UNIVERSITAT POLITÈCNICA DE CATALUNYA

DEGREE IN AEROSPACE TECHNOLOGY

Reliability, Availability and Maintainability Study of a Light Rail Transit System

MEMORY

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ABSTRACT

This study is a first approach to the Preliminary Engineering Analysis of a Light Rail Transit (LRT) System. The study is divided into four interrelated parts. The first one consists on a presentation of the RAM Discipline, by a development of its theoretical foundations and the four Key Performance Indicators used through all the study. The methodology employed during the analysis and actual methods used for RAM analysis are also described in this section. Then, it has been developed a Failure Mode and Effects Criticality Analysis (FMECA) with a subsequent Sensitive Analysis to ensure that the results are binary in terms of probability. With that, a consequent Fault Tree Analysis (FTA) has been carried out. After that, the third part of the study provides the LRT RAM Requirements Apportionment and last, but not least, Preventive/Corrective Actions have been proposed.

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Acknowledgements

First of all, I would like to express my deep gratitude to my Co-Director, Mr. David Martin, for guiding me from the beginning, giving me his support and confidence so that I could learn and exert with a comprehensive vision.

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1. Introduction

Reliability, Availability and Maintainability (RAM) Study can be characterized as a qualitative and quantitative indicator of the degree that a LRT system, or the sub-systems comprising the system, can be relied upon to function as specified and to be both available and reliable.

1.1. Document Aims and Objectives

The goal of a LRT System is to achieve a defined level of service in a given time. This RAM Study pretends to describe the confidence with which the system can guarantee the achievement of this goal.

The objectives of this study will define the process for the specification of the Reliability, Availability, and Maintainability requirements for a LRT System.

1.2. Document Scope

This document describes:

- The numerical RAM requirements at system level.
- The methodology to achieve RAM targets and tools to be used.
- The process to perform the preliminary engineering RAM apportionment to LRT systems showing that the overall system Service Availability will be achieved. The apportionment process relies on the System Breakdown Structure (SBS)
- Definition of each Key Performance Indicator (KPI).
- Means and procedures for the measurement of each KPI.
- Definition of a RAM methodology that complies with EN 50126 [1] standard and CLC/TR 50126-3 [3].

This Preliminary LRT RAM Analysis will also provide evidence of the effective implementation of the EN 50126 life cycle and demonstrates the apportionment of RAM requirements to the LRT Systems and Subsystems such that the Service Availability requirements are satisfied.

Finally, the RAM requirements provided in this document will contribute to a number of other engineering processes –implemented on other stages - including:

- Design by equipment and system topology selection guided by probabilistic reliability modelling and reliability demonstration through observed failure data.
- System safety by estimating the likelihood of system failures due to random equipment failure.
- Operational & maintenance by guiding the operational and maintenance procedures.
- Continual improvement through a reliability growth program.

1.3. Requirements

Table 1 lists the numerical RAM requirements for the LRT System considered in this study. The requirement is expressed in terms of 'service availability'.

Service Availability Requirement
The overall service availability shall be at least 99.8%.

Table 1 Service availability requirements for the LRT System analyzed

1.4. Justification of the usefulness

This document will provide a RAM Preliminary Engineering Study about LRT System. But for what reason does the study focus on a LRT?

Nowadays, the LRTs are considered a modern, comfortable, environmentally friendly, accessible, on-time, quick and safe mode of transport. It also optimizes urban space, as each LRT can carry even double passengers than one bus and it is the most accessible mode of transport, as it has direct access at street level, with no stairs, providing passengers the facility to ride into it. It is very light and quiet because it is an electric vehicle and it can also start and stop faster.

But all these advantages for the LRT would not be possible if there was not a study that ensures its levels of safety and availability. Then, if the tramway was always delayed, taking to the passengers a lot of time waiting for it or anomalies with the subsystems happened and passengers could not finish their trip, they definitively would not use it. And that would mean a huge amount of money lost on its construction.

In other words, without a good RAM study, none of the advantages mentioned before would be possible and this is why this document provides a Reliability, Availability and Maintainability Study in order to guarantee all the advantages that the Light Rail Transit System has, had and will have.

2. RAM Discipline

2.1. RAM Concepts

The Service Availability is the top objective of the RAM Requirements. This availability will be affected by a combination of failure rates, repair times and operational issues. The overall numerical availability requirements for an LRT system will require modeling at the system level and then numerical reliability, availability and maintainability requirements apportioned across the subsystem level and then further to the component level.

Numerical RAM requirements are typically expressed as:

- Availability of systems to perform their intended functions
- Mean time between failures, MTBF: reliability measure of a defined function (for repairable systems / components)
- Mean time to failure, MTTF: reliability measure of a defined function (for non-repairable systems / components)
- Mean time to restore, MTTR, maintainability measure.

A deep explanation of the following terms strongly related with the RAM discipline can be found in Appendix I: RAM Concepts. They perform an important role as they are essential for a correct understanding of the document

- ***System Architecture***
- ***System Failures***
- ***Failure Rate***
- ***Reliability***
- ***Reliability Prediction***
- ***Availability***
- ***Maintainability***

2.2. Abbreviations and Definitions

Abbreviation	Meaning
AFC	Automatic Fare Collection
APU	Auxiliary Power Unit
ATP	Automatic Train Protection
CCTV	Closed Circuit Television
CEN	European Committee for Standardization
CENELEC	European Committee for Electro Technical Standardization
CLC/TR	CENELEC Technical Report
CS	Commercial Speed
E/E/PES	Electrical /Electronic /Programmable Electronic Systems
FMECA	Failure Mode and Effects Criticality Analysis
FRACAS	Failure Reporting, Analysis & Corrective Action System
FTA	Fault Tree Analysis
HVAC	Heating Ventilation Air Conditioning
LRT	Light Railway Transit/Tram
MCBF	Mean Cycles Between Failure
MDT	Mean Down Time
MEP	Mechanical, Electrical and Plumbing
MKBF	Mean Distance (Kilometres) Between Failures
MTBF	Mean Time Between Failure
MTBSAF	Mean Time Between Service Affecting Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Restore
MUT	Mean Up Time
MV	Medium Voltage
NEB	Number of Emergency Braking
NUS	Number of Unexpected Stops
O&M	Operation and Maintenance
OCC	Operations Control Centre
OCS	Overhead Catenary System
OHL	Overhead Line
PA	Public Address
PICS	Key Performance Indicator for Commercial Speed

Abbreviation	Meaning
PIDT	Key Performance Indicator for Departure Times
PIS	Passenger Information System
PITE	Key Performance Indicator for Train Evacuations
PIUS	Key Performance Indicator for Unscheduled Stops
Q	Unavailability
RAM	Reliability, Availability, Maintainability
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagrams
ROW	Right of way
SA	Service Availability
SBS	System Breakdown Structure
ST	Scheduled Trip
TAL	Trip Achievement Level
TDT	Total Down Time
TUT	Total Up Time
W	Failure Frequency
1oo2	One out of two

Table 2 Abbreviations likely to be encountered in this document

For the purpose of this document, the terms and definitions given in EN 50126-1 [1] and the following apply:

Term	Meaning
Accident	An unintended event or series of events that results in death, injury, loss of system or environmental damage (EN50129).
Apportionment	A process whereby the dependability (RAMS) elements for a system are sub-divided between the various items which comprise the system to provide individual targets (EN50126).
Assessment	The process of analysis to determine whether the design authority and the validator have achieved a product that meets the specified requirements and to form a judgment as to whether the product is fit for its intended purpose (EN50129).
Availability	The ability of a product to be in a state to perform a required function under given conditions at a given instant in time or over a given time interval assuming that the required external resources are provided (EN50129).

Term	Meaning
Dependability	The ability of a system to perform one or several required functions under given conditions
European Standard	A European Standard (EN) is a standard that has been adopted by one of the three recognized European Standardization Organizations (ESOs): CEN, CENELEC or ETSI. It is produced by all interested parties through a transparent, open and consensus based process.
Failure	A deviation from a specified performance of a system. A failure is the consequence of a fault or error in the system (EN50129).
Hazard	A physical situation with a potential for human injury (EN50129).
Reliability	The probability that an item can perform a required function under given conditions for a given period of time (EN50129)
Risk	The combination of frequency, or probability, and the consequence of a specified hazardous event (EN50129).
Safety	Freedom from unacceptable risk (EN50126).
System	System comprises subsystems that are combined to fulfil a required function under given condition. It is the highest level of description.
System Life cycle	The activities occurring during a period of time that starts when a system is conceived and end when the system is no longer available for use, is decommissioned and is disposed (EN50126).
Trip	A trip is the journey of one trainset from the first to the last stops on the scheduled route. The trip time is measured from the moment when the first train door starts the closing movement for leaving the first stop; to the moment when all train doors are fully open at the last stop.
Validation	The activity applied in order to demonstrate, by test and analysis, that the product meets in all respects its specified requirements (EN 50129).
1oo2	A configuration architecture of two redundant elements, performing the same function, where the function is executed by either of the two elements, and where both elements have to be in a failed state for the function to fail.

Table 3 Definitions likely to be required in LRT System

3. Light Rail Transit (LRT) System

3.1. LRT Project Background

The RAM Study has been developed to plan the RAM management activities of a generic LRT and to illustrate how the RAM requirements would be apportioned, implemented, and demonstrated. In order to give a brief description of the project that this Study takes into account, it is important to keep in mind the following.

The project taken into consideration presents a total right of way (ROW) for the LRT of 27.5km, and provides service to a large area of land, with different neighborhoods. This network is configured in the following way:

- Line 1 – 15.1 km long and 24 stations
- Line 2 – 12.4 km long and 21 stations

The double tracked network would be integrated and harmonized with other Public Transport modes, accessible for the mobility impaired people, safe, environmentally friendly and adapted to the weather of the emplacement.

The network considered in this study is intended to be street-running. At the same time the network will be segregated from traffic in order to achieve shorter trip times that will help to improve the passenger experience.

The sustainability goals to be met with this kind of transport system will include, but not be limited to:

- Minimizing impact on environment
- Acoustic and vibration mitigation
- Improving mobility for inhabitants

Figure 1 Night perspective of an LRT stop.

http://www.khaleejtimes.com/DisplayArticle09.aspxfile=data/theuae/2012/March/theuae_March851.xml

So, after the description of the infrastructure where the LRT would run, it is important to give an explanation specifying the LRT system.

A Light Rail Transit System is a system of transport used mainly for the transport of passengers, employing parallel rails which provide support and guidance for vehicles carried on flanged wheels, and in respect of which:

a) The rails are laid in a place to which the public have access.
b) On any part of the system, the permitted speed of operation of the vehicles is limited to that which enables the driver of any such vehicle to stop it within the distance he can see to be clear ahead.

LRT systems can be divided into three categories:

<u>Integrated on-street</u>
In this category the operation is by line-of-sight, the rails are laid in the highway and the part of the highway occupied by the rails may be capable of being used by other vehicles or by pedestrians.

<u>Segregated on-street</u>
In this category the operation is by line-of-sight, the rails are laid within the boundaries of a highway and the part of the highway occupied by the rails may be crossed by pedestrians, and by other vehicles at designated crossing points, but is not normally shared with other road vehicles except vehicles for maintenance purposes.

<u>Off-street</u>

In this category the operation is by either line-of-sight or signaled, or by a combination of the two, the track is wholly segregated form any highway, and the alignment is wholly separated from any highway.

The system analyzed in this Study can be identified as the second of the categories, which means an segregated on-street Light Rail Transit System.

Figure 2 An LRT System running on-street.

3.2. Interfaces to Other Programmes and Activities

3.2.1. Links with Safety Activities

It is considered that particular equipment defined to achieve the safety and comfort of passengers shall have a high level of reliability and availability. Equipment such as transmission systems that take part in the implementation of the safety functions shall also have a high level of reliability and availability.

Safety requirements would have to be set through the process defined in a System Safety Management Plan and shall take them into account in the RAM analysis. The management of reliability, availability and maintainability is an important contribution to system safety and evidence of that management will be an important element of the LRT safety case. Although, this links are out of the scope of this LRT Study. A next stage study with this document base will consider this section in its scope.

3.2.2. Links with Quality

It would have to be considered that RAM requirements of the system are based upon its level of quality: a Quality Management System would have to be defined in order to minimize errors and control their impact throughout the life-cycle of the system.
Again, this links are out of the scope of this LRT Study, but a next stage study would have to take this section into consideration.

3.3. Assumptions

The following events are excluded from the scope of this LRT Study for the RAM Analysis:

- Declared national disaster such as: earthquake, overall flooding, etc.
- Terrorism, sabotage, vandalism, madness, war.
- Use of system for other than intended purpose.
- Incorrect maintenance done by other personnel.
- Deliberate infringement to Safety and Health regulations by individuals.
- Deliberate infringement to procedures and instructions by individuals.
- Electricity supplied out of the specified values.
- Wrongful suspension or operation of the LRT system by the LRT Operator.
- Overrun of maintenance times by the LRT Operator.

Additionally, this specification does not concern the safety-related requirements and actions defined in order to ensure the safety of the transportation system. These requirements and actions would be managed by a safety organization.

3.4. Applicable Standards

Reference	Title
[1]	EN 50126-1:1999 Railway Applications - The specification and demonstration of reliability, availability, maintainability and safety (RAMS), Part 1: Basic requirements and generic process.
[2]	CLC/TR 50126-2:2007 Railway Applications - The specification and demonstration of reliability, availability, maintainability and safety (RAMS), Part 2: Guide to the application of EN 50126-1 for safety.
[3]	CLC/TR 50126-3:2006 - Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 3: Guide to the application of EN 50126-1 for rolling stock RAM
[4]	EN 50128:2001 Railway Applications - Communication, signalling and processing systems - software for railway control and protection systems.
[5]	EN 50129:2003 Railway Applications - Communication, signalling and processing systems - safety related electronic systems for signalling.
[6]	NFPA 130: Standard for fixed guide way transit and passenger rail systems.
[7]	Engineering Safety Management (The Yellow Book) Fundamentals and Guidance), Issue 4 (withdrawn), UK Rail Safety and Standards Board
[8]	ERA/REC/02-2012/SAF European Railway Agency Recommendation on the revision of the common safety method on risk evaluation and assessment and repealing Commission Regulation (EC) No 352/2009
[9]	ISO 9001:2008 – Requirements for Quality Management System
[10]	IEC 61124 Reliability testing — Compliance tests for constant failure rate and constant failure intensity
[11]	IEC 61025:2006 Fault Tree Analysis (FTA)
[12]	MIL-HDBK-472 Maintainability Prediction and Notice 1 1984
[13]	MIL-HDBK-470A Department Of Defense Handbook, *Designing And Developing Maintainable Products And Systems.*
[14]	MIL-STD-2155(AS) Department Of Defense. *Failure Reporting, Analysis and Corrective Action System.*
[15]	Dr David J Smith, 2011, Reliability, Maintainability and Risk 8e: Practical Methods for Engineers including Reliability Centered Maintenance and Safety-Related Systems. Ed. Butterworth-Heinemann
[16]	H. Kumamoto, E. J. Henley, *Probabilistic Risk Assessment and Management for Engineers and Scientists*, IEEE Press, 1996

Table 4 Document references

3.5. LRT System Definition

3.5.1. Systems Breakdown Structure

The activities to be developed during the LRT project have been identified and structured following a System Breakdown Structure (SBS). The project has been organized in a tree structure taking into account phases of execution and work packages which have been clearly identified to avoid overlaps, ambiguities and redundancies.

The level of detail of the SBS has been driven by the following criteria: all the systems and project parts shall be clearly identified by their functional requirements and the definition of their interfaces with other systems and project parts. They can be designed and developed independently following those specifications and afterwards every system can be integrated with others in the same hierarchical level constituting their hierarchical parent in the SBS.

Figure 3 shows the SBS for LRT system. It consists of the following levels:

- Level 01 - Project
- Level 02 - Grouping
- Level 03 - Systems
- Level 04 - Subsystems

Level 01 – Project. It is made up by LRT System.

Level 02 – Grouping. Project parts in that level are the main systems' groups of the transport system.

Level 03 – Systems. They correspond to the work packages or engineering disciplines which take part in the engineering design process.

Level 04 – Subsystems. They correspond to the subdivision of one system in multiple work packages which can be specified individually.

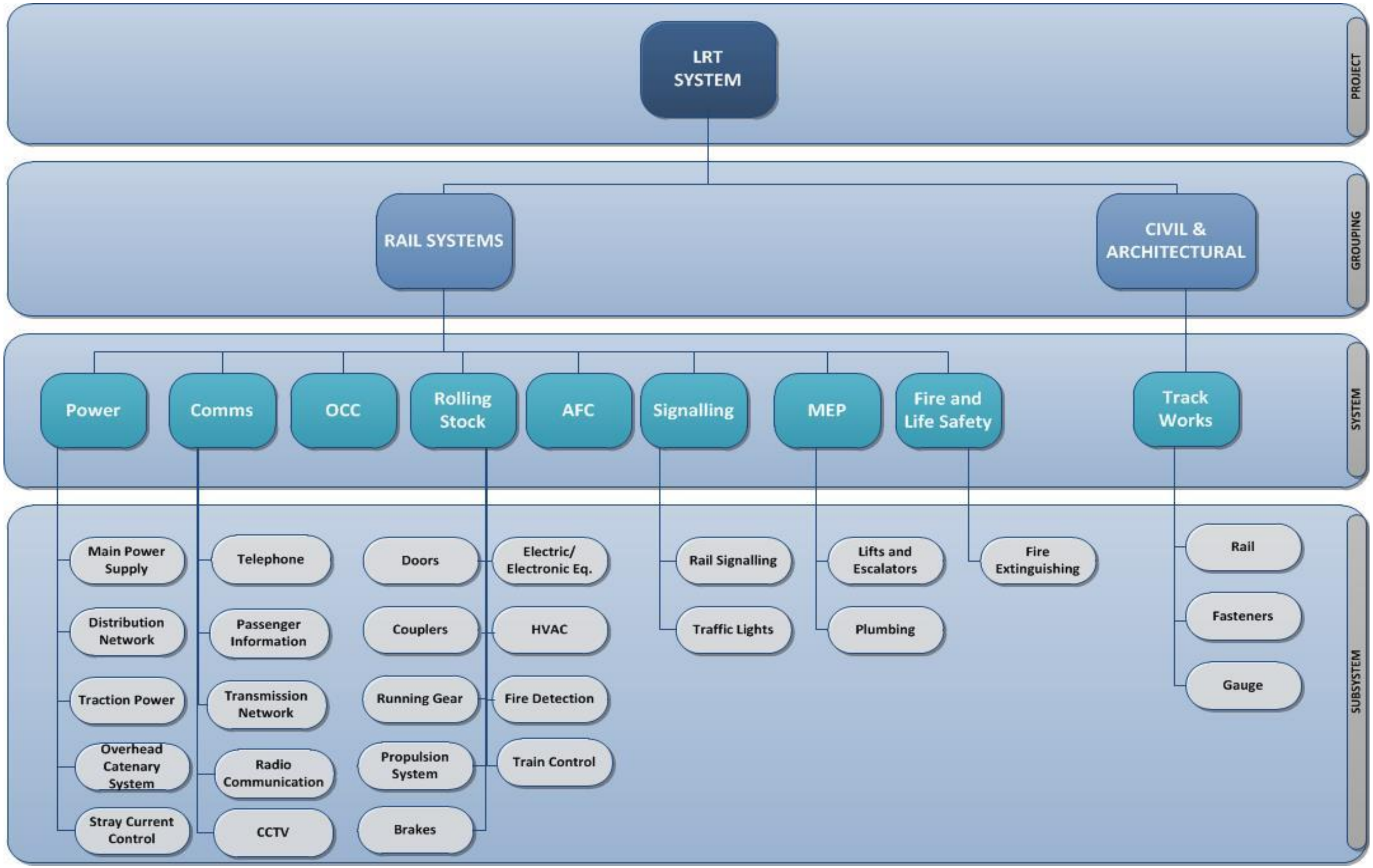

Figure 3 Systems Breakdown Structure

4. RAM Requirements

4.1. Numerical RAM Requirements

The desired RAM characteristics, usually expressed in terms of availability at the highest system level, are specified in the sections below. They will be:

- Estimated at the beginning of the system life-cycle.
- Progressively demonstrated through predictive modelling.
- Measured during actual passenger operations.

This analysis will define for each subsystem the Reliability, Availability and Maintainability objectives to be complied with in order to meet the specified RAM targets. Reliability, Availability and Maintainability objectives will be expressed in common RAM indicators:

- System / sub-system / component failure rates or MTBF/MTTF
- System / sub-system / component minimum availability
- System / sub-system / component maximum MTTR

The numerical RAM requirements specified in this document are classified by:

- Service availability requirements

4.2. Key Performance Indicators for Service Availability (SA)

Table 5 lists the numerical RAM requirements established as a minimum for the LRT System. The requirements are expressed in terms of 'service availability'. The guiding principle is that the 'service availability' should be the same for all lines regardless of length or complexity.

System	Service Availability Requirement
LRT	The overall service availability shall be at least 99.8%.

Table 5 Service availability requirements for LRT System

Service Availability measures the level of achievement of the scheduled transportation service of the System. Service Availability refers to the measurement of each train's availability or the whole schedule.

The Service Availability is calculated using the following formula:

$$SA = \frac{\sum(TAL)}{ST} \tag{1}$$

Where:

- SA is the Service Availability of the System over a considered period,
- $\sum(TAL)$ is the sum of the Trip[1] Achievement Levels of all scheduled trips over the considered period,
- ST is the number of scheduled trips over the considered period.

The Trip Achievement Level (TAL) in equation (1) is defined for each scheduled trip as follows:

$$TAL = PIDT \times PICS \times PITE \times PIUS \tag{2}$$

Where the Key Performance Indicators (KPIs) are defined as follows:

- **PIDT: Departure Times** – This quality criterion indicates if the considered scheduled trip is performed or missed, taking into account the actual headway with the previous trip compared with the scheduled headway.
- **PICS: Commercial Speed** – This quality criterion indicates if the actual commercial speed of the train is lower, equal or higher than the scheduled commercial speed.
- **PITE: Train Evacuations -** This quality criterion considers a train evacuation when the train is evacuated between two stations during the trip.
- **PIUS: Unexpected Stops -** This quality criterion affects the level of achievement of the trip if the train stops outside the nominal stopping points in station, taking into account the number of unexpected stops during the trip (NUS) and the number of emergency braking during the trip (NEB).

It must be noted that equation (1) for the definition of the Service Availability can be used for actual measurement of the system's performance during the Defects and Liability, and Operation phases. The Failure Reporting Analysis and Corrective Action

[1] A trip is the journey of one trainset from the first to the last station on the scheduled route.

System (FRACAS, see [14]) can help collecting the necessary data to measure actual LRT performance for each of the abovementioned Performance Indicators. The accomplished Service Availability will result from direct application of equation (1).

However, as it is a Preliminary Engineering Study for the LRT System, the Service Availability has to be predicted *statistically*, that is:

$$SA = \frac{\sum_{i=1}^{ST} TAL_i}{ST} = \frac{ST \cdot TAL_{Avg}}{ST} = TAL_{Avg}$$

In other words, assuming that all scheduled trips (ST) over the considered period have the same failure distribution $TAL_i = TAL_{Avg} \ \ \forall i$ (i.e. failures can affect any trip over the considered period with equal probability), the predictive results of the analysis of a single Trip can then be applicable to the operation during the considered period.

TAL_{Avg} is modelled and calculated in section 6.5 (Fault Tree Analysis).

4.2.1. Performance Indicator for Departure Times (PIDT)

This measure quantifies the compliance with the planned schedule and headway. The *PIDT* value is either one or zero. *PIDT* is calculated as follows:

$$PIDT_{First\ Trip} = 1 \ \ if \ \ \frac{NSDT - ADT}{NSDT - SDT} \geq 1 \tag{3}$$

$$PIDT_{First\ Trip} = 0 \ \ if \ \ \frac{NSDT - ADT}{NSDT - SDT} < 0 \tag{4}$$

$$PIDT_{Remaining\ Trips} = 1 \ \ if \ \ \frac{SDT - PSDT}{ADT - PADT} \geq 1 \tag{5}$$

$$PIDT_{Remaining\ Trips} = 1 \ \ if \ \ \frac{SDT - PSDT}{ADT - PADT} < 0 \tag{6}$$

Where:

- $PIDT_{First\ Trip}$ is the first scheduled trip
- $PIDT_{Remaining\ Trips}$ are all trips following the first scheduled trip
- $NSDT$ is the next scheduled departure time.
- ADT is the actual departure time of a scheduled trip.
- $PSDT$ is the previous scheduled departure time
- $PADT$ is the previous actual departure time

The following conditions apply:

- $PIDT$ is calculated on a per trip basis and is based on the departure time from the first scheduled station.
- An actual trip can be associated to one scheduled trip.
- A scheduled trip can be associated to one actual trip.
- The first actual trip that departs after scheduled time for the last trip shall be associated with the last scheduled trip; all other scheduled trips shall be associated with the first actual trip that departed between the scheduled departure time and the scheduled departure time of the next trip.
- The $PIDT$ is zero for a scheduled trip that cannot be associated to an actual trip.
- Actual departure times shall be considered to have deviated from scheduled departure time if the actual departure time is 31 seconds, or more, after scheduled departure time.

Figure 4 shows a graphical representation of the several departure times taking part in the Performance Indicator.

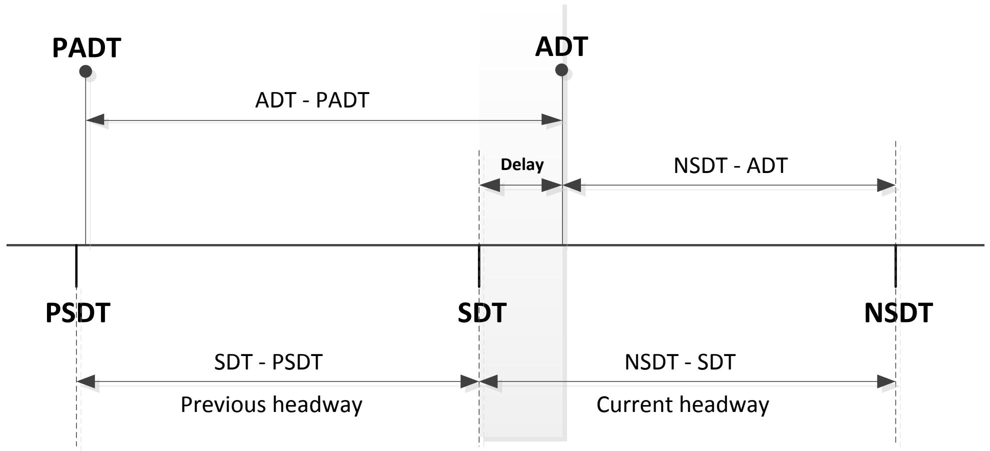

Figure 4 Departure times for scheduled trips

4.2.2. Performance Indicator for Commercial Speed (PICS)

This measure quantifies the compliance with the expected commercial speed. $PICS$ is calculated as follows:

$$PICS = 1 \ \ if \ \ \frac{Actual\ Commercial\ Speed}{Scheduled\ Commercial\ Speed} > 1$$

$$\text{otherwise} \ \ PICS = \frac{Actual\ Commercial\ Speed}{Scheduled\ Commercial\ Speed} \qquad (7)$$

The following conditions apply:

- $PICS$ is calculated on a per trip basis.
- Actual commercial speed is the average speed of the LRT.

  The measurement period is from the close door command at the first scheduled stop until the door open command at the last scheduled stop.

4.2.3. Performance Indicator for Train Evacuations Stops (PITE)

If a train evacuation occurs in the guideway between stops, then $PITE$ will be 0 for that trip, otherwise it shall be 1.

4.2.4. Performance Indicator for Unscheduled Stops (PIUS)

This measure quantifies the ability of the LRT to consistently run without unscheduled stops. $PIUS$ is calculated as follows:

$$PIUS = 1 - 0.1 \times NUS - 0.2 \times NEB \qquad (8)$$

Where:

- NUS is the number of unscheduled[2] stops per trip.
- NEB is the number of emergency stops per trip.

Conditions:

- $PIUS$ is calculated on a per trip basis.
- $PIUS$ does not include evacuations which are considered by Performance Indicator for train evacuations Stops (PITE).

4.3. RAM Apportionment

Based on RAM analysis technique, Railway Support Industry will derive and apportion 'subsystems level' RAM requirements and Contractors will be required to derive and apportion 'component level' RAM requirements. These numerical RAM requirements will be used to calculate a 'system level' availability estimation. This is shown in Figure 5 below.

[2] An unscheduled stop is an unplanned stop between stations of any duration.

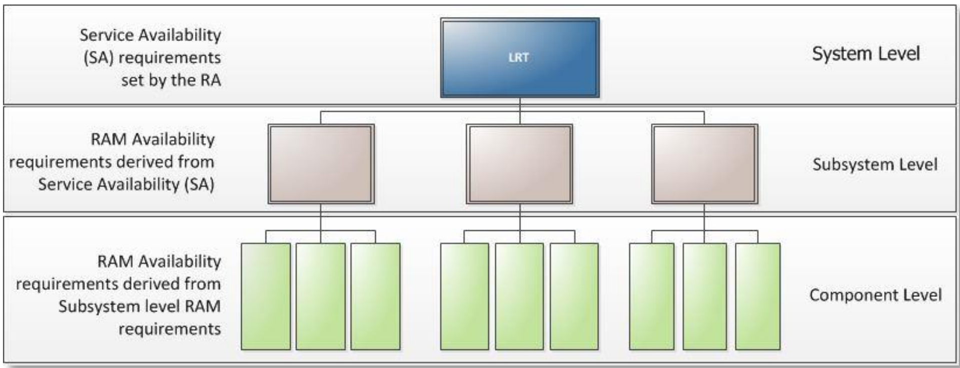

Figure 5 Apportionment of RAM Requirements

4.3.1. Methodology of Analysis

This section shows the methodology of analysis that will be applied to the apportionment of RAM requirements for the LRT System. Firstly the overall flow chart will be discussed showing the steps to be taken in the RAM performance demonstration. The flow chart is shown in Figure 6 below.

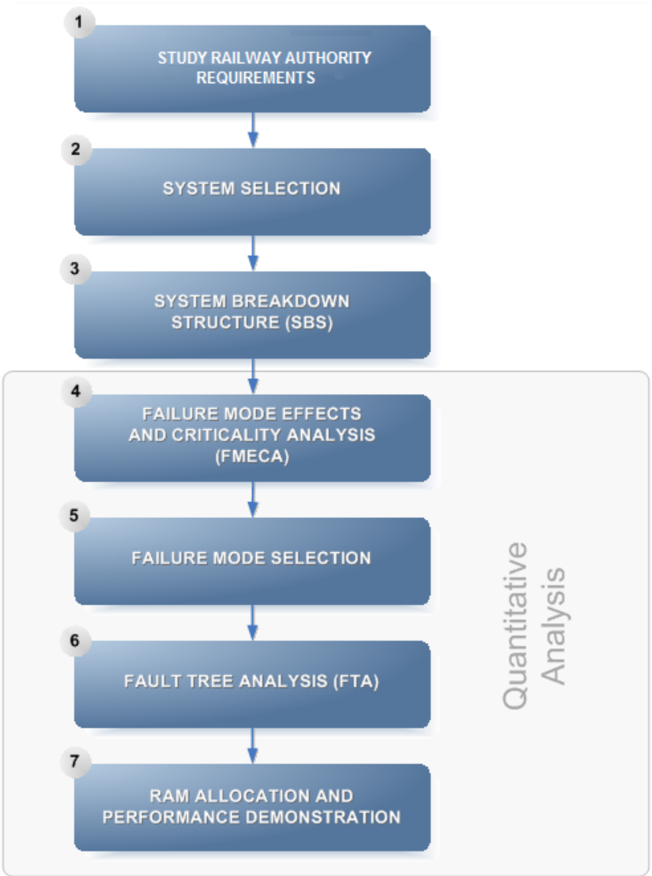

Figure 6 RAM justification method flow chart

Each of these steps is described below:

1. Analyze the scope of the RAM demonstration. The ultimate goal is to demonstrate RAM performances in terms of an overall Service Availability.

2. The System Selection method will further determine the scope of the analysis. As shown in Figure 7, the process for selecting the systems to be included in the analysis considers the RAM Scope, whether the system is essential to or has an impact on the Service Availability (SA), or whether the system has been designed according to an international standard for structural components.

   Only electro-mechanical / electrical / electronic systems, that are essential to meet the required Service Availability, and that are not designed according to an international standard for structural components, are included in this RAM analysis.

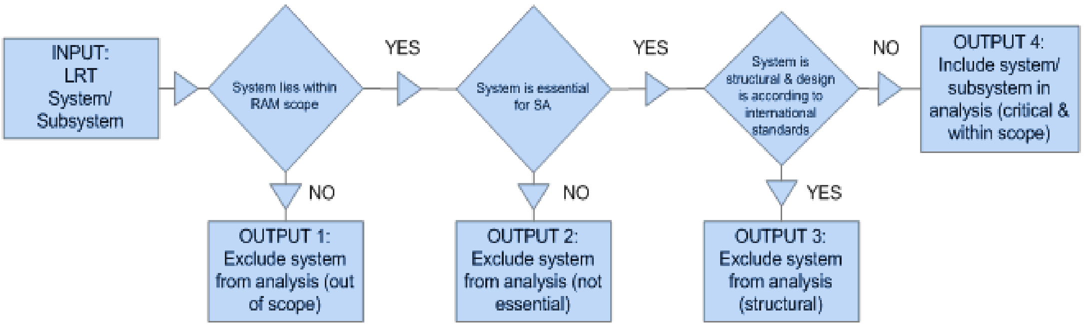

Figure 7 System selection method

3. System Analysis consists in identifying the critical systems within the System Breakdown Structure (SBS). This analysis is performed on the systems that result from the System Selection Method. Section 3.5.1 it has been showed this LRT System Breakdown Structure.

4. For the selected items, the effects of potential failures on the Service Availability will be described, indicating the occurrence rate of each failure mode. For this Preliminary Engineering Study, the FMECA will be completed at subsystem level.

5. In order to determine which failure modes, as identified in the FMECA, should be included in the fault tree analysis, the Failure Mode Selection Method shown in Figure 8 has been employed.

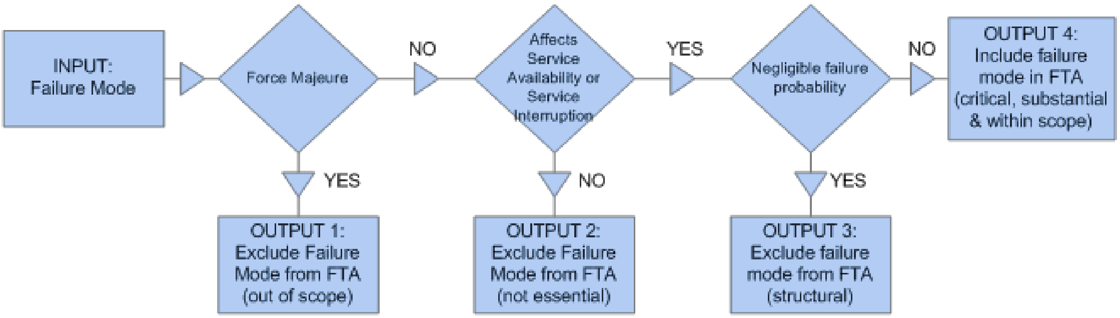

Figure 8 Failure mode selection

6. Following the Failure Mode Selection Method, a quantitative FTA will be developed. That is, failure data will be incorporated into the Fault Tree, with the Service Availability (SA) as the top event of the FTA with a target availability of 99.8%. It will necessary to determine how the different subsystems interact to provoke each of the failures that affect the Service Availability in terms of:

    a. SERVICE AVAILABILITY (SA):

        i. Departure times (PIDT)

        ii. Commercial speed (PICS)

        iii. Train evacuations (PITE)

        iv. Unscheduled stops (PIUS)

    Specific fault tree models will be developed to analyse failures leading to each of the following top events (see Figure 9).

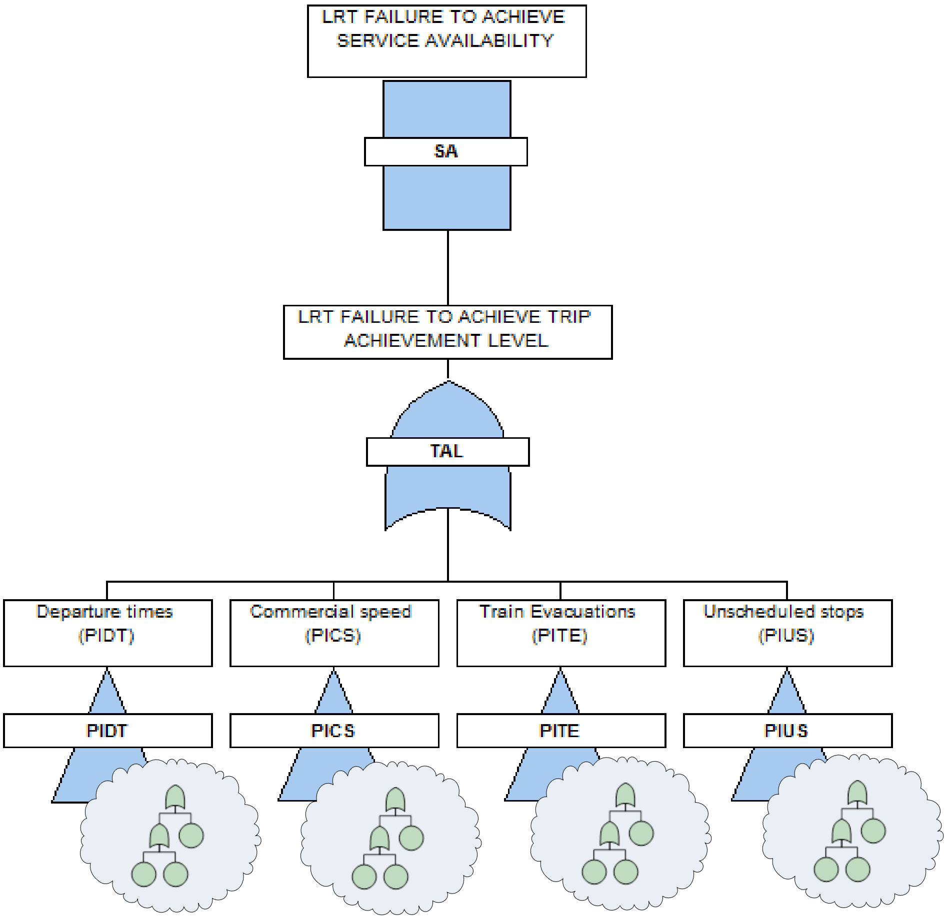

Figure 9 Quantitative fault tree analysis of the service availability

7. Finally, RAM allocation and Performance demonstration will be carried out. For every subsystem, a maximum allowable unavailability will be allocated (the constraint being the top event – i.e. Service Availability must be greater than 99.8%). This shall demonstrate that the proposed LRT System design meets the availability requirements, and will apportion non-availability requirements to the subsystems.

It must be noted that the use of Fault Tree Analysis (FTA) or Reliability Block Diagrams (RBD) is just a matter of choice. The quantitative results of availability are exactly the same for FTA and RBD (math formulation is the same for both) as long as the same software package is used. In this Study I have opted for using FTAs in the RAM analysis and demonstration, as these are better suited to show visually the interrelations of the systems and subsystems to provoke the failure[3].

[3] The fault tree analysis is a widely accepted method of presenting the interaction of system, subsystem and component failures as described in [11], and [2] §E.9.

5. RAM Programme Plan

5.1. Methods and Tools

The methods and tools that can be employed in RAM analysis will include, but not be limited, to the ones described in this section. In section 6.1 can be found the particular methods used in this study in order to demonstrate the SA of the LRT System. This section has been set, therefore, with the intention of providing different methods used in RAM studies, although not all of them are used in this particular study.

5.1.1. Failure Mode, Effects & Criticality Analysis (FMECA)

Aim: To analyse a system design, by examining systematically all possible sources of failure of a system's components and determining the effects of these failures on the behaviour and availability of the system.

Description: The analysis usually takes place through a meeting of engineers. Each component of a system is analysed in turn to give a set of failure modes for the component, their causes and effects (locally and at overall system level), detection procedures and recommendations. If the recommendations are acted upon, they are documented as remedial action taken.

References:

- IEC 60812:2006, *Analysis techniques for system reliability - Procedure for failure mode and effects analysis (FMEA)*
- *Risk Assessment and Risk Management for the Chemical Process Industry* H. R. Greenberg J. J. Cramer, John Wiley and Sons, 1991
- *Reliability Technology*. A. E. Green, A. J. Bourne, Wiley-Interscience. 1972

In the preliminary studies, the FMECA will contain the following information:

- **Failure Mode Code**: An acronym and serial number identification.
- **Description**: Explanation of the failure mode, describing how the system/subsystem or equipment may fail.
- **Effects on the Service Availability**: Refers to the Key Performance Indicators affected (refer section 4.2).
- **Effects on Operation**: Contains the consequences of this Failure Mode on the Operation of the LRT.

- **Failure Rate**: Frequency of occurrence of this Failure Mode, inverse of the Mean Time Between Failures (MTBF).
- **Restore Rate**: Inverse of the Mean Time To Restore (MTTR).
- **Criticality**: Criticality of components which could result in injury, damage or system degradation through single-point failures, in order to determine which components might need special attention and necessary control measures during design or operation.

Required inputs: Prior to the completion of FMECA, functional analysis is necessary for understanding the function of each sub-system. By completing this it is possible to understand the functional failure modes of each sub-system, and determine the criticality of failures that result in, or contribute to, major accidents and/or service disruptions.

5.1.2. Cause Consequence Diagrams

Aim: To analyse and model, in a compact diagrammatic form, the sequence of events that can develop in a system as a consequence of combinations of basic events.

Description: The technique can be regarded as a combination of Fault Tree and Event Tree Analysis[4]. It starts from a critical (initiating) event and the consequence graph is traced forwards by using YES/NO gates describing success and failure of some operations. This allows building event sequences leading either to an accident or to a controlled situation. Then cause graphs (i.e. fault trees) are built for each failure. Then starting from an accidental situation and going in the backward direction gives a global fault tree with this accidental situation as top event. In the forward direction the possible consequences arising from an event are determined. The diagrams can be used for generating fault trees and to compute the probability of occurrence of certain critical consequences. It can also be used to produce event trees.

The following figure shows a basic example of a cause consequence approach:

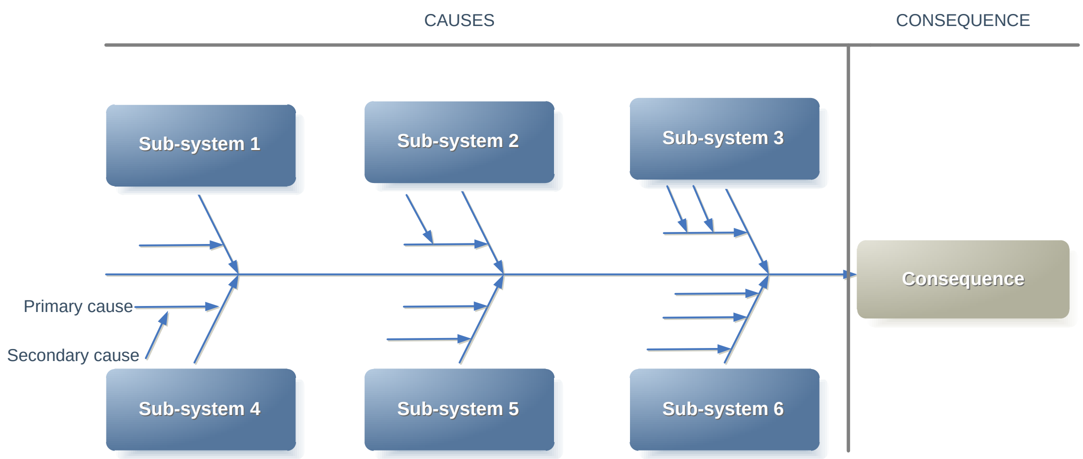

Figure 10 Example of a Cause Consequence Diagram

References:

- IEC 62502. *Analysis techniques for dependability* - Event tree analysis (ETA)
- *The Cause Consequence Diagram Method as a Basis for Quantitative Accident Analysis*. B. S. Nielsen, Danish Atomic Energy Commission. Riso-M-1374, 1971

[4] See section 5.1.3

5.1.3. Event Tree Analysis (ETA)

Aim: To model, in a diagrammatic form, the sequence of events that can develop in a system after an initiating event, and thereby indicate how serious consequences can occur. An event tree is difficult to build from scratch and using consequence diagram is helpful.

Description: On the top of the diagram is written the sequence conditions that are relevant in the progression of events that follow the initiating event. Starting under the initiating event, which is the target of the analysis, a line is drawn to the first condition in the sequence. There the diagram branches off into "yes" and "no" branches, describing how future events depend on the condition. For each of these branches, one continues to the next condition in a similar way. Not all conditions are, however, relevant for all branches. One continues to the end of the sequence, and each branch of the tree constructed in this way represents a possible consequence. The event tree can be used to compute the probability of the various consequences, based on the probability and number of conditions in the sequence.

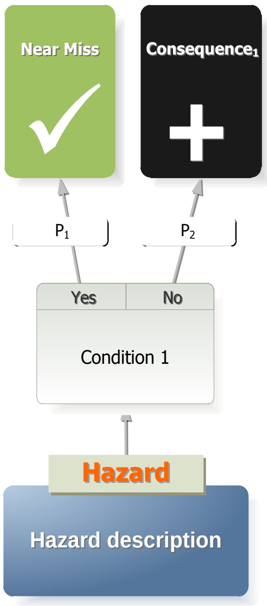

Figure 11 Example of an Event Tree

References:

- IEC 62502, *Analysis techniques for dependability* - Event tree analysis (ETA)
- *Risk Assessment and Risk Management for the Chemical Process Industry*. H.R. Greenberg, J.J. Cramer, John Wiley and Sons, 1991.

5.1.4. Fault Tree Analysis (FTA)

Aim: To aid in the analysis of events, or combinations of events, that will lead to a hazard or serious consequence and to perform the probability calculation of the top event.

Description: Starting at an event which would be the immediate cause of a hazard or serious consequence (the "top event"), analysis is carried out in order to identify the causes of this event. This is done in several steps through the use of logical operators (and, or, etc.). Intermediate causes are analysed in the same way, and so on, back to basic events where analysis stops. The method is graphical, and a set of standardized symbols are used to draw the fault tree. At the end of the analysis, the fault tree represents the logical function linking the basic events (generally components failures) to the top event (the overall system failure).The technique is mainly intended for the analysis of hardware systems, but there have also been attempts to apply this approach to software failure analysis. This technique can be used qualitatively for failure analysis (identification failure scenarios: minimal cut sets or prime implicants), semi quantitatively (by ranking scenarios according to their probabilities) and quantitatively for probabilistic calculations of the top event.

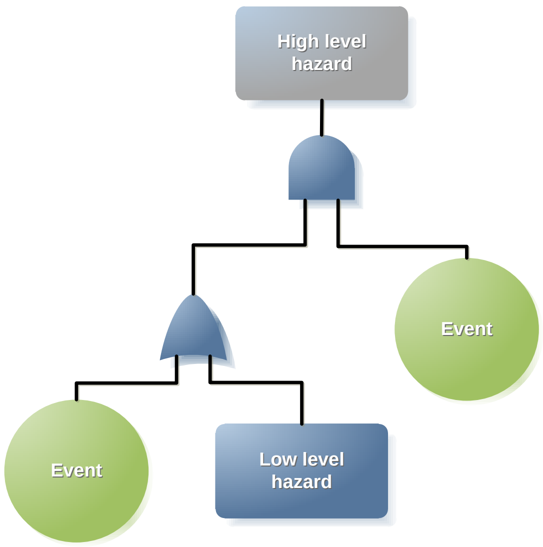

Figure 12 Example of a Fault Tree

References:

- IEC 61025:2006, *Fault tree analysis* (FTA)
- *From safety analysis to software requirements.* K.M. Hansen, A.P. Ravn, A.P, V Stavridou. IEEE Trans Software Engineering, Volume 24, Issue 7, Jul 1998

5.1.5. Markov Models

Aim: To model the behaviour of the system by a state transition graph and to evaluate probabilistic system parameters (e.g., un-reliability, un-availability, MTTF, MUT, MDT, etc.) of a system.

Description: It is a finite state automaton represented by a directed graph. The nodes (circles) represent the states and the edges (arrows) between nodes represent the transitions (failure, repairs, etc.) occurring between the states. Edges are weighted with the corresponding failure rates or repair rates. The fundamental property of homogeneous Markov processes is that the future depends only of the present: a change of state, N, to a subsequent state, N+1, is independent of the previous state, N-l. This implies that all the probabilistic laws of the models are exponential.

The failure events, states and rates can be detailed in such a way that a precise description of the system is obtained, for example detected or undetected failures, manifestation of a larger failure, etc. Proof test intervals may also be modeled properly by using the so-called multi-phase Markov processes where the probabilities of the states at the end of one phase (e.g. just before a proof test) can be used to calculate the initial conditions for the next phase (e.g. the probabilities of the various states after a proof test has been performed).

The Markov technique is suitable for modeling multiple systems in which the level of redundancy varies with time due to component failure and repair. Other classical methods, for example, FMEA and FTA, cannot readily be adapted to modeling the effects of failures throughout the lifecycle of the system since no simple combinatorial formulae exist for calculating the corresponding probabilities.

References:

- IEC 61 165:2006, *Application of Markov techniques*
- *The Theory of Stochastic Processes*. R. E. Cox and H. D. Miller, Methuen and Co. Ltd., London, UK, 1963
- *Finite MARKOV Chains*. J. G. Kemeny and J. L. Snell. D. Van Nostrand Company Inc, Princeton, 1959
- *The Theory and Practice of Reliable System Design*. D. P. Siewiorek and R. S. Swarz, Digital Press, 1982

5.1.6. Reliability Block Diagrams (RBD)

Aim: To model, in a diagrammatic form, the set of events that must take place and conditions which must be fulfilled for a successful operation of a system or a task. It is more a method of representation than a method of analysis.

Description: The target of the analysis is represented as a success path consisting of blocks, lines and logical junctions. A success path starts from one side of the diagram and continues via the blocks and junctions to the other side of the diagram. A block represents a condition or an event, and the path can pass it if the condition is true or the event has taken place. If the path comes to a junction, it continues if the logic of the junction is fulfilled. If it reaches a vertex, it may continue along all outgoing lines. If it exists at least one success path through the diagram, the target of the analysis is operating correctly.

Mathematically a RBD is similar to a fault tree. It represents the logical function linking the states of the individual components (failed or working) to the state of the whole system (failed or working). Therefore the calculations are similar as those described for fault trees.

An example of a simple RBD representation is shown in the following figure:

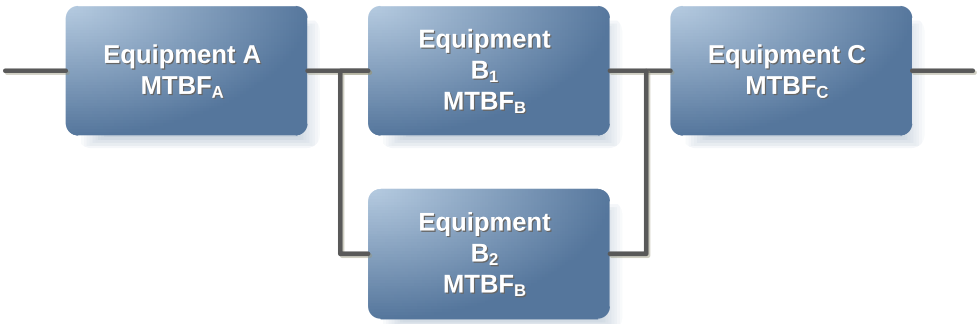

Figure 13 Example of a RBD

References:

- IEC 61078:2006, *Analysis techniques for dependability - Reliability block diagram and boolean methods*
- *Sécurisation des architectures informatiques.* Jean-Louis Boulanger, Hermbs - Lavoisier, 2009

5.2. Follow up of RAM Critical Items

As of the detailed design phases, and in order to follow up, control and solve/mitigate any kind of issue affecting RAM performance, the following tasks will be performed by the LRT contractors and suppliers:

- Identify, as part of the RAM analysis process, critical scenarios affecting Service Availability.
- Classify these scenarios in a hierarchy based on the combination of their estimated frequency of occurrence and their effects on Service Availability (SA).
- Estimate the impact of proposed actions.
- Follow up application of these actions during the design and manufacturing phase.

The action plan shall define and specify requirements, procedures and recommendations about the design, construction and O&M, in order to reach or improve the RAM requirements.

The follow up of RAM critical items shall be carried out by LRT Contractors and is therefore out of the scope of this study

6. LRT RAM Analysis and Prediction

6.1. Decision on the chosen methods

Two of the methods mentioned before that this study adopts are FMECA and FTA. For Fault Tree Analyses, Item Toolkit[5] software will be used. This decision comes from the fact that these two methods are the most extended and representative in RAM studies, although any of others would be also correct to use and the result will be the same.

6.2. Critical System Selection

The critical system selection determines the scope of the analysis. Only electro-mechanical / electrical / electronic systems, that are essential to meet the Service Availability, and that are not designed according to an international standard for structural components, are included in the RAM analysis. In addition, the decision of whether a system can affect or not the SA is given by Engineering Judgement from discipline experts.

6.2.1. Effect on Key Performance Indicators

Table 6 overleaf shows the results of a preliminary identification of the LRT systems that could affect each of the Key Performance Indicators (KPIs):

- red cells indicate that a subsystem failure would affect a SA PI,
- green cells indicate that a subsystem failure cannot affect a SA PI,

It is noted that a failure of a subsystem could affect more than one Performance Indicator, although probably with different failure modes (see section 6.3). For instance, a failure in the rolling stock that provokes a delay in the departure time may be different from a failure in the rolling stock affecting the commercial speed.

Nevertheless, this section provides a preliminary analysis of what systems could have an impact on Service Availability, and is aimed solely at that identifying whether or not the subsystem shall be included in the FTA (section 6.5).

A more accurate analysis is presented in the failure modes analysis shown in section 6.3, where the specific subsystem functions' failures that degrade the overall Service Availability will be analysed.

[5] *http://www.itemsoft.com/item_toolkit.html*

LRT CRITICAL SYSTEM SELECTION				
Rail Systems	**Key Performance Indicators (KPIs)**			
	PIDT Departure Time	**PICS Commercial Speed**	**PITE Train Evacuations**	**PIUS Unscheduled stops**
Power	Power defect can delay/prevent trip start	Power defect can reduce Commercial Speed	Power defect can result in Train Evacuation	Power defect can result in Unscheduled Stops
Comms	Comms defect can delay/prevent trip start	Comms defect can reduce Commercial Speed	Comms defect can result in Train Evacuation	Comms defect can result in Unscheduled Stops
Rolling Stock	Rolling Stock defect can delay/prevent trip start	Rolling Stock defect can reduce Commercial Speed	Rolling Stock defect can result in Train Evacuation	Rolling Stock defect can result in Unscheduled Stops
OCC	OCC defect cannot delay/prevent trip start	OCC defect cannot reduce Commercial Speed	OCC defect cannot result in Train Evacuation	OCC defect cannot result in Unscheduled Stops
MEP	MEP defect cannot delay/prevent trip start	MEP cannot reduce Commercial Speed	MEP defect cannot result in Train Evacuation	MEP defect cannot result in Unscheduled Stops
Signalling	Signalling defect can delay/prevent trip start	Signalling defect can reduce Commercial Speed	Signalling defect can result in Train Evacuation	Signalling defect can result in Unscheduled Stops
AFC	AFC defect can delay/prevent trip start	AFC defect cannot reduce Commercial Speed	AFC defect cannot result in Train Evacuation	AFC defect cannot result in Unscheduled Stops
Fire & Life Safety	Fire & Life Safety can delay/prevent trip start	Fire & Life Safety defect can reduce Commercial Speed	Fire & Life Safety defect cannot result in Train Evacuation	Fire & Life Safety defect cannot result in Unscheduled Stops
Trackworks	Guideway defect can delay/prevent trip start	Guideway defect can reduce Commercial Speed	Guideway defect can result in Train Evacuation	Guideway defect can result in Unscheduled Stops

Table 6 LRT critical system selection

Table 6 shows the selection of the critical LRT systems for the purposes of the reliability and availability starts with development of a list of subsystems which comprise the entire LRT system (refer System Breakdown Structure, in 3.5.1). The system selection method described in section 4.3.1 and presented in Figure 7 has been applied to selection of systems to be analysed in this analysis and prediction report.

Only systems with category output 4 (see Figure 8) are included in the analysis.

6.3. Failure Mode Effects and Criticality Analysis (FMECA)

A preliminary Failure Mode and Effects Criticality Analysis (FMECA) has been carried out for the LRT System described in section 3.1. The purpose of this FMECA is to analyse the possible effects of each failure on the System, from the point of view of the Operation, Maintenance, and the following Key Performance Indicators (see section 4.2):

- PIDT: Departure Times
- PICS: Commercial Speed
- PITE: Train Evacuations
- PIUS: Unscheduled Stops

The objective is to determine the Reliability, Availability and Maintainability critical functions and determine the applicable requirements for each sub-system.

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Power	Main Power Supply	Incomers feed energy from the electrical company through redundant feeder taps.	POW01	Loss of one of the Main Power Supply incoming feeders. **Rationale:** It affects only departure times, while redundant incomer feeder taps and redundant transformers reconfigure. Neither commercial speed nor evacuation or unscheduled stops are affected by this failure because the reconfiguration takes few seconds.	Yes	No	No	No	500000	2
		Transformation of Input Voltage (>35kV) to internal MV distribution Voltage (2-35kV)	POW02	Failure of one transformer or related protection. **Rationale:** Detection of a fault on the Transformer-Rectifier results in its isolation and, for this reason, a loss of feeding to a section of the catenary. It affects only departure times, while redundant system automatically reconfigures in a few seconds.	Yes	No	No	No	500000	2
	Distribution Network	The Distribution Network supplies energy (MV) to all Traction Power Substations along the route.	POW03	Failure of the distribution of MV to Traction Power Substations. **Rationale:** This failure could prevent a tram departing from a Stop, or diminish commercial speed, as a result of the momentary power interruption. It does not affect the evacuation because it would be able to re-start operation after system restoration thanks to the redundant MV substation system. As it is a momentary power interruption, it does not cause an unscheduled stop.	Yes	Yes	No	No	500000	2
	Traction Power	The Transformer/Rectifier Group transforms AC MV distribution voltage to DC traction voltage	POW04	Failure of one Transformer/Rectifier Group **Rationale**: T/R failure could prevent a tram departing from a Stop or result in a diminished commercial speed. In addition, the time needed to investigate the cause of the fault may necessitate train evacuation.	Yes	Yes	Yes	No	500000	4

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Power	Traction Power	Accompanying feeders increase the total OHL cross section	POW05	Loss one of the Traction Power incoming feeders. **Rationale:** Loss one of the Traction Power incoming feeders may limit the power which can be extracted from the catenary and hence affect propulsion equipment performance (commercial speed). So, departure times will be also affected by this failure.	Yes	Yes	No	No	500000	2
	Overhead Catenary System (OCS)	The OCS allows transmission of electrical power to trams operating on the guide-way	POW06	OCS failure **Rationale:** The detection of a fault on the OCS and its isolation means that the affected OCS cannot be connected to the substations until the cause of the fault has been "cleared". In addition to preventing a tram from departing from a station or causing an unscheduled stop between stations, the time needed to investigate the cause of the fault may necessitate train evacuation. It might also prevent the operation of trains and affect commercial speed for trains running between stops.	Yes	Yes	Yes	Yes	500000	4
		OCS segmentation prevents contact wire deformation by temperature variations	POW07	OCS segment failure **Rationale:** The detection of a fault on an OCS segment and its isolation means that the affected OCS section cannot be connected to the adjacent OCS sections until the cause of the fault has been "cleared". This may prevent a train from departing from a Stop. In addition, the time needed to investigate the cause of the fault may necessitate train evacuation.	Yes	No	Yes	No	500000	4
		OCS segments connected by Switching Posts along the route	POW08	Loss of energy at one OCS segment **Rationale:** The lack of energy at the affected segment will prevent a train from departing from a Stop and additionally, an unscheduled stop until the energy supply is recovered.	Yes	No	No	Yes	500000	4
		OCS is supported by poles	POW09	OCS pole failure **Rationale:** This failure implies to stop the tram circulation while the pole is affected; hence it takes place a train evacuation (i.e. the pole falls in the LRT right of way) and, consequently, departure times will be affected.	Yes	No	Yes	No	500000	4

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Power	Stray Current Control	Minimize the leakage of stray currents	POW10	Damage for galvanic corrosion of water or gas pipe under the track originates leak. **Rationale**: This failure may provoke the signalling system malfunction, and as a consequence departure times, train evacuations and unscheduled stops are affected.	Yes	No	Yes	Yes	648000	8
			POW11	Dangerous step and/or touch potentials. **Rationale**: The effects of stray current can create dangerous step and/or touch potentials which could result in service delay due to passenger injury.	Yes	No	Yes	Yes	648000	8
Communications	General Functions	Provide communications in all system's areas (tram, station, tracks, depot /OCC, etc.)	COM01	Failure in information transmission. Unable to establish communication between 2 or more system's areas. **Rationale:** Service delayed. Unable to coordinate traffic.	Yes	No	No	No	100000	1
			COM02	Wrong information transmission. Wrong information give it between 2 or more system's areas. **Rationale:** Service delayed. Bad traffic coordinator.	Yes	No	No	No	100000	1
		Provide human-machine interface for communication	COM03	Unable to manage communication information. Communication operator cannot access to the information. **Rationale:** Service delayed. Unable to coordinate all traffic trams.	Yes	No	No	No	100000	1

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Communications	Transmission Network	To transmit data among the network	COM04	Loss of signalling communication. **Rationale:** Driver should use degraded mode without signalling communications. Driver should communicate with OCC and receive orders (unscheduled stop). The operation of all trains without signalling will mean departures delay and commercial speed impact.	Yes	Yes	No	Yes	100000	1
		Transmit data among the OCC, depot, stations, and through transport network	COM05	Optical-fibre broken. Unable data transmission among all systems. **Rationale:** Service interrupted. All communications system failed. Difficult to repair. Evacuation of the train, due to long time to repair.	Yes	Yes	Yes	Yes	500000	5
			COM06	Loss of data integrity. Wrong data transmission among all systems. **Rationale:** Service interrupted. Wrong instructions transmission, but it does not mean that the tram has to be evacuated.	Yes	Yes	No	Yes	100000	1
	Radio Communications	Provide multi personal communication (between OCC, tram driver, depot, maintenance personal)	COM07	Radio Controller failure. **Rationale:** Service interrupted. Impossible to communicate with the driver. Evacuation of the train, due to long time to repair.	Yes	Yes	Yes	Yes	100000	4
			COM08	Radio Base Station failure (zone affected) **Rationale:** Service interrupted. Impossible to communicate with the driver. Evacuation of the train, due to long time to repair.	Yes	Yes	Yes	Yes	100000	2
		Provide selective communication (communication between individuals or from point to point)	COM09	Train selective radio communication failure. **Rationale:** Operational procedure: to inform when train arrives at stop. Use a handset terminal.	Yes	No	No	No	30000	0.5

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Communications	Closed Circuit Television (CCTV)	Video monitoring at stops, depots, tram wayside and on-board	COM10	Loss of video monitoring at road crossings. **Rationale:** Slight decrease of speed at road crossings without CCTV.	No	Yes	No	No	10000	0.8
Rolling Stock	Doors / Gangway	To allow passengers to board and alight the tram.	RST01	Defect in the door movement which delays or prevents passengers boarding or alighting the tram. **Rationale:** An LRT door temporarily not closing properly at a stop may require that the driver: 1. Notices the problem 2. Identifies where the problem is 3. Tries to mitigate it (probably trying to open all doors, and then closing again). 4. Resume the trip. This may provoke a delay in the departure times.	Yes	No	No	No	23000	0.15
		To ensure passengers alight where and when it is safe to.	RST02	Door opens whilst tram is moving. **Rationale**: This failure will activate the door interlock resulting in the initiation of an emergency brake application (unscheduled stop) affecting the average commercial speed and departure time of the following trams.	Yes	Yes	No	Yes	23000	0.25
		To allow passengers to move along the interior of the entire tram.	RST03	Loss of mechanical integrity. **Rationale:** May result in a partially fall of its components.	Yes	Yes	Yes	Yes	750000	1

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Rolling Stock	Couplers	To provide mechanical and electrical connection between cars.	RST04	Loss of mechanical integrity or electrical continuity. **Rationale:** May result in an emergency brake application (unscheduled stop) or prevent a brake application from being released (i.e. Affects Departures Time). As a result, commercial speed can be affected and evacuation of train may be done.	Yes	Yes	Yes	Yes	2000000	2.5
	Running gear, Bogies & Suspension system	To limit train movement damaging the track	RST05	Fails to limit train movement from damaging track. **Rationale**: The tram is operated at reduce speed (reduced Commercial Speed) until it can be removed from service. The following trams may experience delays on departure times.	Yes	Yes	No	No	230000	0.7
		To provide a comfortable ride for passengers	RST06	The tram gives a poor ride comfort. **Rationale**: The tram is operated at reduce speed (reduced Commercial Speed) until it can be removed from service. The following trams may experience delays on departure times.	Yes	Yes	No	No	230000	0.7
	Propulsion System	To provide control for acceleration and deceleration	RST07	Reduced performance. **Rationale**: A degradation of the rate of acceleration and/or maximum speed may reduce commercial speed. The following trams may experience delays on departure times.	Yes	Yes	No	No	90000	8
			RST08	Propulsion system failure. **Rationale**: Failure results in train stopping between stops (Unscheduled Stop). If the failure occurs at a Stop, it may also affect departure times, and reduce commercial speed.	Yes	Yes	No	Yes	90000	8
	Brakes	To provide speed in order to ensure that a tram can be stopped properly.	RST09	Reduction or loss of brake effectiveness. **Rationale**: This failure will result in an emergency brake application by the driver or the ATP system.	Yes	Yes	No	Yes	46000	0.9

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Rolling Stock	Train control and communications equipment.	Train control network shall connect all the train equipment.	RST10	Loss of communication between the train equipment (traction, brake, on-board signalling equipment, etc.). **Rationale:** It may affect commercial speed (traction communication failure), departure times and may provoke unscheduled stops (if emergency brake is activated).	Yes	Yes	No	Yes	150000	0.9
	Electrical and Electronic equipment	Auxiliary Power Unit (APU) used to convert power from the catenary into supplies required for the operation of auxiliary systems	RST11	Failure to supply auxiliary systems. Loss of Heating, Ventilation and Air Conditioning (HVAC) functionality. Batteries provide emergency lighting and enables doors to continue to operate. **Rationale:** If batteries fail, doors will not operate; hence a train evacuation will take place.	No	No	Yes	No	50000	3
		Power collector allows electrical energy to be drawn from catenary power to supply the electrical system on the vehicle.	RST12	Loss of pantograph. **Rationale:** Loss of pantograph may result in inability to move away from a location where it has stopped (in a stop or between stops). This results in a Train Evacuation.	No	No	Yes	No	90000	0.45
	General	Rolling Stock failure requiring technician to recover the tram	RST13	Exceptional failure in which it is impossible to continue the service without the assistance of a technician to recover the failed tram. **Rationale:** Train evacuation will take place in this situation, in addition to the affectation of unscheduled stops due to that exceptional failure.	No	No	Yes	Yes	30000	2
	Heating, Ventilation and Air Conditioning (HVAC)	Maintains passenger compartment temperature within comfort limits	RST14	Failure of one or more HVAC units requires passengers to be detrained and the train taken out of service due the challenging climate conditions **Rationale**: HVAC failure provokes that compartment temperature exceeds the specified comfort values; hence it affects the Train Evacuation.	No	No	Yes	No	100000	1

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Rolling Stock	Fire Detection and Alarm	Fire Detection and Alarm	RST15	Failure of vehicle Fire and Life Safety (F&LS) system gives a false fire alarm. **Rationale:** Activation of a fire alarm will cause the driver to stop the tram, therefore affecting PIUS, and probably evacuate the tram therefore affecting PITE.	No	No	Yes	Yes	100000	1
Operations Control Centre (OCC)	Operational Staff	Traffic Operator	OCC01	Incorrect Operation or Sabotage. **Rationale:** Even though this failure would impact on any of the four performance indicators, this event is out of the scope of RAM analyses (See section 3.3 - Human error/Sabotage)	Yes	Yes	Yes	Yes	26280	0.25
	Building	OCC Building	OCC02	Damage resulting from terrorism or other deliberate external factor. **Rationale:** Even though this failure would impact on any of the four performance indicators, this event is out of the scope of RAM analyses (See section 3.3)	Yes	Yes	Yes	Yes	175200	4
Signalling	Rail signalling	Detect and provide tram position	SIG01	Unable to detect trains due to a failure on a tram detection device (Wayside Axle counters). **Rationale**: Unable to set routes for a line section requiring the suspension of services on the affected line section. This failure can result in unscheduled stops. Suspension of services on a line section will impact on departure times with the affected section.	Yes	No	No	Yes	500000	2
			SIG02	Unable to detect switch position. **Rationale:** Unable to detect switch position which will need the driver or other agent actuation (affecting commercial speed).	No	Yes	No	No	500000	2
			SIG03	Train detected in a track section where there is no LRT. **Rationale:** This failure will provoke that trams will not be allowed to depart from a Stop; hence it will affect departure times.	Yes	No	No	No	500000	2

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Signalling	Rail signalling	Protect system against incompatible routes	SIG04	Unable to switch point machine (failure of interlocking). **Rationale:** This failure will result in a train evacuation. Inability to remotely operate switch machines may affect commercial speed.	No	Yes	Yes	No	500000	2
		Manage Shunting Signals	SIG05	Failure of the interlocking. **Rationale:** This failure will result in an unscheduled stop and hence a possible LRT evacuation if it cannot be repaired.	No	No	Yes	Yes	500000	2
			SIG06	Permissive aspect is displayed. Trains have permissive when they should not. (Failure of interlocking). **Rationale:** Signal passed at danger may provoke collisions and hence train evacuations.	No	No	Yes	No	500000	2
		Manage Shunting Signals	SIG07	Non permissive aspect is displayed. Trains do not have permissive when they should. (Failure of interlocking) **Rationale:** Trains may be stuck on Stops affecting departure times. It may also provoke an unscheduled stop, due to a non-permissive aspect of a wayside signal.	Yes	No	No	Yes	500000	2
			SIG08	Proceed aspect is displayed. Trains have permissive when they should not (Failure of a signal) **Rationale:** Unnoticed signal passed at danger may lead to a collision with a subsequent train evacuation. Commercial speed may also be affected.	No	Yes	Yes	No	500000	2

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Signalling	Rail signalling	Manage Point Machines (Switches)	SIG09	Incorrect point machine position monitoring. Uncontrolled routes of LRT. **Rationale:** Inability to remotely operate switch machines may affect Train Departures. Inability to detect wayside equipment may affect Commercial Speed.	Yes	Yes	No	No	500000	2
			SIG10	Position of point machine is not controlled. LRT moves to an incorrect track section **Rationale:** Inability to remotely operate switch machines may affect Train Departures. Inability to detect wayside equipment may affect Commercial Speed.	Yes	Yes	No	No	500000	2
			SIG11	Possible LRT movement to an incorrect track section. **Rationale**: This failure may prevent trains from departing from Stop, therefore affecting departure times. Inability to detect wayside equipment may affect Commercial Speed.	Yes	Yes	No	No	500000	2
	Traffic Lights	Degraded mode operation (interlocking manual operation)	SIG12	Manual operation of interlocking is not available. System inoperative. **Rationale**: As the system is inoperative, the driver will have to run on sight until the next stop. That means that the commercial speed would be diminished and that will provoke a delay on next departure times.	Yes	Yes	No	No	15000	1
			SIG13	Proceed command is sent both for road vehicles and for LRT. LRT during normal operation and road vehicles move to an intersection. **Rationale**: This failure provokes a reduction of commercial speed due to the degraded mode operation and hence, a delay on the departure times. The tram does not stop at all, so it does not generate an unscheduled stop.	Yes	Yes	No	No	15000	1

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Signalling	Traffic Lights	Manage signalling of Tram-Road intersections	SIG14	Stop command sent to LRT. LRT must stop at intersection. **Rationale**: This command has to be respected by the driver, who will stop the tram until next orders; hence it also affects departure times for next trams.	Yes	No	No	Yes	15000	1
		Coordinate Road traffic lights	SIG15	Permissive aspect is displayed. Road vehicles/pedestrians have permissive when they should not. (Failure of traffic regulator). **Rationale**: This failure provokes a reduction of commercial speed due to a potential collision and hence, a delay on the departure times. The tram does not stop at all, so it does not generate an unscheduled stop.	Yes	Yes	No	No	15000	1
			SIG16	Non permissive aspect is displayed. Road vehicles/pedestrians do not have permissive when they should. (Failure of traffic regulator). **Rationale**: Although it does not affect directly to tram, a potential collision will appear if vehicles/pedestrian do not respect its road traffic lights due to the failure of the traffic regulator. Hence, tram speed would be diminished and departures times affected.	Yes	Yes	No	No	15000	1
Automatic Fare Collection (AFC)	Automatic Fare Collection (AFC)	Validation functionality	AFC01	Failure of one validator machine (either check-in or check-out). Passengers need to use an alternative validator. **Rationale**: Departure times will be affected if passengers cannot validate tickets and have to wait for another machine to validate it.	Yes	No	No	No	100000	1
			AFC02	Failure of all validators or the concentrator (either check-in or check-out). Passengers cannot validate their tickets. **Rationale**: Departure times will be affected if passengers cannot validate their tickets.	Yes	No	No	No	130000	1

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Fire & Life Safety	Fire Extinguishing	Extinguish the fire	FLS01	Fire extinguisher system fails to extinguish fire in substations or technical rooms. **Rationale**: If a substation fails as a consequence of fire, it may affect the power fed into the catenary, and hence the commercial speed may be affected.	No	Yes	No	No	10000	1
			FLS02	Fire extinguisher system fails to extinguish fire in stops. **Rationale:** A fire in a Stop may affect departure times, as the Stop could be closed to passengers, or passengers may be distracted/panic by the fire and difficult the boarding/alighting.	Yes	No	No	No	10000	1
Trackworks	Rail	Provides physical support and guidance to the vehicle	TRK01	Manufacturing defects or defective mounting of rails. **Rationale:** These defects will wear and tear due to cycling loading, which may affect commercial speed.	No	Yes	No	No	$2{,}08\cdot10^{6}$	1.5
			TRK02	Fracture in rail due to fatigue and stress cracking. **Rationale:** This may have an effect on any of the four KPIs, as failure in the rail has a direct impact on all aspects of service.	Yes	Yes	Yes	Yes	236000	4
			TRK03	Resonance and excessive rail stresses **Rationale:** Resonance and excessive rail stresses due to rail corrugation on the running surface of the rail may lead to a reduced commercial speed.	No	Yes	No	No	$2{,}08\cdot10^{6}$	1.5

Rail systems	Subsystem	Description	Failure Mode Code	Failure Description	Key Performance Indicator (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Trackworks	Fasteners	To fasten the rail to the track structure	TRK04	Fasteners inadequately fixed during construction or maintenance. **Rationale**: This wear and tear on rails affecting by slight vertical and horizontal movements of rails, therefore affecting commercial speed.	No	Yes	No	No	$2{,}08 \cdot 10^{6}$	0.15
	Gauge	Track gauge allows the vehicle to be operated on the track.	TRK05	Failure in track gauge due to defective mounting and implementation. **Rationale:** May affect commercial speed due to excessive forces on wheels, bogies.	No	Yes	No	No	$1{,}52 \cdot 10^{6}$	1.5

Table 7 Failure Mode and Effects Criticality Analysis (FMECA) for LRT System

6.4. Sensitive Analysis on Key Performance Indicators

The Service Availability is defined as a series (i.e. multiplication) of several factors or Key Performance Indicators, so that a variation in a single Key Performance Indicator provokes the Service Availability to decrease (see section 4.2). The required SA is 99.8%; consequently if a single Key Performance Indicator is reduced by more than 0.2%, the system will fail to meet the required SA.

It must be noted however, that the SA is obtained by multiplying not binary factors (i.e. Key Performance Indicators are not binary). This provokes that, without the proper justification, the SA cannot be modelled using reliability modelling tools usually used in reliability analysis (e.g. FTA) since these can only be used to model binary events[6]. Giving the proper justification for this is therefore of prime importance in order to permit and underpin the use of FTAs in this report.

The purpose of this section is hence twofold;

- firstly, to study how many and what type of failures provoke that the KPIs decrease by the aforementioned 0.2%, and
- secondly, and more importantly, to demonstrate that the event "failure to meet 99.8%" for each Key Performance Indicator can be considered (i.e. safely approximated by) a binary event[7] (i.e. any failure makes the Key Performance Indicators go below the 99.8% barrier).

In light of the above discussion, the impact of each Key Performance Indicators on the Trip Achievement Level is analysed in the following sections.

[6] It can be demonstrated by how Availability is usually measured: A = MUT / (MDT+ MUT), see for instance [15]. That is, we need to measure, at a specific instant of time, whether the system is either 100% Up (MUT) or 100% Down (MDT). It is not correct (and could not be taken into account in the above formula) to have the system 80% Up (or, alternatively, 20% Down), which is otherwise allowed by the definition of SA (for instance in the case of all factors in TAL equal to 1, except IPCS, being, for example, 0.9 - 90% of the scheduled commercial speed). Then the system would be "90% Up".

[7] Following from the previous example, if very small variations of the commercial speed (e.g. 1 km/h) brings the SA below the required 99.8% we may safely approximate it as a binary event (i.e. "any" failure to meet the commercial speed affects the service availability) and therefore the use of FTAs would be allowed. This rationale also holds for the other Performance Indicators.

6.4.1. Impact of PIDT on the Service Availability

$PIDT$ has been defined in section 4.2.1 as:

$$PIDT = \frac{NSDT - ADT}{NSDT - SDT} \tag{9}$$

for the first scheduled trip of the operating day, and

$$PIDT = \frac{SDT - PSDT}{ADT - PADT} \tag{10}$$

for the rest of scheduled trips, where:

- SDT is the departure time of the considered scheduled trip.
- $PSDT$ is the departure time of the previous scheduled trip.
- $NSDT$ is the departure time of the next scheduled trip.
- ADT is the departure time of the actual trip that is linked to the considered scheduled trip.
- $PADT$ is the departure time of the actual trip that departed before the actual trip that is linked to the considered scheduled trip.

Assuming that the previous actual trip departed on time (i.e. $PADT \approx PSDT$), the Performance Indicator can be approximated by (see Figure 14):

$$PIDT_{First\ scheduled\ trip} = \frac{NSDT - ADT}{NSDT - SDT} = \frac{NSDT\ -\ SDT\ -\ Delay}{Current\ headway} = \frac{Current\ headway\ \text{-}\ Delay}{Current\ headway} \tag{11}$$

$$PIDT_{Rest\ of\ scheduled\ trips} = \frac{SDT - PSDT}{ADT - PADT} \approx \frac{Previous\ headway}{ADT - PSDT} = \frac{Previous\ headway}{Previous\ Headway + Delay} \tag{12}$$

This is shown graphically in Figure 14:

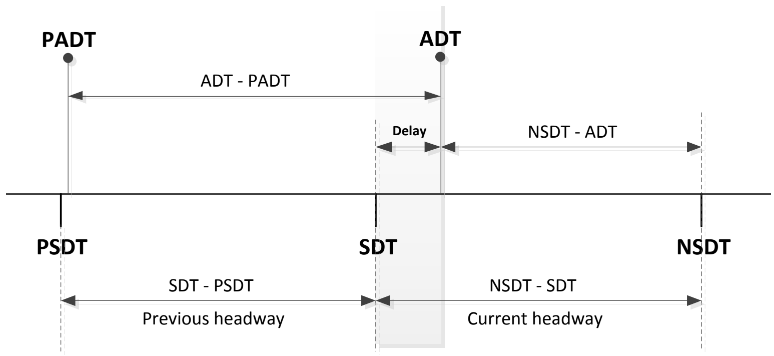

Figure 14 Departure times for scheduled trips

Taking into account that during peak periods[8], the headway shall not exceed 3 minutes (worst case), and during off-peak periods, the headway shall not exceed 6 minutes in the worst case (see 0), the effect of the delay on the quality factor, and hence on the overall Service Availability can be calculated. Additionally, the LRT lines shall be capable of operating shorter headways of 2 minutes. Both tables have been created to present typical LRT headways for this Study.

LRT HEADWAYS – WINTER (units are minutes)			
Hour	**Labour day**	**Friday**	**Saturday**
5 to 6	**9**	**15**	**9**
6 to 7	**6**	**10**	**6**
7 to 10	**3**	**6**	**5**
10 to 14	**8**	**6**	**8**
14 to 19	**3**	**6**	**5**
19 to 00	**8**	**10**	**8**
			Peak hours

LRT HEADWAYS – SUMMER (units are minutes)			
Hour	**Labour day**	**Friday**	**Saturday**
5 to 6	**9**	**15**	**9**
6 to 7	**6**	**10**	**6**
7 to 10	**3**	**7**	**5**
10 to 14	**8**	**7**	**8**
14 to 19	**3**	**7**	**5**
19 to 00	**8**	**10**	**8**
			Peak hours

Table 8   LRT headways (in minutes) for L1 and L2

The effect of the several headways on the Performance Indicator of Departure Times is shown in Figure 15.

[8] The morning peak period starts at 7:00 and ends at 10:00. The evening peak period starts at 14:00 and ends at 19:00. LRT timetables have been provided in order to provide an example to the Study.

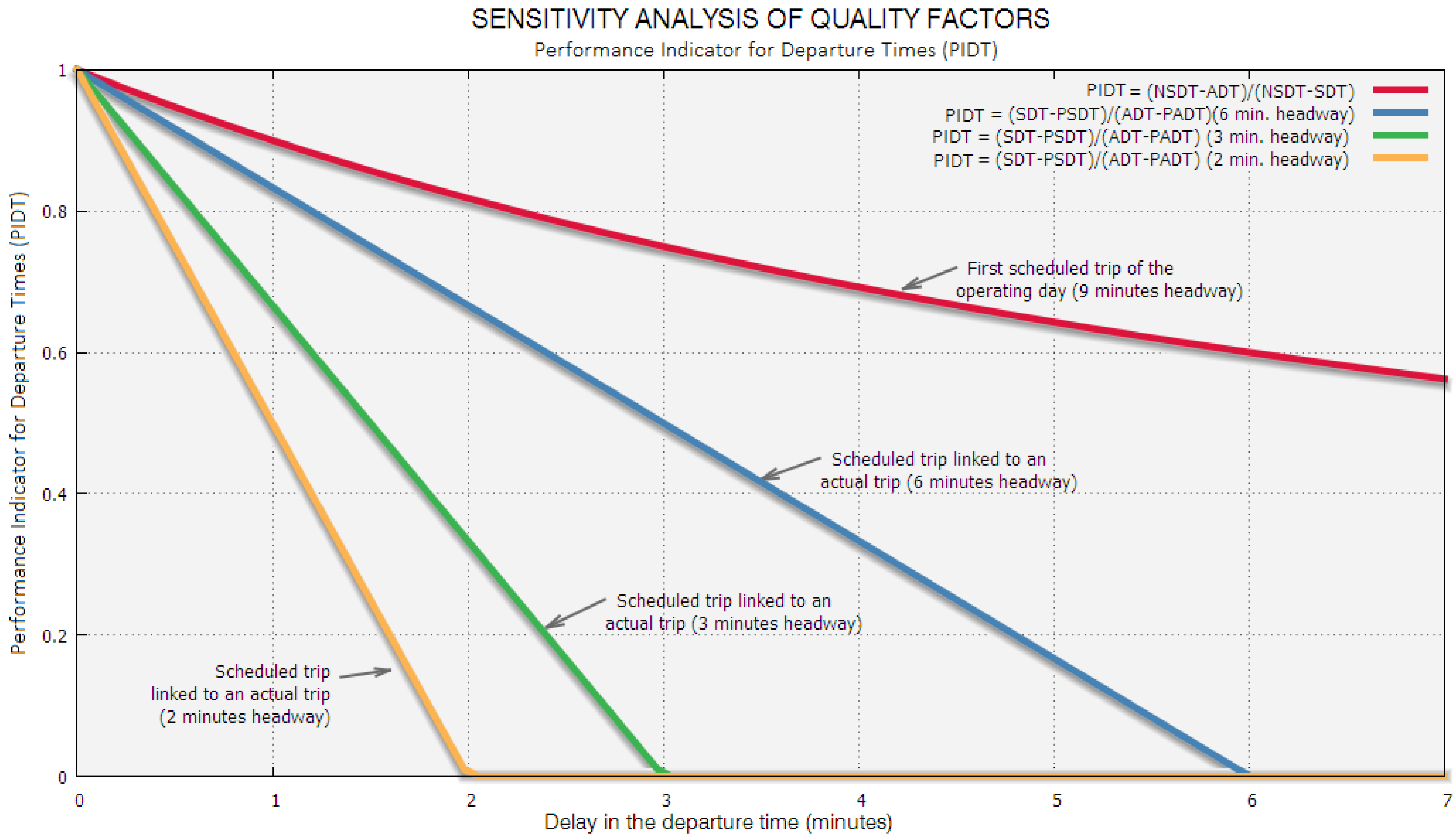

Figure 15 Impact of the PIDT on the Trip Achievement Level

Figure 15 shows that the effect of a delay in the departure time is much more important with a reduced headway, as it is used in the formula as a reference to measure relative deviation. The first scheduled trip of the day is the least affected by a delay.

To put this in context, it must be calculated the amount of delay necessary such that the Performance Indicator is reduced by 0.2%:

- PIDT = 99.8% → Delay = 1.08 seconds (off-peak hours, 9 minutes headway)
- PIDT = 99.8% → Delay = 0.72 seconds (off-peak hours, 6 minutes headway)
- PIDT = 99.8% → Delay = 0.36 seconds (peak hours, 3 minutes headway)
- PIDT = 99.8% → Delay = 0.24 seconds (peak hours, 2 minutes headway)

In summary, it can be safely stated that any practical delay in the departure time brings the Service Availability below the required 99.8% level.

With these conditions it can be stated that, for instance, if the service had a common delay of 5 minutes, the service would suffer a big decrease on the SA due to the reduction of the PIDT contribution.

Using equation (12), the Performance Indicator for Departure Times would become:

- Delay = 5 minutes → PIDT = 44.4% (off-peak hours, 9 minutes headway)
- Delay = 5 minutes → PIDT = 54.5% (off-peak hours, 6 minutes headway)
- Delay = 5 minutes → PIDT = 37.5% (peak hours, 3 minutes headway)
- Delay = 5 minutes → PIDT = 28.6% (peak hours, 2 minutes headway)

These PIDT values demonstrate that even if the SA was, for instance, 99%, the service availability would be highly lower due to the delay on the departure. Appendix V: Impact of the PIDT for Different Delay Times shows PIDT[9] affectation.

[9] It is a double entry table. At the top there are the tens, which shall be selected in order to have its contribution with the corresponding unit value (leftmost column) for each cell.

6.4.2. Impact of PICS on the Service Availability

PICS has been defined in section 4.2.2 as

$$PICS = 1 \ \ if \ \ \frac{Actual\ Commercial\ Speed}{Scheduled\ Commercial\ Speed} > 1$$
$$otherwise \ \ PICS = \frac{Actual\ Commercial\ Speed}{Scheduled\ Commercial\ Speed} \tag{13}$$

The measurement period is from the close door command at the first scheduled stop until the door open command at the last scheduled stop.

Actual commercial speed is the average speed of the LRT. It can be shown that:

$$Actual\ Commercial\ Speed = \frac{L}{T} \tag{14}$$

where L is total length of the line, and T is the total trip time, which can be approximated by:

$$T = \sum_{i=1}^{N-1} \frac{L_i}{S_i} + \sum_{i=1}^{N-2} DT_i \tag{15}$$

where N is the number of stops of the line, L_i is the interval length between stations $i-1$ and i , S_i is the average speed between stations $i-1$ and i, and DT_i is the dwell time at station $i+1$. For the sake of simplicity it can be assumed an average speed equal for all intervals ($S_i = S_{avg}\ \forall i$), and a dwell time equal for all stations ($DT_i = DT_{avg}\ \forall i$), the actual commercial speed can be approximated by:

$$Actual\ Commercial\ Speed = \frac{L}{T} \approx \frac{L}{\frac{\sum_{i=1}^{N-1} L_i}{S_{avg}} + \sum_{i=1}^{N-2} DT_{avg}}$$
$$= \frac{L}{\frac{L}{S_{avg}} + (N-2)DT_{avg}} \tag{16}$$

S_{avg} is a value that needs to be calculated. The commercial speed for the whole trip has been set at least 20 km/h for L1 and L2, as it is a typical value for LRT Systems.

Using equation (16) it is possible to calculate the necessary S_{avg} between stations for each of the 2 lines. This is shown in Table 9, where dwell times have been calculated for the two lines (proposed in section 3.1) L1 and L2[10]:

Line	CS (km/h)	N	Length (km)	DT_{avg} (sec.)	S_{avg} (km/h)
1	20	24	15,12	20,8	**24.0**
2	20	21	11,80	21,4	**24.7**

Table 9 Average speed between LRT stops for L1 and L2 lines

Using equation (13) it is possible to calculate the effect (on the PICS for a specific line) of a reduction of the Actual Commercial Speed in each interval. This is shown in Figure 1 and Figure 17. Numerical values are provided in Table 10 and Table 11.

It must be noted that this Key Performance Indicator is dependent on the number of stations per line, and hence, will vary for L1 and L2 lines. Figure 1 and Figure 17 show that a decrease in the actual speed in the shorter intervals has less impact on the overall Service Availability as compared to longer intervals, where a decrease in the average speed has much more noticeable effect on the actual speed for the whole trip.

Also, the fewer number of stations a line has, the more it is affected by a decrease of the commercial speed. In general (except by the shorter intervals), it is apparent that in a majority of cases a decrease of just a few km/h in a specific interval (e.g. 1 to 2 km/h), affects the PICS by more than 0.2%, hence being unable to meet the required Service Availability of 99.8%.

Having a reduction of 1 or 2 km/h in the actual average speed between stops can therefore be safely considered as a binary event (i.e. any failure that provoke a decrease of the commercial speed, will make the system unable to reach the required SA).

[10] 20 sec. in regular stops and 30 sec. in stops with intermodal connectivity.

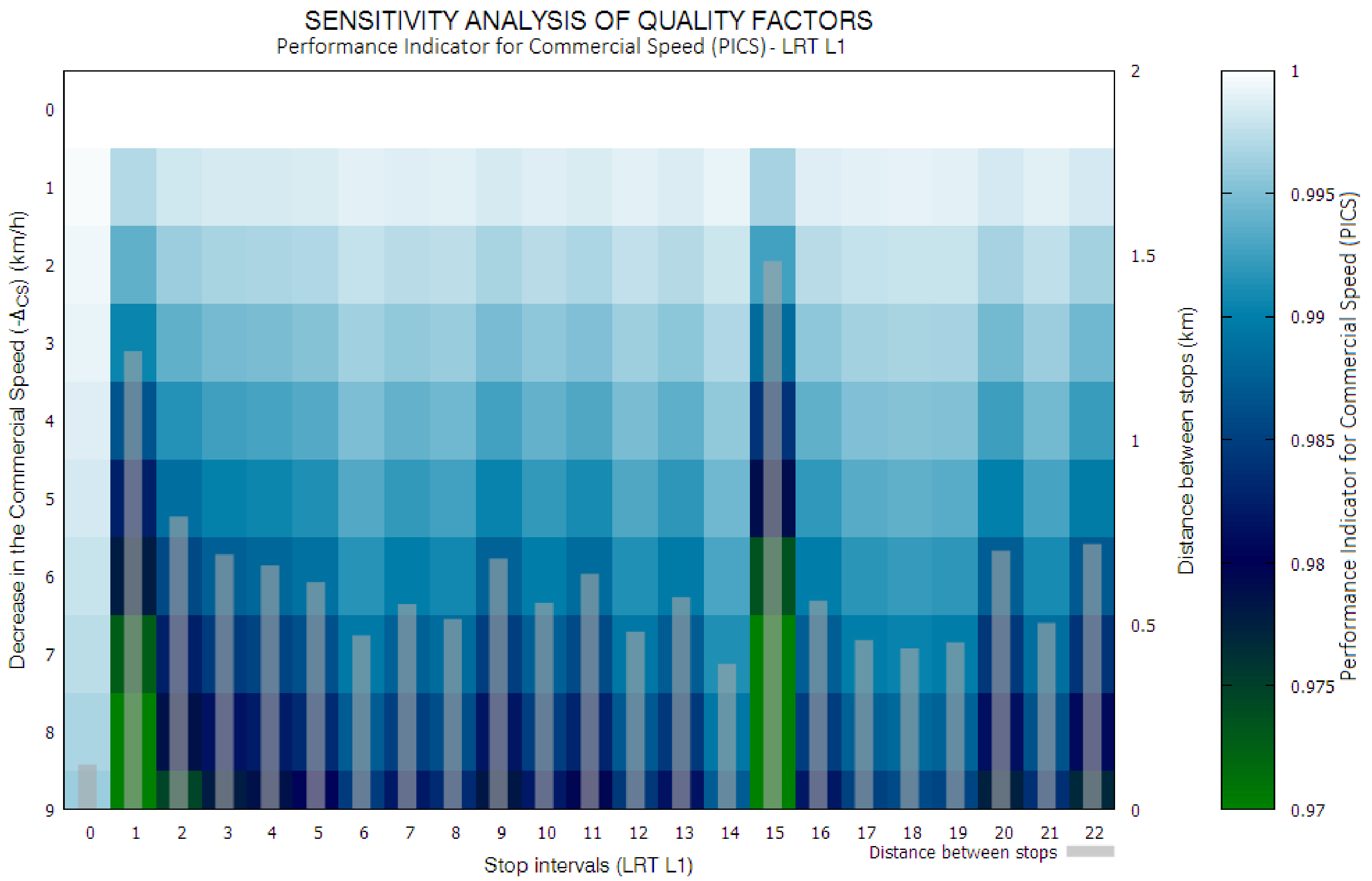

Figure 16 Impact of the PICS on the TAL of LRT L1 – with Gnuplot software

Performance Indicator for Commercial Speed (PICS) (LRT L1)												
			Decrease in the Commercial Speed (-ΔCS) (km/h)									
	Stop	St-to-St (m)	0	1	2	3	4	5	6	7	8	9
1	SL1001	120,0	1,0000	0,9997	0,9994	0,9991	0,9987	0,9983	0,9978	0,9973	0,9967	0,9961
2	SL1002	1240,0	1,0000	0,9970	0,9938	0,9904	0,9866	0,9824	0,9778	0,9727	0,9671	0,9608
3	SL1003	792,0	1,0000	0,9981	0,9961	0,9938	0,9914	0,9887	0,9857	0,9824	0,9787	0,9746
4	SL1004	689,5	1,0000	0,9984	0,9966	0,9946	0,9925	0,9901	0,9875	0,9847	0,9814	0,9778
5	SL1005	660,5	1,0000	0,9984	0,9967	0,9948	0,9928	0,9905	0,9881	0,9853	0,9822	0,9787
6	SL1006	615,0	1,0000	0,9985	0,9969	0,9952	0,9933	0,9912	0,9889	0,9863	0,9834	0,9802
7	SL1007	470,7	1,0000	0,9989	0,9977	0,9963	0,9949	0,9932	0,9915	0,9895	0,9872	0,9847
8	SL1008	555,2	1,0000	0,9987	0,9972	0,9957	0,9939	0,9920	0,9899	0,9876	0,9850	0,9820
9	SL1009	514,9	1,0000	0,9988	0,9974	0,9960	0,9944	0,9926	0,9907	0,9885	0,9861	0,9833
10	SL1010	678,4	1,0000	0,9984	0,9966	0,9947	0,9926	0,9903	0,9877	0,9849	0,9817	0,9782
11	SL1011	558,7	1,0000	0,9987	0,9972	0,9956	0,9939	0,9920	0,9899	0,9875	0,9849	0,9819
12	SL1012	636,9	1,0000	0,9985	0,9968	0,9950	0,9931	0,9909	0,9885	0,9858	0,9828	0,9795
13	SL1013	480,3	1,0000	0,9989	0,9976	0,9962	0,9948	0,9931	0,9913	0,9893	0,9870	0,9844
14	SL1014	574,6	1,0000	0,9986	0,9971	0,9955	0,9937	0,9918	0,9896	0,9872	0,9845	0,9814
15	SL1015	392,5	1,0000	0,9991	0,9980	0,9969	0,9957	0,9944	0,9929	0,9912	0,9893	0,9872
16	SL1016	1484,0	1,0000	0,9965	0,9926	0,9885	0,9840	0,9790	0,9736	0,9675	0,9609	0,9534
17	SL1017	564,0	1,0000	0,9987	0,9972	0,9956	0,9938	0,9919	0,9898	0,9874	0,9848	0,9818
18	SL1018	458,0	1,0000	0,9989	0,9977	0,9964	0,9950	0,9934	0,9917	0,9898	0,9876	0,9851
19	SL1019	434,8	1,0000	0,9990	0,9978	0,9966	0,9952	0,9938	0,9921	0,9903	0,9882	0,9859
20	SL1020	451,2	1,0000	0,9989	0,9978	0,9965	0,9951	0,9935	0,9918	0,9899	0,9878	0,9854
21	SL1021	699,9	1,0000	0,9983	0,9965	0,9945	0,9924	0,9900	0,9874	0,9844	0,9812	0,9775
22	SL1022	504,1	1,0000	0,9988	0,9975	0,9961	0,9945	0,9928	0,9909	0,9887	0,9864	0,9837
23	SL1023	718,0	1,0000	0,9983	0,9964	0,9944	0,9922	0,9897	0,9870	0,9840	0,9807	0,9769
24	SL1024	822,0	1,0000	0,9980	0,9959	0,9936	0,9911	0,9883	0,9852	0,9818	0,9779	0,9737

Table 10 Impact of the PICS on the TAL of LRT L1 (Numerical)

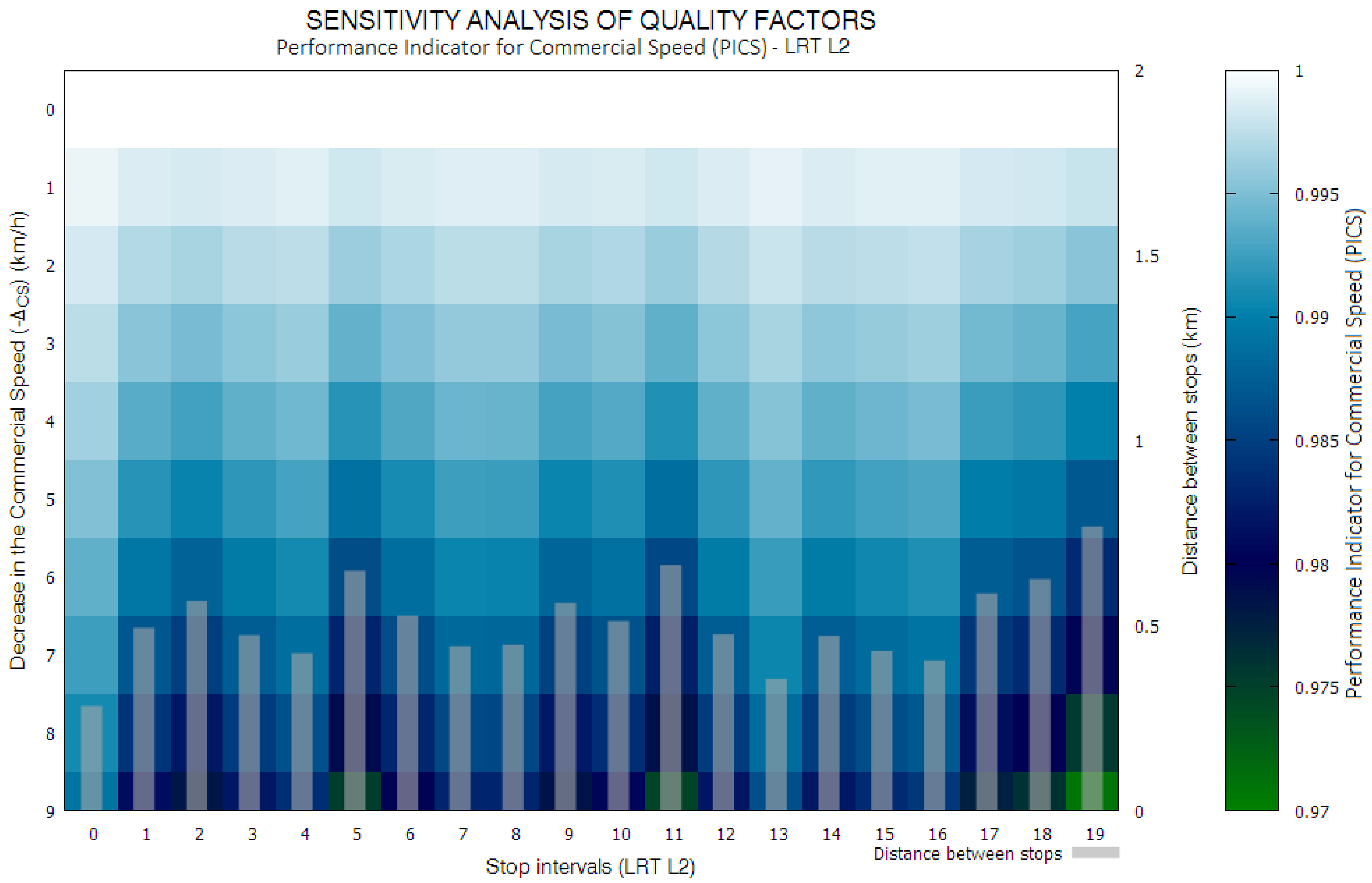

Figure 17 Impact of the PICS on the TAL of LRT L2 – with Gnuplot software

Performance Indicator for Commercial Speed (PICS) (LRT L2)												
			Decrease in the Commercial Speed (-ΔCS) (km/h)									
Station		St-to-St (m)	0	1	2	3	4	5	6	7	8	9
1	SL2001	282,0	1,0000	0,9992	0,9983	0,9973	0,9963	0,9951	0,9938	0,9924	0,9908	0,9891
2	SL2002	493,5	1,0000	0,9986	0,9970	0,9954	0,9935	0,9915	0,9893	0,9868	0,9841	0,9810
3	SL2003	566,4	1,0000	0,9984	0,9966	0,9947	0,9926	0,9903	0,9877	0,9849	0,9818	0,9783
4	SL2004	473,8	1,0000	0,9986	0,9972	0,9955	0,9938	0,9918	0,9897	0,9873	0,9847	0,9818
5	SL2005	425,4	1,0000	0,9988	0,9974	0,9960	0,9944	0,9927	0,9908	0,9886	0,9863	0,9836
6	SL2006	647,6	1,0000	0,9981	0,9961	0,9939	0,9915	0,9889	0,9860	0,9828	0,9792	0,9752
7	SL2007	526,6	1,0000	0,9985	0,9968	0,9950	0,9931	0,9909	0,9886	0,9860	0,9830	0,9798
8	SL2008	443,0	1,0000	0,9987	0,9973	0,9958	0,9942	0,9924	0,9904	0,9882	0,9857	0,9829
9	SL2009	447,0	1,0000	0,9987	0,9973	0,9958	0,9941	0,9923	0,9903	0,9881	0,9856	0,9828
10	SL2010	560,0	1,0000	0,9984	0,9966	0,9947	0,9927	0,9904	0,9879	0,9851	0,9820	0,9785
11	SL2011	511,1	1,0000	0,9985	0,9969	0,9952	0,9933	0,9912	0,9889	0,9864	0,9835	0,9804
12	SL2012	663,6	1,0000	0,9981	0,9960	0,9938	0,9913	0,9886	0,9856	0,9824	0,9787	0,9747
13	SL2013	475,7	1,0000	0,9986	0,9971	0,9955	0,9938	0,9918	0,9897	0,9873	0,9847	0,9817
14	SL2014	356,0	1,0000	0,9990	0,9979	0,9966	0,9953	0,9939	0,9922	0,9905	0,9885	0,9862
15	SL2015	472,0	1,0000	0,9986	0,9972	0,9956	0,9938	0,9919	0,9897	0,9874	0,9848	0,9818
16	SL2016	431,0	1,0000	0,9988	0,9974	0,9959	0,9943	0,9926	0,9906	0,9885	0,9861	0,9834
17	SL2017	405,3	1,0000	0,9988	0,9976	0,9962	0,9947	0,9930	0,9912	0,9892	0,9869	0,9844
18	SL2018	586,7	1,0000	0,9983	0,9965	0,9945	0,9923	0,9899	0,9873	0,9844	0,9811	0,9775
19	SL2019	624,7	1,0000	0,9982	0,9962	0,9941	0,9918	0,9893	0,9865	0,9834	0,9799	0,9761
20	SL2020	767,3	1,0000	0,9978	0,9954	0,9928	0,9900	0,9869	0,9834	0,9797	0,9755	0,9708
21	SL2021	1641,0	1,0000	0,9953	0,9902	0,9847	0,9788	0,9723	0,9652	0,9575	0,9490	0,9396

Table 11   Impact of the PICS on the TAL of LRT L2 (Numerical)

6.4.3. Impact of PITE on the Service Availability

$PITE$ is a binary quality criterion (if the train is evacuated between two stations during the trip, then $PITE = 0$ for the considered trip). No further analysis is needed to evaluate the impact of the PITE on the overall service availability.

6.4.4. Impact of PIUS on the Service Availability

$PIUS$ has been defined in section 4.2.4 as:

$$PIUS = 1 - 0.1 \times NUS - 0.2 \times NEB \tag{17}$$

Where:

- NUS is the number of unscheduled stops per trip.
- NEB is the number of emergency stops per trip.

The impact of the PIUS on the Trip Achievement Level is shown in Table 12 and Figure 18. This Key Performance Indicator is independent of the number of stops, and hence independent of the Line.

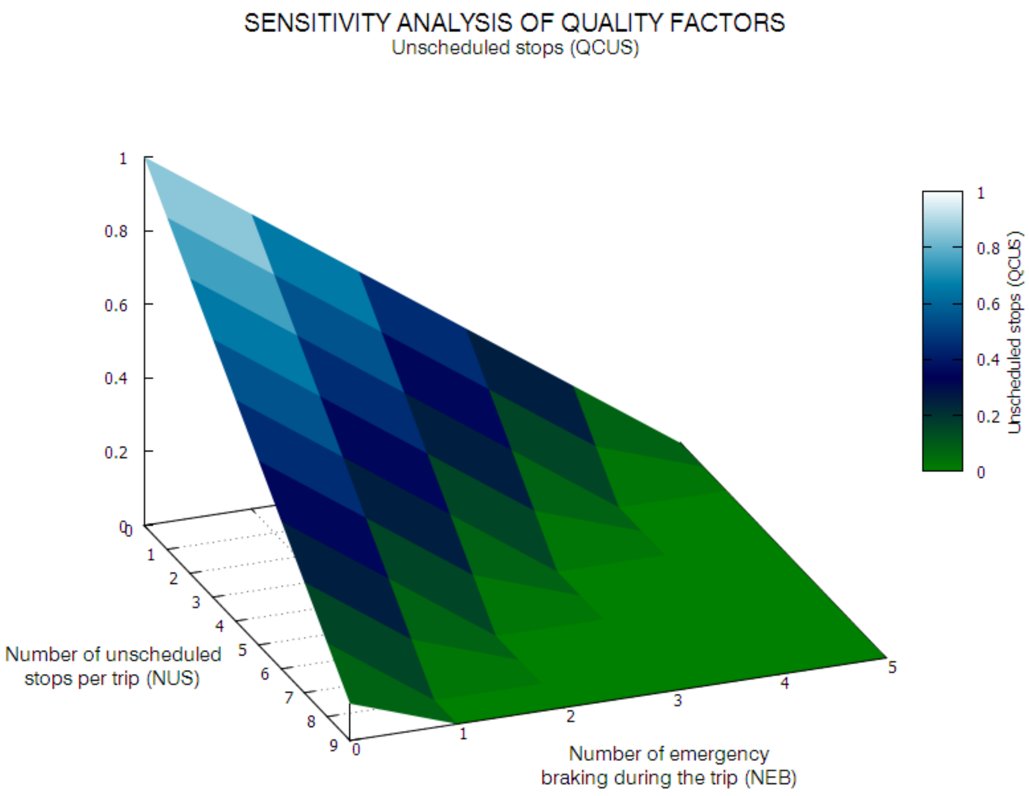

Figure 18 Impact of the PIUS on the Trip Achievement Level

Unscheduled Stops (PIUS)											
		Number of unscheduled stops per trip (NUS)									
		0	1	2	3	4	5	6	7	8	9
Number of emergency braking during the trip (NEB)	0	1,00	0,90	0,80	0,70	0,60	0,50	0,40	0,30	0,20	0,10
	1	0,80	0,70	0,60	0,50	0,40	0,30	0,20	0,10	0,00	0,00
	2	0,60	0,50	0,40	0,30	0,20	0,10	0,00	0,00	0,00	0,00
	3	0,40	0,30	0,20	0,10	0,00	0,00	0,00	0,00	0,00	0,00
	4	0,20	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 12 Impact of the PIUS on the Trip Achievement Level (Numerical)

It is shown that any unscheduled stop or emergency braking during the trip entails that the target Service Availability (99.8%) is not achieved, therefore PIUS can be considered a binary event.

6.5. Fault Tree Analysis

This section provides the complete Fault Tree Analysis Model developed for the Preliminary Engineering RAM allocation of a LRT System. The analysis has been quantified and kept in a subsystem level, according to the failure modes identified in section 6.3.

6.5.1. General Layout of the Service Availability Fault Tree

The following FTA describes the direct relationship between Service Availability (SA) and the different Key Performance Indicators. The Service Availability (SA) is defined as a series; therefore it will be affected by a decrease of any of the Key Performance Indicators.

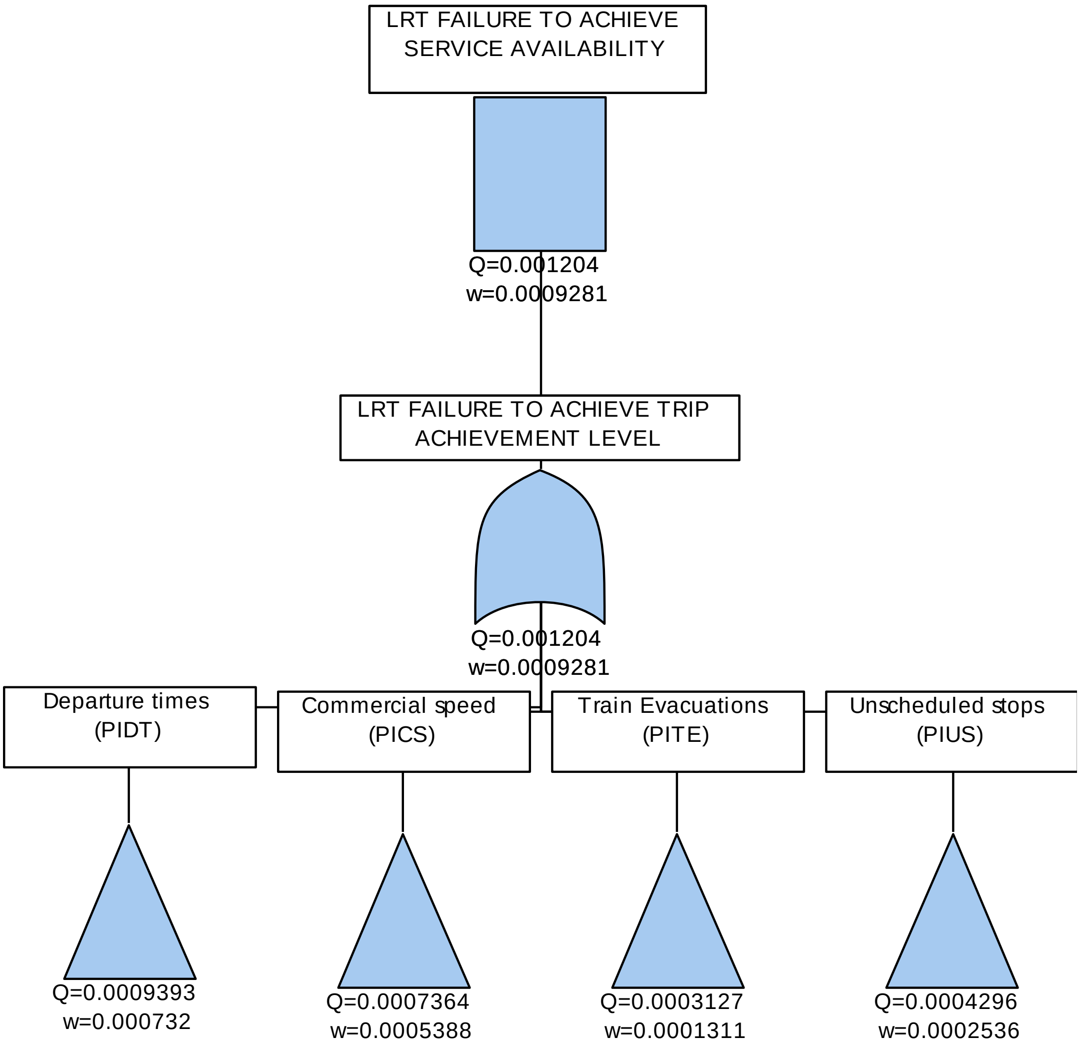

Figure 19 General Layout of the Service Availability Fault Tree

6.5.2. Key Performance Indicators Modelling Techniques

The following sub-sections develop the four Key Performance Indicators used in the previous section. The bottom events' code in the following Fault Trees are Failure Modes Codes taken from the FMECA (section 6.3 of this document).

6.5.2.1. PIDT: Departure Times

Quality Criteria for Departure Times is modelled as follows. *Q* (unavailability) and *MTTF* (Mean time to failure) are provided overleaf.

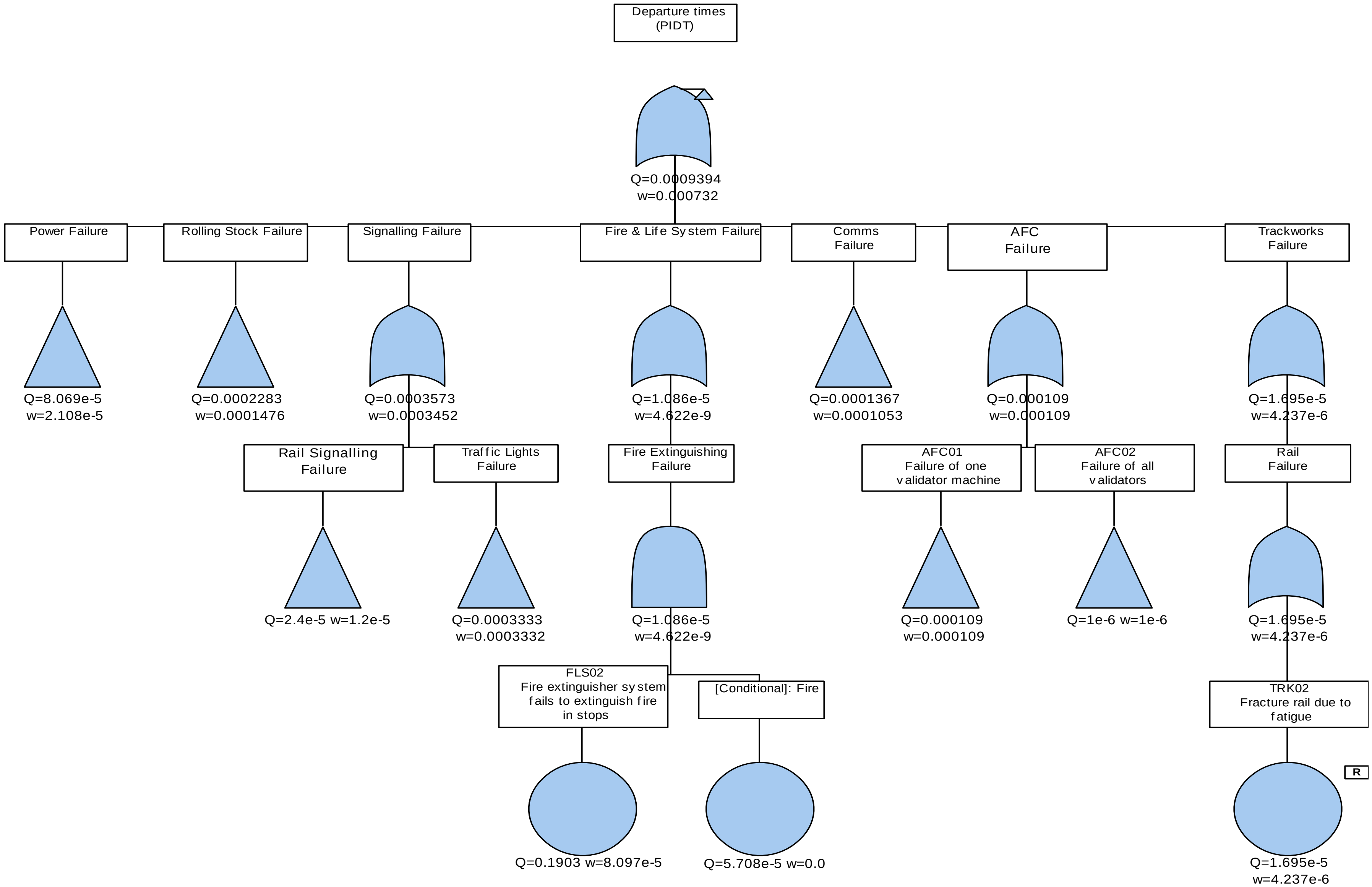

Figure 20 PIDT: Departure Times Fault Tree

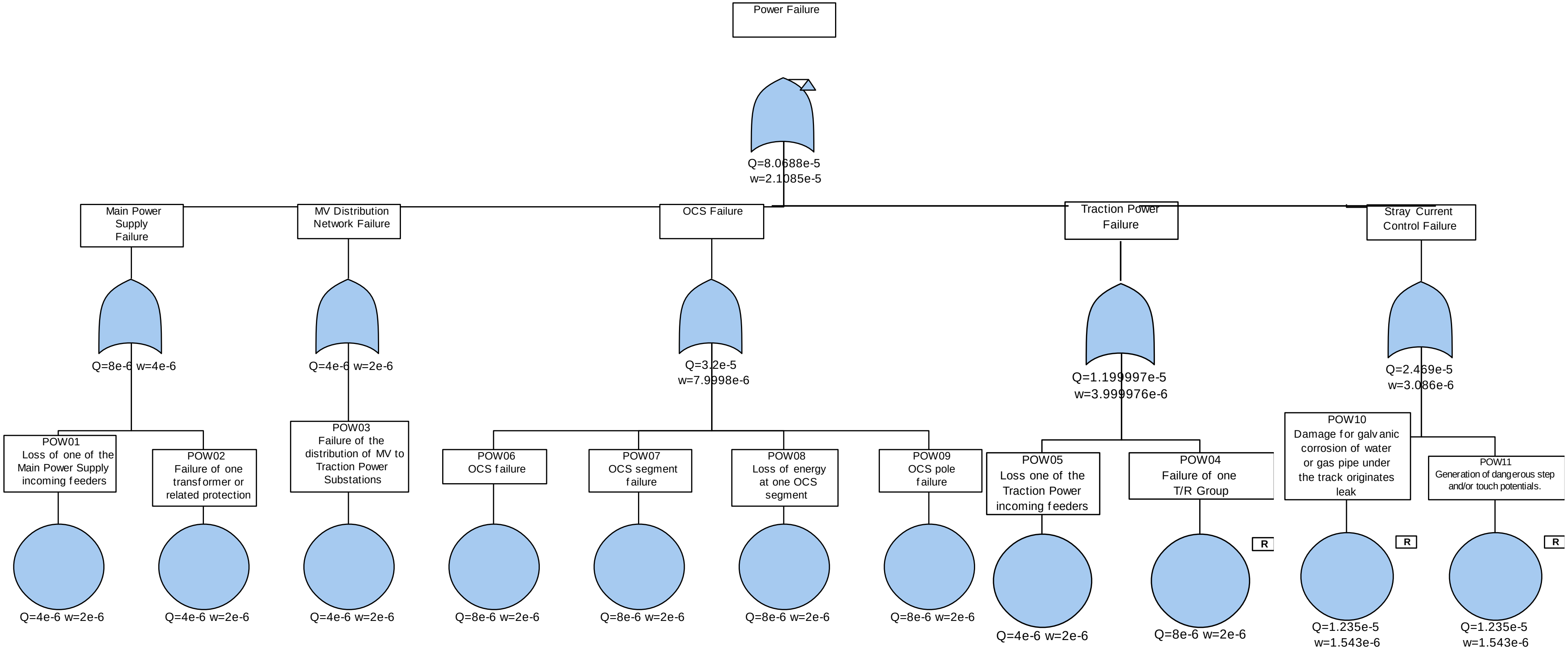

Figure 21 PIDT: Power Failure Fault Tree

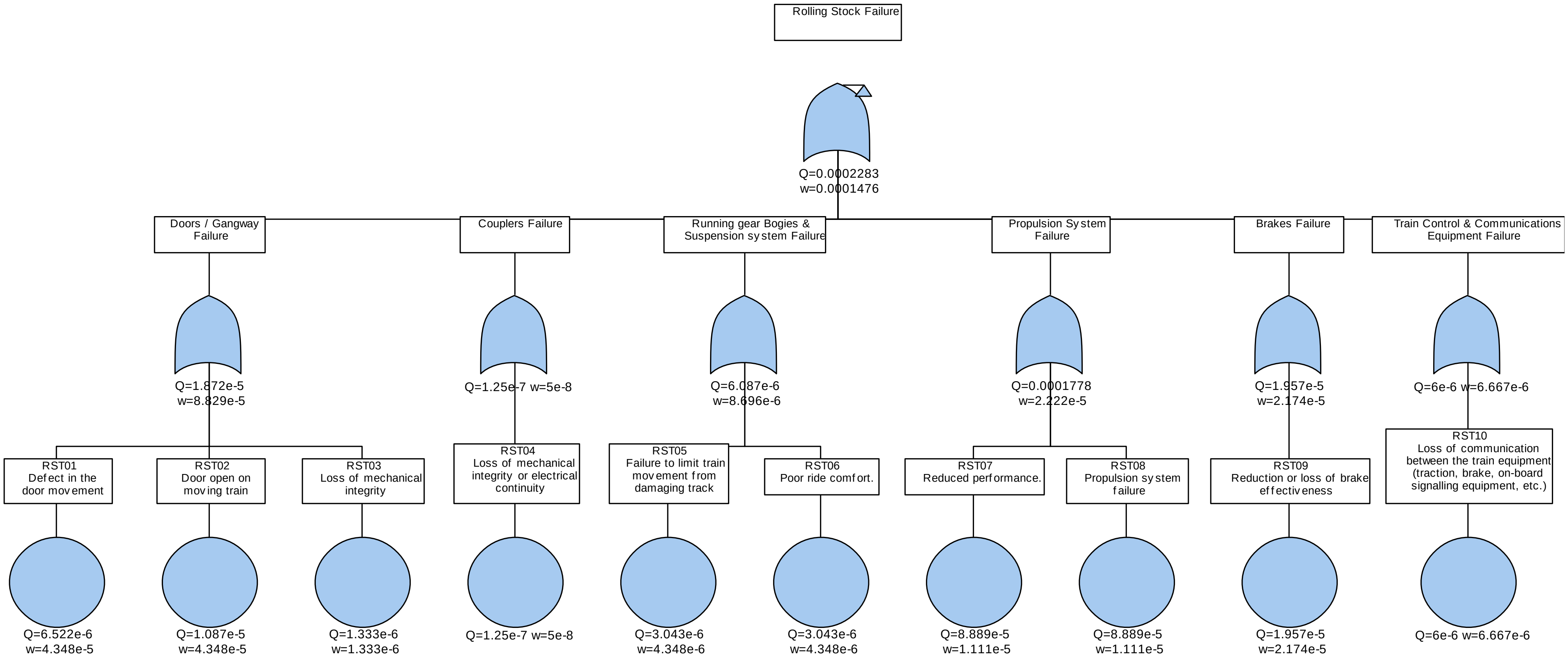

Figure 22 PIDT: Rolling Stock Failure Fault Tree

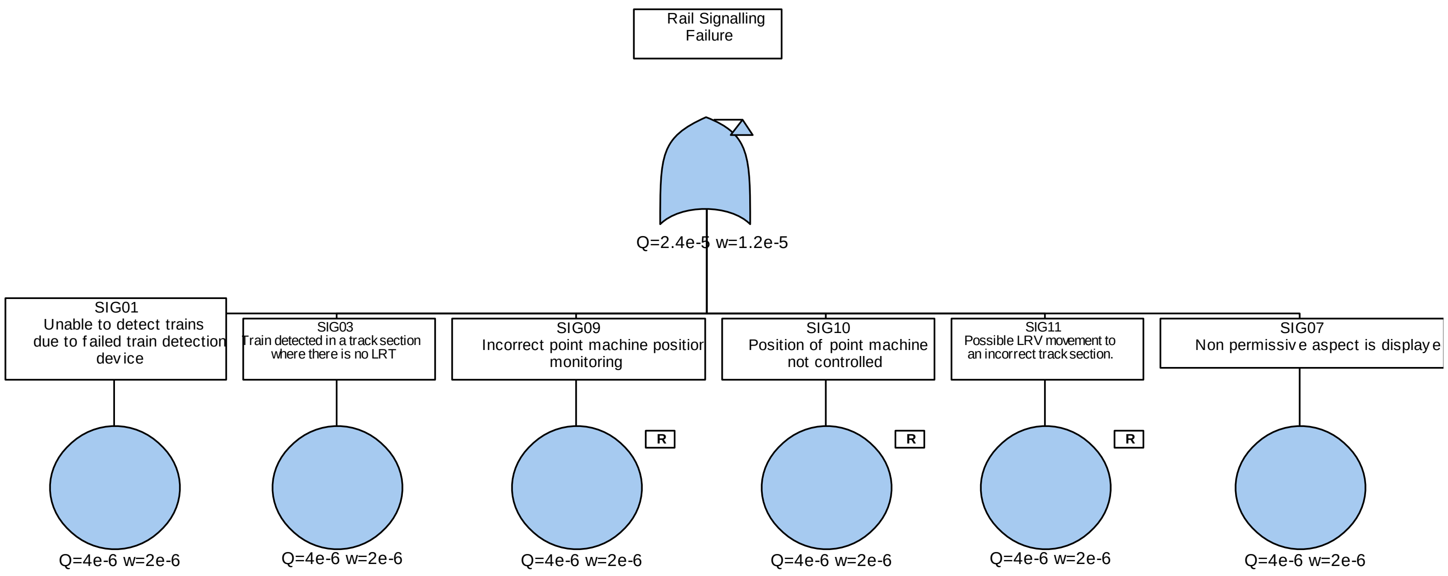

Figure 23 PIDT: Rail Signalling Failure Fault Tree

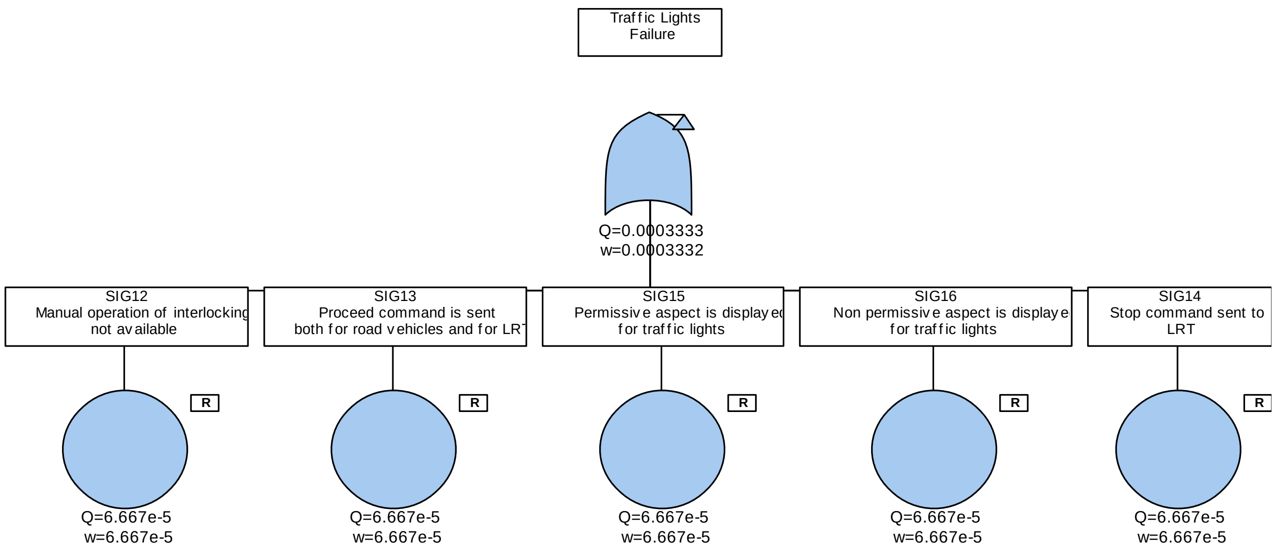

Figure 24 PIDT: Traffic Lights Failure Fault Tree

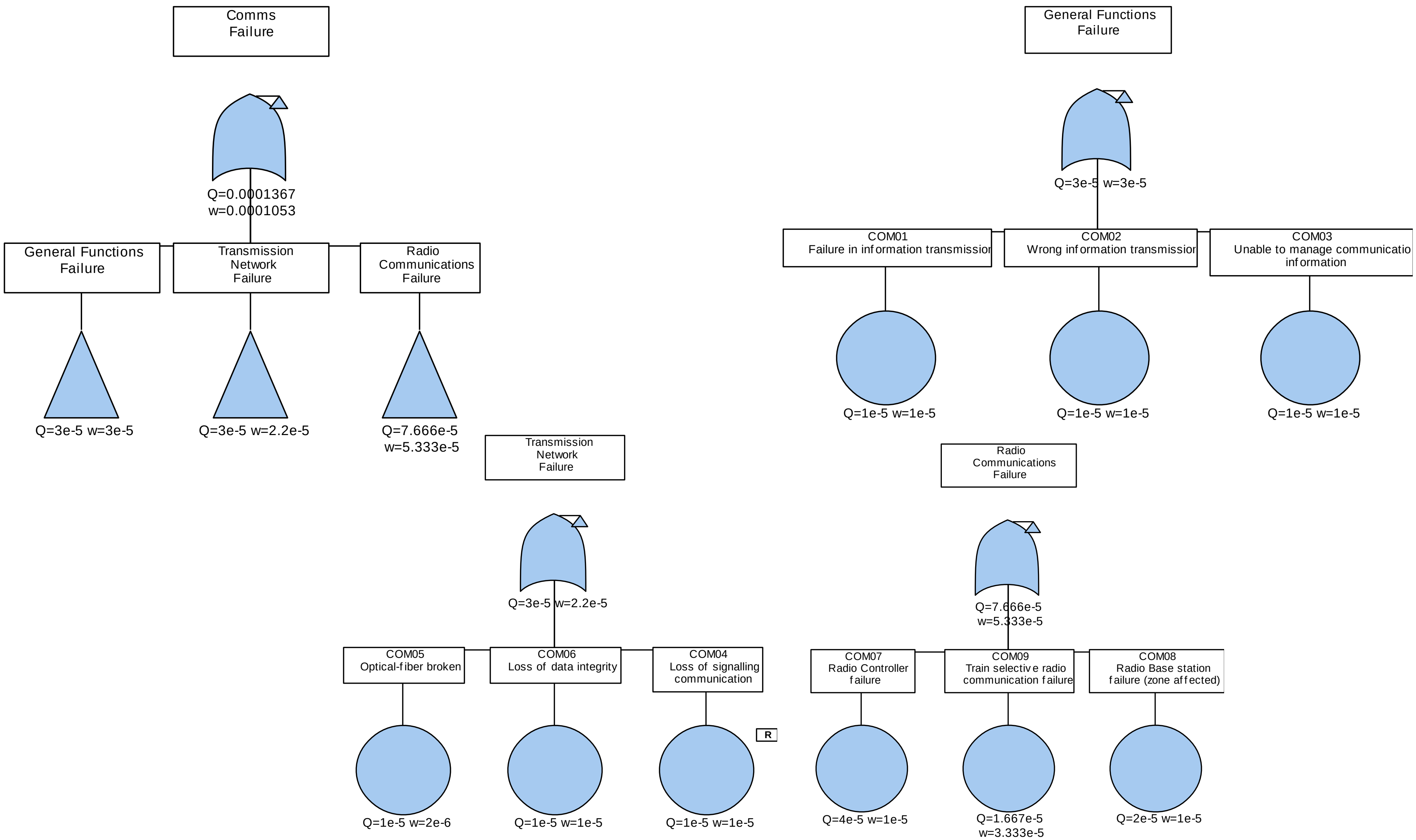

Figure 25 PIDT: Communications Failure Fault Tree

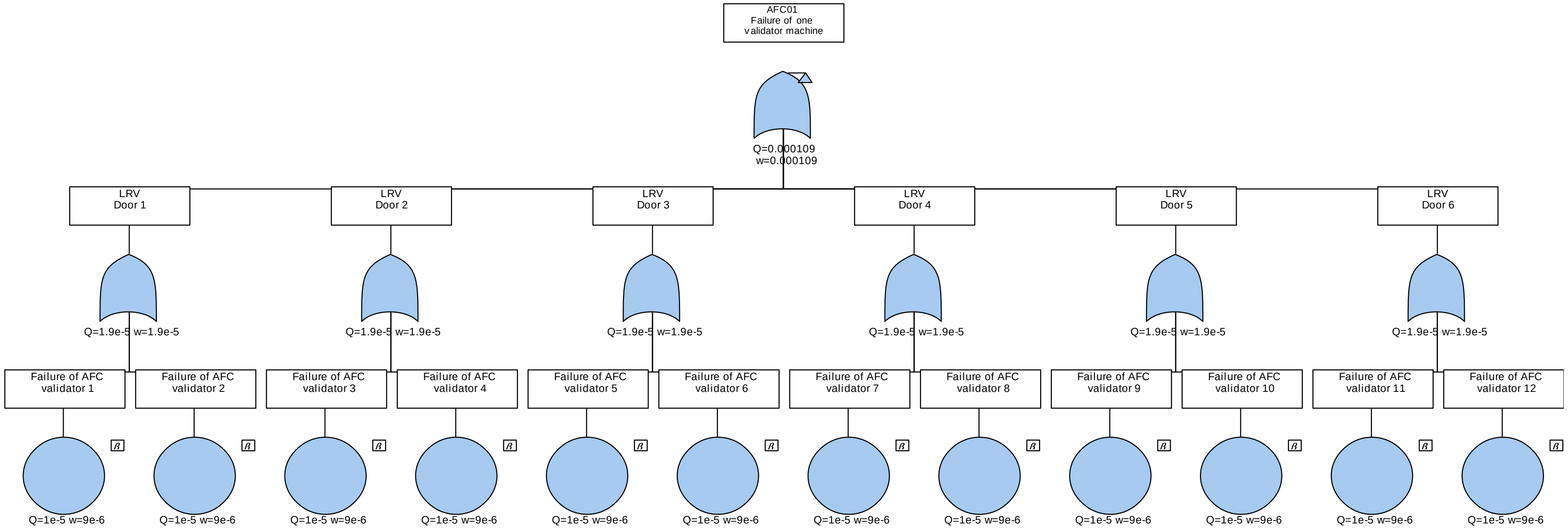

Figure 26 PIDT: AFC01 Failure of one validator machine Fault Tree

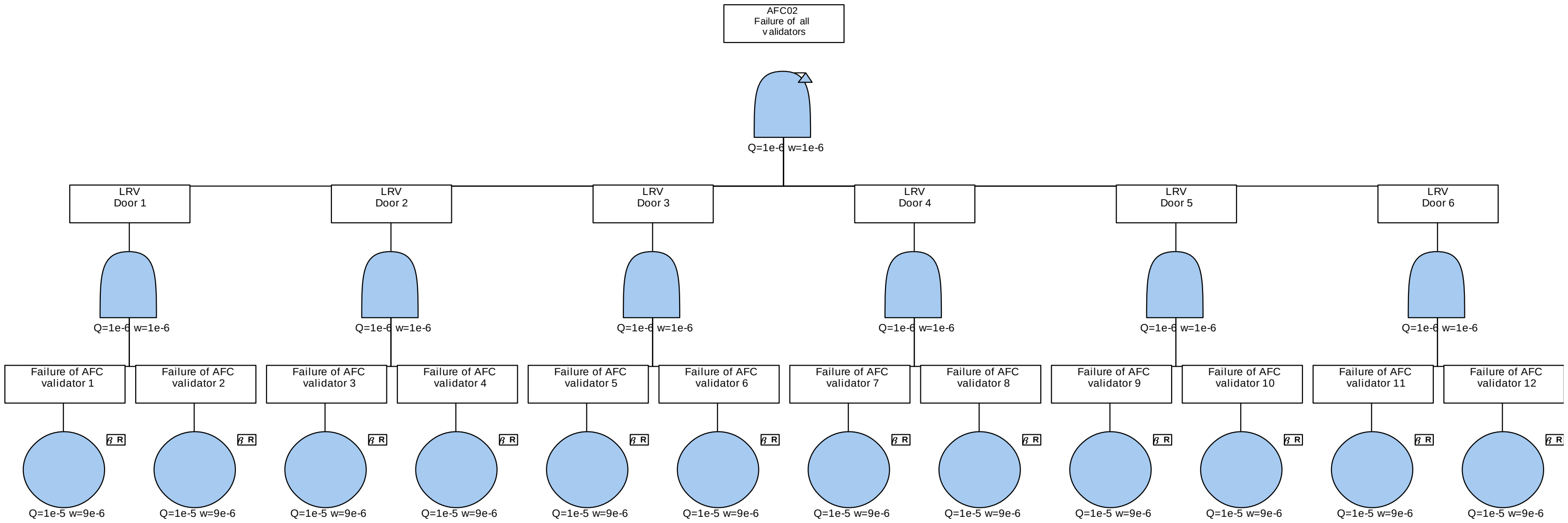

Figure 27 PIDT: AFC02 Failure of all validators machines Fault Tree

6.5.2.2. PICS: Commercial Speed

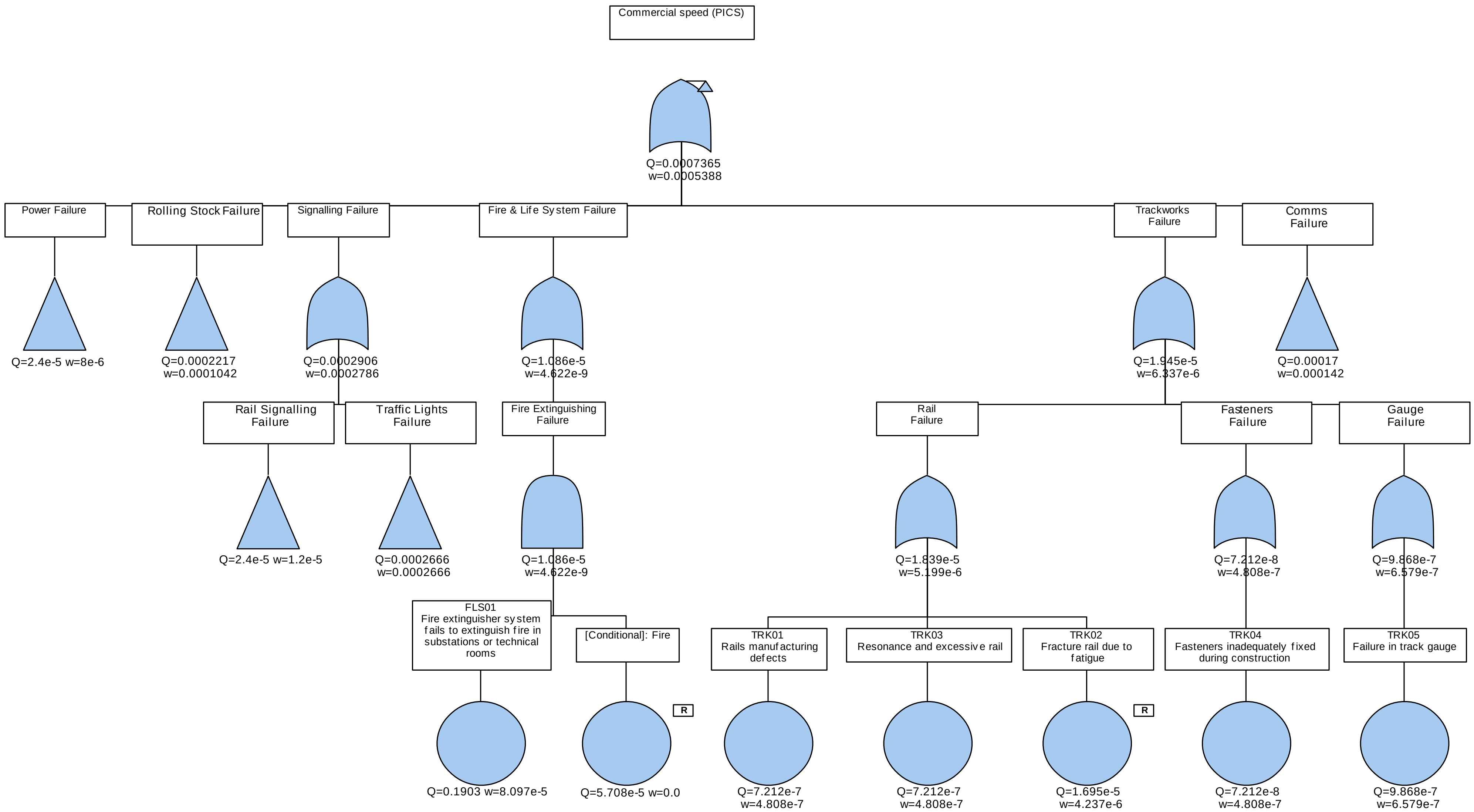

Figure 28 PICS: Commercial Speed Fault Tree

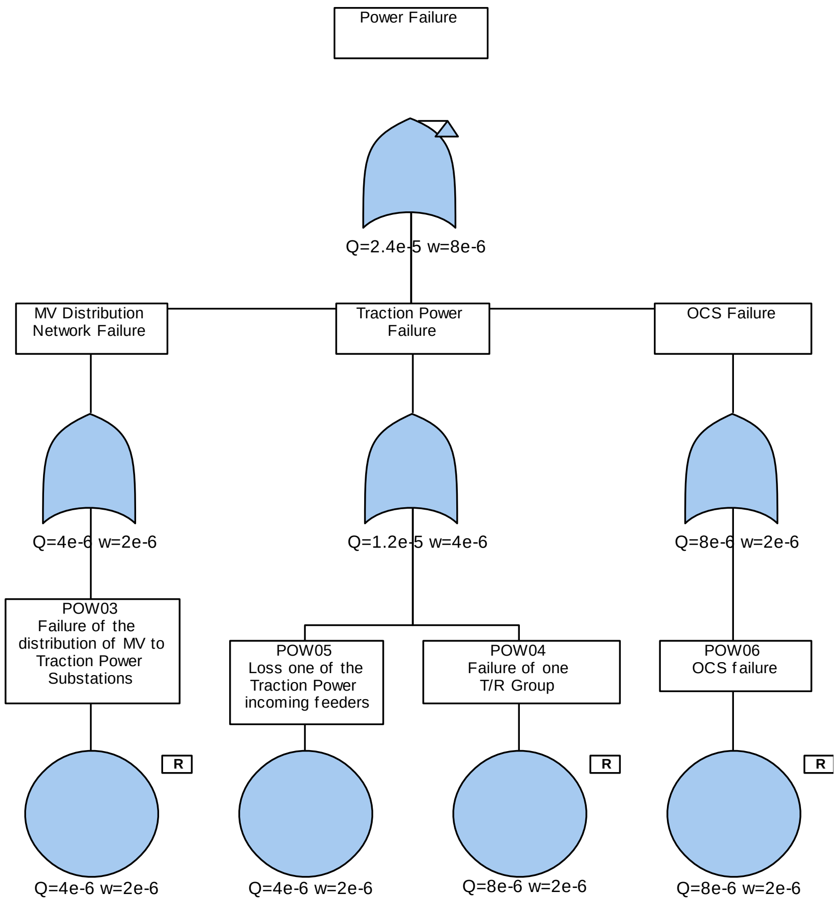

Figure 29 PICS: Power Failure Fault Tree

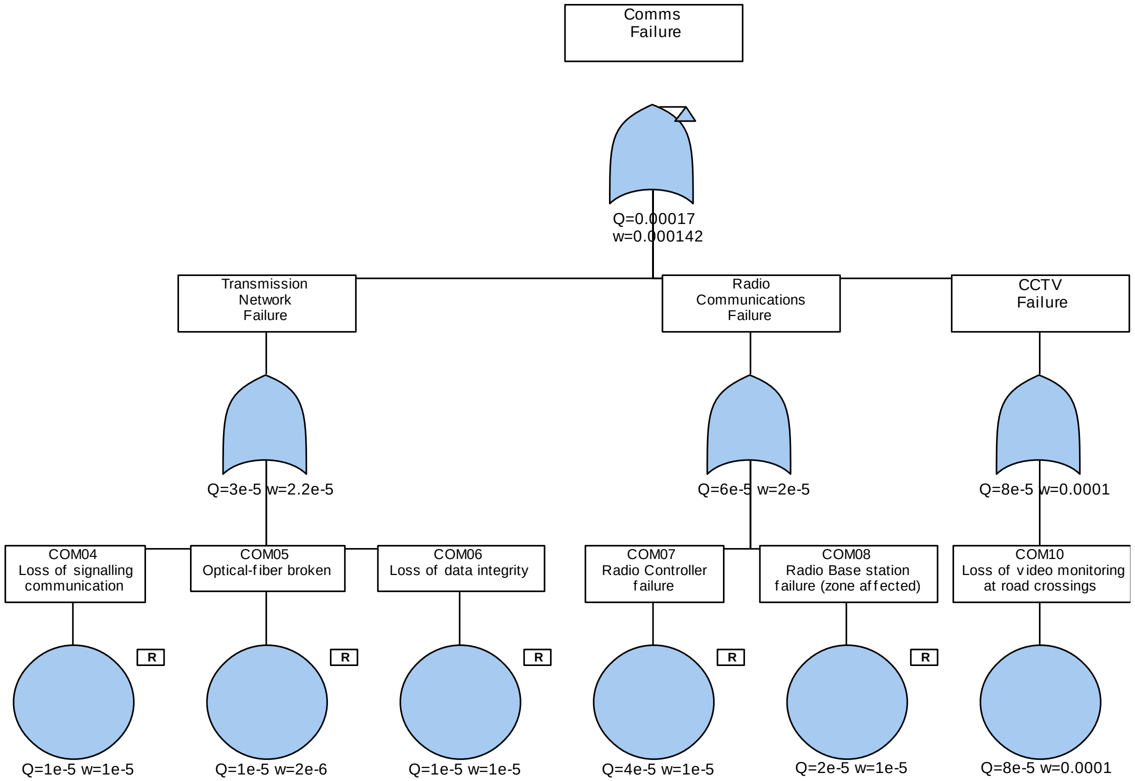

Figure 30 PICS: Communications Failure Fault Tree

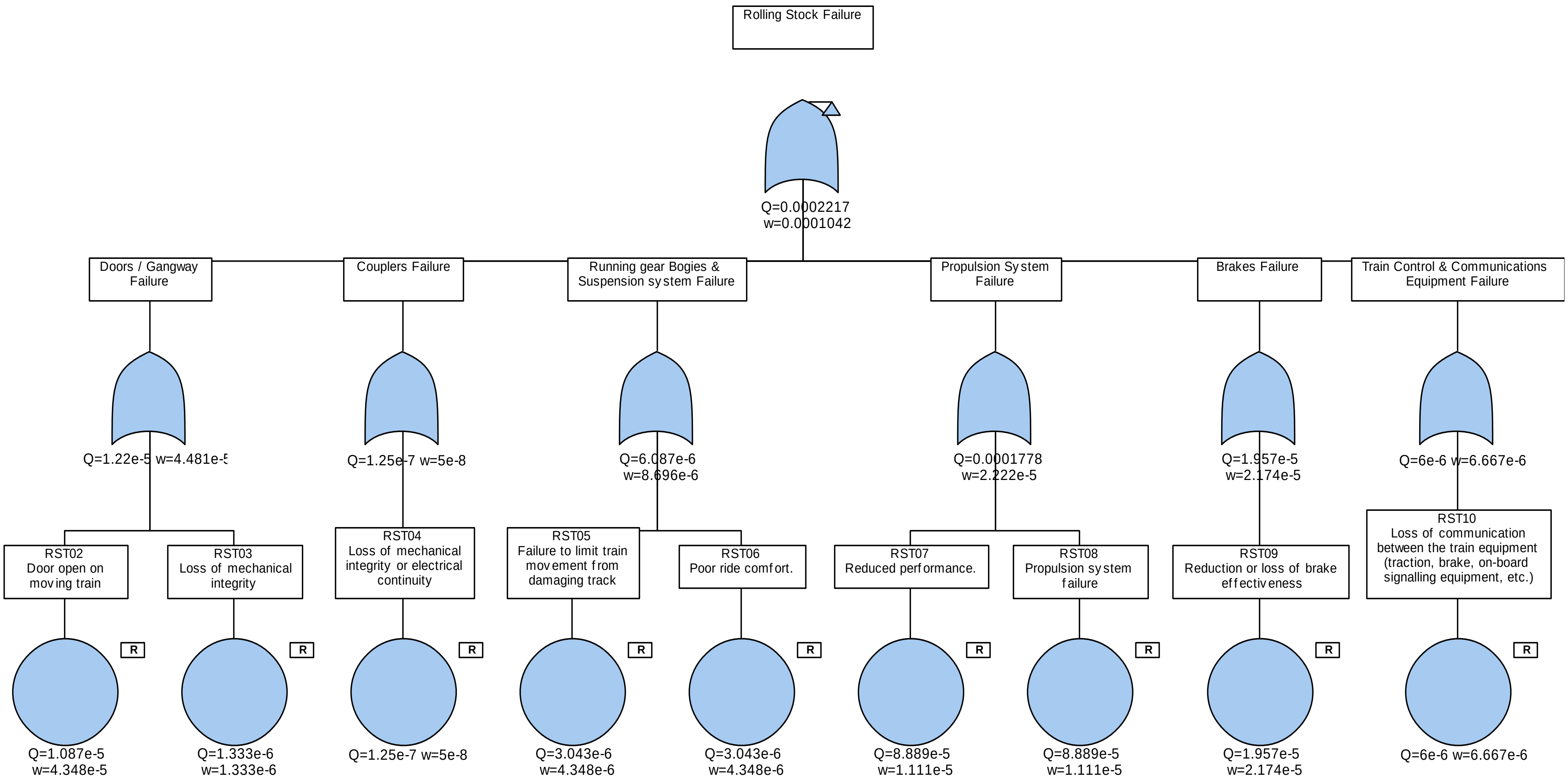

Figure 31 PICS: Rolling Stock Failure Fault Tree

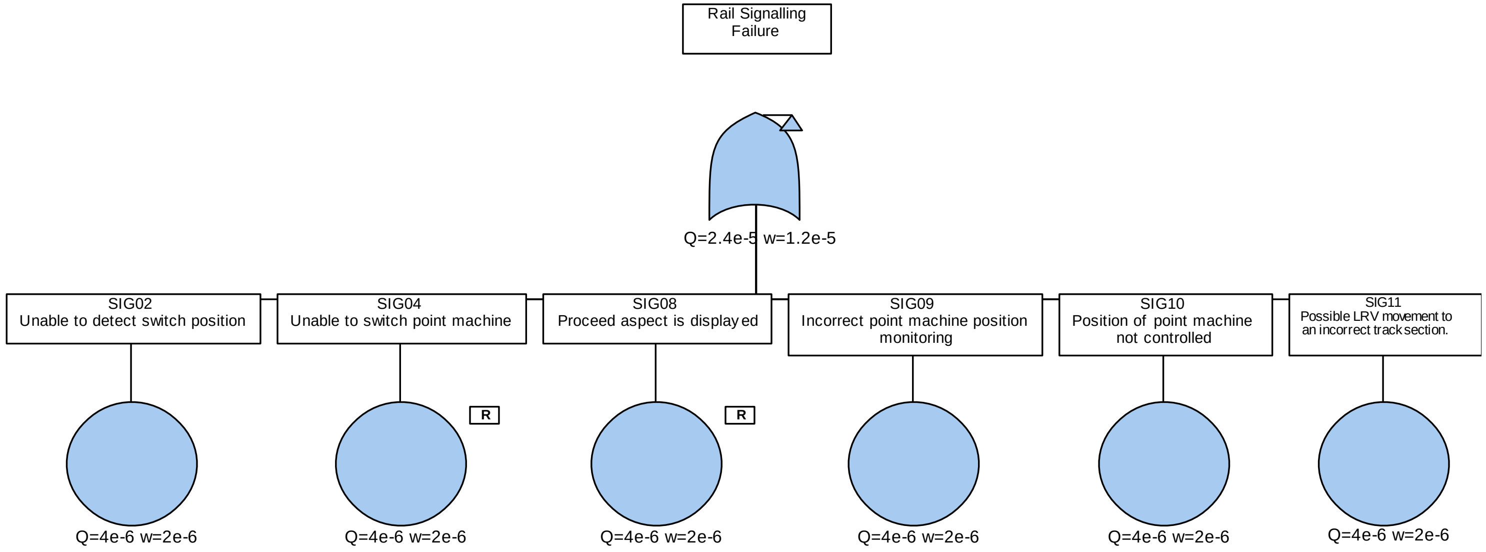

Figure 32 PICS: Rail Signalling Failure Fault Tree

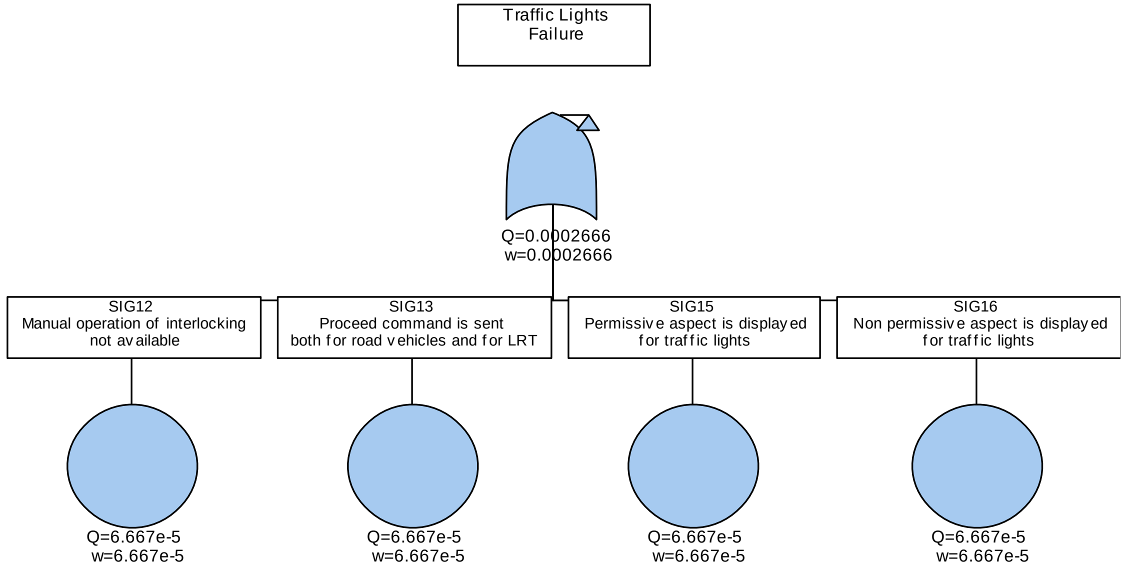

Figure 33 PICS: Traffic Lights Failure Fault Tree

6.5.2.3. PITE: Train Evacuations

Performance Indicator for Train Evacuations is modelled as follows. Q (unavailability) and MTTF (Mean time to failure) are provided.

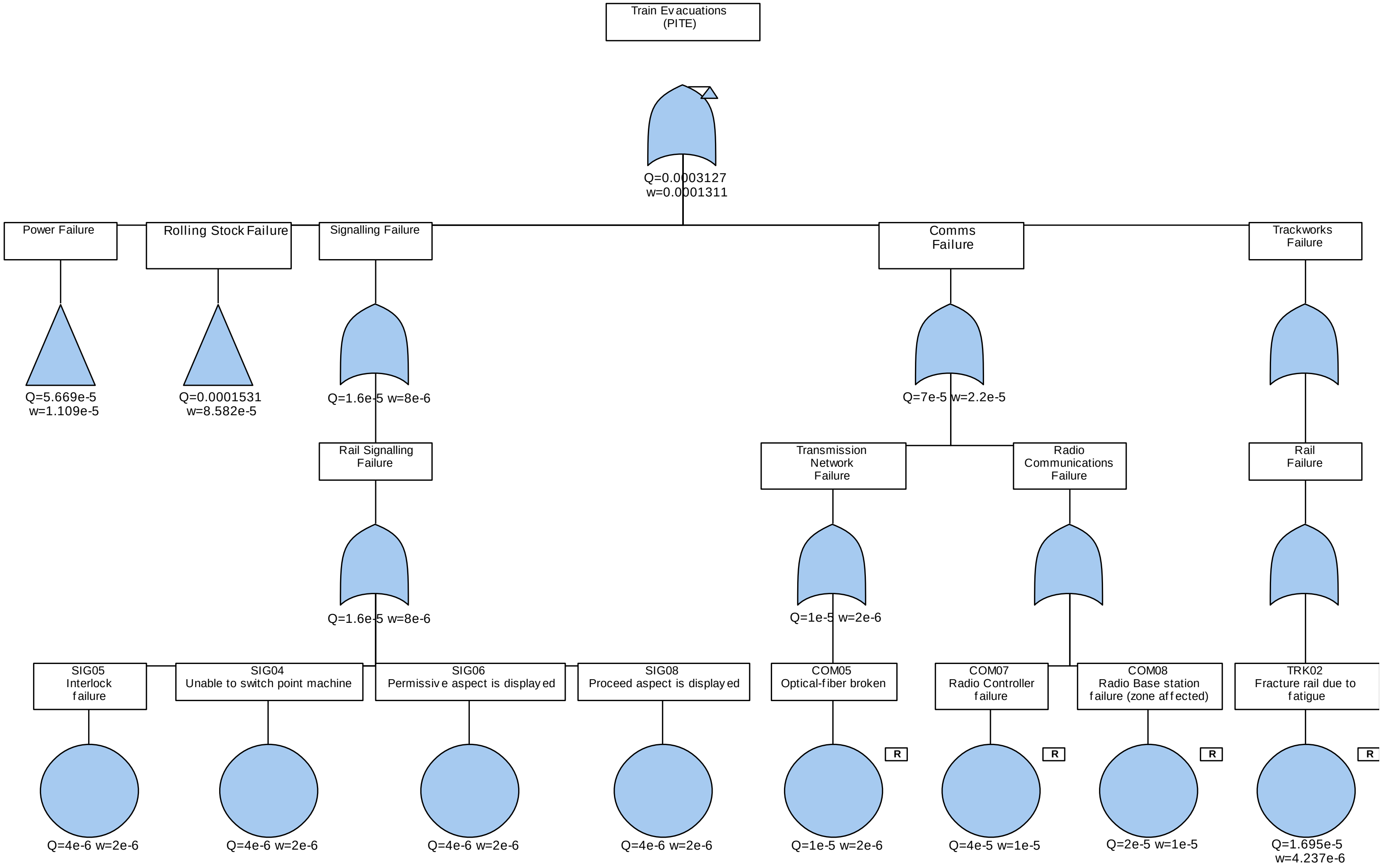

Figure 34 PITE: Train Evacuations Fault Tree

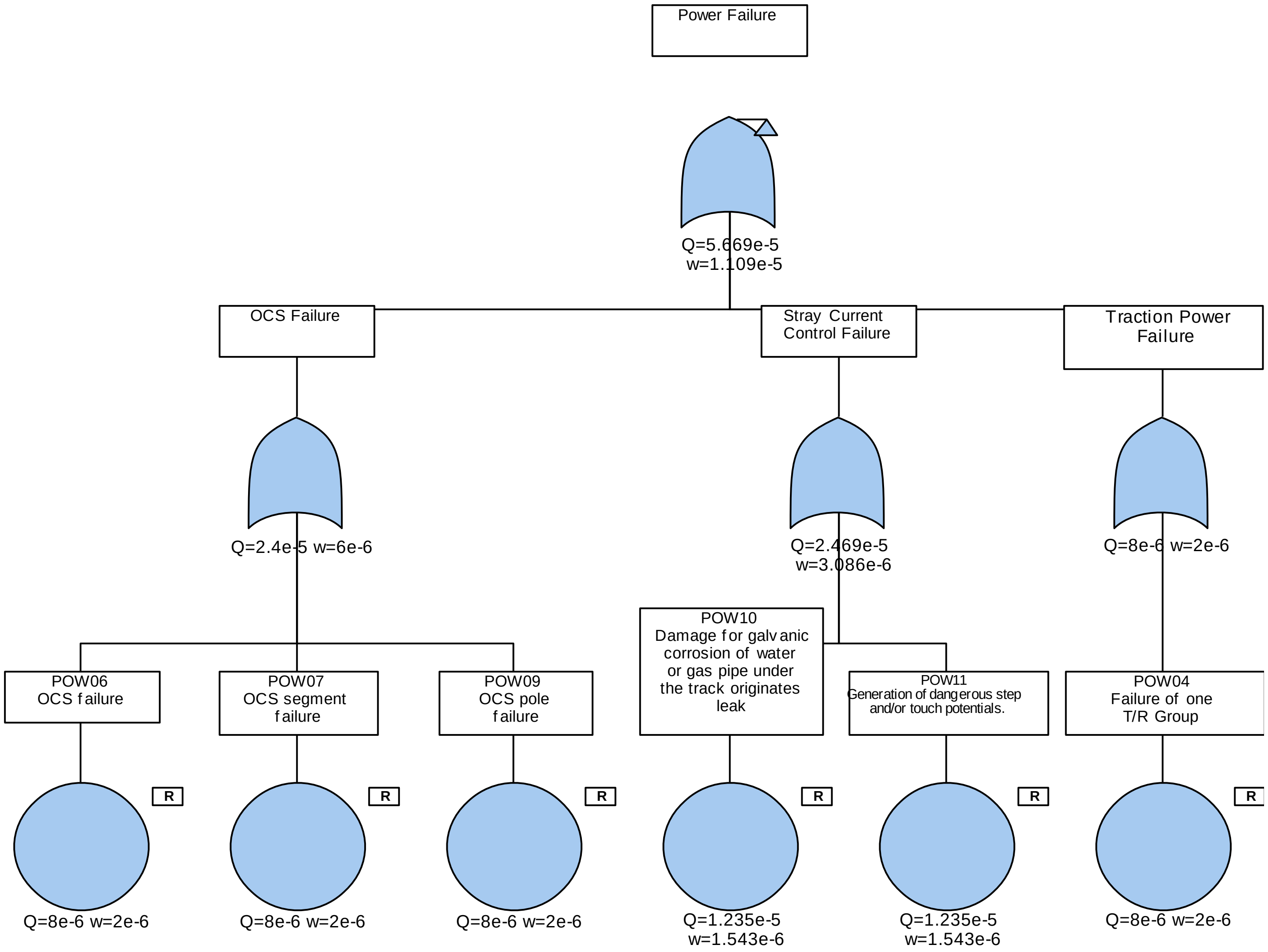

Figure 35 PITE: Power Failure Fault Tree

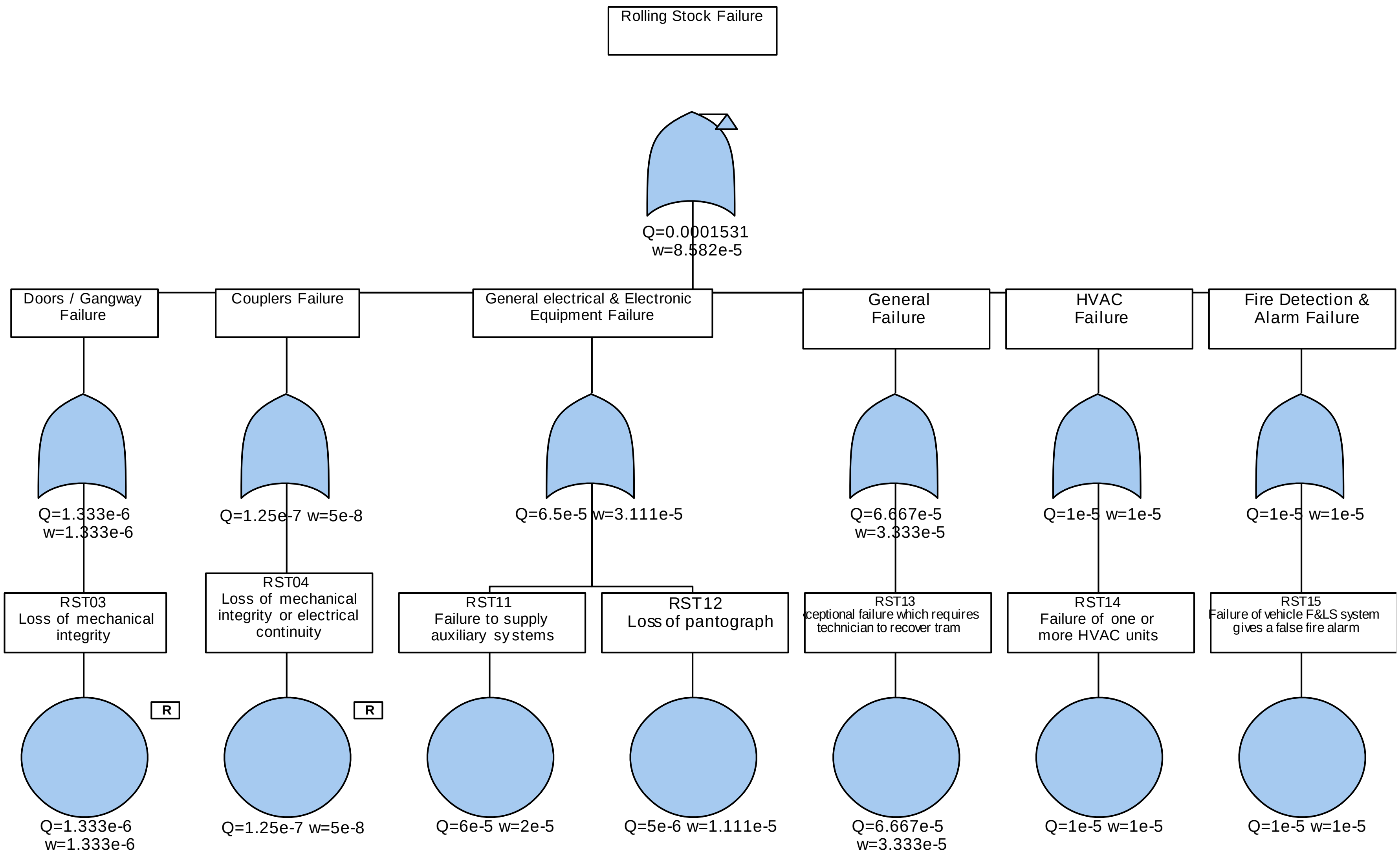

Figure 36 PITE: Rolling Stock Failure Fault Tree

6.5.2.4. PIUS: Unscheduled Stops

Performance Indicator for Unscheduled Stops is modelled as follows. Q (unavailability) and MTTF (Mean time to failure) are provided.

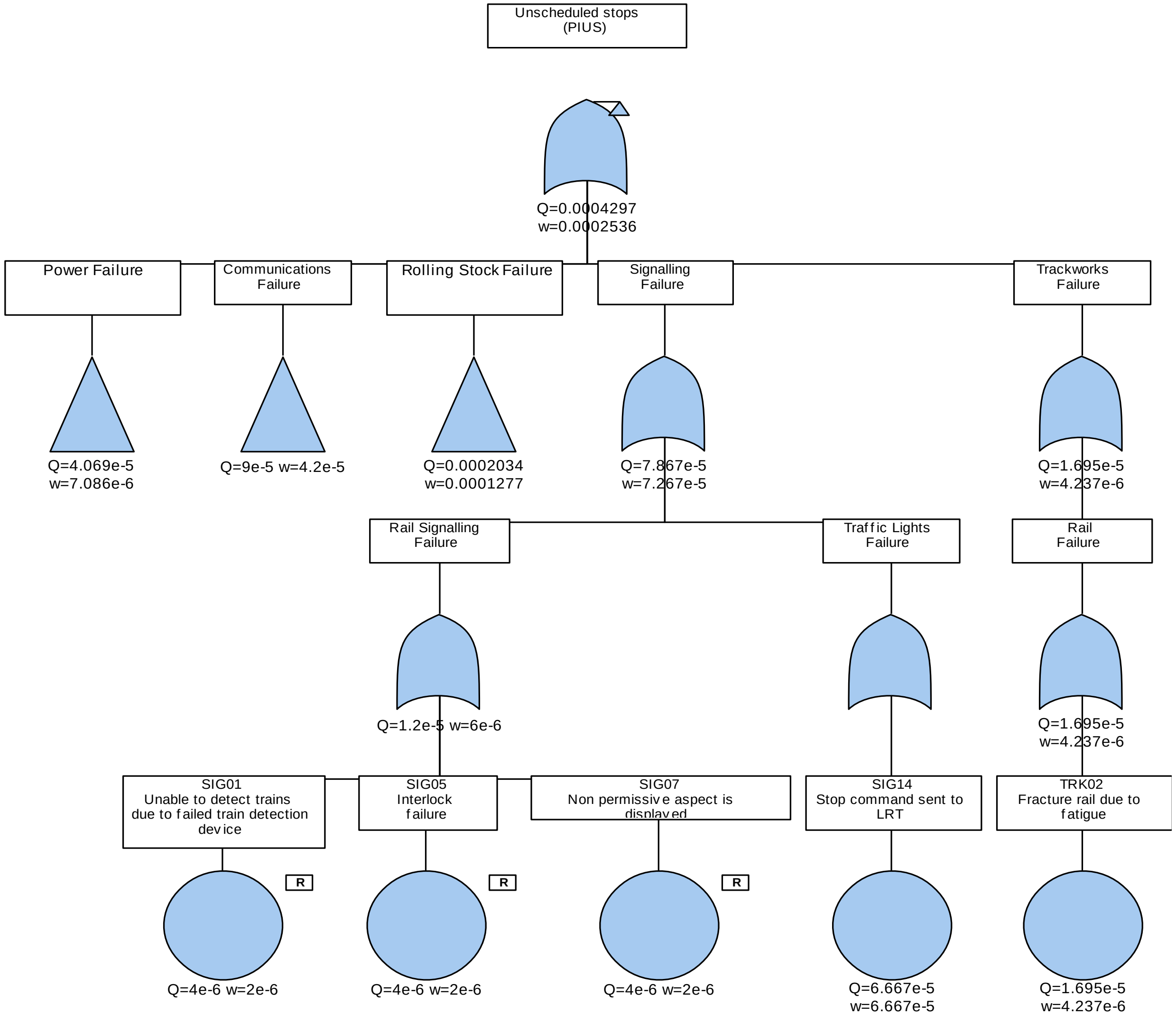

Figure 37 PIUS: Unscheduled Stops Fault Tree

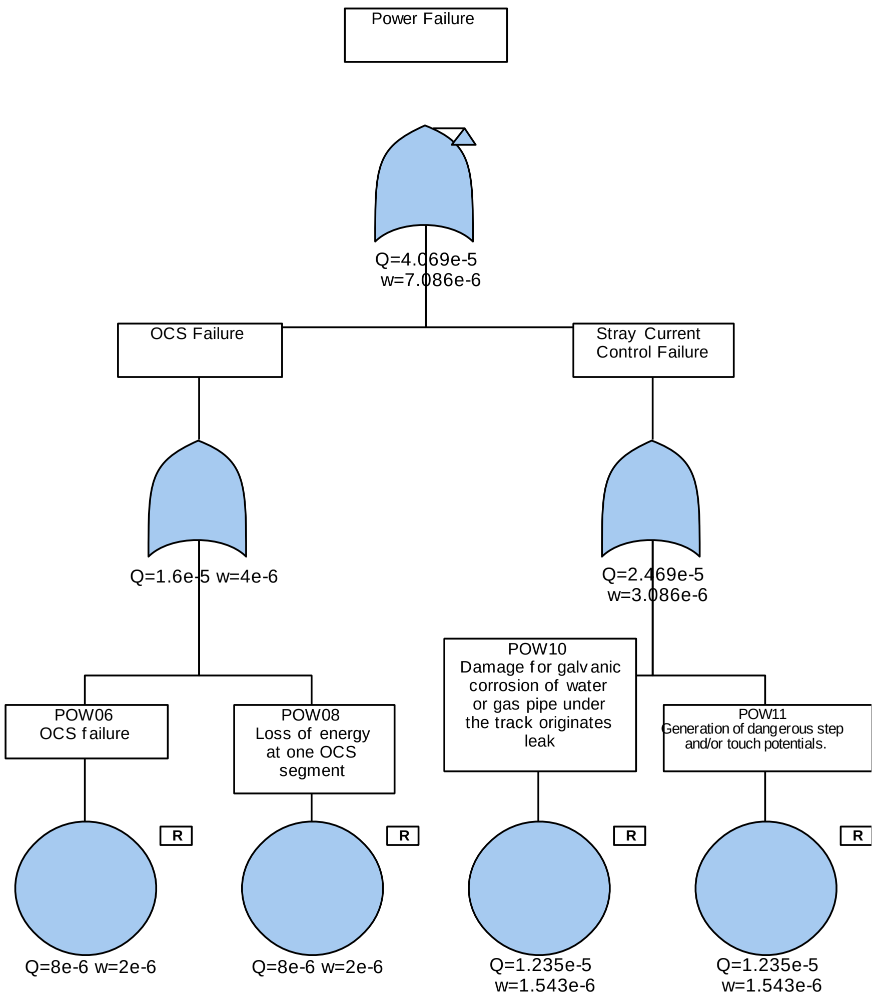

Figure 38 PIUS: Power Failure Fault Tree

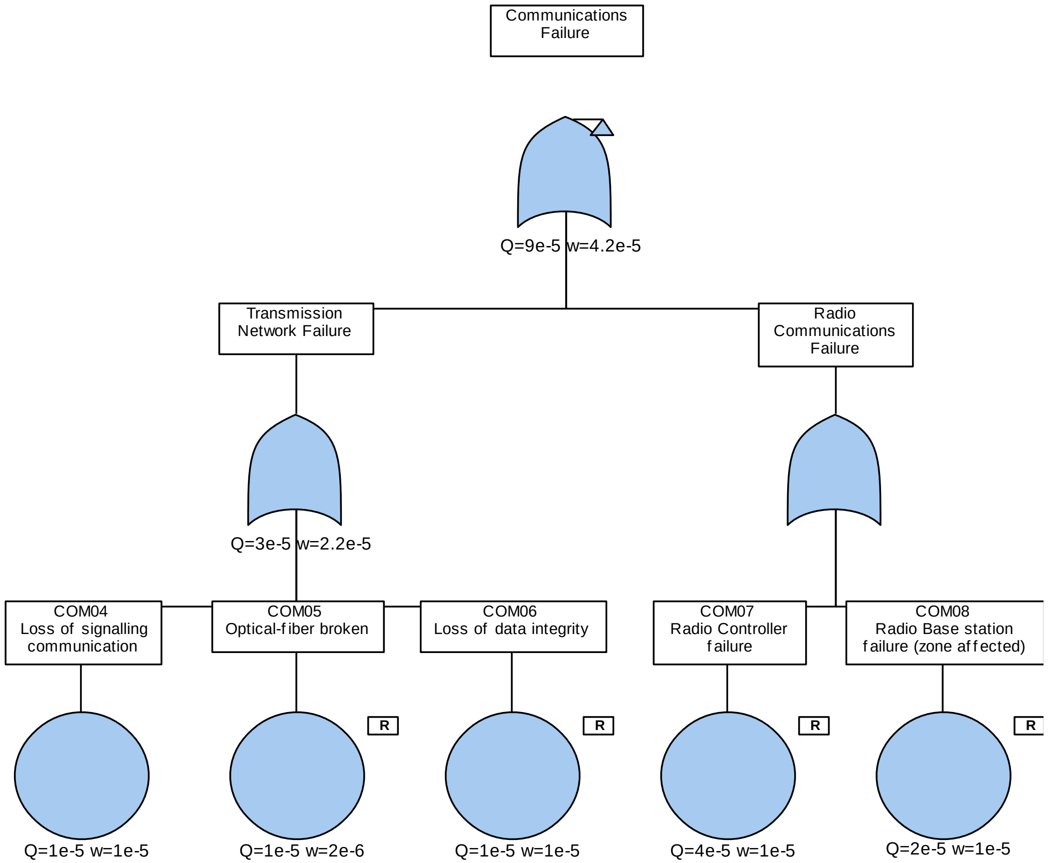

Figure 39 PIUS: Communications Failure Fault Tree

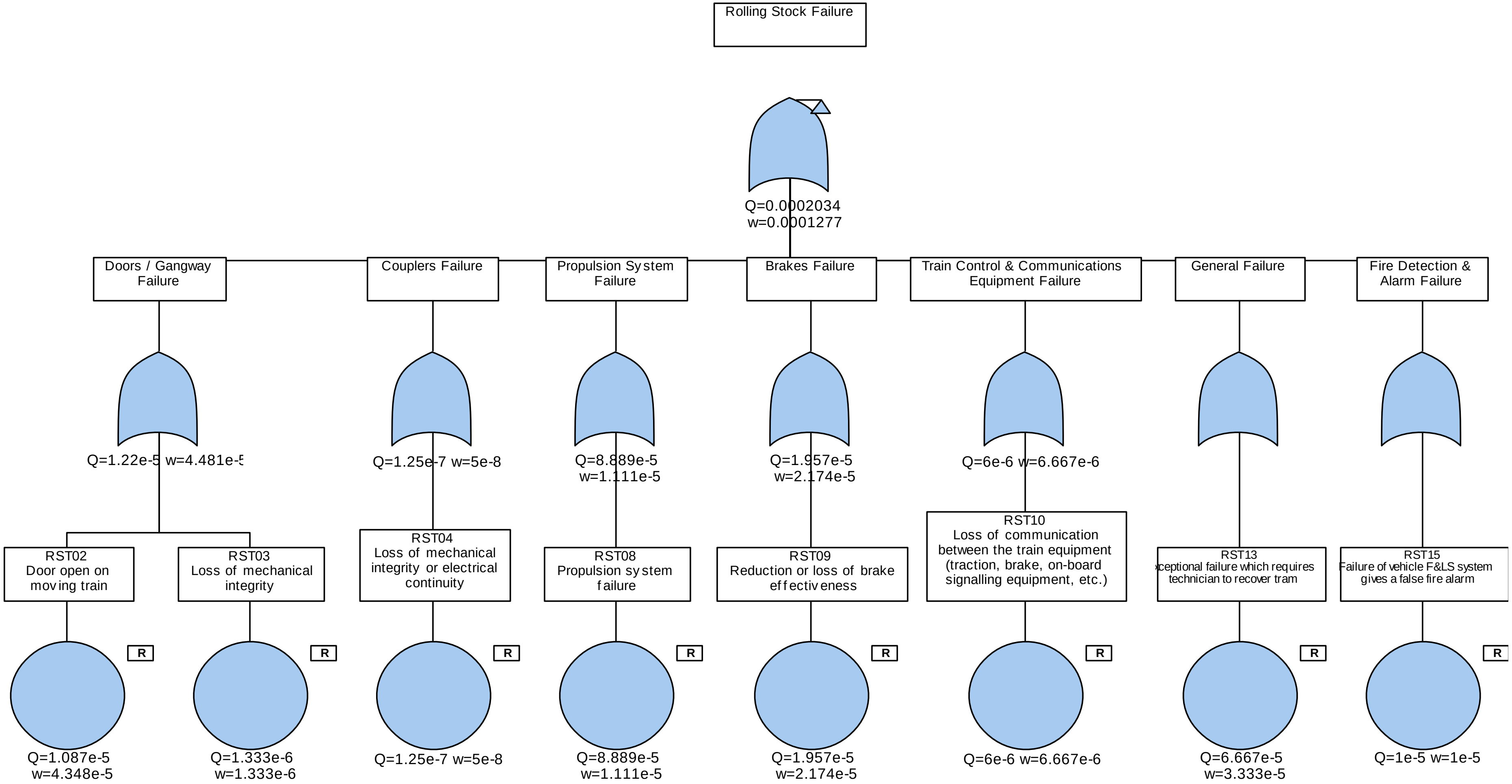

Figure 40 PIUS: Rolling Stock Failure Fault Tree

6.5.3. Results

The following table shows the quantified results of the Fault Tree Analysis[11]. The table includes individual contributions from all Performance Indicators. The system life time has been considered 30 years for the calculation of up and down times[12].

Parameter	Service Availability (SA)	PIDT	PICS	PITE	PIUS
Unavailability (Q)	0.00120412	0.0009393	0.00073649	0.0003127	0.0004296
Failure Frequency (W)	0.00092813	0.000732	0.0005388	0.0001311	0.0002536
Expected Failures	193.09827	152.2929	112.1033	27.2785	52.7622
Total Down Time (hours)	249.3998	194.5819	152.4714	64.7365	88.9467
Total Up Time (hours)	207800.60	207855.41	207897.52	207985.26	207961.05
MTBF (hours)	1077.4307	1366.1172	1855.8778	7626.8819	3943.1644
MTTF (hours)	1076.1392	1364.8395	1854.4518	7624.5087	3941.4786
MTTR (hours)	1.2916	1.2777	1.3601	2.3732	1.6858
Service Availability	**99.8796%**	**99.9061%**	**99.9264%**	**99.9687%**	**99.9570%**

Table 13 Service Availability results - quantified results of the Fault Tree Analysis

[11] Numerical results for the Fault Tree Analysis have been calculated by the FTA software used-Item Software: Item Toolkit Fault Tree Analyses *http://www.itemsoft.com/fault_tree.html*, according to the mathematical formulae of Kumamoto and Henley, [16]. See Appendix II for an unavailability quantification example.

[12] That is 208050 h (= 30 years x 365 days/year x 19h/day)

7. RAM Requirements Apportionment

Qualitative RAM Requirements provide specifications for system and subsystem level about maintenance staff, maintenance operations, accessibility, ability to clean and wash, etc.

RAM requirements have been derived from the Failure Effects and Criticality Analysis (Section 6.3)

7.1. System RAM Requirements

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
RAM-001	The overall Service Availability (SA) of the LRT shall be at least 99.8%.	General
RAM-002	The overall Service Availability for the LRT shall be calculated as described in Section 4.2.	General
RAM-003	The service availability shall be the same for all lines regardless of length or complexity.	General
RAM-004	The Control System shall be able to automatically calculate the overall Service Availability (SA) for a given LRT and for a given period of time.	General

Table 14 System RAM Requirements

7.2. Subsystem RAM Requirements

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
	NUMERICAL RAM TARGETS	
RAM-005	The Contractor shall meet numerical RAM targets for the LRT subsystems specified in Section 6.3.	General
RAM-006	The Contractor shall apportion their RAM targets contractually to any subcontractors or suppliers, if necessary.	General
	QUALITATIVE RAM REQUIREMENTS	
	GENERAL MAINTAINABILITY REQUIREMENTS	
	Failure Diagnosis	
RAM-007	The Control System shall inform the Operator of any failure, disruption or event that will degrade the performance of the system.	General
RAM-008	The Control System shall inform the Maintainer of all detected failures, degraded and other conditions that require maintenance intervention.	General

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
RAM-009	The Contractor shall identify with tags: cables, connectors, relay, switches, fuses, circuit breakers, test spots as well as any devices that the maintainer should have to manipulate.	General
	Maintenance Staff	
RAM-010	All maintenance tasks other than heavy maintenance shall be able to be undertaken by one person including testing to bring into service.	General
	Maintenance Operations	
RAM-011	The Contractor shall design the LRT system in order to facilitate cleaning and preventive maintenance operations.	General
RAM-012	For equipment interfaced with the Public, the Contractor shall design solutions and typologies of materials that minimize cleaning operations and repair of damages.	General
RAM-013	The access removal and installation of LRTs shall meet specified MTTRs.	General
RAM-014	The Contractor shall design the LRT system in order to allow maintenance of the lines to be carried out during operational hours where possible.	General
RAM-015	There shall be always a replacement part in stock for broken components.	General
	General Maintenance Requirements	
RAM-016	The Contractor shall determine the logistical times and the MTTR in the recovery time calculations of the RAM predictions studies.	General
RAM-017	The Contractor shall define in the maintainability prediction studies, the unavailability and maintainability times of each failure of the LRT system.	General
RAM-018	The Contractor's RAM predictions shall be validated by the actual measured RAM times. If the times measured during the tests are higher than the times predicted by the Contractor, the Contractor shall update the RAM studies, demonstrating that the overall Service Availability is still met.	General
RAM-019	Preventative maintenance shall be performed on all LRT equipment.	General
	Accessibility	
RAM-020	The Contractor shall consider the actual travel and access times of LRT Operator Staff and emergency services in RAM and safety studies.	General
	POWER	
	Main Power Supply	
RAM-021	A loss of one of the main power supply incoming feeders shall be reported to the Main Power Supply Control System in the OCC.	Rail Systems
RAM-022	Redundant incomers feed taps and redundant transformers shall enable the reconfiguration of the power supply in a short period of time (few seconds).	Rail Systems

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
	Distribution Network	
RAM-023	In case of failure, an alternative way within MV ring shall provide power.	Rail Systems
	Traction Power	
RAM-024	A failure of one Transformer/Rectifier group shall be reported to the Traction Power Control System in the OCC.	Rail Systems
RAM-025	A loss of one of the Traction Power incoming feeders shall be reported to the Traction Power Control System in the OCC via the Power and Traction Control RTU.	Rail Systems
	Overhead Catenary System (OCS)	
RAM-026	An Overhead Catenary System (OCS) failure shall be reported to the OCC via the SCADA system.	Rail Systems
RAM-027	An OCS section failure shall be reported to the OCC via the SCADA system.	Rail Systems
RAM-028	A loss of energy at one OCS section shall be reported to the OCC via the SCADA system.	Rail Systems
RAM-029	An OCS support failure shall be reported to the OCC via the SCADA system.	Rail Systems
	Stray Current Control	
RAM-030	Visual inspection and testing of the rail insulation shall be carried out in order to avoid leakage of stray currents.	O&M
RAM-031	Running rails and the power supply negative pole shall be separated from the general ground (earth).	Rail Systems
	COMMUNICATIONS	
RAM-032	A failure in information transmission shall be reported to the Communications Control system in the OCC.	Rail Systems
RAM-033	Communications equipment shall be designed to meet the specified availability targets for communication systems.	Rail Systems
RAM-034	Wrong information transmission failures shall be reported to the Communications Control System in the OCC.	Rail Systems
RAM-035	Equipment shall be available to back-up system servers.	Rail Systems
RAM-036	Power failures at any time at any level shall not lead to loss or corruption of data.	Rail Systems
RAM-037	The proposed solution shall be future proof and be the latest hardware and software versions at build completion of the network.	Rail Systems
RAM-038	The Contractor shall incorporate into the design of the system, all security features necessary to protect the network against cyber-attack and shall comply with ISO 27001 requirements.	Rail Systems
RAM-039	The Contractor shall develop a disaster recovery Plan which shall include plans and facilities for recovering from major system incidents, such as providing off-site storage of backups.	Rail Systems
RAM-040	It shall have common equipment in all location to ensure low maintainability	Rail Systems

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
	Transmission Network	
RAM-041	The transmission network shall be designed with enough redundancy so that a failure of the transmission network does not provoke a loss of signalling communication.	Rail Systems
RAM-042	There shall be redundant fibre optic routes for the transmission network.	Rail Systems
RAM-043	All communications subsystems connected to the transmission network shall monitor the status and report network problems.	Rail Systems
RAM-044	The Contractor shall determine the capacity of the network and shall provide capacity model to demonstrate that the proposed network design has been correctly sized to support the predicted service demand.	Rail Systems
	Radio Communications	
RAM-045	Selective communication failures (communication between individuals or from point to point) shall be reported to the OCC by Operations and Maintenance staff.	O&M
	CCTV	
RAM-046	The CCTV system shall be designed with high redundancy in critical areas (i.e. more than one camera for crossing, overlapping coverage). A single camera could be sufficient inside shelters.	Rail Systems
RAM-047	Loss of video monitoring at road crossings shall be reported to the Communications Control System in the OCC.	Rail Systems
	ROLLING STOCK	
RAM-048	Well proven and classical solutions shall be proposed in order to facilitate maintenance activities and to provide low lifecycle cost vehicle.	Rolling Stock
RAM-049	Rolling Stock design shall ensure compliance with the mandatory laws and regulations applicable to hygiene and safety, in force on the date of commissioning of the Rolling Stock.	Rolling Stock
RAM-050	The arrangements and materials used shall, as much as possible, deter hooligans from committing actions such as graffiti, lacerations, disassembly, breakage, etc. Windows shall be equipped with anti-graffiti covering.	Rolling Stock
RAM-051	Screws shall be hidden and cannot be unscrewed or damage by passengers. All wires shall be protected and cannot be touched by passengers.	Rolling Stock
RAM-052	Lights shall be protected to avoid misuse passengers’ manipulations.	Rolling Stock
RAM-053	All coverings of modular design shall be removed easily and quickly and are replaceable independent of one another during maintenance, while remaining difficult to remove by a non-specialist.	Rolling Stock
	Train Control System	

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
RAM-054	The TCS shall detect and report to the OCC at least the following failures: · RST01 - Defect in the door movement · RST02 - Door opens whilst tram is moving · RST05 - Inadequate train movement · RST06 - Poor ride comfort · RST07 - Reduced performance of the traction system · RST08 - Failure of the traction system · RST09 - Reduction of brake effectiveness · RST10 - Loss of communications between train equipment · RST11 - Loss of electrical supply to auxiliary systems · RST12 - Loss of pantograph · RST13 - Failures that need the assistance of a technician · RST14 - Failure of an HVAC unit	Rolling Stock
RAM-055	An integrated software maintenance and diagnostic assistance system at driver's and maintenance staff disposal is required to permit easy detection of any faults.	Rolling Stock
	<u>OPERATIONS CONTROL CENTRE - OCC</u>	
RAM-056	In case of power failure, the data in each computer shall be saved until the power is restored.	Rail Systems
RAM-057	All critical equipment and functions shall be identified and redundancy provided, backup and monitoring of such equipment and functions such that no single-point service affecting failure shall result in failure of a system essential for LRT operations.	Rail Systems
RAM-058	Failed equipment shall not provoke the failure of adjacent parts or equipment.	Rail Systems
RAM-059	Failure of the OCC equipment or breaking of the communication link shall not have effect on line equipment functions.	Rail Systems
	Operational Staff	
RAM-060	Competence management, performance management and people management techniques should be applied to minimise the probability of human error.	O&M
RAM-061	Hierarchical operation levels shall be defined in order to minimize the time needed to recover from a human error/sabotage.	O&M
	<u>SIGNALLING</u>	
	Rail Signalling	
RAM-062	All signalling equipment along the LRT line shall be monitored by the OCC.	Rail Systems
RAM-063	All vehicles' position on the LRT line shall be monitored by the OCC.	Rail Systems
RAM-064	Alarms of signalling system shall be received in the OCC.	Rail Systems

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
RAM-065	The local controls or the local manual command boxes should be used to service operation and manage incidents in case of: • failure to detect switch position, • failure of the interlocking, • non permissive aspect is displayed (trams are not allowed to proceed, when they should), • proceed aspect is displayed (trams are allowed to proceed, when they should not), • incorrect point machine position monitoring (uncontrolled routes of LRV on main line), • position of point machine is not controlled (LRV moves to an incorrect track section).	O&M
	Traffic Lights	
RAM-066	The signalling system shall be designed to avoid single-point failures. Equipment with a single point of failure shall be avoided.	Rail Systems
	AUTOMATIC FARE COLLECTION (AFC)	
RAM-067	Passengers shall be clearly informed of the failure of one validator machine, and prompted to use an alternative working unit.	Rail Systems
RAM-068	The OCC must be requested to replace the faulty train for a working one as quick as possible.	O&M
	FIRE & LIFE SAFETY	
	Fire Extinguishing	
RAM-069	The fire extinguishing system in substations, technical rooms, and stops shall be monitored by the local Fire Alarm Panel and the Fire Detection and Alarm System in the OCC via the SCADA system.	Rail Systems
RAM-070	The fire extinguishing system shall be designed to meet specified availability targets.	Rail Systems
	TRACKWORKS	
RAM-071	The guide-way components shall be designed in order to allow the maintainability and modifications of the system.	Civil and Structural
RAM-072	All equipment and parts shall be standardized in order to achieve standardization with equipment from other suppliers.	Civil and Structural
RAM-073	All equipment has to be supplied by a certified manufacturer.	Civil and Structural
RAM-074	Supervision, control and QA shall be applied during the construction period, and taking into account the geotechnical conditions.	O&M
RAM-075	Removal or replacement or repair of any components of the track structure (rails, fasteners, etc.) shall be carried out during non-operation hours, unless the track is closed due to failure, in which case repair should take place during Operating Hours.	O&M

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
	Rail	
RAM-076	Quality assurance processes and control shall be applied during rail manufacturing, implementation and mounting in order to avoid manufacturing defects or defective mounting of rails.	Civil and Structural
RAM-077	A schedule of periodic rail inspections and maintenance activities shall be defined.	O&M
RAM-078	Ultrasonic and visual inspections shall be carried out on rails in order to detect fractures in rails due to fatigue and stress cracking.	O&M
RAM-079	Implementation and rail mounting shall be carried out by qualified operators.	O&M
	Fasteners	
RAM-080	Visual inspections shall be carried out in order to detect fasteners inadequately fixed during construction / maintenance.	O&M
	Gauge	
RAM-081	Mechanical and Visual inspections are required during the testing and commissioning period and also after maintenance tasks, in order to detect failures in track gauge due to defective mounting and implementation.	O&M

Table 15 Subsystem RAM Requirements

8. Reliability Critical Items List

8.1. Proposal of Preventive/Corrective Actions

The Reliability Critical Items List defines those reliability critical failures with an impact on Service Availability or LRT Operation. In addition, this study provides possible design mitigations (Preventive/Corrective Actions).

The Reliability Critical Items List has been kept to a functional level, following the critical failure selection done in the Failure Mode Effects and Criticality Analysis (see section 6.3).

The Reliability Critical Items List is a table with all failure modes that have been found to have an effect on the Service Availability, determining with Table 16 its severity and its frequency. With this two variables, the criticality can be set for each of the failures modes identified in the FMECA (Section 6.3)

			Extreme	Significant Failure	Major Failure	Minor Failure	Negligible
			C5	C4	C3	C2	C1
			>2 h	≥30 minutes < 2 hour	≥ 15 minutes <30 minutes	≥ 2 minutes <15 minutes	< 2 minutes
Frequent	F6	10	**1**	**1**	**2**	**3**	**4**
Probable	F5	1	**1**	**2**	**3**	**4**	**5**
Occasional	F4	0,1	**2**	**3**	**4**	**5**	**6**
Remote	F3	0,01	**3**	**4**	**5**	**6**	**7**
Improbable	F2	0,001	**4**	**5**	**6**	**7**	**7**
Incredible	F1	0,0001	**5**	**6**	**7**	**7**	**7**

Table 16 Criticality definition for Reliability Critical Items List

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
RST11	Failure to supply auxiliary systems. Loss of Heating, Ventilation and Air Conditioning (HVAC) functionality. Batteries provide emergency lighting and enables doors to continue to operate.	**Preventive actions**: Proper maintenance and testing **Corrective action**: Detrainment and train taken out of service	F5	C5	**1**
POW06	OCS failure	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Connect the OCS that failed to the substation.	F4	C5	**2**
POW07	OCS segment failure.	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Change the OCS segment that failed.	F4	C5	**2**
POW08	Loss of energy at one OCS segment	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Design redundant substation system to enable system restoration in a short period of time (few seconds).	F4	C5	**2**
POW09	OCS pole failure	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Change the OCS pole and OCS segment that failed.	F4	C5	**2**
POW10	Damage for galvanic corrosion of water or gas pipe under the track originates leak.	**Preventive Actions**: Routine maintenance. **Mitigation in the design phase:** Running rails and the power supply negative pole shall be separated from the general ground (earth). **Corrective Actions**: Repair the damaged pipes.	F4	C5	**2**
POW11	Dangerous step and/or touch potentials.	**Preventive Actions**: Routine maintenance. **Mitigation in the design phase:** Running rails and the power supply negative pole shall be separated from the general ground (earth). **Corrective Actions**: Action to be taken depending on the cause, which can be due to stray currents or circuit failure.	F4	C5	**2**
COM05	Optical-fibre broken. Unable data transmission among all systems.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have redundant optical-fibre routes **Corrective Actions**: Repair procedures	F4	C5	**2**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
COM07	Radio Controller failure.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have high redundancy and availability of Radio system. **Corrective Actions**: Repair procedures	F4	C5	**2**
COM10	Loss of video monitoring at road crossings.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have high redundancy and availability of CCTV system, more than one camera for crossing and overlapping coverage. **Corrective Actions**: Repair procedures	F5	C4	**2**
RST07	Reduced performance.	**Preventive actions**: Proper maintenance **Corrective action**: Train taken out of service at end of route	F4	C5	**2**
RST08	Propulsion system failure.	**Preventive actions**: Proper maintenance **Corrective action**: Train taken out of service at end of route	F4	C5	**2**
RST09	Reduction or loss of brake effectiveness.	**Preventive actions**: Proper maintenance **Corrective action**: Train taken out of service at end of route	F5	C4	**2**
RST13	Exceptional failure in which it is impossible to continue the service without the assistance of a technician to recover the failed tram.	**Preventive actions**: Proper maintenance and testing **Corrective action**: Train taken out of service at end of route	F5	C4	**2**
SIG12	Manual operation of interlocking is not available. System inoperative.	**Preventive Actions**: Routine maintenance **Corrective Actions**: Repair procedures.	F5	C4	**2**
SIG13	Proceed command is sent both for road vehicles and for LRT. LRT during normal operation and road vehicles move to an intersection.	**Preventive Actions**: Routine maintenance **Corrective Actions**: Repair procedures.	F5	C4	**2**
SIG14	Stop command sent to LRT. LRT must stop at intersection.	**Preventive Actions**: Routine maintenance **Corrective Actions**: Repair procedures.	F5	C4	**2**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
SIG15	Permissive aspect is displayed. Road vehicles/pedestrians have permissive when they should not. (Failure of traffic regulator).	**Preventive Actions**: Routine maintenance **Corrective Actions**: Repair procedures.	F5	C4	**2**
SIG16	Non permissive aspect is displayed. Road vehicles/pedestrians do not have permissive when they should. (Failure of traffic regulator).	**Preventive Actions**: Routine maintenance **Corrective Actions**: Repair procedures.	F5	C4	**2**
FLS01	Fire extinguisher system fails to extinguish fire in substations or technical rooms.	**Preventive Actions**: Routine maintenance. **Corrective Actions:** Need for external extinguisher system. For the RAM Study a fire rate = 0.5 event/year has been used.	F5	C4	**2**
FLS02	Fire extinguisher system fails to extinguish fire in stops.	**Preventive Actions**: Routine maintenance. **Corrective Actions:** Need for external extinguisher system. For the RAM Study a fire rate = 0.5 event/year has been used.	F5	C4	**2**
TRK02	Fracture in rail due to fatigue and stress cracking.	**Preventive Actions:** Routine inspections and maintenance during operation are required. **Corrective Actions:** Flash butt welds to be carried out by qualified welders. Supervision, control and QA during implementation, mounting and maintenance tasks.	F4	C5	**2**
POW01	Loss of one of the Main Power Supply incoming feeders.	**Preventive Actions:** Routine maintenance. **Corrective Actions**: Design redundant incomer feed taps and redundant transformers to enable the reconfiguration of the power supply in a short period of time (few seconds)	F4	C4	**3**
POW02	Failure of one transformer or related protection.	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Design redundant system to enable the reconfiguration of the power supply in a short period of time (few seconds)	F4	C4	**3**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
POW03	Failure of the distribution of MV to Traction Power Substations.	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Design redundant MV substation system to enable system restoration in a short period of time (few seconds).	F4	C4	**3**
POW04	Failure of one Transformer/Rectifier Group	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Design redundant T/R system to enable system restoration in a short period of time (few seconds).	F4	C4	**3**
POW05	Loss one of the Traction Power incoming feeders.	**Preventive Actions**: Routine maintenance. **Corrective Actions**: Design redundant incomer feeders to enable system restoration in a short period of time (few seconds).	F4	C4	**3**
COM01	Failure in information transmission. Unable to establish communication between 2 or more system's areas.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have a high availability on communications **Corrective Actions**: Repair procedures.	F4	C4	**3**
COM02	Wrong information transmission. Wrong information give it between 2 or more system's areas.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have a high availability on communications **Corrective Actions**: Repair procedures.	F4	C4	**3**
COM03	Unable to manage communication information. Communication operator cannot access to the information.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have a high availability on communications **Corrective Actions**: Repair procedures.	F4	C4	**3**
COM04	Loss of signalling communication.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have a redundant communication system **Corrective Actions**: Repair procedures.	F4	C4	**3**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
COM06	Loss of data integrity. Wrong data transmission among all systems.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** Design shall guarantee an integrity robustness solution **Corrective Actions**: Repair procedures	F4	C4	**3**
COM08	Radio Base Station failure (zone affected)	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have high redundancy and availability of Radio system **Corrective Actions**: Repair procedures.	F4	C4	**3**
COM09	Train selective radio communication failure.	**Preventive Actions**: Routine maintenance **Mitigation in the design phase:** System shall have high redundancy and availability of on-board Radio system. **Corrective Actions**: Repair procedures.	F5	C3	**3**
RST04	Loss of mechanical integrity or electrical continuity.	**Preventive Actions:** Proper maintenance and inspections. **Corrective Actions**: Failure reported to the OCC and repair procedures taken.	F3	C5	**3**
RST05	Fails to limit train movement from damaging track.	**Preventive actions**: Proper maintenance **Corrective action**: Train taken out of service at end of route	F4	C4	**3**
RST06	The tram gives a poor ride comfort.	**Preventive actions**: Proper maintenance **Corrective action**: Train taken out of service at end of route	F4	C4	**3**
RST10	Loss of communication between the train equipment (traction, brake, on-board signalling equipment, etc.).	**Preventive actions**: Proper maintenance and testing **Corrective action**: Train taken out of service at end of route	F4	C4	**3**
RST14	Failure of one or more HVAC units requires passengers to be detrained and the train taken out of service due the challenging climate conditions	**Preventive actions**: Proper maintenance and testing **Corrective** action: Detrainment and train taken out of service	F4	C4	**3**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
RST15	Failure of vehicle Fire and Life Safety (F&LS) system gives a false fire alarm.	**Preventive actions**: Proper maintenance and testing **Corrective action**: Detrainment and train taken out of service	F4	C4	**3**
SIG01	Unable to detect trains due to a failure on a tram detection device (Wayside Axle counters).	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG02	Unable to detect switch position.	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG03	Train detected in a track section where there is no LRT.	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG04	Unable to switch point machine (failure of interlocking).	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG05	Failure of the interlocking.	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG06	Permissive aspect is displayed. Trains have permissive when they should not. (Failure of interlocking).	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG07	Non permissive aspect is displayed. Trains do not have permissive when they should. (Failure of interlocking)	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG08	Proceed aspect is displayed. Trains have permissive when they should not (Failure of a signal)	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
SIG09	Incorrect point machine position monitoring. Uncontrolled routes of LRT.	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG10	Position of point machine is not controlled. LRT moves to an incorrect track section	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
SIG11	Possible LRT movement to an incorrect track section.	**Preventive actions**: Proper maintenance **Corrective action**: The local controls or the manual command boxes located locally can be used to service operation and manage incidents.	F4	C4	**3**
AFC01	Failure of one validator machine (either check-in or check-out). Passengers need to use an alternative validator.	This kind of failure may produce little interference with the service. The equipment will be held "off-line" and a signal will be produced to show the trouble (a beep, a red light, a message in the display, etc...). Moreover, the situation could be reinforced by the on-board Public Address (e.g. "Please, use the working validators" message) or Passenger Information System (displaying "Some validators are not working, please, use the working ones"). Regarding the passengers, it is considered that the impact may be small since passengers can use an alternative validator unit.	F4	C4	**3**
AFC02	Failure of all validators or the concentrator (either check-in or check-out). Passengers cannot validate their tickets.	Passengers will be allowed to use the transport without validation (payment free) until the train ends the service reaching line's head. OCC must be warned to replace the faulty train for a working one as quick as possible.	F4	C4	**3**
RST01	Defect in the door movement which delays or prevents passengers boarding or alighting the tram.	**Preventive Actions:** Proper maintenance and inspections. **Corrective Actions**: Failure reported to the OCC and repair procedures taken.	F5	C2	**4**
RST02	Door opens whilst tram is moving.	**Preventive Actions:** Proper maintenance and inspections. **Corrective Actions**: Failure reported to the OCC and repair procedures taken.	F5	C2	**4**

Failure Mode Code	Failure Description (from FMECA)	Preventive/Corrective Actions	Frequency	Severity	Criticality
RST03	Loss of mechanical integrity.	**Preventive Actions:** Proper maintenance and inspections. **Corrective Actions**: Failure reported to the OCC and repair procedures taken.	F3	C4	**4**
RST12	Loss of pantograph.	**Preventive actions**: Proper maintenance and testing **Corrective action**: Detrainment and train taken out of service	F4	C3	**4**
TRK01	Manufacturing defects or defective mounting of rails.	**Preventive Actions**: Periodic inspections and maintenance schedule. **Corrective Actions:** Specifications and Quality Procedures during manufacturing. Supervision and QA control during implementation and mounting.	F3	C4	**4**
TRK03	Resonance and excessive rail stresses.	**Preventive Actions**: Scheduled inspection and maintenance of rail sections during operation are required. **Corrective Actions:** Grinding during non-operational hours.	F3	C4	**4**
TRK05	Failure in track gauge due to defective mounting and implementation.	**Preventive Actions**: Scheduled inspection and maintenance of rail sections during operation are required. **Corrective Actions:** Supervision, control and QA during construction and maintenance periods. Implementation and rail mounting to be carried out by qualified operators.	F3	C4	**4**
TRK04	Fasteners inadequately fixed during construction or maintenance.	**Preventive Actions**: Scheduled inspection and maintenance of rail sections during operation are required. **Corrective Actions:** Supervision, control and QA during construction/ maintenance periods.	F3	C2	**6**

Table 17 Proposal of Preventive/Corrective Actions

9. Economic Evaluation

The only costs associated with this study are those related to the employee remuneration, software licenses, hardware equipment and energy consumption[13].

A summarizing table is presented below with the total cost and major budget items (more details can be found in the Budget Document itself.

Concept	***Total*** (€)
Employee remuneration	12450
Software licenses	6670
Hardware expenses	2400
Other costs	135
Total	**21655 €**

Table 18 Summary of the total cost of the study

It is important to keep in mind that these values shall be taken as estimation because it can vary depending on different aspects such as the price per hour of the employee who develop the study, the computer used or the price of electricity consumption.

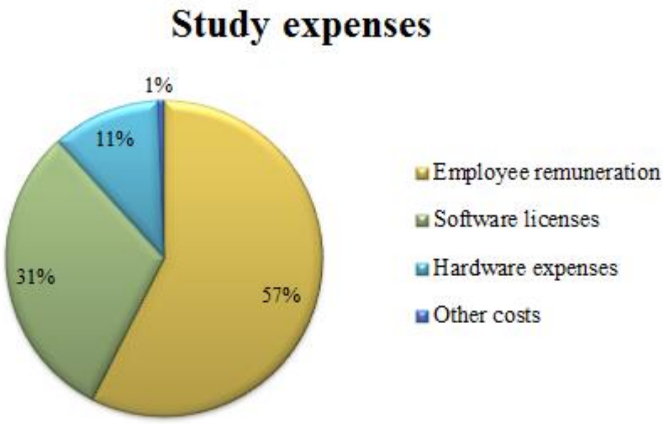

Figure 41 Summary of study expenses

Also note that "Other costs" such as power consumption and office material are almost negligible compared with the rest, being the main expenses those related with the remuneration of the engineering hours dedicated.

[13] Note that the travels for client meetings are not included.

10. Analysis and Assessment of Environmental Implications

This section is conceived in order to find out environmental implications derived from the *"Reliability, Availability and Maintainability Analysis of a Light Rail Transit System"*. As its name indicates, it is a study and, for this reasons, it does not have direct environmental implications itself.

As this document is a Preliminary Study for a project that its intention would be to allow the LRT system to be put in service, and therefore, to be operable after a design and its construction, the environmental implication taken into account are going to be those in which the LRT system would interact.

The main goal for an urban transit system, such as LRT system, is to provide frequent and reliable services covering a dense developed area, providing as good accessibility as possible. So, with the development of the project that this document analyzes, the mobility of the area where the system is allocated will be solved. The decongestion of city traffic and mobility improving will provide a better quality of life. But this cannot happen alone. An environmental integration is absolutely required in order to make the LRT system be a part of a whole and not be one mean of transportation independent.

For this reason, the environmental impact needs to be kept to a minimum, incorporating in the design of the tracks, stations, depot and associated structures/facilities.

In order to have an efficient and effective LRT system, safe and secure, and also environmentally friendly, it is necessary to have environmental awareness, comply with regulations, use non-hazardous materials, control the air quality and noise and report environmental incidents so it can be treated and improved.

The LRT System described in this document must preserve the natural environment of the city where it is emplaced. In this way, as it describes a segregated on-street LRT, its guideway would help to achieve a more sustainable environment with new trees plantation or grass, helping to be more visually attractive.

As the ISO 14001 standard indicates, the system shall be designed to be capable of operate in site temperature conditions, but that cannot mean a worse material selection, as they have to minimize the deleterious effects of ultraviolet radiation. It shall be also electromagnetically compatible with its environment, as the system shall not produce electromagnetic emissions that interfere with the normal operation of electromagnetic devices or equipment used in and around the site.

10.1. Potential Environmental Impacts and Mitigation Measures

The intention of the LRT System described in this document is to provide a reduction of vehicles by its establishment on the site and contribute to the diminishment of their associated air pollutant emissions.

For this reason, it is need to present in this section, the environmental concern during the operation of the LRT system that include air and noise pollution, landscape and visual impact, between others.

10.1.1. Air Quality

On the next stage of this document, the LRT system analyzed would have to be constructed. Its construction will provoke dust generation from areas where the activity would be taken place. Such dust would have to be suppressed with water sprayers in order not to impact local population, sensitive habitats, species and existing buildings and structures near the project site.

Also, in order to reduce air pollutant emissions from heavy equipment and machinery needed in the construction, fuels as much clean as possible will have to be used. And regular maintenance of machinery and vehicles take place.

10.1.2. Geology

During LRT system construction, changes in soil and groundwater system from excavation works would change or alter the existing natural soil.

Restriction on movements of heavy traffic would be a mitigation measure to prevent this geological impact.

10.1.3. Noise and Vibration

Noise impacts may arise as a result of traction motors, electric generator or noise from rolling stock. In the design, there would be mitigation measures such as isolation of the track to minimize both noise and vibration or noise barriers.

10.1.4. Landscape

Where the term stations have appeared in this document, they were specially designed in order to have as minimum as possible visual impact. Also, for the LRT rolling stock, sustainable materials and design would be incorporated.

10.1.5. Fire

Although this item has been already treated in previous sections, it is important to notice that when a failure related to power takes place, in the design it has to be contemplated how this failure will interact with its environment.

That means that near the OHS, traction power substations or other electrically related components, it would have to be firewall materials that would prevent its expansion if that failure happens and ends in a fire.

11. Planning and Scheduling

11.1. Tasks identification

A detailed list of tasks carried out during the study is presented below:

A. INFORMATION RESEARCH
A.1 Research of applicable guides and standards
B. DEVELOPMENT OF WRITEN REPORT
B.1 Aim, scope, requirements and justification
B.2 RAM Discipline
B.2.1 RAM Concepts
B.3 Light Rail Transit (LRT) System
B.3.1 Project Background
B.3.2 System Breakdown Structure
B.4 RAM Requirements
B.4.1 Key Performance Indicators
B.4.2 Methodology of Analysis
B.4.3 Methods and Tools
B.5 LRT RAM Analysis and Prediction
B.5.1 Decision of chosen methods
B.5.2 Critical system selection
B.5.3 FMECA
B.5.4 Sensitive Analysis on KPIs
B.5.5 FTA
B.6 RAM Requirements Apportionment
B.7 Reliability Critical Items List
B.8 Environmental Impact Study
B.9 Conclusions and Recommendations
B.10 Revision of the Report
C. BUDGET
C.1 Development of the budget

D.	**DELIVERY AND REVISION**
	D.1 Provisional delivery
	D.2 Recommended modifications
	D.3 Final delivery
E.	**ORAL PRESENTATION**
	E.1 Preparation of oral presentation

Table 19 Tasks Identification

11.2. Brief tasks description

A.1 Research of applicable guides and standards: Get knowledge enough over LRT System, Railway applications, System Analysis, Inductive Methods, Reliability, Maintainability and Risk, etc.

B.1 Aim, scope, requirements and justification: Define the first important points of the report in order to develop the study over these objectives.

B.2 RAM Discipline

B.2.1 RAM Concepts: Explanation of RAM terms and concepts strongly related with RAM discipline.

B.3 Light Rail Transit (LRT) System:

B.3.1 Project Background: Description of the LRT project for which this study analyses the Service Availability (SA)

B.3.2 System Breakdown Structure: Definition of different system levels for which activities have to be analyzed during the LRT project.

B.4 RAM Requirements

B.4.1 Key Performance Indicators: Explanation of the four quality criterion that would be essential to be able of measuring the Trip Achievement Level, and so, the SA.

B.4.2 Methodology of Analysis: Description of the methodology of analysis that will be applied to the apportionment of RAM requirements for the LRT System in this study.

B.4.3 Methods and Tools: Explanation of selected methods and tools that can be employed in the RAM analyses.

B.5 LRT RAM Analysis and Prediction

B.5.1 Decision of chosen methods: Identification of the applicable methods to be used during the study from the previous described.

B.5.2 Critical system selection: Identification of the systems to be analysed in order to fit the scope of the analysis.

B.5.3 FMECA: Analysis of the possible effects of each failure on the System.

B.5.4 Sensitive Analysis on KPIs: Justification to be able to model the SA using reliability modelling tools usually used in reliability analysis due to its binary events restriction.

B.5.5 FTA: Development of complete Fault Tree Analysis Model developed for the Preliminary Engineering RAM allocation of a LRT System.

B.6 RAM Requirements Apportionment: Qualitative RAM Requirements description to provide specifications for system and subsystem level.

B.7 Reliability Critical Items List: Definition of reliability critical failures with an impact on Service Availability or LRT Operation. It also provides possible design mitigations (Preventive/Corrective Actions).

B.8 Environmental Impact Study: Environmental implications related with the study.

B.9 Conclusions and Recommendations: Summarize the main issues addressed in the study and make some conclusions and recommendations.

B.10 Revision of the Report: review the entire document in order to correct the spelling mistakes and give it proper cohesion.

C.1 Development of the budget: Develop a budget taking into account all aspects related to the development of this study.

D.1 Provisional delivery: Delivery of the project in digital format.

D.2 Recommended modifications: Inclusion of first review on format.

D.3 Final delivery: Final delivery on June 2014.

E.1 Preparation of oral presentation: Development of the presentation template and selection of the project information for a correct exposure in time and quality.

11.3. Interdependence relationship among tasks and effort

Code of task	Task description	Preceding task	Level of effort (h)
A.	**Information Research**		
A.1	Research of applicable guides and standards	-	30
B.	**Development of written report**		
B.1	Aim, scope, requirements and justification	A.1	10
B.2	RAM Discipline		
B.2.1	RAM Concepts	A.1, B.1	10
B.3	Light Rail Transit (LRT) System		
B.3.1	Project Background	A.1	8
B.3.2	System Breakdown Structure	A.1, B.3.1	10
B.4	RAM Requirements		
B.4.1	Key Performance Indicators	A.1, B.3	30
B.4.2	Methodology of Analysis	A.1, B.2, B.4.1	25
B.4.3	Methods and Tools	A.1,B.2, B.4.2	10
B.5	LRT RAM Analysis and Prediction		
B.5.1	Decision of chosen methods	B.4.3	5
B.5.2	Critical system selection	B.5.1	5
B.5.3	FMECA	B.2,B.3, B.4, B.5.1, B.5.2	50
B.5.4	Sensitive Analysis on KPIs	B.5.3	70
B.5.5	FTA	B.5.3	30
B.6	RAM Requirements Apportionment	B.5.5	40
B.7	Reliability Critical Items List	B.5.3, B.5.5	25
B.8	Environmental Impact Study	B.7	10
B.9	Conclusions and Recommendations	B.5., B.6, B.7, B.8	10
B.10	Revision of the Report	B.9	5
C.	**Budget**		
C.1	Development of the budget	B.9	20
D.	**Delivery and Revision**		
D.1	Provisional delivery	C.1	1
D.2	Recommended modifications	D.1	10
D.3	Final delivery	D.2	1
E.	**Oral presentation**		
E.1	Preparation of oral presentation	D.3	20

Table 20 Relationship among tasks and effort

11.4. Gantt chart

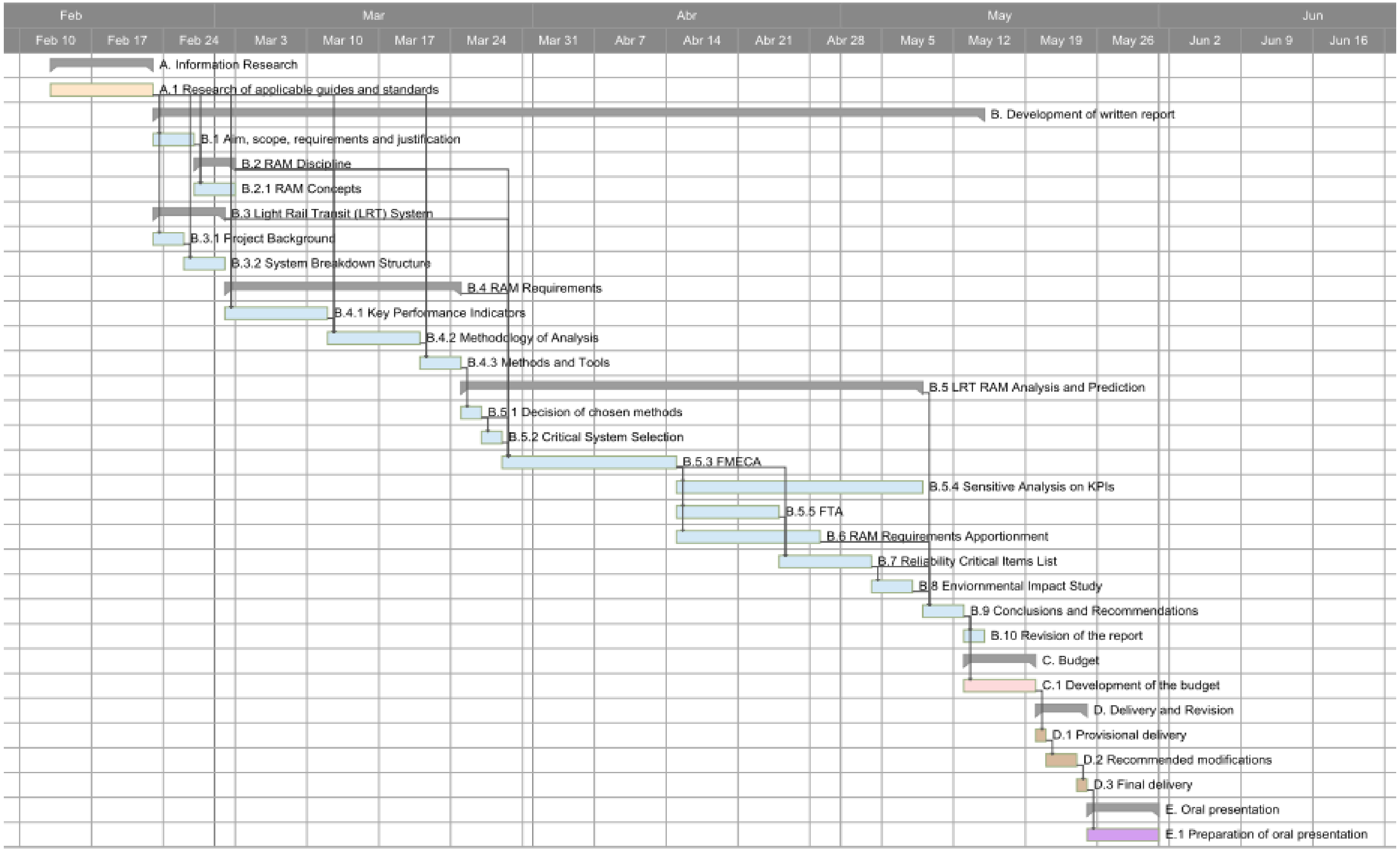

Figure 42 Gantt chart for study activities

On the previous Gantt diagram, one can see the development of the work in order to get this document. Moreover, on the following Gantt chart, it is represented the next stage tasks that could be done after this study. That means that although the study has been developed for an early and preliminary stage, a deeper and more detailed study can be done after the *"Reliability, Availability and Maintainability Study of a Light Rail Transit System"* using it as a base document in order to get more accurately to its actual extension.

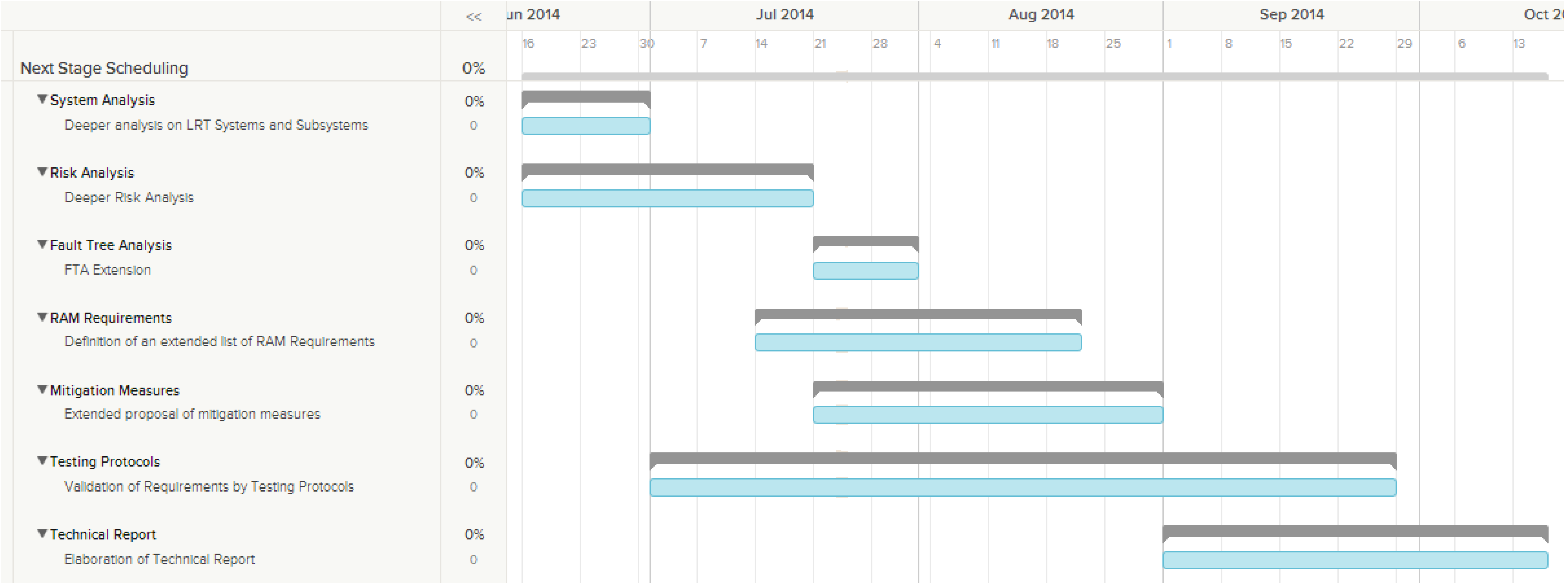

Figure 43 Gantt chart for next stage study activities

12. Conclusions and Recommendations

Quantified results predict that the proposed design for the LRT System achieves a total Service Availability of 99.87%, therefore meeting the required Service Availability of 99.8% established:

$$SA = \frac{\sum(PIDT \times PICS \times PITE \times PIUS)}{ST} \tag{18}$$

Reliability, Availability, and Maintainability requirements have been apportioned to LRT Systems and Subsystems by means of identified failure modes affecting the Service Availability and Service Interruption, and taking into account repair, access and logistic times.

Due to the project's size and complexity, it has been considered a good practice to develop a quantitative Failure Mode Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA) to perform the LRT RAM Analysis and prediction. The system failure mode analysis has been carried out in terms of the Mean Time Between Service Affecting Failures (MTBSAF), identifying the effects of potential failures of the LRT Systems and Subsystems on the Key Performance Indicators driving the overall system Service Availability.

Table 21 shows, over an estimated system lifetime of 30 years, the following data:

- Unavailability (Q)
- Failure Frequency (W)
- Expected number of failures
- Total Down Time (TDT)
- Total Up Time (TUT)
- Mean Time Between Failures (MTBF)
- Mean Time To Failure (MTTF)
- Mean Time To Restore (MTTR)

for each Key Performance Indicator and overall Service Availability:

- PIDT: Departure Times – This performance indicator means that if the considered scheduled trip is performed or missed, taking into account the actual headway with the previous trip compared with the scheduled headway.
- PICS: Commercial Speed – This performance indicator means that if the actual commercial speed of the train is lower, equal or higher than the scheduled commercial speed.

- PITE: Train Evacuations - This performance indicator considers a train evacuation when the train is evacuated between two stations during the trip.
- PIUS: Unscheduled Stops

Parameter	**Service Availability (SA)**	**PIDT**	**PICS**	**PITE**	**PIUS**
Unavailability (Q)	0.0012041	0.0009393	0.0007364	0.0003127	0.0004296
Failure Frequency (W)	0.00092813	0.000732	0.0005388	0.0001311	0.0002536
Expected Failures	193.09827	152.2929	112.1033	27.2785	52.7622
Total Down Time (hours)	249.3998	194.5819	152.4714	64.7365	88.9467
Total Up Time (hours)	207800.60	207855.41	207897.52	207985.26	207961.05
MTBF (hours)	1077.4307	1366.1172	1855.8778	7626.8819	3943.1644
MTTF (hours)	1076.1392	1364.8395	1854.4518	7624.5087	3941.4786
MTTR (hours)	1.2916	1.2777	1.3601	2.3732	1.6858
Service Availability	**99.8796%**	**99.9061%**	**99.9264%**	**99.9687%**	**99.9570%**

Table 21 Service Availability summary

So, in this study, a thorough sensitivity analysis of the impact of each Performance Indicator on the Trip Achievement Levels (TAL) has demonstrated that the Service Availability can be degraded by any single failure affecting the Key Performance Indicators.

This study has been carried out as a Preliminary Engineering Study for the Light Rail Transit System. In order to implement this LRT System, it is recommended to follow the next step in the design which would be detailed design, production planning and tool design, and finally production.

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Appendixes

Appendix I: RAM Concepts

System Architecture

A system is a collection of components, arranged in various architectures, in order to perform the desired function.

A system, or set of components, are said to be in a 'series' architecture if the failure of any component would cause the system to fail performing the desired function.

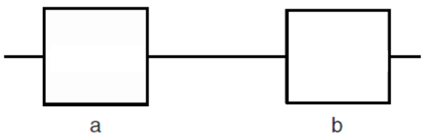


Figure 44 System 'series' architecture

A system or set of components are said to be in a 'redundant' (or parallel) architecture if the system can continue to perform the desired function if a component fails.

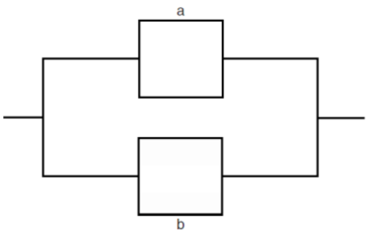


Figure 45 System 'parallel' 1oo2 architecture

There are various redundancy architectures. However, the ones that are mostly used are:

- One out of two (1oo2) where one component out of two must be functioning for the system to function
- Two out of three (2oo3) where two components out of three must be functioning for the system to function

A repairable system is one in which a failed component can be replaced, for example a bearing in a car.
A non-repairable system is one in which a failed component cannot be replaced, for example a missile or a space craft.
A non-repairable component is on that is disposed of, for example a light bulb or a brake pad.

System Failures

System failures can be caused by a variety of different causes, or combination of causes, for example:

- Equipment failure
- Software errors
- Environmental issues
- Human errors

Failures can be either random or systematic.

Systematic failures are deterministic and are managed through engineering and quality management processes.

Random failures are managed through component and system topology selection (e.g. redundancy) guided by probabilistic reliability modeling and reliability demonstration through observed failure data.

It is the combination of reliability and maintainability which dictates the proportion of time that any system or component is available for use (availability), the key parameters being failure rate and downtime.

Failure Rate

Every component has a failure rate (λ) which is the number of components failing per unit time. This failure rate changes over the lifetime of the component:

- Early failure period, where the component exhibits the 'infant mortality rate' which is primarily due to manufacturing defects or material weakness. Ideally these components are detected by the manufacturer through 'burn in' tests
- Constant failure rate period, where the component can fail randomly (with equal probability)
- Wear-out period, where the component has come to the end of its useful life and the failure rate starts increasing (no longer constant). Wear-out is due to such factors as ageing corrosion or fatigue.

This is illustrated in Figure 46. The useful life of the component is where it exhibits a constant failure rate. Reliability modeling assumes a constant failure rate and for the reliability prediction to hold true, only components operating in this region should be deployed. That is, the component should be 'burnt-in' before installation and should be replaced before the wear out period commences.

It is essential that the reliability modeling assumptions are captured (as requirements requiring validation in the requirements management tool) and reflected into the operation and maintenance documentation.

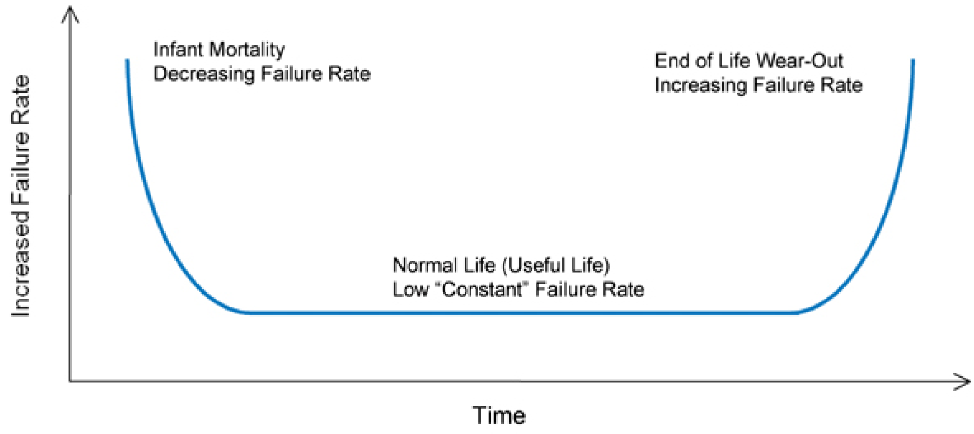


Figure 46 'Bathtub' curve failure rate

Reliability

Reliability is defined as the probability that an item (system/component) can perform a required function under given conditions for a given time interval [1].

It is expressed as a number between 0 and 1. It is represented by symbol $R(t_1, t_2)$.

The reliability of a component operating within its useful life period and with a constant failure rate can be expressed as:

$$R_t = e^{-\lambda t} \quad (19)$$

Where:

- e = exponential function
- λ = constant failure rate
- t = time

The Mean Time Between Failures (MTBF) is a measure of reliability for repairable systems and is the arithmetic mean of the time between failures.

$$MTBF = \frac{1}{\lambda} \quad (20)$$

Where:

- λ is the constant failure rate

Other measures of reliability include:

- Mean Cycles Between Failures (MCBF): this would be applicable, for systems such as platform screen doors or fare gate systems
- Mean Kilometers Between Failures (MKMBF): this would be applicable to a rolling stock Service Affecting Failure
- Service Affecting Failure: A failure that provokes that a train be withdrawn from service or a station be closed for use.

Reliability Prediction

Actual failure rate data is not available during the early phases of the life cycle and thus RAM actual performance cannot be measured. During these early life cycle phases, RAM assurance is based upon predictive analyses by modeling the design topology and applying failure rate information from equivalent systems / components.

Prediction of system reliability through modeling based on failure rates generally reveals only very approximate reliability values. This is caused by:

- Wide variability of the failure rates of identical components
- Actual systems / components are not identical to those for which the failure rate data applies
- Systems / components are not used in the same mode as that for which the failure rate data applies
- Systems / components are not used in the same environment as that for which the failure rate data applies
- Systems / components are not maintained in the same environment as that for which the failure rate data applies

Therefore the degree of complexity of reliability modeling should be balanced against the expected accuracy and the modeling costs.

The main benefit of reliability prediction modeling of complex systems is not in the absolute reliability estimate, but in the ability to model the system using different parameters to compare design approaches or topologies and identify critical elements. For example:

- Component selection
- Repair times
- Redundancy arrangements

RAM predictive analysis shall be performed in concert with design, in order to inform design, and shall be complete prior to the completion of the design phase.

Reliability prediction analysis estimates the system failure rate (λ), or mean time between failures, MTBF (1/λ) based upon system architecture and component failure rates.

For redundant repairable systems, the reliability estimate depends on the repair times for the redundant components.

Availability is then predicted based on mean time between failures and an estimate of the mean time to restore, MTTR, those failures.

Availability

Availability is defined as the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over time interval assuming that the required external resources are provided.

It is expressed as a ratio or percentage and is represented as:

$$A = \frac{Up\ Time\ (available\ to\ function)}{Total\ Time} = \frac{\sum UP_t}{\sum UP_t + \sum DN_t} \quad (21)$$

Where:

- UP_t = Up Time
- DN_t = Down Time

The Mean Time Between Failures (MTBF) can be expressed as:

$$MTBF = \frac{Total\ time}{Number\ of\ failures} \quad (22)$$

And the Mean Down Time (MDT):

$$MDT = \frac{\sum DN_t}{Number\ of\ failures} \quad (23)$$

Availability can then be expressed as:

$$A = \frac{MTBF}{MTBF + MDT} \quad (24)$$

Maintainability

Maintainability is defined as the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.

Maintainability is the ease with which repairs and other maintenance work can be carried out. Maintenance activities can be either:

- Corrective maintenance (repair), where maintenance is required to restore a system from a failed to an operational state. Corrective maintenance is quantified as the mean time to restore (MTTR)
- Preventive maintenance, which seeks to retain the system in an operational or available state and test for undetected failures.

Both corrective and preventative maintenance directly affect availability. The time taken to repair failures and the time taken for routine preventative maintenance can remove the systems from the available state.

Maintainability is directly governed by design. The design determines such features as:

- Accessibility of equipment
- Ease of test and diagnosis
- Ease of repair and calibration
- The level of skill required
- The periodicity of preventative maintenance
- The need for specialist tools / equipment

Appendix II: MTTF Failure Model Quantification

MTTF is Mean Time to Failure. MTTF Model is a time based model and assumes constant failure rate in terms of failures per hour over the life time of the system. Here the failure rate and the repair rate are given by:

$$\lambda = \frac{1}{MTTF} \qquad (25)$$

MTTR to repair rate:

$$\mu = \frac{1}{MTTR} \qquad (26)$$

Unavailability at time t, or Lifetime:

$$Q(t) = \frac{\lambda}{\lambda + \mu}\left[1 - e^{-(\lambda+\mu)t}\right] \qquad (27)$$

Failure Frequency at time t, or Lifetime:

$$\omega(t) = \big(1 - Q(t)\big)\lambda \qquad (28)$$

Where:

$$Q(t) = Component\ unavailability$$

$$\omega(t) = Component\ failure\ frequency$$

$$MTTF = Mean\ time\ to\ failure$$

$$MTTR = Mean\ time\ to\ repair$$

$$\lambda = Component\ failure\ rate$$

$$\mu = Component\ repair\ rate$$

And:

$$MTBF = MTTF + MTTR$$

$$MTTF = MTBF - MTTR \qquad (29)$$

Where:

$$MTBF = Mean\ time\ between\ failures$$

Numerical results for the Fault Tree Analysis have been calculated by the FTA software used: Item Software - Item Toolkit Fault Tree Analyses;

http://www.itemsoft.com/fault_tree.html,

according to the mathematical formulae of Kumamoto and Henley, [16].

An unavailability quantification example is provided in Table 22 for failure mode COM04 - *Loss of signalling communication*.

COM04 Loss of signalling communication	
MTBF	100000
MTTF	99999
MTTR	1
λ	1,00001E-05
μ	1
t	208050
Q(t)	0,00001
ω(t)	0,00001

Table 22 Unavailability calculation example – COM04

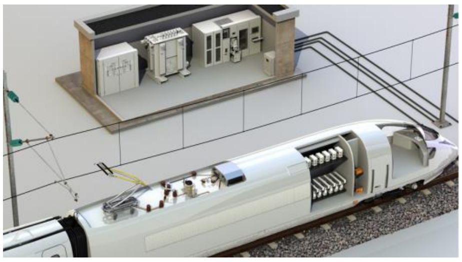
Appendix III: FMECA – Subsystems Not Affecting SA

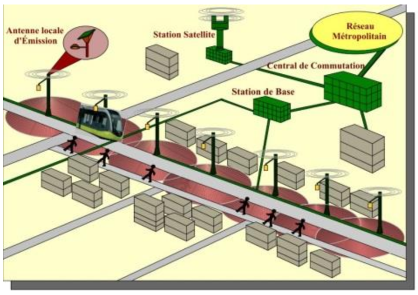
Rail systems	Subsystem	Function	Failure Mode Code	Failure Description	Key Performance Indicators (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
Communications	General Functions	Enable backup of system servers	COM11	Wrong data storage. Unable to storage correctly all servers information.	No	No	No	No	N/A	N/A
			COM12	Failure data storage. Unable to storage all servers information.	No	No	No	No	N/A	N/A
	Telephone	Provide voice communications	COM13	Telephone does not work properly in with the elevator. Unable to establish voice communication by Telephone with the elevator	No	No	No	No	N/A	N/A
		Provide acoustic signalling and visual signalling.	COM14	Unable to do calls out of the system.	No	No	No	No	N/A	N/A
		Communicate with external emergency departments	COM15	Unable to establish voice communication with external emergency departments	No	No	No	No	N/A	N/A
	Passenger Information Systems	Show visual passenger information (such as late arrival, commercial ads, …)	COM17	PIS show wrong message. Wrong visual information showed.	No	No	No	No	N/A	N/A
			COM18	PIS out of service. Unable to show visual information.	No	No	No	No	N/A	N/A
		Update automatically the incoming tram information (estimated time of arrival of the next tram and terminal station)	COM19	PIS show wrong message. Wrong visual information showed.	No	No	No	No	N/A	N/A
			COM20	PIS out of service. Unable to show visual information	No	No	No	No	N/A	N/A

Rail systems	Subsystem	Function	Failure Mode Code	Failure Description	Key Performance Indicators (KPIs)				MTBSAF (h)	MTTR (h)
					DT	CS	TE	US		
	Multiservice Network	Transmit time signal (through transmission network) to the clock equipment, PIDs, AFC machines, CCTV equipment along light rail tram system	COM21	Unable transmit time signal. Loss of correct time reference.	No	No	No	No	N/A	N/A
	CCTV	Video monitoring at stops, depots, wayside and on-board	COM23	Loss of video monitoring at stops, depots	No	No	No	No	N/A	N/A
			COM24	Loss of video monitoring on-board rolling stock.	No	No	No	No	N/A	N/A
		Monitor people movement (stations, substations, OCC, elevator and depot)	COM25	Camera broken. Unable to transmit visual images	No	No	No	No	N/A	N/A
			COM26	Camera dirty. Bad images transmitted.	No	No	No	No	N/A	N/A
		Provide human-CCTV interface	COM27	Screen broken. Unable to see visual images.	No	No	No	No	N/A	N/A
			COM28	Wrong screen performance. Bad quality images transmitted	No	No	No	No	N/A	N/A
	Public Address (PA)	Audio announcements	COM29	Loss of annunciation	No	No	No	No	N/A	N/A
MEP	Lifts & Escalators	Ingress / egress from different building's levels	MEP01	Lifts & Escalators failure	No	No	No	No	N/A	N/A
	Plumbing	Plumbing	MEP02	Plumbing failure	No	No	No	No	N/A	N/A
AFC	AFC	Vending / Payment functionality	AFC03	Failure at vending / payment process. Commercial transaction can't be done.	No	No	No	No	N/A	N/A

Table 23 Subsystems Not Affecting Service Availability

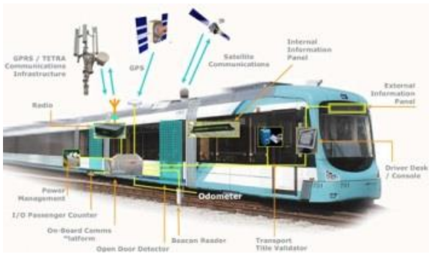
Appendix IV: Graphic Description of FMECA Subsystems

Rail systems	Subsystem	Function
Power	Main Power Supply	 Source: http://www.jamindo.net/de/
	Distribution Network	 Source: http://transmissionelectricity.blogspot.com.es/
	Traction Power	 Source: http://www.secheron.com/Applications/DC-traction-power-substation
	Overhead Catenary System (OCS)	 Source: http://citytransport.info/Trams02.htm

Rail systems	Subsystem	Function
Power	Stray Current Control	 Source: http://www.apwa.net/Resources/Reporter/Articles/2007/9/Stray-current-mitigation-in-Portlands-Transit-Mall
Communications	Transmission Network	 Source: http://departements.telecom-bretagne.eu/optique/research/capilr/
	Radio Communications	 Source: http://tram.cb.radio.product.info/
	CCTV	 Source: http://lumiplan.com/en/menu-video protection-retrovision-securite-voyageurs

Rail systems	Subsystem	Function
Rolling Stock	Doors / Gangway	 Source: http://www.vicsig.net/photo/13074
	Couplers	 Source: http://www.rmweb.co.uk/community/index.php?/blog/74/entry-3130-light-rail-excursion-around-frankfurt-20-march-2010-part-2/
	Running gear, Bogies & Suspension system	 Source: http://photo.tramscape.com/?pict=tram/freiburg/tech/combino_w_bogie
	Propulsion System	 Source: http://hampage.hu/trams/amszterdamparade/e_index.html

Rail systems	Subsystem	Function
Rolling Stock	Brakes	 Source: http://www.raillynews.com/2014/train-brake-systems-will-manufactured-turkey/
	Train control and communications equipment.	 Source: http://railnutternewsau.tripod.com/SydneyMonorailAndLightRail.html
	Electrical and Electronic equipment	 Source: http://www.railway-technical.com/etracp.shtml
	Heating, Ventilation and Air Conditioning (HVAC)	 Source: http://ttmrail.com.au/hvac.php
	Fire Detection and Alarm	 Source: http://www.epotos.com/home/helpful-information/

Rail systems	Subsystem	Function
Operations Control Centre (OCC)	Operational Staff	 Source: http://www.mhi-global.com/discover/graph/feature/no173.html
	Building	 Source: http://www.mhi-global.com/discover/graph/feature/no173.html
Signalling	Rail signalling	 Source: http://railsystem.net/railwaysignalling.htm
	Traffic Lights	 Source: http://www.citytransport.info/Signals.htm

Rail systems	Subsystem	Function
Automatic Fare Collection (AFC)	Automatic Fare Collection (AFC)	 Source: http://ov-chipkaart-kopen.nl/automatisch-opladen/
Fire & Life Safety	Fire Extinguishing	 Source: http://www.railway-technology.com/contractors/fire_fighting/gallery.html
Trackworks	Rail	 Source: http://www.rgbstock.com/bigphoto/2dpdyXh/Railway
	Fasteners	 Source: http://www.d2sint.com/antwerp-embedded-tram-track
	Gauge	 Source: http://en.wikipedia.org/wiki/Dual_gauge

Table 24 Graphic Description of FMECA Subsystems

Appendix V: Impact of the PIDT for Different Delay Times

Performance Indicator for Departure Times (PIDT) — OFF-PEAK HOURS - 9 minutes headway																															
Units	**Tens of seconds**																														
Delay (sec)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	**1,000**	0,981	0,963	0,944	0,926	0,907	0,889	0,870	0,852	0,833	0,815	0,796	0,778	0,759	0,741	0,722	0,704	0,685	0,667	0,648	0,630	0,611	0,593	0,574	0,556	0,537	0,519	0,500	0,481	0,463	**0,444**
1	**0,998**	0,980	0,961	0,943	0,924	0,906	0,887	0,869	0,850	0,831	0,813	0,794	0,776	0,757	0,739	0,720	0,702	0,683	0,665	0,646	0,628	0,609	0,591	0,572	0,554	0,535	0,517	0,498	0,480	0,461	0,443
2	0,996	0,978	0,959	0,941	0,922	0,904	0,885	0,867	0,848	0,830	0,811	0,793	0,774	0,756	0,737	0,719	0,700	0,681	0,663	0,644	0,626	0,607	0,589	0,570	0,552	0,533	0,515	0,496	0,478	0,459	0,441
3	0,994	0,976	0,957	0,939	0,920	0,902	0,883	0,865	0,846	0,828	0,809	0,791	0,772	0,754	0,735	0,717	0,698	0,680	0,661	0,643	0,624	0,606	0,587	0,569	0,550	0,531	0,513	0,494	0,476	0,457	0,439
4	0,993	0,974	0,956	0,937	0,919	0,900	0,881	0,863	0,844	0,826	0,807	0,789	0,770	0,752	0,733	0,715	0,696	0,678	0,659	0,641	0,622	0,604	0,585	0,567	0,548	0,530	0,511	0,493	0,474	0,456	0,437
5	0,991	0,972	0,954	0,935	0,917	0,898	0,880	0,861	0,843	0,824	0,806	0,787	0,769	0,750	0,731	0,713	0,694	0,676	0,657	0,639	0,620	0,602	0,583	0,565	0,546	0,528	0,509	0,491	0,472	0,454	0,435
6	0,989	0,970	0,952	0,933	0,915	0,896	0,878	0,859	0,841	0,822	0,804	0,785	0,767	0,748	0,730	0,711	0,693	0,674	0,656	0,637	0,619	0,600	0,581	0,563	0,544	0,526	0,507	0,489	0,470	0,452	0,433
7	0,987	0,969	0,950	0,931	0,913	0,894	0,876	0,857	0,839	0,820	0,802	0,783	0,765	0,746	0,728	0,709	0,691	0,672	0,654	0,635	0,617	0,598	0,580	0,561	0,543	0,524	0,506	0,487	0,469	0,450	0,431
8	0,985	0,967	0,948	0,930	0,911	0,893	0,874	0,856	0,837	0,819	0,800	0,781	0,763	0,744	0,726	0,707	0,689	0,670	0,652	0,633	0,615	0,596	0,578	0,559	0,541	0,522	0,504	0,485	0,467	0,448	0,430
9	0,983	0,965	0,946	0,928	0,909	0,891	0,872	0,854	0,835	0,817	0,798	0,780	0,761	0,743	0,724	0,706	0,687	0,669	0,650	0,631	0,613	0,594	0,576	0,557	0,539	0,520	0,502	0,483	0,465	0,446	0,428

Table 25   Impact of the PIDT on the TAL (Numerical) for different Delay times - 9 minutes headway

Performance Indicator for Departure Times (PIDT)																															
	OFF-PEAK HOURS - 6 minutes headway																														
Units	**Tens of seconds**																														
Delay (sec)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	**1,000**	0,973	0,947	0,923	0,900	0,878	0,857	0,837	0,818	0,800	0,783	0,766	0,750	0,735	0,720	0,706	0,692	0,679	0,667	0,655	0,643	0,632	0,621	0,610	0,600	0,590	0,581	0,571	0,563	0,554	**0,545**
1	0,997	0,970	0,945	0,921	0,898	0,876	0,855	0,835	0,816	0,798	0,781	0,764	0,748	0,733	0,719	0,705	0,691	0,678	0,665	0,653	0,642	0,630	0,620	0,609	0,599	0,589	0,580	0,571	0,562	0,553	0,545
2	0,994	0,968	0,942	0,918	0,896	0,874	0,853	0,833	0,814	0,796	0,779	0,763	0,747	0,732	0,717	0,703	0,690	0,677	0,664	0,652	0,641	0,629	0,619	0,608	0,598	0,588	0,579	0,570	0,561	0,552	0,544
3	0,992	0,965	0,940	0,916	0,893	0,872	0,851	0,831	0,813	0,795	0,778	0,761	0,745	0,730	0,716	0,702	0,688	0,675	0,663	0,651	0,639	0,628	0,617	0,607	0,597	0,587	0,578	0,569	0,560	0,551	0,543
4	0,989	0,963	0,938	0,914	0,891	0,870	0,849	0,829	0,811	0,793	0,776	0,759	0,744	0,729	0,714	0,700	0,687	0,674	0,662	0,650	0,638	0,627	0,616	0,606	0,596	0,586	0,577	0,568	0,559	0,550	0,542
5	0,986	0,960	0,935	0,911	0,889	0,867	0,847	0,828	0,809	0,791	0,774	0,758	0,742	0,727	0,713	0,699	0,686	0,673	0,661	0,649	0,637	0,626	0,615	0,605	0,595	0,585	0,576	0,567	0,558	0,550	0,541
6	0,984	0,957	0,933	0,909	0,887	0,865	0,845	0,826	0,807	0,789	0,773	0,756	0,741	0,726	0,711	0,698	0,684	0,672	0,659	0,647	0,636	0,625	0,614	0,604	0,594	0,584	0,575	0,566	0,557	0,549	0,541
7	0,981	0,955	0,930	0,907	0,885	0,863	0,843	0,824	0,805	0,788	0,771	0,755	0,739	0,724	0,710	0,696	0,683	0,670	0,658	0,646	0,635	0,624	0,613	0,603	0,593	0,583	0,574	0,565	0,556	0,548	0,540
8	0,978	0,952	0,928	0,905	0,882	0,861	0,841	0,822	0,804	0,786	0,769	0,753	0,738	0,723	0,709	0,695	0,682	0,669	0,657	0,645	0,634	0,623	0,612	0,602	0,592	0,583	0,573	0,564	0,556	0,547	0,539
9	0,976	0,950	0,925	0,902	0,880	0,859	0,839	0,820	0,802	0,784	0,768	0,752	0,736	0,721	0,707	0,694	0,681	0,668	0,656	0,644	0,633	0,622	0,611	0,601	0,591	0,582	0,572	0,563	0,555	0,546	0,538

Table 26 Impact of the PIDT on the TAL (Numerical) for different Delay times - 6 minutes headway

Performance Indicator for Departure Times (PIDT)

PEAK HOURS - 3 minutes headway

Units	**Tens of seconds**																														
Delay (sec)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	1,000	0,947	0,900	0,857	0,818	0,783	0,750	0,720	0,692	0,667	0,643	0,621	0,600	0,581	0,563	0,545	0,529	0,514	0,500	0,486	0,474	0,462	0,450	0,439	0,429	0,419	0,409	0,400	0,391	0,383	**0,375**
1	0,994	0,942	0,896	0,853	0,814	0,779	0,747	0,717	0,690	0,664	0,641	0,619	0,598	0,579	0,561	0,544	0,528	0,513	0,499	0,485	0,472	0,460	0,449	0,438	0,428	0,418	0,408	0,399	0,390	0,382	0,374
2	0,989	0,938	0,891	0,849	0,811	0,776	0,744	0,714	0,687	0,662	0,638	0,616	0,596	0,577	0,559	0,542	0,526	0,511	0,497	0,484	0,471	0,459	0,448	0,437	0,427	0,417	0,407	0,398	0,390	0,381	0,373
3	0,984	0,933	0,887	0,845	0,807	0,773	0,741	0,711	0,684	0,659	0,636	0,614	0,594	0,575	0,557	0,541	0,525	0,510	0,496	0,483	0,470	0,458	0,447	0,436	0,426	0,416	0,406	0,397	0,389	0,381	0,373
4	0,978	0,928	0,882	0,841	0,804	0,769	0,738	0,709	0,682	0,657	0,634	0,612	0,592	0,573	0,556	0,539	0,523	0,508	0,495	0,481	0,469	0,457	0,446	0,435	0,425	0,415	0,405	0,396	0,388	0,380	0,372
5	0,973	0,923	0,878	0,837	0,800	0,766	0,735	0,706	0,679	0,655	0,632	0,610	0,590	0,571	0,554	0,537	0,522	0,507	0,493	0,480	0,468	0,456	0,444	0,434	0,424	0,414	0,404	0,396	0,387	0,379	0,371
6	0,968	0,918	0,874	0,833	0,796	0,763	0,732	0,703	0,677	0,652	0,629	0,608	0,588	0,570	0,552	0,536	0,520	0,506	0,492	0,479	0,466	0,455	0,443	0,433	0,423	0,413	0,404	0,395	0,386	0,378	0,370
7	0,963	0,914	0,870	0,829	0,793	0,759	0,729	0,700	0,674	0,650	0,627	0,606	0,586	0,568	0,550	0,534	0,519	0,504	0,490	0,477	0,465	0,453	0,442	0,432	0,422	0,412	0,403	0,394	0,385	0,377	0,370
8	0,957	0,909	0,865	0,826	0,789	0,756	0,726	0,698	0,672	0,647	0,625	0,604	0,584	0,566	0,549	0,533	0,517	0,503	0,489	0,476	0,464	0,452	0,441	0,431	0,421	0,411	0,402	0,393	0,385	0,377	0,369
9	0,952	0,905	0,861	0,822	0,786	0,753	0,723	0,695	0,669	0,645	0,623	0,602	0,583	0,564	0,547	0,531	0,516	0,501	0,488	0,475	0,463	0,451	0,440	0,430	0,420	0,410	0,401	0,392	0,384	0,376	0,368

Table 27   Impact of the PIDT on the TAL (Numerical) for different Delay times - 3 minutes headway

Performance Indicator for Departure Times (PIDT)																															
	PEAK HOURS - 3 minutes headway																														
Units	**Tens of seconds**																														
Delay (sec)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	1,000	0,923	0,857	0,800	0,750	0,706	0,667	0,632	0,600	0,571	0,545	0,522	0,500	0,480	0,462	0,444	0,429	0,414	0,400	0,387	0,375	0,364	0,353	0,343	0,333	0,324	0,316	0,308	0,300	0,293	**0,286**
1	0,992	0,916	0,851	0,795	0,745	0,702	0,663	0,628	0,597	0,569	0,543	0,519	0,498	0,478	0,460	0,443	0,427	0,412	0,399	0,386	0,374	0,363	0,352	0,342	0,332	0,323	0,315	0,307	0,299	0,292	0,285
2	0,984	0,909	0,845	0,789	0,741	0,698	0,659	0,625	0,594	0,566	0,541	0,517	0,496	0,476	0,458	0,441	0,426	0,411	0,397	0,385	0,373	0,361	0,351	0,341	0,331	0,323	0,314	0,306	0,299	0,291	0,284
3	0,976	0,902	0,839	0,784	0,736	0,694	0,656	0,622	0,591	0,563	0,538	0,515	0,494	0,474	0,456	0,440	0,424	0,410	0,396	0,383	0,372	0,360	0,350	0,340	0,331	0,322	0,313	0,305	0,298	0,291	0,284
4	0,968	0,896	0,833	0,779	0,732	0,690	0,652	0,619	0,588	0,561	0,536	0,513	0,492	0,472	0,455	0,438	0,423	0,408	0,395	0,382	0,370	0,359	0,349	0,339	0,330	0,321	0,313	0,305	0,297	0,290	0,283
5	0,960	0,889	0,828	0,774	0,727	0,686	0,649	0,615	0,585	0,558	0,533	0,511	0,490	0,471	0,453	0,436	0,421	0,407	0,393	0,381	0,369	0,358	0,348	0,338	0,329	0,320	0,312	0,304	0,296	0,289	0,282
6	0,952	0,882	0,822	0,769	0,723	0,682	0,645	0,612	0,583	0,556	0,531	0,508	0,488	0,469	0,451	0,435	0,420	0,405	0,392	0,380	0,368	0,357	0,347	0,337	0,328	0,319	0,311	0,303	0,296	0,288	0,282
7	0,945	0,876	0,816	0,764	0,719	0,678	0,642	0,609	0,580	0,553	0,529	0,506	0,486	0,467	0,449	0,433	0,418	0,404	0,391	0,379	0,367	0,356	0,346	0,336	0,327	0,318	0,310	0,302	0,295	0,288	0,281
8	0,938	0,870	0,811	0,759	0,714	0,674	0,638	0,606	0,577	0,550	0,526	0,504	0,484	0,465	0,448	0,432	0,417	0,403	0,390	0,377	0,366	0,355	0,345	0,335	0,326	0,317	0,309	0,302	0,294	0,287	0,280
9	0,930	0,863	0,805	0,755	0,710	0,670	0,635	0,603	0,574	0,548	0,524	0,502	0,482	0,463	0,446	0,430	0,415	0,401	0,388	0,376	0,365	0,354	0,344	0,334	0,325	0,317	0,308	0,301	0,293	0,286	0,280

Table 28   Impact of the PIDT on the TAL (Numerical) for different Delay times - 2 minutes headway

Appendix VI: Subsystem RAM Requirements

This appendix has been created in order to describe RAM Requirements that LRT Subsystems do not affect any of the Key Performance Indicators (See Appendix III: FMECA – Subsystems Not Affecting SA)

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
	COMMUNICATIONS	
RAM-082	Wrong data storage during a backup of system servers shall be reported to the Communications Control System in the OCC.	Rail Systems
RAM-083	A failure in data storage during a backup of system servers shall be reported to OCC.	Rail Systems
	Telephone	
RAM-084	A failure to establish voice communication by telephone with the elevator shall be reported to the Communications Control System in the OCC via the SCADA system.	Rail Systems
RAM-085	A failure to provide acoustic or visual signalling on incoming telephone calls shall be reported to the Communications Control System in the OCC.	Rail Systems
RAM-086	There shall be redundancy of public telephony providers.	Rail Systems
RAM-087	A failure of the line with Emergency Services shall be reported to the Communications Control System in the OCC.	Rail Systems
RAM-088	There shall be a backup for the line with Emergency Services.	Rail Systems
	Passenger Information Systems	
RAM-089	PIS out of service failure shall be reported to the Communications Control System in the OCC.	Rail Systems
RAM-090	After failure of the PIS system, the PA system should be used to provide information to passengers.	O&M
	Transmission Network	
RAM-091	The communications system shall be able to work without a continuous time reference.	Rail Systems
	CCTV	
RAM-092	Loss of video monitoring on-board rolling stock shall be reported to the OCC.	Rail Systems
RAM-093	A broken camera that is unable to transmit visual images shall be reported to the OCC.	Rail Systems
RAM-094	Any camera suffering an image degradation that is noticeable to the OCC operators shall be reported to the OCC.	Rail Systems
RAM-095	A broken CCTV screen shall be reported to the OCC.	O&M

REQ. ID	REQUIREMENT TEXT	DISCIPLINE
RAM-096	A CCTV screen showing bad performance (bad quality images transmitted) shall be reported to the OCC.	O&M
	Public Address (PA)	
RAM-097	The Public Address system shall be designed with enough redundancy, so that a single PA failure does not provoke a loss of audio announcements.	Rail Systems
	MECHANICAL / ELECTRICAL / PLUMBING (MEP)	
	Lifts & Escalators	
RAM-098	A lifts or escalators failure shall be reported to the Stops local Building Automation and Control System (BACS) and to the OCC.	Rail Systems
	Plumbing	
RAM-099	A plumbing failure shall be reported by the Operations and Maintenance Staff.	O&M

Table 29 Subsystems RAM Requirements