3_1+D3_2+D3_3+D3_4;
D_ERTMS=D_ERTMS1+D_ERTMS2+D_ERTMS3;

%cascades
D_C2=D_ERTMS1;
D_C3=D_ERTMS1+D_ERTMS2;
D_C=D_C2+D_C3;

%delay due to dwell time
D_dwell=D_total-D_ERTMS-D_C;

%proportion
P_ERTMS=D_ERTMS/D_total
P_dwell=D_dwell/D_total
P_C=D_C/D_total
```

B.6 Availability in RAMS Engineering

(shall follow B.4)

```
uptime=n*(82+101+132+79);
downtime=sum(T_2)+sum(T_4)+sum(T_6)+sum(T_8)-uptime;
digits(8)
a=vpa(uptime/(uptime+downtime))%original definition
```

B.7 Resilience Assessment of the Single-train System

```
%basic parameters
n=80000;
m=3000;%for plotting figures
mu=(0.598854667/60);

%time to failure and repair
T=zeros(1,n);
for i_n=1:n
    T(1,i_n)=100;%fixed time to failure
end

M=zeros(1,n);
for i_n=1:n
    M(1,i_n)=exprnd(1/mu);%random time to repair
end

%total time
t=zeros(1,n);
for i_n=1:n
    t(1,i_n)=394+M(1,i_n);
end

%maximum time
T_max=max(t);

%availability matrix
X=zeros(n,m);
for i_n=1:n
    X(i_n,:)=[ones(1,fix(m*T(1,i_n)/T_max)) zeros(1,fix(m*M(1,i_n)/T_max))
        ones(1,m-fix(m*T(1,i_n)/T_max)-fix(m*M(1,i_n)/T_max))];%working-
        failure-warking
end

```

```matlab
%average availability
A=mean(X',2)';

%time vector for plotting figures
T_x=linspace(0,T_max,m);

%find the post-shock steady-state time
Sum=sum(X,2);
[a,b]=find(Sum==min(Sum));
zero=find(X(a,:)==0);
k=length(zero);
first_zero=zero(1);
last_zero=zero(k);

%take the post-shock steady-state part
Down=X([1:n],[first_zero:last_zero]);
T_down=T_x([1:1],[first_zero:last_zero]);
A_down=mean(Down',2)';

%definite integral
R=trapz(T_down,A_down)
%missing part
Missing=T_max-394-R

figure(1)
area(T_down,ones(1,length(T_down)),'FaceColor',[96 96 96]/255)
hold on
area(T_down,A_down,'FaceColor','y')
hold on
plot(T_x,A,'b',linspace(last_zero*T_max/m,last_zero*T_max/m,10),linspace(-0.1,1.1,10),'r','LineWidth',2.2),xlabel('time'), ylabel('availability')
xlim([0, T_max]);
ylim([0, 1.1]);
```

B.8 Resilience Assessment of the Triple-train System

```
%basic parameters
n=50000;
m=3000;%for plotting figures
mu=(0.598854667/60);

%time to failure and repair
T=zeros(1,n);
for i_n=1:n
    T(1,i_n)=100;%fixed time to failure
end

M=zeros(1,n);
for i_n=1:n
    M(1,i_n)=exprnd(1/mu);%random time to repair
end

%total time
t=zeros(1,n);
for i_n=1:n
    t(1,i_n)=394+M(1,i_n);
end

t_2=zeros(1,n);
for i_n=1:n
    if M(1,i_n)≤25
        t_2(1,i_n)=394;
    else
        t_2(1,i_n)=394+M(1,i_n)-25;
    end
end

t_3=zeros(1,n);
for i_n=1:n
```

```
    if M(1,i_n)≤50
        t_3(1,i_n)=394;
    else
        t_3(1,i_n)=394+M(1,i_n)-50;
    end
end

%maximum time
T_max=max(t);
T_max2=max(t_2);
T_max3=max(t_3);

%availability matrix for first train
X=zeros(n,m);
for i_n=1:n
    X(i_n,:)=[ones(1,fix(m*T(1,i_n)/T_max)) zeros(1,fix(m*M(1,i_n)/T_max)) ones(1,m-fix(m*T(1,i_n)/T_max)-fix(m*M(1,i_n)/T_max))];%working-failure-working
end

%determine the time vector length for train 2 and 3
m_2=fix(m*T_max2/T_max);
m_3=fix(m*T_max3/T_max);

%availability matrix for train 2 and 3
X_2=zeros(n,m_2);
X_3=zeros(n,m_3);

for i_n=1:n
    if M(1,i_n)≤25
        X_2(i_n,:)=ones(1,m_2);%working normally
    else
        X_2(i_n,:)=[ones(1,fix(m_2*T(1,i_n)/T_max2)) zeros(1,fix(m_2*(M(1,i_n)-25)/T_max2)) ones(1,fix(m_2-fix(m_2*(M(1,i_n)-25)/T_max2)-fix(m_2*T(1,i_n)/T_max2)))];%working-cascades-working
    end
```

```
end

for i_n=1:n
    if M(1,i_n)≤50
        X_3(i_n,:)=ones(1,m_3);
    else
        X_3(i_n,:)=[ones(1,fix(m_3*T(1,i_n)/T_max3)) zeros(1,fix(m_3*(M(1,i_n)-50)/T_max3)) ones(1,fix(m_3-fix(m_3*(M(1,i_n)-50)/T_max3)-fix(m_3*T(1,i_n)/T_max3)))];
    end
end

%individual average availability
A=mean(X',2)';
A_2=mean(X_2',2)';
A_3=mean(X_3',2)';

%time vector for plotting figures
T_x=linspace(0,T_max,m);
T_x2=linspace(30,T_max2+30,m_2);
T_x3=linspace(60,T_max3+60,m_3);

figure(1)
plot(T_x,A,'b',T_x2,A_2,'g',T_x3,A_3,'r'),xlabel('time'), ylabel('availability')

%find the post-shock steady-state time
Sum=sum(X,2);
[a,b]=find(Sum==min(Sum));
zero=find(X(a,:)==0);
k=length(zero);
first_zero_1=zero(1);

Sum_3=sum(X_3,2);
[a_3,b_3]=find(Sum_3==min(Sum_3));
zero_3=find(X_3(a_3,:)==0);
```

```
k_3=length(zero_3);
last_zero_3=zero_3(k_3);

t_unit=T_max/m;
m_total=fix(max(T_x3)/t_unit);
T_xtotal=linspace(0,max(T_x3),m_total);

%align the matrix
X_total=[X,ones(n,m_total-m)];
X_total2=[ones(n,fix(30/t_unit)),X_2,ones(n,m_total-fix(30/t_unit)-m_2)];
X_total3=[ones(n,m_total-m_3),X_3];

%individual average avialability (aligned)
A_total1=mean(X_total',2)';
A_total2=mean(X_total2',2)';
A_total3=mean(X_total3',2)';

%overall average avialability (aligned)
A_total=(A_total1+A_total2+A_total3)/3;

%take the post-shock steady-state part
T_down_total=T_xtotal([1:1],[first_zero_1:(m_total-m_3+last_zero_3)]);
A_down_total=A_total([1:1],[first_zero_1:(m_total-m_3+last_zero_3)]);
l=length(T_down_total);

%definite integral
R=trapz(T_down_total,A_down_total)
%missing part
Missing=T_max3+60-394-R

figure(2)
area(T_down_total,linspace(1,1,l),'FaceColor',[96 96 96]/255)
hold on
area(T_down_total,A_down_total,'FaceColor','y')
hold on
```

```
plot(T_xtotal,A_total,'b',linspace((last_zero_3+m_total-m_3)*t_unit,(
    last_zero_3+m_total-m_3)*t_unit,10),linspace(-0.1,1.1,10),'r'),xlabel('
    time'), ylabel('availability')
xlim([0, max(T_x3)]);
ylim([0, 1.1]);
```

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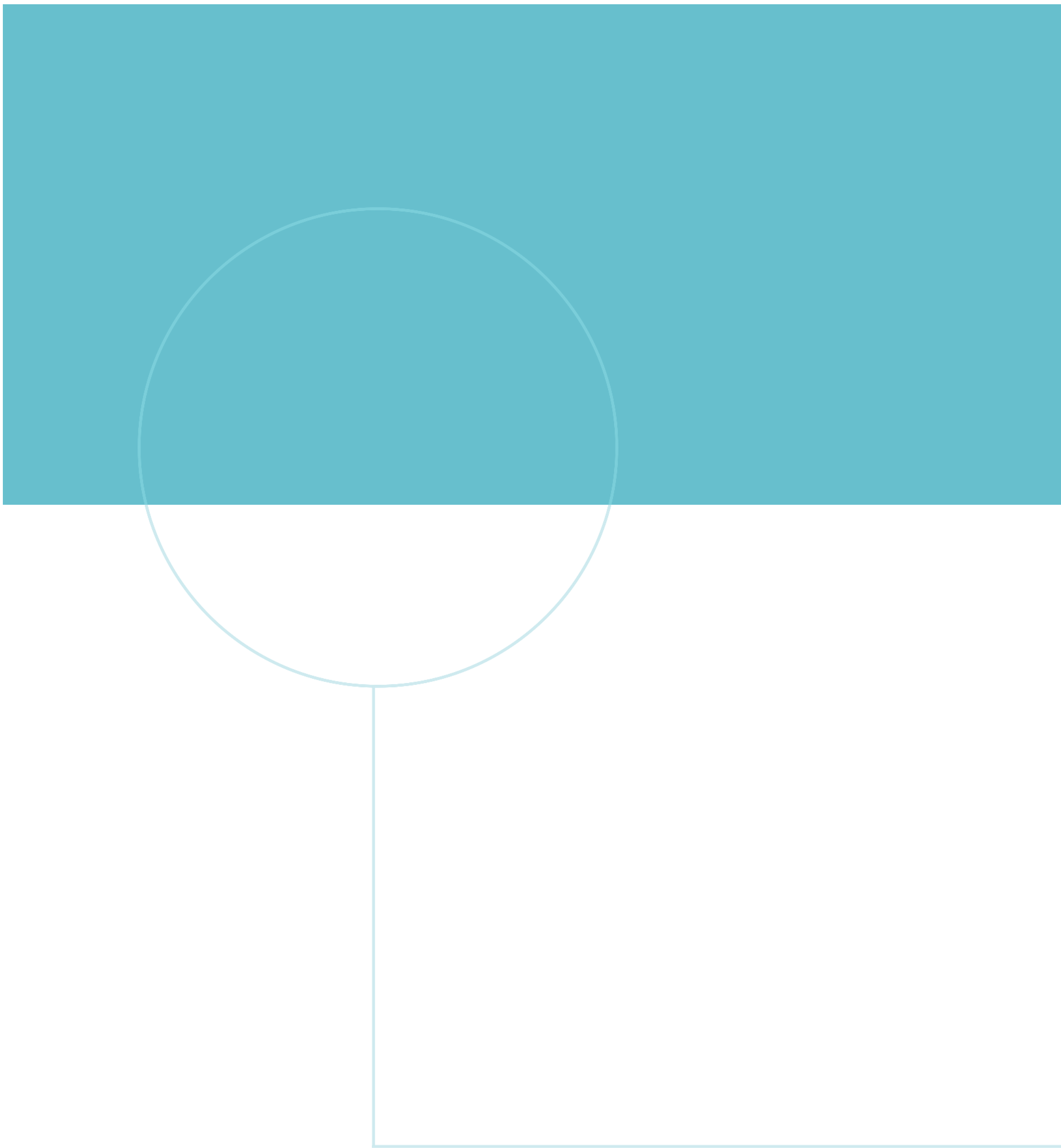

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