

DEVELOPMENT OF RISK MODELS FOR GENERIC HAZARDS OF THE JERUSALEM LIGHT RAIL TRANSIT SYSTEM

by

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Abstract

Quantitative safety risk models (SRMs) for mainline railways are designed to enhance safety performance in the mainline sector. They are used to identify the safety risks most affecting railway systems by quantifying the predicted outcomes of the risks, in terms of frequency and level of seriousness. This study focusses on tramway systems operating according to line-of-sight principles. During the literature review phase of his research, the author was not able to identify a single generic safety risk model for a tramway system along the lines of the UK SRM that had been developed for the mainline railway. He also did not discover a specific safety risk model associated with a particular hazard inherent in the operation of tramway systems. However, at a later stage of writing the thesis the author came across a paper that discusses the application of a random effects negative binomial model to examine the frequency of accidents involving trams.

The present study aims to quantify the risks associated with three generic tramway operation hazards, namely, excessive jerk, collisions between trams due to signals passed at danger events (SPADs) and overturning of a tram on a sharp curve due to excessive speed. The author demonstrates that SRMs can be developed for line-of-sight tram operations. The risk modelling and quantification are based on statistical models and fault tree/event tree models. SRMs for SPAD and overturning of trams on sharp curves were developed to assess the potential risk, given the limited occurrence of these hazards. Since they are considered rare events with sparse data, the model results were validated against expert judgement. The risk evaluation and acceptance were based on the criteria set by the Jerusalem Master Plan Team (JTMT) and international criteria. The findings indicate that a comprehensive SRM can be developed for the Jerusalem Light Rail Transit (JLRT) network, a system that operates according to line-of-sight tram operation, using modelling techniques developed for the mainline sector. The models developed in this study are based mainly on past accident reports from the JLRT network; they show that the existing residual risks are Undesirable and cannot be accepted and therefore additional mitigation measures must be applied. This study makes an original contribution to quantitative risk assessment by creating a practical methodology for the study of low-frequency, high-consequence events. Moreover, the results of the risk

modelling and the expert judgement resulted in the decision to adopt additional mitigation measures that will upgrade the safety level of the JLRT network.

List of Publications based on this Thesis

Borowsky A., Shinar D., Palacci N. and Itzhaki M. (in press) The assessment of hazard awareness skills among light rail drivers. *Transportation Research Part F: Psychology and Behaviour*.

Itzhaki M. and Schmid F. (in press) Assessing the risk of collisions between trams due to SPADs in conflict areas of an LRT network. *Transportation Research Record*. See Appendix E – Documents Showing Status of Publications

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List of Abbreviations

Term	Explanation / Meaning / Definition
AIS	Abbreviated Injury Scale
ALARP	As Low As Reasonably Practicable [NEW]
APTA	American Public Transportation Association
ATP	Automatic Train Protection
AVLS	Automatic Vehicle Location System
BEvn	Basic Event / Braking Event
BOStrab	German Federal Regulations for the construction and operation of light rail transit systems
CBA	Cost Benefit Analysis
CCTV	Closed-Circuit Television
CENELEC	European Committee for Electrotechnical Standardization
CI	Confidence Intervals
COMAH	Control of Major Accident Hazards
CR	Collective Risk
CV	Contingent Valuation
DBO	Design Build Operate
DNV GL	Company offering risk management and quality assurance services
EB	Emergency Braking
EJ	Excessive Jerk
EPC	Engineering Procurement and Construction
ERA	European Union Agency for Railways
ET	Event Tree
ETA	Event Tree Analysis
FT	Fault Tree
FTA	Fault Tree Analysis
FWI	Fatality Weighted Injuries / Fatality Weighted Index
FWSI	Fatalities and Weighted Serious Injuries
GAMAB	Globalement Au Moins Aussi Bon (Globally at least as good)
GB	Great Britain (England, Scotland and Wales)
HP	Hazard Perception
HPT	Hazard Perception Test
IEC	International Electrotechnical Commission
ISA	Independent Safety Assessor
ISS	Injury Severity Score
JLRT	Jerusalem Light Rail Transit
JTMT	Jerusalem Master Plan Team
LRT	Light Rail Transit / Light Rapid Transit
LU	London Underground
MEM	Minimum Endogenous Mortality (for new systems)
MIL-HDBK-338B	Military Handbook, Electronic Reliability Design Handbook
MMI	Man Machine Interface, also Human Machine Interface

Term	Explanation / Meaning / Definition
MODSafe	Modular Urban Transport Safety and Security Analysis
MOT	Ministry of Transportation
NIS	New Israeli Shekel
NPV	Net Present Value
NUREG-0492	Fault Tree Handbook U.S. Nuclear Regulatory Commission
OCC	Operation Control Centre
OCS	Overhead Contact System
ORR	Office of Rail and Road
O&M	Operation and Maintenance
PHA	Preliminary Hazard Analysis
PIM	Precursor Indicator Model
PPP	Public Private Partnership, an approach to funding public projects
PSA	Petroleum Safety Authority
PVC	Present Value Coefficient
QRA	Quantitative Risk Assessment
RAIB	Rail Accident Investigation Branch
RAMS	Reliability, Availability, Maintainability and Safety
RENB	Random Effects Negative Binomial (Distribution)
RIG	RSD Internal Guidance
RSD	Railway Safety Directive, Office of Rail and Road
RSSB	Rail Safety and Standards Board
RTSS	Road Traffic Signalling System
SAE ARP4761	Society of Automotive Engineers, Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
SCADA	Supervisory Control And Data Acquisition
SFAIRP	So Far As Is Reasonably Practicable [NEW]
SG	Standard Gamble
SII	Standards Institution of Israel
SMIS	Safety Management Information System
SPAD	Signal Passed At Danger
SRM	Safety Risk Model
S&SD	Safety and Standards Directorate (a part of the former Railtrack, UK)
STRMTG	Service Technique des Remontées Mécaniques et des Transports Guidés, French national technical agency for transport systems
TPA	Transport Project Appraisal
TSS	Tram Signalling Systems
UITP	International Association of Public Transport
VBZ	Verkehrsbetriebe Zürich
VPF	Value of a Prevented Fatality
WTP	Willingness to Pay

A term with a specific safety / reliability meaning is capitalised where it should be read as such, e.g., Tolerable, Undesirable, Remote, Improbable, Not Acceptable, Acceptable.

1 Introduction

1.1 Background

Most tramway and light rail transit (LRT) systems (UITP, 2019) operate according to line-of-sight principles over parts or most of their routes (BOStrab, 2007). Where these principles are not deemed safe enough, trackside signalling authorises the drivers to proceed into and through so-called 'controlled sections'. The trams of the Jerusalem Light Rail Transit (JLRT) system operate largely within the street network of the city, although the tracks are generally segregated from the road traffic. Occasionally though, a tram driver might apply emergency braking (EB) to avoid a collision with a third party, which may lead to excessive jerk (EJ), or pass through tram signals that show restrictive aspects, an event called a SPAD (Signal Passed at Danger (ORR, 2019)), or disregard a speed signal and enter a sharp curve at excessive or even overturning speed.

Excessive jerk is considered a high-frequency, low-consequence event and it may result in an uncomfortable journey in a tram. It is considered a hazard that may cause passengers to lose their balance and to fall and injure themselves inside the tram, with potentially lasting damage. The main cause for this hazard is EB, during which drivers brake to avoid collisions with third parties. During the years 2014-2016, nearly 900 EB events occurred in the JLRT system, where over 6% of EB ended with injuries.

Signal passed at danger events are considered low-frequency, high-consequence events that create the hazard of collisions between trams or derailments at points that face the wrong direction, and they are frequently attributed to driver distraction and inattention (Naweed, 2013). During the years 2014-2016, 38 SPAD events occurred across the JLRT system. Of these, 19 events led to potential collisions between trams.

Overturning of a tram on a sharp curve due to excessive speed is also considered a low-frequency, high-consequence event. The overturning speed is defined as the speed at which a vehicle derails or overturns because centrifugal forces overcome gravity (National Academy of Sciences, 2012). The event of a tram overturning while negotiating a sharp curve is an accident that occurs mainly due to drivers disregarding speed limit signals or restrictions.

Risk is defined in EN 50128 as a “combination of the rate of occurrence of accidents and incidents resulting in harm (caused by a hazard) and the degree of severity of that harm” (CENELEC , 2011). In other words, risk is the probability of occurrence of a safety event, multiplied by its consequences. Quantitative risk analysis and modelling techniques can thus be used to identify which safety risks are most affecting the system and its operator, for both tram systems and mainline systems. This is done by quantifying the predicted value of the risks, mainly in terms of fatalities and weighted injuries (FWI). By accurately quantifying the magnitude of the risk, evaluating its tolerability and the costs involved to mitigate it as low as reasonably practicable (ALARP), decision makers can consider whether the mitigation costs are proportionate to the safety benefits achieved.

During the literature review phase of his research, the author was not able to identify a generic safety risk model for a tramway system that had been created along the lines of the UK SRM that was developed for the mainline railway. He also did not discover a specific safety risk model associated with a particular hazard inherent in the operation of tramway systems. However, at a later stage of writing the thesis the author came across a paper by Farhana et al. (Farhana, Graham, David, & Majid, 2016) that discusses the application of a random effects negative binomial model to examine the frequency of accidents and incidents involving tramway vehicles. The UK mainline railway SRM, developed by the Rail Safety and Standard Board (RSSB), is based on a series of fault tree (FT) and event tree (ET) models representing 110 hazardous events that collectively define the overall level of risk in the railway system (Dennis, Somaiya, Small, & Singh, 2002). This model has been designed to consider both high-frequency, low-consequence events and low-frequency, high-consequence events. The model measures the risk in terms of fatalities and weighted injuries (FWI) and the output is used to support development of the three-year safety plans and to identify safety investments.

1.2 Motivation for the Study

Modelling of the risks associated with hazards that fall into two categories, high-frequency, low-consequence events and low-frequency, high-consequence, events was identified as a useful activity. The modelling can form the basis for creating, in the future a broader safety

risk model for a tramway system that is similar to the SRM that has been developed for the mainline railway.

The hazards, that is, Excessive Jerk, collision between trams due to SPADs, and overturning of trams, are inherent in the operation of the trams. In an emerging system, where new tram lines are being built, such as that of Jerusalem, the risks arising from these hazards might increase, due to the fact that more tram signalling systems (TSS) (SII, 2002) are being installed, sharp curves are being added and the interactions with third parties, i.e., the pedestrian population, cyclists and other road vehicles, are increasing. This creates a good opportunity to re-examine the effectiveness of the current safety mitigation measures and to determine the feasibility of investing in new technologies to minimise the risks of these hazards

The CENELEC standard EN 50128 defines safety as the “freedom from unacceptable levels of risk of harm to people” (CENELEC , 2011). That is an objective worth striving for and it sometimes involves high costs that must be considered in terms of cost-effectiveness. The common objective is to reach an acceptable level of risk in accordance with national regulations. It is important to achieve this safety objective as improving the trams’ operational safety saves lives. It is impossible to reach a state of absolute safety where there is no risk to people or technical systems, even though some stakeholders cannot accept this.

Finally, an accident that occurred in Croydon, England, in 2016, where a tram overturned on a curve with a radius of 30 m and the knowledge that the JLRT system has also tight curves along the line contributed to the motivation to model the risk of a tram overturning on a sharp curve.

1.3 Hypothesis and Research Question

1.3.1 Hypothesis

It is possible to create a tailored safety risk model (SRM) for the Jerusalem LRT system, which operates in line-of-sight operation mode. It is expected that such a model, once established, can be adopted by other LRT systems.

1.3.2 Research Questions

- i. Is it possible to model and quantify the safety risk associated with three hazards that were identified on the JLRT system? The hazards are (a) Excessive Jerk, a high-frequency, low-consequence event; (b) Signal Passed at Danger; and (c) Overturning of Tram due to Overspeed on Curves, both of which are considered low-frequency, high-consequence events, for which the accident data are sparse.
- ii. Are there any generic safety risk models associated with tramway systems that are similar to the UK SRM for mainline railways?
- iii. What methods and techniques have been used for modelling and quantifying safety risks in the railway sector and can the existing statistical and reliability modelling techniques be used to model and quantify the risks associated with the hazards defined in question (i)?
- iv. What are the existing methods for modelling the risks of rare events and what methods are used to validate the results of these models?
- v. Is there any national guidance on risk evaluation and risk acceptance?

1.4 Study Objectives and Model Success Criteria

- i. The author of this study aimed to quantify the risks associated with the generic tram hazards, i.e., EJ, collisions between trams due to SPAD events and overturning of trams on sharp curves due to overspeeding, and thus prove the hypothesis that it is possible to create a safety risk model for the line-of-sight-operation of the Jerusalem LRT system which can be adopted by other LRT systems.
- ii. The primary objectives of these models will be to obtain an understanding of the nature of the safety risks on the JLRT system and to provide relevant risk information and risk profiles to support the assessment of the impact of possible risk mitigation measures; therefore, the models shall meet the following success criteria:
 1. *Comprehensiveness: the models shall meet the criterion of comprehensiveness, meaning that the safety risk models should enable the assessment of the collective risk associated with the selected hazards and should determine the frequency and the consequences associated with the hazards.*

2. *Practicality: the models shall meet the criterion of practicality, meaning it shall be easy to obtain practical insights from the models' results with regard to the acceptability of the risks.*
3. *The models shall enable ALARP assessments*
4. *The models shall enable the assessment of the change in risks that can result from changes in technology and support implementation of these changes in the construction of the current and new Jerusalem tram lines.*
5. *Accuracy: the models results shall be reasonable and the risk prediction shall be as accurate as possible.*
6. *Usability: the models shall meet the criterion of usability, meaning that they must be easy to use by people.*
7. *Maintainability: the models shall meet the criterion of maintainability, meaning the models need to be easy to maintain.*
8. *The models shall provide a basis for continuous safety improvement and confidence that the JLRT system can operate safely.*

1.5 Scope

Safety performance indicators are used to assess the JLRT system's operational safety performance. The list of indicators comprises a variety of accidents and incidents associated with different generic operational hazards. These hazards are monitored by the JLRT operator and the author's department and their yearly consequences are reported to the Ministry of Transport. The present study is limited to developing risk models for those hazards that are capable of creating significant consequences, i.e., risks that may cause serious harm to passengers and staff on board the trams. Two major hazards were selected from that list, namely, excessive jerk due to activation of EB and SPAD which potentially can cause collisions between trams. The third hazard chosen for the study was overturning of trams on sharp curves. This hazard does not appear in the list as it was not monitored in Jerusalem; however, it was chosen because of an accident that occurred in Croydon, England, in 2016, where a tram overturned due to overspeed on a curve with a radius of 30 m and the fact that the JLRT system also has tight radii.

Following the selection of the hazards the author developed a risk model for each one, which predicts the annual collective risk (CR) in terms of fatalities and weighted injuries (FWI).

1.6 Methodology

1.6.1 Course at York University

The author participated in a course entitled “Safety and Risk Management in the Development Process”, at York University. The course provided the author with tools to process hazard identification, hazard analysis, system safety analysis, fault tree (FT) construction and analysis. This course significantly contributed to the development of the risk models in this thesis.

1.6.2 Literature Review

The author conducted a comprehensive literature review that examines the existence of safety risk models in the public transportation sector, with an emphasis on the steel wheel on steel rail (tramways and railways) sector, while also examining the existence of safety risk models which specifically quantify the risks of excessive jerk, SPADs and overturning of trams on sharp curves. An additional purpose of this review was to identify common models, methods and techniques which are used in quantifying safety risks in the tramway and railway domains, as well as in other industries.

1.6.3 Data Collection and Model Development

Choosing an approach to build a risk model is influenced by the availability of the data; in that respect, the lack of extensive and reliable data constitutes a serious obstacle. The main difficulty was to obtain past accident data for modelling the risk of collision between trams due to SPADs and the risk of overturning of trams on sharp curves. European tram operators could not share their information due to confidentiality, an information centre at the EU-level which collects data on tram accidents does not exist, and the one that the European Union Agency for Railways (ERA) maintains (ERA, 2019) has limited information, as do other websites, journals and books. Further details regarding data availability outside of the JRLT network are provided in Section 2.9.1.1.3.

Different approaches to quantifying the risks were examined by the author, aiming to overcome the lack of data. Finally, a closer examination of the JLRT post-SPAD investigation reports, which were generated by the JLRT operator, and, specifically, the photographs of the locations, and a review of the investigations themselves, produced the evidence that there had indeed been no actual accident as a result of a SPAD; however, there were several near-

miss situations. This led to the understanding that a risk model can be based on the risk of potential collision, i.e., a near miss collision between trams due to SPAD, rather than a collision itself. In the situation of a near-miss, the SPADing tram continues its movement toward an occupied controlled zone where another tram is already running or is about to enter.

Given the above evidence, the SPAD risk assessment could be based on the data of the SPAD investigation reports generated by the Jerusalem tram operator, and, thus, the probability that a SPAD will lead to a potential collision was assessed using fault tree analysis (FTA). An assessment was made for each individual intersection within the signalled zones; the possible consequences were then calculated, based on the number of passengers travelling in the conflict areas and past accidents that occurred in other tram systems. Knowing the probability and the potential consequences, the annual potential risk was calculated using event tree analysis (ETA) (IEC, 2010).

In summary, the SPAD risk model presented in the current thesis assesses the potential risk by assessing the occurrence of conflicts between trams in controlled sections. Such conflicts can be considered to be precursors, suggesting the likelihood of an accident occurring. Thus, the SPAD risk model may be considered a precursor indicator model (PIM). To validate the results of the quantified risk the author used expert judgement.

The risk of a tram overturning on a sharp curve was also modelled as a PIM. In this case, the precursor indicating the risk of such an accident occurring was the number of events in which a tram driver enters a curve with a radius of 25 m at a speed close to the threshold speed above which the tram might overturn. The probability was aligned with that of the precursor and the consequence(s) were based on similar events that have occurred elsewhere, e.g., on other tramway and light railway networks. To validate the results of the quantified risk the author used expert judgement.

1.6.4 Risk Analysis and Risk Quantification

The probability of the occurrence of each hazard was quantified using statistical models or fault tree (FT) models (CENELEC, 2007) or both. The model input data were drawn from the historical performance of the JLRT system. The consequences in the case of excessive jerk were taken from past accidents occurring in the JLRT system while, in the case of SPADs, the

consequences were based on past accidents that occurred elsewhere and the number of passengers travelling in the conflict areas of the JLRT network. The same method was applied in the case of overturning of trams on a sharp curve. Knowing the probability and the consequences, the annual potential risk was quantified using ETA (IEC, 2010) and statistical models. Due to the fact that SPADs and overturning events are rare, an expert judgement exercise was carried out to validate the results of the SPAD safety risk model, and the results of the safety risk model of overturning of a tram.

Throughout this phase, the author held meetings and phone calls with his supervisor. Through these sessions and conversations, the intermediate results of the models developed by the author were reviewed.

2 Literature Review

2.1 Introduction

Safety Risk Models (SRMs) for mainline railways have been developed by several countries for the purpose of improving the safety of their networks. The models use different techniques to predict the residual safety risk after the implementation of safety measures in the engineering, procurement and construction (EPC) phase.

The need to improve operational safety also exists in the operation of tramway systems; therefore, the purpose of the literature review is to answer the following questions: Have such models been developed for tramway systems? What methods and techniques have been used for modelling and quantifying the risks? What are the possible generic hazards to which passengers may be exposed during tram operation? Is there any national guidance in Israel for risk evaluation and risk acceptance? Finally, the review addresses the hypothesis that it is possible to create a risk model for line-of-sight tram operation.

2.2 Definitions

2.2.1 Accident

The Israeli Railways Ordinance (MOT, 2012) divides the definition of an accident into categories according to the results of the accident:

Accident: An incident relating to tramway operation, in which serious property damage was caused and

Accident with casualties: an incident relating to tramway operation in which a person was killed or seriously injured;

The Railway Safety Directive 2004/49/EC (ERA, 2004) defines accidents in terms of the severity of the consequences.

“Accident means an unwanted or unintended sudden event or a specific chain of such events which have harmful consequences; accidents are divided into the following categories: collisions, derailments, level-crossing accidents, accidents to persons caused by rolling stock in motion, fires and others” and;

“Serious accident means any train collision or derailment of trains, resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other similar accident with an obvious impact on railway safety regulation or the management of safety; ‘extensive damage’ means damage that can immediately be assessed by the investigating body to cost at least EUR 2 million in total”;

EN 50129 (CENELEC, 2018) defines an accident as: “unintended event or series of events that results in death, injury, loss of a system or service, or environmental damage”

In summary, the ERA definition is more specific, defining the types of accidents and what can be considered a serious accident in terms of the severity of its consequences.

2.2.2 Accident Precursor

“An event or condition that increases the probability of an accident which could result in the injury or death of a passenger, employee, contractor or third party or indicates that the probability of such an accident is increased” (Kyriakidis, Hirsch, & Majumdar, 2012).

2.2.3 Assessment Body

An assessment body can be appointed by any railway company to carry out independent safety assessment. The body must have been approved to carry out this function.

2.2.4 Broadly Acceptable Risk

“Risks resulting from hazards may be classified as broadly acceptable when the risk is so small that it is not reasonable to implement any additional safety measure” (ERA, 2013).

2.2.5 Catastrophic Consequence(s)

“Means fatalities and/or multiple severe injuries and/or major damage to the environment resulting from an accident” (ERA, 2013).

2.2.6 Common Safety Methods (CSMs)

The methods to be developed to describe how safety levels and achievement of safety targets and compliance with other safety requirements are assessed (ERA, 2004).

2.2.7 Design-Build-Operate (DBO)

A public private partnership (PPP) structure, in which a government entity enters into a single contract with a private sector party to design, construct and operate a project for a fixed fee.

2.2.8 Hazard

EN 50126 standard "Railway applications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)" defines a hazard as: "condition that could lead to an accident" (CENELEC, 2017).

2.2.9 Hazard Identification

The UK's RSSB divides the process of hazard identification into two stages: the first is to identify the hazardous events that could potentially lead to injury or fatality of passengers or any other people who are exposed to the tram operation or maintenance. The second stage is to identify the precursors, i.e., the system and subsystem failures, or human failures, which can result in the occurrence of each hazard event (RSSB, 2009). R I Muttram, Director of S&SD of Railtrack UK (1997-2000), summed up the process as identifying the "generic injury mechanisms by which a person can be killed or injured". The question to be asked is: "How can this type of injury be caused by a railway system?" (Muttram R. I., 2002).

2.2.10 Hazard Analysis

Hazard analysis is an integrated process which includes "identifying hazards and analysing their causes, and the derivation of requirements to limit the likelihood and consequences of hazards to a tolerable level" (CENELEC, 2017).

2.2.11 Hazard Log

"Document in which hazards are identified, decisions are made, solutions are adopted and their implementation status is recorded or referenced" (CENELEC, 2017).

2.2.12 Line Of Sight Driving

Line of Sight Driving is an operating mode for light rail networks: "In this mode, the light rail vehicle driver is responsible for maintaining, in all circumstances, a safe distance from any preceding light rail vehicle, as well as any road vehicle, pedestrian or cyclist in respect to service-braking capability. The light rail vehicle driver ascertains the occupancy rights and clearance of gauge for the section of track ahead. In this mode, the light rail vehicle driver adapts the speed of the vehicle according to designated speed limits and warning signs as provided, so as to ensure the safe movement of the vehicle" (Transport for NSW, 2018).

2.2.13 Rail Signalling

“Rail signalling is used where warranted by a risk assessment, to provide protection for light rail vehicles from collision with other light rail vehicles, and to protect against derailment. Rail signalling shall display proceed aspect only when all the designed rail risks are controlled” (Transport for NSW, 2018).

2.2.14 Reference System

“Means a system proven in use to have an acceptable safety level and against which the acceptability of the risks from a system under assessment can be evaluated by comparison” (ERA, 2013).

2.2.15 Risk

Risk is defined in EN 50128 as the “combination of the rate of occurrence of accidents and incidents resulting in harm (caused by a hazard) and the degree of severity of that harm” (CENELEC , 2011). In other words, risk is the probability of occurrence of a safety event, multiplied by its consequences, as shown in Equation 1.

$$\text{RISK} = \text{PROBABILITY (Frequency of hazard event)} \times \text{CONSEQUENCES (Severity of event)}$$

Equation 1: Risk Quantification

2.2.16 Individual and Collective Risk

Individual risk is the “risk, resulting from e.g. a product, process or system, to which an individual person is exposed” while the collective risk (CR) is defined as the “risk, resulting from e.g. a product, process or system, to which a population or group of people is exposed” (CENELEC , 2017) Equation 2 is based on RSSB guidance (RSSB, 2009).

$$\text{COLLECTIVE RISK (expected FWIs per year)} = \text{FREQUENCY (of hazard event per year)} \times \text{CONSEQUENCES (no. of FWIs per event)}$$

Equation 2: Collective Risk Quantification (RSSB, 2009)

These terms are clearly explained by (Sgobba, Wilde, Rongier, & Allahdadi, 2013) using an example of a common global individual risk where a person is killed by lightning. In that case, the individual risk can be assessed as the average number of people killed by lightning per year divided by the total population of the world. The outcome of any individual risk is an

adverse result to a single person, thus individual risk from an event is always a quantity which is bounded between zero and one, where zero means that the event is certain not to occur while one means that it is certain to occur. In contrast, the collective risk of fatalities caused by lightning on an annual basis is the mean number of people killed by lightning each year. Thus the collective risk is the mean of the adverse consequences resulting from a repeated event over a specified interval of exposure.

2.2.17 Risk Analysis

A systematic process to identify the hazards and estimate their risk (CENELEC, 2017).

2.2.18 Risk Evaluation

According to (CENELEC, 2017) it is a process based on risk analysis to determine whether a tolerable risk has been achieved.

EU Regulation 402/2013 definition is: “A procedure based on the risk analysis to determine whether an acceptable level of risk has been achieved” (ERA, 2013).

The difference is that tolerability does not mean acceptability; it requires demonstration that no reasonably practicable options to reduce risk further exist.

2.2.19 Risk Assessment

“The overall process comprising a risk analysis and a risk evaluation” (ERA, 2013).

2.2.20 Risk Acceptance Criteria

“Means the terms of reference by which the acceptability of a specific risk is assessed; these criteria are used to determine that the level of a risk is sufficiently low that it is not necessary to take any immediate action to reduce it further” (ERA, 2013).

2.2.21 Risk Acceptance Principle

“Means the rules used in order to arrive at the conclusion whether or not the risk related to one or more specific hazards is acceptable” (ERA, 2013).

2.2.22 Risk Model

“Tool designed to draft the risk profile of an entity which could be a railway organization or a Member State” (DNV GL, 2015).

2.2.23 Safety

EN 50128 defines safety as the “freedom from unacceptable levels of risk of harm to people” (CENELEC , 2011).

Safety is a concept that includes all the measures and practices taken to preserve the lives, health and physical integrity of people (Safeopedia, 2020) .

2.2.24 Safety Management System (SMS)

“In essence, it is a formal arrangement for a safer working environment. A safety management system defines roles and responsibilities, sets arrangements for safety mechanisms, involves workers in the process and ensures continuous improvement” (ORR, 2021).

2.2.25 Tolerable Risk

Means that we do not consider the risk as negligible or something to be ignored, but rather as something we need to keep under review and reduce further, if and as we can (Haugen & Rausand, 2011).

2.2.26 Tramway System

The American Public Transportation Association (APTA) defines light rail transit (LRT) as: “An electric railway system characterized by its ability to operate single or multiple car consists along exclusive rights-of-way at ground level, on aerial structures, in subways or in streets, able to board and discharge passengers at station platforms or at street, track, or car-floor level and normally powered by overhead electrical wires” (National Academy of Sciences, 2012).

2.3 Risk Management Process

2.3.1 Introduction

EU Regulation 402/2013 " (ERA, 2013) established a ‘common safety method’ (CSM) on risk evaluation and assessment. The CSM applies when any technical, operational or organisational change is being proposed to the railway system. A person making the change (known as ‘the proposer’) needs first to decide if the change has an impact on safety; if it has an impact then the proposer needs to decide if a change is significant or not by using CSM criteria. If the change is significant the proposer must apply the risk management process in

the CSM. The risk management process is described in Figure 1 and further details are provided below:

2.3.2 General Principles of the Risk Management Process

If the proposer decides that the change is significant as explained in 2.3.1, the proposer shall implement the risk management process, which starts with the system definition and ends when compliance of the system with all the safety requirements necessary to accept the risks. The risk management process comprises the following activities:

- a) “Risk assessment process which shall identify the hazards, the risks, the associated safety measures and the resulting safety requirements to be fulfilled by the system under assessment”;
- b) “Demonstration of the compliance with the identified safety requirements; and
- c) “Management of all identified hazards and the associated of safety measures”.

2.3.3 Risk Assessment Process

The risk assessment process is a repetitive process as described in Figure 1. The process comprises the following actions:

2.3.3.1 System Definition

System definition includes 1) objective of the system; 2) system functions and elements; 3) system boundaries; 4) system interfaces; 5) system environment; and 6) existing safety measures.

2.3.3.2 Risk analysis including hazard identification

The process includes three major actions: 1) using expertise to identify the hazards; 2) estimation of risk; and 3) risk reduction. Once the risk has been evaluated and considered acceptable, the proposer shall classify the hazards according to their estimated risk and register the hazards in the hazard record, including their safety measures.

2.3.3.3 Risk evaluation

At this the stage the proposer shall determine whether an acceptable level of risk has resulted from the risk analysis thanks to using the following principles:

a. Codes of practice

A code of practice may include domestic rules and standards and/or national standards. However, they need to comply with the following criteria: 1) be widely accepted in the railway sector such as TSIs, EU standards, ISO etc.; 2) be relevant for the control of the specific hazard; and 3) be available to an assessment body. In addition, other codes of practice used in different sectors, such as aviation and maritime, can be used if they are considered acceptable by the assessment body.

b. Reference systems

The reference system can be considered Acceptable and its safety requirements can be used for the system under assessment if the reference system complies with the following requirements: 1) the reference system has similar functions and interfaces; 2) the reference system works under the same operational conditions; and 3) the reference system works under similar environmental conditions.

c. Explicit risk estimation and evaluation

Explicit risk estimation is an assessment of the risks associated with the hazard, either quantitative or qualitative, or a combination of the two. "The acceptability of the estimated risks shall be evaluated using risk acceptance criteria either derived from or based on requirements contained in Union legislation or in notified national rules. If the estimated risk is not acceptable, additional safety measures shall be identified and implemented in order to reduce the risk to an acceptable level". The following are two criteria for risk acceptability:

- 1) *"For technical systems where a functional failure has a credible direct potential for a catastrophic consequence, the associated risk does not have **to be reduced** further if the rate of that failure is less than or equal to 10^{-9} per operating hour"*
- 2) *The ORR has set another criterion for critical accident which is defined as an accident that has an adverse outcome on a small number of people and results in at least one fatality, so that: "In cases where a failure has a credible potential to lead directly to a critical accident, the associated risk does not have to be reduced further if the frequency of the failure is less than 10^{-7} per operation hour" (ORR, 2018).*

2.3.4 Demonstration of Compliance with the Safety Requirements

The second principle of the risk management process determines that the proposer shall demonstrate to an assessment body the fulfilment of the safety requirement resulting from the risk assessment phase.

2.3.5 Management of all identified Hazards and their associated Safety Measures

The hazard records shall be registered and maintained by the system operator as an integrated part of its safety management system and shall include the hazards, together with their safety measures and system assumptions identified during the risk assessment process.

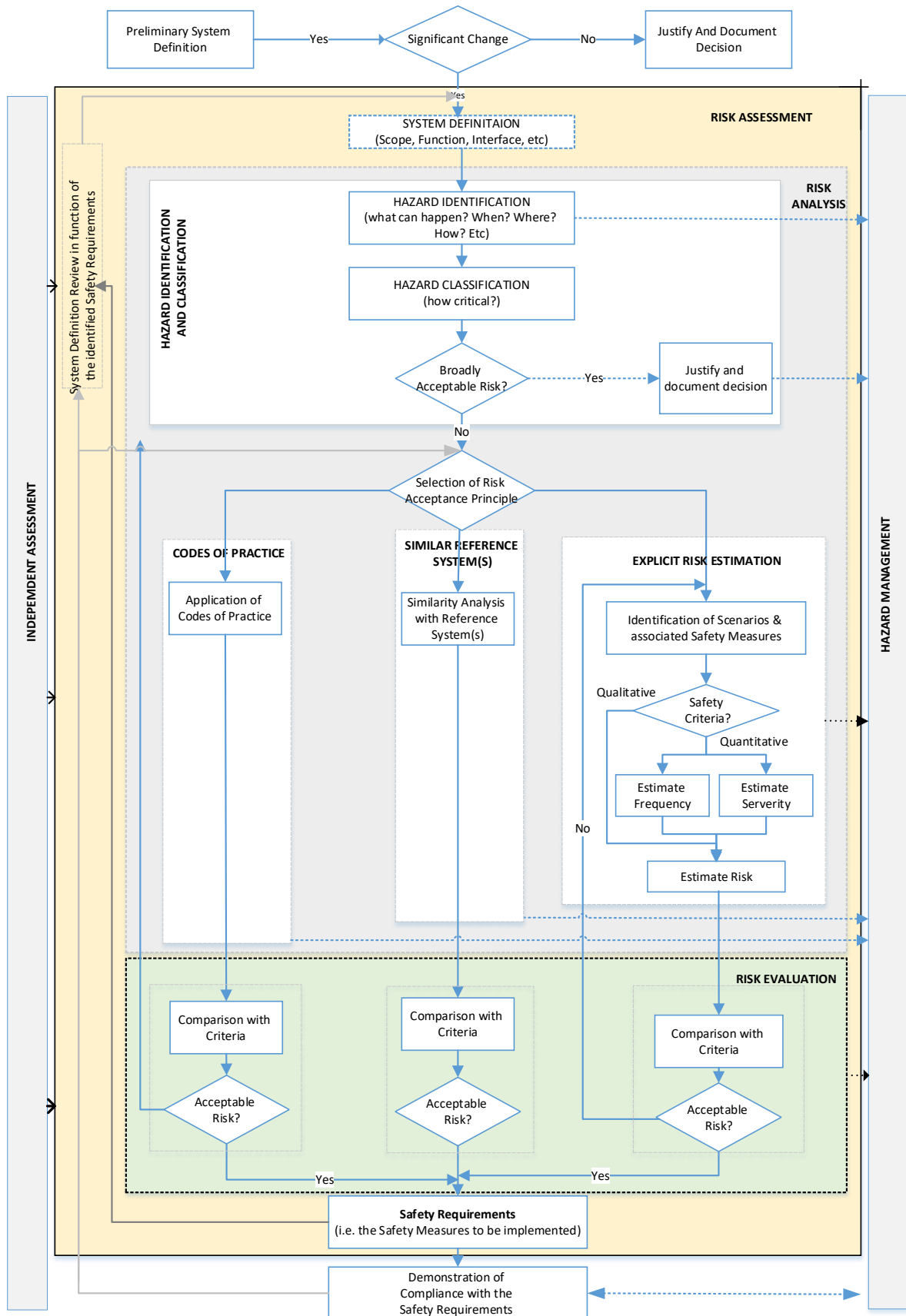


Figure 1: Risk Management Process and Independent Assessment (ERA, 2013)

2.4 Qualitative and Quantitative Risk Assessment and Evaluation

Explicit risk estimation and evaluation can be qualitative, quantitative or combination of the two, as described in Figure 1. Qualitative analysis evaluates the likelihood of risk occurrences and their impacts based on the subjective judgement of experts, while quantitative risk analysis provides the quantitative measures of these parameters.

Qualitative risk assessment methods are useful as an initial screening process to identify hazards and risks. They are also used when the estimated level of risk does not justify the time and effort required to collect the vast amount of data needed for quantitative risk assessment, and when the possibility of obtaining numerical data is limited (Westen & Greiving, 2017).

2.4.1 Quantitative Risk Analysis

Quantitative risk analysis and risk modelling techniques are discussed in detail in Section 2.9.

2.4.2 Qualitative Risk Analysis

Qualitative risk analysis is usually associated with expert judgement and qualitative risk ranking. Based on their experience and the records of similar systems the experts can qualitatively analyse the frequency and severity of hazards and obtain the frequency level and severity.

EN 50126-1 (CENELEC, 2017) provides qualitative terms and typical categories of frequency of occurrence of a hazard event and a description of each category. For example, “frequent” means that the hazard is likely to occur, “occasional” means that the hazard is likely to occur approximately once a year and ‘Improbable’ means that the hazard is unlikely to occur.

EN50126-1 (CENELEC, 2017) also describes typical hazard severity levels and their consequences. For example, “catastrophic” would mean a large number of injured people and multiple fatalities, and/or extreme damage to the environment, while “negligible” would mean less than minor injury, and minor system damage.

According to the results of qualitative analysis of frequency and severity, the risk matrix shown in Table 1 can be used to qualitatively evaluate the risk and apply the following actions (CENELEC, 2017):

- 1) **Intolerable:** “The risk shall be eliminated”.

- 2) **Undesirable:** “The risk shall only be accepted if its reduction is impracticable and with the agreement of the railway duty holders or the responsible Safety Regulatory Authority”.
- 3) **Tolerable:** “The risk can be tolerated and accepted with adequate control and with the agreement of the responsible railway duty holders”.
- 4) **Negligible:** “The risk is accepted provided adequate control is maintained”

Table 1: Risk Acceptance Categories (CENELEC, 2017)

Frequency of occurrence of an accident	Severity of an accident (caused by a hazard)			
	Catastrophic	Critical	Marginal	Negligible
Frequent	Intolerable	Intolerable	Intolerable	Undesirable
Probable	Intolerable	Intolerable	Undesirable	Tolerable
Occasional	Intolerable	Undesirable	Undesirable	Tolerable
Rare	Undesirable	Undesirable	Tolerable	Negligible
Improbable	Tolerable	Tolerable	Negligible	Negligible
Highly Improbable	Negligible	Negligible	Negligible	Negligible

2.4.3 Expert Elicitation

Elicitation of experts plays an important role in decision-making. The most difficult decisions are those where the consequences are subjected to significant uncertainty and these uncertainties cannot be easily judged (O'Hagan, et al., 2006). Yet, when major decisions need to be made in the presence of significant uncertainty, expert judgement is essential to minimize that uncertainty (Leung & Verga, 2007). Expert elicitation is in fact a methodology of scientific consensus; it is often used in the study of rare events and it allows “educated guessing” for the subject under consideration (Wikipedia, 2014). The elicitation of experts is a sensitive process, as the human mind tends to use intuitive strategies that are not necessarily rational or optimal (O'Hagan, et al., 2006). Leung and Verga (Leung & Verga, 2007) also claim that studies in psychology have shown that the capability of the human mind to judge probabilities accurately is limited by biases and by the tendency to use heuristics. Experts tend to produce distributions that are too narrow compared to their true state of knowledge. In estimating the frequency of major accidents in industrial facilities, it can also be assumed that

this bias can be expressed in the opposite direction; That is, a very conservative expert can produce a much wider distribution of his state of knowledge (Apostolaiis, 1990). However, expert opinions are required because safety assessments must deal with rare incidents. The issue is how to process this judgement and how to combine it with observations and frequencies. To achieve this, the rules of subjectivist probability theory are applied; that is, the judgement should be coherent, and it is synonymous with being objective (Apostolaiis, 1990).

2.5 Common Risk Acceptance Principles

2.5.1 ALARP Principle

The ALARP (as low as reasonably practicable) principle classifies the safety risks into three zones as described hereunder and in Figure 2. Further discussion on the ALARP boundaries is provided in Section 2.6.

- a. Unacceptable region: the risk is too high to be Acceptable and risk reduction measures must be implemented.
- b. Tolerable region or ALARP: the risk is below the Unacceptable region; however, it is not Acceptable without considering further measures to reduce it given that a cost benefit analysis is in favour of these measures.

“Tolerability does not mean acceptability. It refers to a willingness to live with a risk so as to secure certain benefits and in the confidence that it is being properly controlled. To tolerate a risk means that we do not regard it as negligible or something we might ignore, but rather as something we need to keep under review and reduce still further if and as we can” (HSE, 1992).

- c. Broadly acceptable region, the risk as broadly acceptable and no further measures are necessary. “For a risk to be 'acceptable' on the other hand means that for purposes of life or work, we are prepared to take it pretty well as it is” (HSE, 1992).

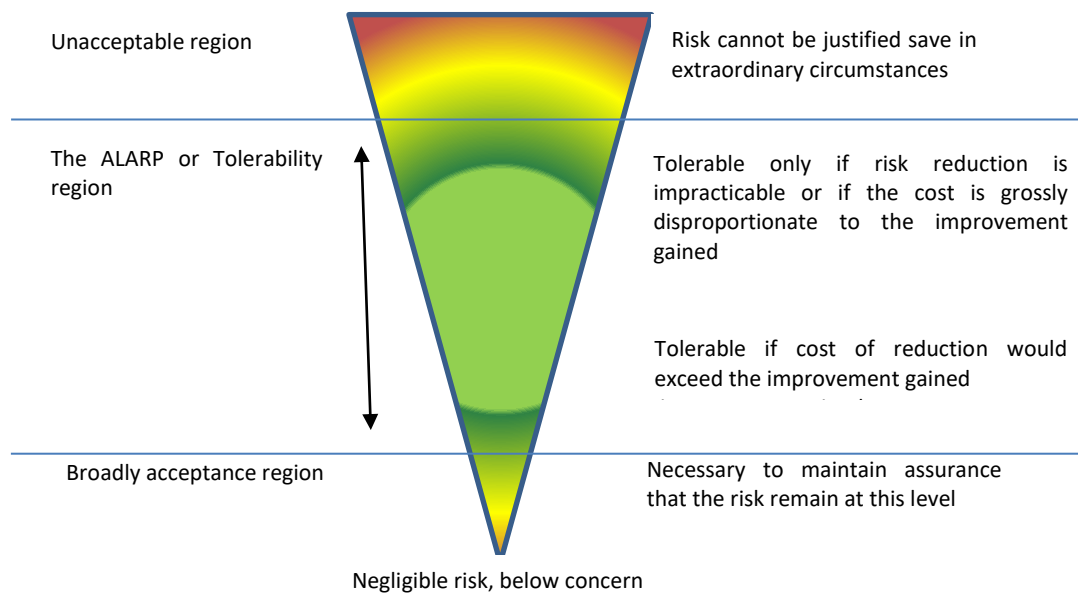


Figure 2: ALARP Principle (Haugen & Rausand, 2011)

2.5.2 SFAIRP Principle

SFAIRP (so far as is reasonably practicable) is widely used in health and safety legislation in the UK. ALARP and SFAIRP are two terms which mean essentially the same thing. At their core is the concept of “reasonably practicable”; this involves weighing a risk against costs to control it (HSE, 2021).

The SFAIRP is: “Similar to ALARP, but usually refers to a situation where no “lower limit” (negligible risk) is defined. In practice: risk should always be reduced” (Haugen & Rausand, 2011).

2.5.3 GAMAB Principle

GAMAB (globalement au moins aussi bon, that is, globally at least as good) is used in France in relation to transport systems. Basically it determines that a new guided transport system must offer a level of risk globally at least as good as the one offered by any equivalent existing system. Unlike the ALARP principle, GAMAB does not require decision makers to prove the cost effectiveness of a safety system.

2.5.4 MEM Principle

MEM (minimum endogenous mortality) is applied in Germany. It is applicable to transport systems. The principle means that the implementation of the new system cannot increase the probability of casualties. In Germany, casualties caused by rail transit systems are below the

country's lowest natural mortality rate, which for the 5–15 years old age group is 2×10^{-4} fatalities per year. Thus, the rail transit system in general set the safety objective to $R_m = 10^{-5}$ fatalities per year, where R_m refers to 'minimum endogenous mortality'.

2.6 Risk Evaluation and Risk Acceptance in the Railway Sector UK vs. Israel

2.6.1 UK Legal Requirements and Guidance

2.6.1.1 ORR guidance

According to ORR guidance on the application of Commission Regulation (EU) 402/2013, Chapter 3.41, "Explicit risk estimation", the risk acceptance principle to be used is SFAIRP; according to RSSB "this criterion is sometimes referred to as the 'ALARP principle'" (RSSB, 2014). ORR RIG-2099-05 states that the duty holders must "identify and implement the measures needed to deliver appropriate risk control including, where appropriate" to make a suitable risk assessment and cost benefit analysis in which they "compare the cost of implementing risk control measures (in terms of money, time and effort) against the reduction in risk those measures might achieve, and whether there is a gross disproportion between them". Such an analysis will help decision-making in support of safety-related investment (ORR, 2017). The ORR CSM provides additional criteria for risk acceptability as described in Section 2.3.3.3.

2.6.1.2 RSSB guidance

RSSB guidance on the preparation of risk assessment within the railway safety case (RSSB, 2002) sets criteria for individual passenger risk, individual employee risk and individual member of public risk, which are derived from the HSE's Guidance on ALARP Decisions in COMAH (HSE, 2021). The criteria for individual passenger and employee risk are presented in Table 2: Individual Risk Criteria .

Table 2: Individual Risk Criteria (RSSB, 2002)

Group	Upper limit of tolerability(probability of fatalities per year)	Railway group safety plan 2009 targets (probability of fatalities per year)	Broadly acceptance (probability of fatalities per year)
Individual passenger risk (regular traveller)	1×10^{-4} (1 in 10,000 per year)	1 in 133 million passenger journeys i.e. 3.75×10^{-6} (based on 500 journeys/year)	1×10^{-6} (1 in 1,000,000 per year)
Individual employee risk (any group of staff)	1×10^{-3} (1 in 1000 per Year)	5×10^{-5} (1 in 20,000 per year)	1×10^{-6} (1 in 1,000,000 per year)

Table 2: Individual Risk Criteria sets boundaries for the ALARP region for individual risk as shown in Figure 3 for passengers.

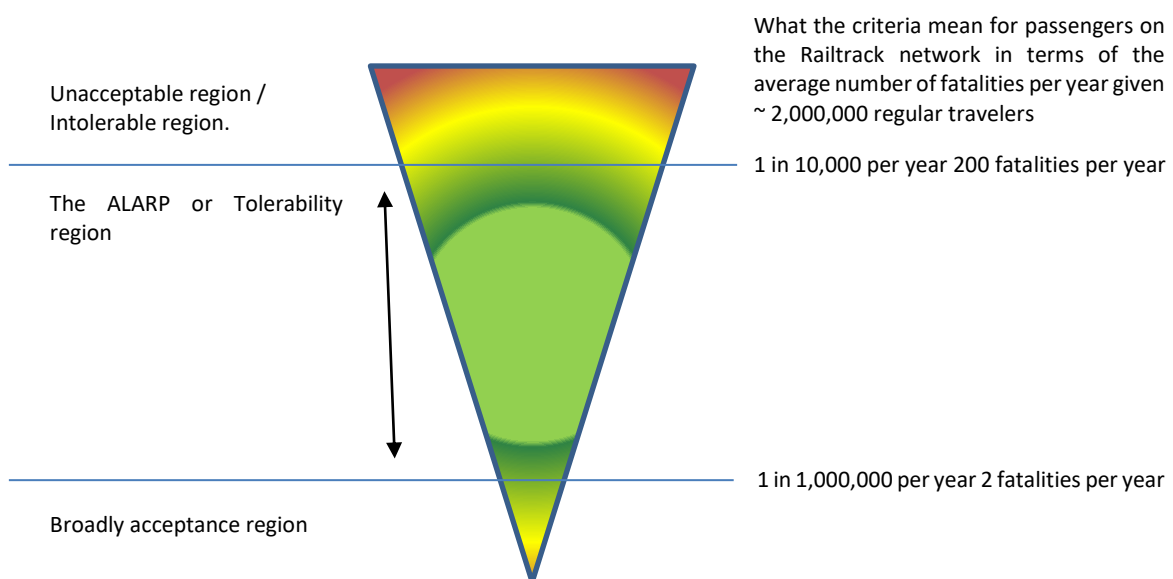


Figure 3: Individual Risk Criteria for Passengers (RSSB, 2002)

In their guidance (RSSB, 2002), based on the HSE guidance (HSE, 1999), RSSB note an important issue to be considered regarding the individual risk criteria defined in Figure 3: “the individual risk criteria relate to the total individual risk (sum of the individual risk for all hazardous events) and not the individual risk estimated for each hazardous event. It is not therefore acceptable to compare the individual risk results for each hazardous event with the individual risk criteria”.

2.6.2 Israel's Legal Requirements and Guidance

2.6.2.1 *The Ministry of Labor*

In 2013 the Ministry of Labor issued “Regulations for Labor Inspection Organization (Safety Management Program) – 2013” (Israel Ministry of Labor, 2013) in which it defines Acceptable Risk as: “A risk that has been reduced to a level defined as acceptable by the employer, taking into account his obligations under law and the safety policy of the workplace”. In fact, the legislation imposes the responsibility on the employer to define the risk acceptability level. The law mentioned in the above regulations specifies provisions regarding safety and hygiene and maintaining the health of workers but does not provide any risk acceptance criteria.

2.6.2.2 *Ministry of Energy*

The Israel Ministry of Energy issued “guidelines for petroleum and natural gas drilling and production” (Israel Ministry of Energy, 2016), based on which the operators are entitled to select any international norms existing in the petroleum industry to prepare their safety management plan, while maintaining a level of risk that is as low as possible based on the ALARP principle. However, neither the Ministry of Labor nor the Ministry of Energy has determined any explicit safety targets or risk acceptance criteria through which the operator can verify that the risk has been reduced to an Acceptable level.

2.6.2.3 *Ministry of Transportation (MOT)*

In 2012 the MOT and the Ministry of finance issued guidelines for Transport Projects Appraisal (TPA) (Israel Ministry of Finance; Israel Ministry of Transport, 2012). The TPA suggests using a cost-benefit analysis to examine investments in transportation projects, including those related to improving transportation service and safety. Section 2.11.4 provides further details on these guidelines.

In March 2018, the MOT, the railway regulator, defined explicit national safety targets for the national mainline railway, which were calculated based on the 2009/460 / EC Directive (EC, 2009); as a result, the following risk matrix (Table 3) was defined for evaluating risk tolerability in the mainline railway.

Table 3: National Risk Matrix for the Israeli Mainline Railway (MOT, 2018)

Frequency of occurrence of an accident (caused by a hazard)	Severity of an accident (Caused by a Hazard)			
	Insignificant FWSI ~ 0.01	Marginal FWSI ~ 0.1	Critical FWSI ~ 1	Catastrophic FWSI ~ 10
<i>Frequent</i> $> 10^{-3} h^{-1}$	Undesirable	Intolerable	Intolerable	Intolerable
<i>Probable</i> $10^{-3} - 10^{-4} h^{-1}$	Tolerable	Undesirable	Intolerable	Intolerable
<i>Occasional</i> $10^{-4} - 10^{-5} h^{-1}$	Negligible	Tolerable	Undesirable	Intolerable
<i>Remote</i> $10^{-5} - 10^{-6} h^{-1}$	Negligible	Negligible	Tolerable	Undesirable
<i>Improbable</i> $10^{-6} - 10^{-7} h^{-1}$	Negligible	Negligible	Negligible	Tolerable
<i>Incredible</i> $< 10^{-7} h^{-1}$	Negligible	Negligible	Negligible	Negligible

Table 4: National Risk Acceptance for the Israeli Mainline Railway (MOT, 2018)

Risk Category	Actions to be applied against each category
Intolerable	Shall be eliminated
Undesirable	The risk is required to be treated according a defined priority order and plan
Tolerable	The risk does not require any action on the basis of existing safety and working procedures. There is an obligation to make sure that the risk does not develop into a higher risk category
Negligible	No action is required

2.6.2.4 Jerusalem Transportation Master Plan Team (JTMT)

The Israeli state-owned entity (JTMT), which is responsible for the design and tendering of the future Jerusalem LRT lines, has defined safety requirements guidance for risk classification and assessment, as well as risk acceptance principles and criteria, that the DBO (Design-Build-Operate) concessionaire must implement in every phase of the project. This guidance is generally in line with EN 50126-1:2017, Section 2.4.2 above. The following are the guidance principles as described in the tender documents Volume 3 - Part 4 Safety Requirements Document number: K4200_TP_09.00X000_ERA_TN_01088_G_07.

Safety risk acceptability shall be analysed and evaluated based on the following safety risk acceptance principles which are in line with CSM, Section 2.3.3.3:

- a. The application of codes of practice
- b. Comparison with similar reference system(s)
- c. An explicit safety risk estimation

In all these cases, the prescriptions stated in EN50126 are applicable and shall be respected to select and properly apply any of these Risk Acceptance Principles. When possible, a comparison with similar reference system criteria shall be used, i.e., the GAME principle, as it is assumed that the original un-retrofitted units, which have been in JLRT service since 2010, constitute an adequate reference system in terms of safety.

In the case of application of the 'Explicit Safety Risk Estimation', the following Risk Acceptance Criteria defined in the tender document apply:

1) Severity

The severity indicates the level of gravity of the consequences of a hazard. Table 5: Hazard Severity Level describes the levels of severity and the consequences associated with each one:

Table 5: Hazard Severity Level (JTMT, 2019)

Cate gory	Severity Level	Consequence to Persons or Environment	Consequence to Service
4	Catastrophic	Death	
3	Critical	Severe injury, severe occupational illness	Loss of a major system
2	Marginal	Minor injury, occupational illness	Severe system damage
1	Negligible	Less than minor injury, occupational injury	Minor system damage

2) Frequency

The frequency indicates the frequency of occurrence of a hazard turning into an accident. The frequency and its definition are illustrated in Table 6.

Table 6: Frequency of Occurrence of Hazard Events (JTMT, 2019)

Category	Frequency level	Description	Frequency of Occurrence of Hazard Event per Operation Hour
A	Frequent	Likely to occur frequently. The hazard will be continually experienced	$P > 10^{-3}$
B	Probable	Will occur several times per year. The event is expected to occur frequently	$10^{-3} > P > 10^{-4}$
C	Occasional	Likely to occur around once per year. The event is expected to occur several times in the system lifecycle	$10^{-4} > P > 10^{-5}$
D	Remote	Likely to occur sometime in the system lifecycle. The event is reasonably expected to occur several times	$10^{-5} > P > 10^{-7}$
E	Improbable	Unlikely to occur, but possible. It may be assumed that the event will occur exceptionally	$10^{-7} > P > 10^{-9}$
F	Incredible	Extremely unlikely to occur. It may be assumed that the event will not occur	$P < 10^{-9}$

3) Risk Matrix

Table 7 presents the risk matrix, stating the risk acceptance categories resulting from the combination of severity and frequency levels.

Table 7: Frequency – Consequence Matrix (Risk Evaluation and Acceptance) (JTMT, 2019)

Frequency of Occurrence	Category	Severity Level Hazard Consequence			
		Catastrophic	Critical	Marginal	Negligible
		4	3	2	1
Frequent	A	Intolerable	Intolerable	Intolerable	Undesirable
Probable	B	Intolerable	Intolerable	Undesirable	Tolerable
Occasional	C	Intolerable	Undesirable	Undesirable	Tolerable
Remote	D	Undesirable	Undesirable	Tolerable	Insignificant
Improbable	E	Tolerable	Tolerable	Insignificant	Insignificant
Incredible	F	Insignificant	Insignificant	Insignificant	Insignificant

4) Actions to be applied against each category

Table 8: Risk Acceptance

Risk Category		Action to be applied against each category
R1	Intolerable	Shall be eliminated
R2	Undesirable	Shall only be accepted with the agreement of the State
R3	Tolerable	Acceptable with adequate control and with the agreement of the State
R4	Insignificant	Acceptable without the agreement of the State

2.6.2.5 Discussion

According to the ORR report (ORR, 2019): 1) “There is no specific health and safety legislation for tramway systems”; and passenger safety is managed by the Health and Safety at Work etc. Act 1974 (HSWA); 2) there is no written safety management system (SMS) appropriate for the tramway activities; 3) tramways are not covered by the common safety method on risk evaluation and assessment (CSM-RA) (Section 2.3). The mainline railway CSM-RA is not compulsory for the tramway; and 4) tramways are outside the scope of the Railway Safety Regulations 1999; therefore, they are not obligated to comply with the railways rules where a ‘train protection’ system should be installed to apply the brakes if a stop signal is passed where this potentially could lead to a collision.

There are additional gaps between the mainline railway and the tramway reflected in the abovementioned ORR report. ORR expects the tramway sector to deliver continual improvement in the health and safety of passengers, workforce, and the public to achieve ORR’s vision of “zero industry caused fatalities and major injuries to passengers, the public, and the workforce”.

However, although the tramways are not obligated to comply with the railway rules, they must comply with the UK’s Health and Safety at Work etc. Act 1974 (HSE, 1974), which requires risks to employees, and others, to be reduced so far as is reasonably practicable (SFAIRP). Risk assessments are also required by the Management of Health and Safety at Work Regulations, Regulation 3 (HSE, 1999). Regulation 4 of the COMAH requires operators to “take all measures necessary to prevent major accidents”. This is interpreted as the equivalent of reducing risks “as low as reasonably practicable” (ALARP) (HSE, 2021). Moreover, the

boundaries of the ALARP principle have also been defined by the Health and Safety at Work Act, as shown in Figure 3.

The situation in Israel is different from that in the UK, in as much as there is no explicit legislation for the tramway sector or any explicit law that defines safety risk targets and tolerability criteria. Moreover, there is no governmental uniform guidance on common safety methods for risk evaluation and risk acceptance or instructions obligating the tram operators to install ATP system. The state-owned entities are the ones who generate safety risk acceptance principles and criteria as described in Section 2.6.2.4.

The issue with these criteria is that there is no safety target except for the risk matrix. This is a real problem because the risk matrix has very wide bands of acceptability and many hazards may fall into the Undesirable and tolerable categories. For these hazards there must be a clear path to measure risk acceptability, and the proposed use of GAME or similar principles is inadequate because of the weakness inherent in the GAME principle which can be explained on the basis of the Croydon accident. The Croydon trams were not equipped with an ATP system, so when the driver fell into a microsleep and the tram entered a tight curve at three times the allowable speed there was no ATP system to stop the tram before the curve and it overturned. Now, suppose we had a similar line to that of Croydon and we had performed a risk assessment prior to the Croydon event; the decision regarding an ATP system would have been that there is no need for an ATP system. To overcome this situation of no explicit safety targets or risk acceptance criteria in Israeli law, the author suggests implementing European common practice as identified in the EU directive for Common Safety Methods (CSM), Section 2.3.3.3, clause C and the UK law, Section 2.6.1.2.

The obvious question is why does this situation exist in Israel? The answer is clear: the light rail sector has developed only in the last decade and, as of 2021, the only operational line exists in Jerusalem. The railway regulatory department in the Ministry of Transport was also established only in the last decade and focused mainly on national railway safety. However, the fact that the development of light rail systems has gained momentum in recent years in Israel will eventually also lead to the development of appropriate regulations related to risk assessment and acceptance.

2.7 JLRT System

The JLRT system is located between two termini: Mount Herzl and Pisgat Ze'ev. It is a double track line running 13.8 km in each direction (JLRT Operator, 2011). The system was certified by an ISA prior to the commencement of commercial operations in November 2011. The Depot is connected to the main line through two single tracks (North link and South link). There are 23 stations along the line, 3 control sections (areas with tram signals) and 10 block zones where the track slope is greater than 7% (Figure 4). Rectifier stations supply power to the system; the traction power is 750V DC. The operation principle is line-of-sight.

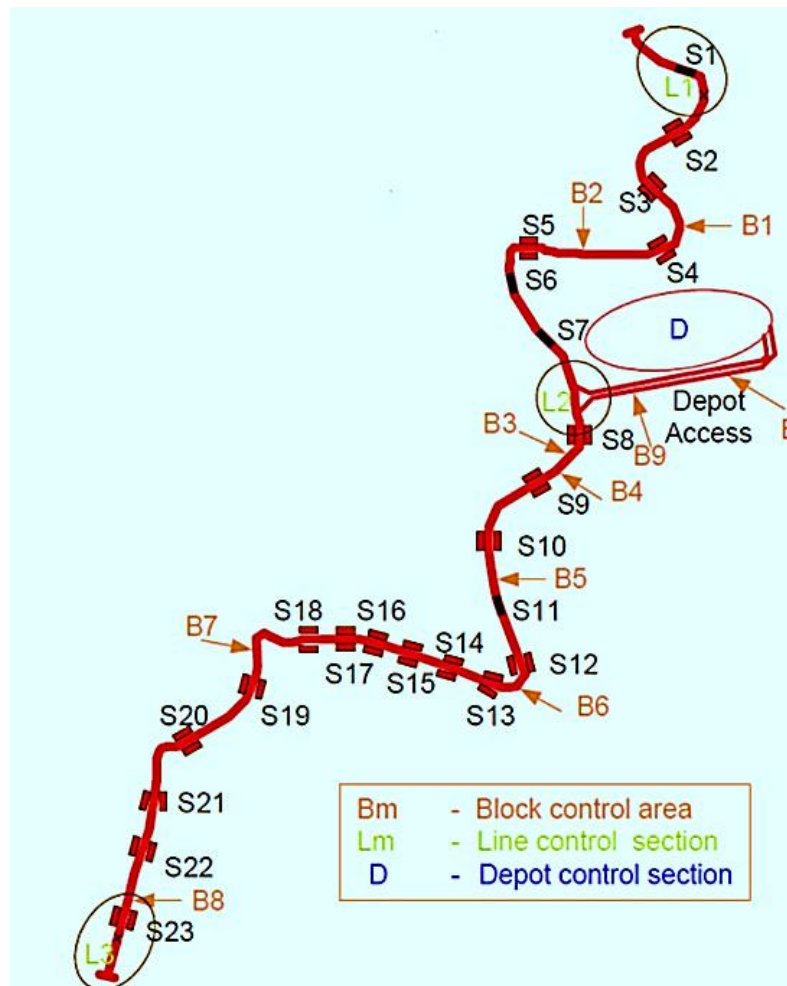


Figure 4: JLRT RED LINE

Train movements are monitored and dispatched from an Operating Control Centre (OCC), with an Automatic Vehicle Location System (AVLS). The OCC personnel direct, control, and supervise the system by means of radio communication, a public address system, a passenger

information system, CCTV, and telephones, as well as the AVLS and SCADA subsystems, 24 h per day. The terminus crossovers, and the crossover that connects the mainline to the Depot, are controlled by motorised point machines and protected by the signalling system. Additional crossovers are controlled by manual point machines designed to enable short service and recovery of operation.

The rolling stock fleet consists of 46 modular CITADIS 302 bi-directional vehicles that can be operated as double unit or single unit vehicles. Each unit has all three bogies motorised. There are six access doors on each side of the vehicle for passenger boarding and alighting.

2.8 Generic Hazards in Urban Guided Transport, MODSafe PHA

2.8.1 The MODSafe Project

MODSafe, Modular Urban Transport Safety and Security Analysis, was a project for the European Transport sector (MODSafe, 2012). Twenty-two parties took part in this project, including urban guided transport operators, universities, consulting companies and more. The main objective of this project was to propose an agreed and harmonised urban guided transport hazards list and a risk analysis process. One of the products of the project was a generic preliminary hazard analysis (PHA) for urban guided transport. Table 9: First Level Categorisation of MODSafe PHA presents the first level categorization of the MODSafe PHA.

The PHA was given to the author; however, for confidentiality reasons, the author cannot reveal it. Nevertheless, the author compared this PHA to the one drafted for the JLRT red line and noted that there were no major discrepancies. Section 2.8.2 describes the comparison made for the hazards studied.

Table 9: First Level Categorisation of MODSafe PHA

1. Tram Movement	6. Operations Control Centre (OCC)
2. Tram Interior	7. Maintenance
3. Tram to Station Interface (with tram present)	8. Emergency – Evacuation
4. Tram to Station Interface (without tram)	9. Environment (force of nature)
5. Depot	

2.8.2 The Presence of the Studied Hazards in the MODSafe PHA

The author examined whether the three hazards analysed in this thesis were identified in the generic MODSafe PHA, and if so, what are the causes of the hazards and what are the safety measures suggested by MODSafe.

2.8.2.1 *Excessive jerk (EJ)*

This hazard was identified in the MODSafe PHA and defined under two categories, Excessive Deceleration and Excessive Acceleration, where the cause of the hazard in both categories is ATP failure or driver error. The suggested safety measure in the case of driver error was “employ trained and well-educated staff only”. No ATP system is installed on the JLRT system; therefore, this cause for excessive jerk is not relevant as it cannot be examined.

MODSafe identified EB as a primary hazard; the hazard cause was defined as ‘any reason’ and the recommended safety measures were “ensure a limitation of braking force to an unarmful level for passenger” and “prevent unnecessary emergency brakes by passenger”.

2.8.2.2 *Signal Passed At Danger (SPAD)*

This hazard was not identified in the MODSafe PHA, for some unknown reason. This is puzzling because the MODSafe PHA refers to failures in the ATP system, which is designed to also protect against SPADs.

2.8.2.3 *Overspeeding of a tram*

This hazard was identified in the generic MODSafe PHA as “wrong speed command”. One of the hazard causes was “wrong command by driver” and the consequence was “derailment”. The recommended safety measure was “training of staff i.e. driver”.

Knowing the consequences of the tram accident in Croydon, UK, and the fact that after the accident it was decided that London’s Croydon tram network will be equipped with an automatic braking system (IRJ, 2019), as suggested by RAIB recommendation S37, report number 18/2017 (RAIB, 2017); therefore it can be determine that the MODSafe recommended safety measures are insufficient and should also include a recommendation to use technology to intervene if a tram approaches a speed restriction too fast. The accident in Croydon, England, occurred on 9 November 2016. The tram approached the Sandilands south curve,

which has a radius of 30 m, slowed to approximately 73 km/h (45 mph) as it entered the curve and overturned. The speed sign located at the start of the curve denotes 20 km/h. The consequences of this accident included 7 fatalities and 19 serious injuries among the passengers (RAIB, 2017).

2.9 Quantitative Risk Analysis and Risk Modelling Techniques

Quantitative risk analysis and modelling techniques play a major role in the safety management process. They are used to identify which safety risks are affecting the transportation system and its operator the most. This is done by quantifying the predicted value of the risks, mainly in terms of fatalities and fatality weighted injuries (FWI). As discussed in Section 1.1, by accurately quantifying the magnitude of the risk, evaluating its tolerability and the costs involved to mitigate it ALARP, decision makers can consider whether the mitigation costs are proportionate to the safety benefits achieved.

During the original literature review phase of his research, the author was not able to identify a generic safety risk model for a tramway system. However, such models exist in the mainline railway sector, and these can be adapted to the tramway domain.

2.9.1 Safety Risk Models

2.9.1.1 *Research on risk models at the European level, DNV GL report*

The European Railway Agency (ERA) commissioned the DNV GL company to study the relevant safety risk models used in mainline railway sectors. DNV GL focused on quantitative risk models. Some of their insights and findings are summarised below (DNV GL, 2015):

2.9.1.1.1 The objectives of risk modelling

DNV GL noted three major objectives for risk modelling in their report. These important objectives are common to all transportation systems, and they should prevent complacency among decision makers: (1) “For low frequency, high consequence events, in which accidents can occur only once every few years, a model can be used to provide an indication of underlying risk, so that years with no accident are not viewed as overly safe and years with an accident as overly dangerous”; (2) “To identify areas of the overall risk profile that should be subject to greater supervisory or management attention”; and (3) “To assess the impact of

changes in technology or operational practice on the risk profile, and support the case for investing in these changes”.

2.9.1.1.2 Types of risk models in the railway sector

Risk models in the railway sector include statistical models, FT/ET models, safety management models, and simulation models.

2.9.1.1.3 Data availability

DNV GL found that the availability of information on rail accidents varies among EU countries. At the level of a particular operator, data availability is generally very good. But these data are rarely consolidated or aggregated at the EU level.

The approach chosen to build a risk model for mainline railways or tramway systems is influenced by data availability. The author developed the SPAD risk model as a precursor indicator model (PIM), because past accident data were limited. The author could not obtain data from foreign tram operators, due to confidentiality. The author searched for information on SPAD accidents on the ERA website (<https://erail.era.europa.eu/>), which contains information on tram and metro accidents occurring in European countries. No accidents resulting from tram SPADs were identified in these data. The author also searched for such information on the RAIB website (<https://www.gov.uk/government/organisations/rail-accident-investigation-branch>) but could not identify accidents of this kind.

While searching for databases on tram accidents, the author met with a project manager from the ERA safety unit on 13/06/2017. He was told that "ERA is trying to push the industry to adopt risk models but the lack of extensive and reliable data sets seems to be an obstacle in that direction" (D'Agostino, 2017). The author's opinion is that developing and building an EU-level information centre to collect and filter data on tram accidents occurring in EU countries and to share these with all operators is an important mission that will allow tramway operators to quantify the predicted level of risks inherent in their operation and to evaluate the acceptability of these risks.

The DNV GL survey conducted in 2015 found that a few EU member states use safety risk models, where some are qualitative risk models and others are quantitative risk models. All of the quantitative models are confidential.

Of these quantitative models it is worth mentioning the SRM and PIM models developed by RSSB for the UK mainline railway. The UK model input is based on a record of all accident and incident events. The model uses FTA and ETA to identify accident precursors and possible outcomes. The model measures risk in FWI and the output is used to support development of the three-year safety plan and identify safety investments.

The SRM and PIM models are confidential. “The PIM provides an assessment of the underlying risk of train accident risk, which is considered to be a potentially high-risk train accident, such as train derailments and train collisions. The input may be a simple count of the incidents or a risk-based assessment of the incidents. For the latter, the assessment of significance refers to the potential for the incident to have become an accident if the circumstances were slightly different, and if so, what the consequences might have been” (DNV GL, 2015).

According to RSSB “the Precursor Indicator Model measures the underlying risk for train accidents by tracking changes in accident precursors, and is calibrated against the Safety Risk Model” (Dacre, 2019). Yet, in the literature, the author was unable to obtain details about the PIM describing its structure and how it measures the underlying risks.

2.9.1.2 Statistical models

2.9.1.2.1 Poisson distribution

The basic model of accident occurrence in a given system is that accidents are presumed to occur randomly at a rate, λ , per unit of activity such as tram-kilometres (OECD, 2010; Evans, 2003). The basic model thus assumes that the accidents are Poisson-distributed. A Poisson distribution is a discrete probability distribution represented by Equation 3.

$$p(x) = \frac{(\lambda * k)^x * e^{-\lambda * k}}{x!}$$

Equation 3: The Poisson Distribution

The Poisson variable, x , is a count of the number of occurrences of an event in a fixed unit of time or distance. “If the events are occurring randomly and independently, in other words, knowing that one event happens gives no information about when or whether another event will occur. In addition, knowing that the theoretical rate, λ , at which the events are occurring does not change through time or distance, then it can be said that the random variable, x , has a Poisson distribution”. (Balka J, 2013).

2.9.1.2.2 Negative Binomial Distribution

A negative binomial distribution is a discrete probability distribution for a random variable, X , which is the number of independent trials required to obtain a certain number of successes r . The parameters of the negative binomial are r and p . Given independent trials, where each trial may result in one of two possible outcomes: success (s) or failure (f), then p is the probability of success (s) and $(1 - p)$ is the probability of failure (f). Since we want r successes then X has to be at least r and X could be any positive integer greater or equal to r . In the event that X is equal to n , n trials are required to be performed until a total of r successes is accumulated; therefore, the n^{th} trial must result in success so the first $n - 1$ trials should result in $r - 1$ successes. Therefore, the number of ways that $n - 1$ trials result in $r - 1$ successes is: $\binom{n-1}{r-1}$ and the probability distribution of the random variable, X , the number of trials in which the r^{th} success occurs, is given by Equation 4.

$$P(X = n) = \binom{n-1}{r-1} p^r (1-p)^{(n-r)}$$

Equation 4: Negative Binomial Distribution (Walpole, Myers, Myers, & Ye, 1978)

The Expectation of the negative binomial distribution is: $E(X) = \frac{r}{p}$

The variance of the negative binomial distribution is: $V(X) = \frac{r(1-p)}{p^2}$

2.9.1.2.3 Negative Binomial (NB) regression

The Poisson regression model assumes that **mean = variance**, an assumption which is not often supported by real world data. Often the variance is higher or lower than the mean, meaning over-dispersion or under-dispersion, respectively; in such cases the model to be used

should not assume “equi-dispersion assumption”. The Negative Binomial (NB) regression is a model that does not make the assumption that **variance = mean**. Instead, the NB model requirement is to define a parameter, **k**, which it uses to express the variance in terms of the mean (μ) (Sachin Date, 2019) as follows (Equation 5):

$$\text{Variance} = \mu + k * \mu^2$$

Equation 5 : The NB2 Model’s Variance Function (Sachin Date, 2019)

2.9.1.2.4 The random effects negative binomial (RENB) model

The random effects negative binomial (RENB) model deals with the relationship between the expected number of collisions and an independent variable that can influence the outcome of a given statistical trial (Farhana, Graham, David, & Majid, 2016). Farhana et al. used the RENB regression model to identify key traffic, transit and route factors that affect the frequency of tram accidents along sections of tram lanes in Melbourne. The model is based on tram accident data collected from 101 tram route sections over five years. The study is based on the form of the negative binominal (NB) model represented by Equation 6:

$$E(A) = \exp(\alpha + \beta X)$$

Equation 6: The Form of Negative Binomial Model (Farhana, Graham, David, & Majid, 2016)

Where: $E(A)$ represents the predicted number of collisions per year; X is the vector of explanatory variables; β is the vector of estimable parameter; α is the intercept of the model. The structure of the RENB model is represented by Equation 7:

$$E(A_{it}) = \exp(\beta X_{it} + u_i + \varepsilon_{it})$$

Equation 7: The Structure of the RENB Model (Farhana, Graham, David, & Majid, 2016)

Where:

$E(A_{it})$ = the predicted number of crashes along tramroute section i in year t ,

X_{it} = vector of explanatory variables,

β = vector of estimable parameters, u_i = random effects for the ith location group,

ε_{it} = vector of residual errors

Some of estimated parameters resulting from the NB and RENB models are presented below.

The parameters were estimated using the statistical software STATA version 13:

- a) The dispersion parameter $\alpha = 0.27$ meaning that the NB model is more suitable than the Poisson model.
- b) The analysis results showed that the involvement of trams in collisions increases with the increase in tram service frequency ($\beta = 2.71$), which is expectable.
- c) The analysis results indicated that the involvement of trams in collisions considerably decreases with the increase in tram stop spacing ($\beta = -0.42$).
- d) The analysis results also showed that the involvement of trams in collisions increases with the increment of tram route section length ($\beta = 0.31$).

The model identifies additional significant factors affecting the frequency of involvement of trams in collisions. It can be summarized that the method represents a useful planning tool to improve safety performance.

2.9.1.2.5 Normal distribution

The normal distribution is also known as the Gaussian distribution. It is a continuous probability distribution with a probability density function as described in Equation 8:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}$$

Equation 8: Probability Density Function of the Normal Distribution (Balka J, 2013)

The random variable, x , can take values $-\infty < x < \infty$. There are two parameters for this distribution: the mean, μ , and the standard deviation, σ . The mean also takes values $-\infty < \mu < \infty$ and the standard deviation, σ , takes positive values. The notation $N(\mu, \sigma^2)$ means normally distributed with mean, μ , and variance, σ^2 (Balka J, 2013). The normal distribution is symmetric about μ , as shown in Figure 5.

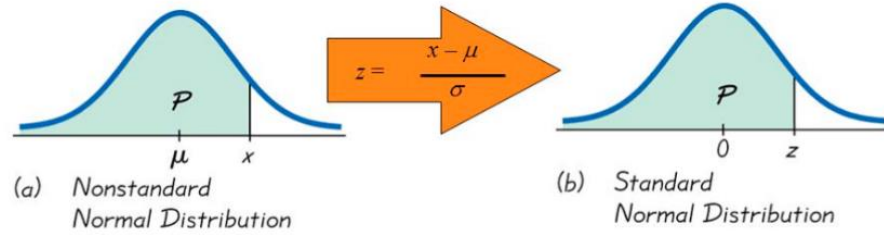


*Figure 5: Converting a Nonstandard Normal Distribution to a Standard Normal Distribution
(Triola, 2015)*

Application of the normal distribution

The standard normal distribution is a normal distribution with $\mu=0$ and $\sigma=1$. A random variable, x , which has a normal distribution with any μ and σ can be converted into a random variable, z , that has the standard normal distribution. The conversion formula is shown in Equation 9 and Figure 5.

$$Z = (x - \mu) / \sigma$$

Equation 9: Conversion Formula for the Normal Distribution

This method helps to calculate the probability of any random variable, x , which has a normal distribution with any μ and σ . In the current study, this method was used to model the risk of a tram overturning on a sharp curve. Specifically, the method was used to estimate the probability that a tram will approach a sharp curve at a speed close to the overturning speed.

2.9.1.3 Fault tree and event tree analysis models

“Reliability analysis is the study of both the probability and the process of failure of a system. For that purpose, several tools are available, for example, fault tree and event tree techniques. These tools are often complementary and address different aspects of the questions. Fault trees lay out relationships among events. Event trees lay out sequences of events linked by conditional probabilities” (Pate-Cornell, 2006). These complementary tools were used in the development of the EJ and SPAD risk models.

2.9.1.3.1 Fault tree analysis (FTA)

The FTA methodology is widely used in major fields of engineering including system safety and reliability engineering. The International Standard IEC 61025 describes FTA and provides guidance on its application, as do other standards NUREG-0492, SAE ARP4761, MIL-HDBK-338B. According to the IEC standard, FTA is “concerned with the identification and analysis of conditions and factors that cause or may potentially cause or contribute to the occurrence of a defined top event” (IEC, 2006). Another definition of FTA states that “Fault tree analysis is used to assess the frequency of an incident. A fault tree is a diagram that shows how primary causes produce events, which can contribute to a particular hazard” (Coker, 2007).

An FT is formed of events described by binary variables connected by logical functions, essentially OR and AND gates. The output of a gate is exactly equal to the Boolean function of the inputs of the gate. Each input event can be the result of a logical function of a set of events, down to the point where all inputs are basic events that cannot be practically analysed any further. The FT allows logical connection between the “top event” and a set of basic events. Based on these connections, the probability of the top event can be computed as a function of the probabilities of the basic events using Boolean algebra and probabilistic analysis (Pate-Cornell, 2006). Figure 6 shows the basic structure of an FT. Figure 7 describes the FT notation.

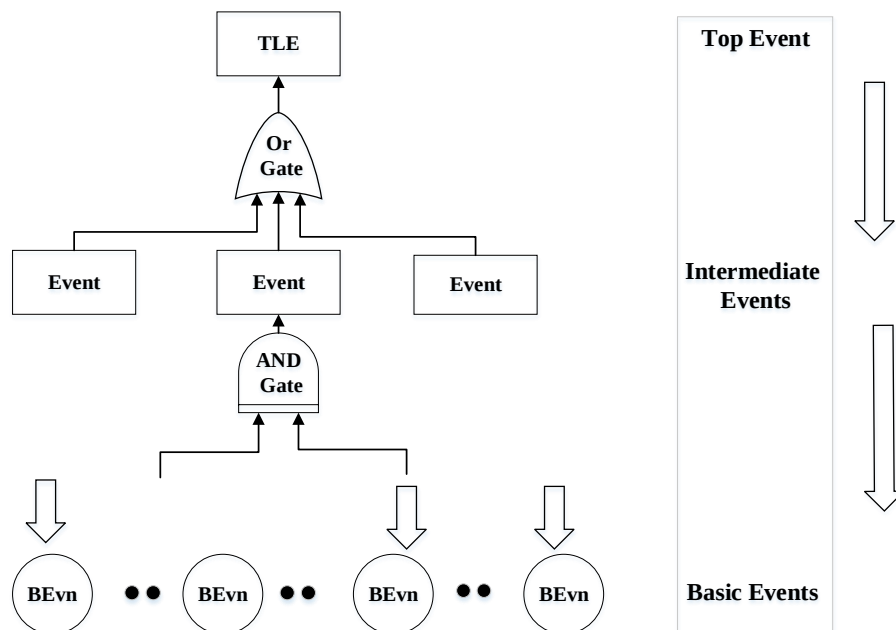


Figure 6: Structure of a Fault Tree (The University of York, 2015)

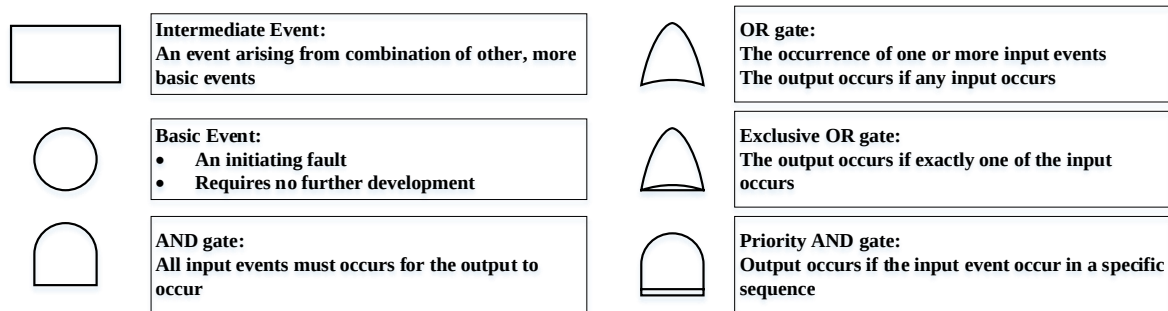


Figure 7: Fault Tree Notation (The University of York, 2015)

The literature describes the widespread application of FTA for assessing safety risk in the railway sector, e.g.; the UK safety risk model “consists of series of fault tree and event tree models representing 110 hazardous events which collectively define the overall level of risk on RSI” (Muttram R. I., Railway Safety’s Safety Risk Model, 2002). The Slovakian SRM evaluates the frequency of each hazardous event from the historical accident data and structured expert judgements using the FTA technique and the ETA technique (Leitner, 2017). The study “Derailment-based Fault Tree Analysis on Risk Management of Railway Turnout Systems” (Dindar, Kaewunruen, An, & Gigante-Barrera, 2017), investigates environmental causes of derailments at Railway Turnout Systems (RTS) using FTA. This is a small set of examples, but it demonstrates the widespread use of FTA in national safety risk models, as well as in specific cases.

Advantages and disadvantages of FTA

FTA carries with it advantages and disadvantages (Hasofer, Beck, & Bennetts, 2007). The main advantages are that it provides a systematic method for identifying faults that can exist within a system and forces the analyst to understand the system thoroughly. By contrast, the main disadvantages include the possibility of omission of significant failure modes; difficulties in applying Boolean logic to describe failures of system components that can be partially successful in operation; and a frequent lack of pertinent failure data for quantitative analysis.

2.9.1.3.2 Event tree analysis

“An event tree analysis (ETA) is an inductive procedure that shows all possible outcomes resulting from an accidental (initiating) event, taking into account whether installed safety barriers are functioning or not” (Rausand & Hoyland, 2003). Figure 8 describes the main steps

in building an event tree (ET). The relationship between the FTA and the ETA is illustrated in Figure 9.

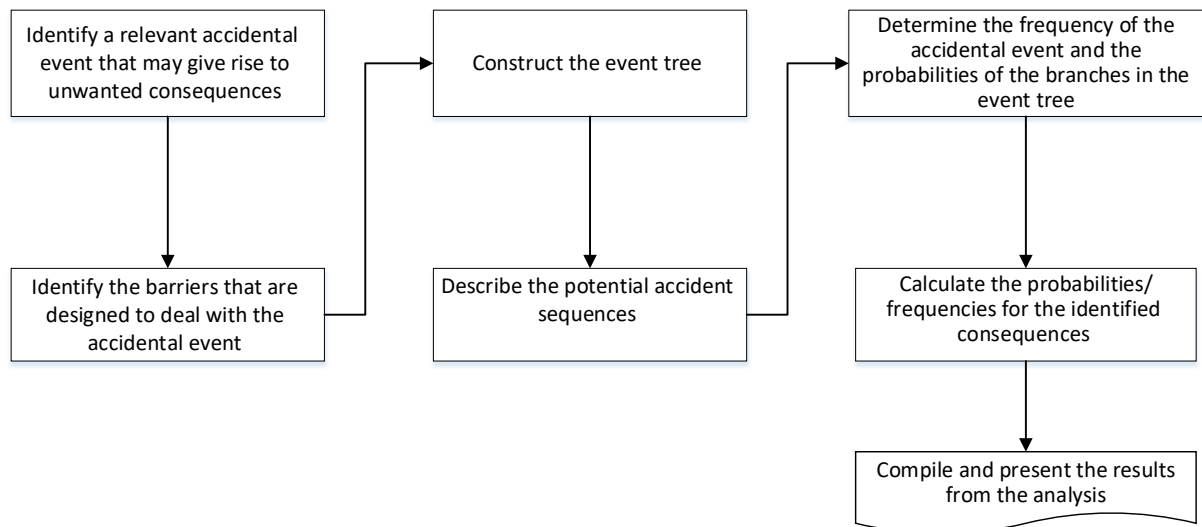


Figure 8: Building an Event Tree (Rausand & Hoyland, 2003)

2.9.1.3.3 The relationship between FTA and ETA

Event trees are often used together with FTs. Figure 9 shows an FT linked to an ET. Neither tree is fully developed; however, the figure demonstrates the data flow between them. The FT analyses the probability that a train will derail due to certain causes while the ET uses this data to further analyse the consequences, i.e., the risk resulting from the derailment in terms of FWI.

The ETA is a bottom-up analysis tool. It takes as its starting point the event that is found to be probable and can affect the system (derailment) and tracks it forward through sequences of interfacing system components to determine the possible consequences. It examines all possible outcomes for the initiating event. Each outcome of a branch is usually binary i.e., the outcome occurs or does not occur. By assigning a probability to each branch, the probabilities of all possible outcomes following the initiating event can be determined (Erkut, Tjandra, & Verter, 2007).

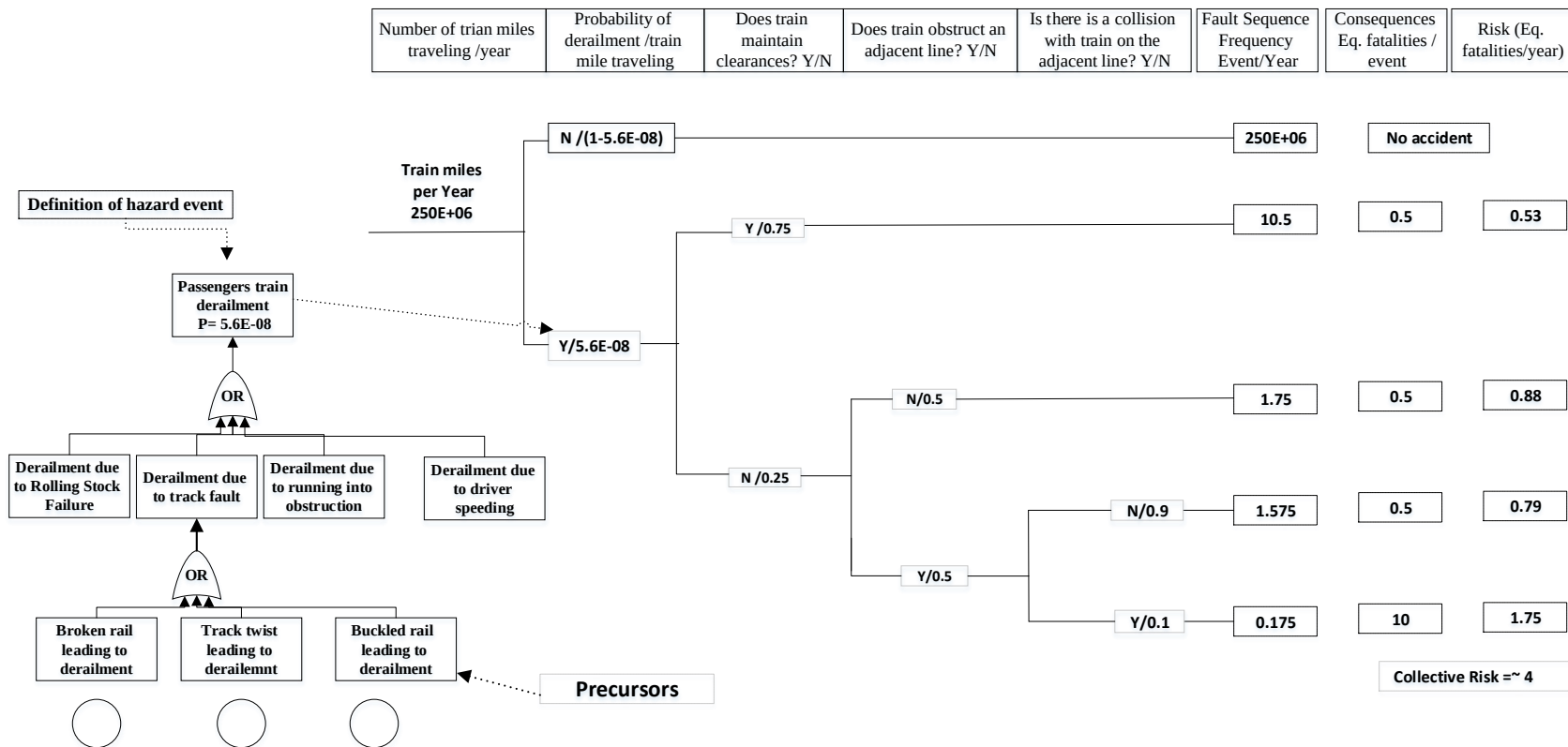


Figure 9: Relationship between Fault Tree and Event Tree Analyses (Muttram R. I., Railway Safety's Safety Risk Model, 2002)

2.9.2 Comparison of Fault Tree and Bayesian Networks for Modelling Safety Critical Components in Railway Systems

Signal passed at danger (SPAD) events can lead to train derailment, collisions, and other negative consequences. The classical method for modelling such events is Fault Tree (FT) analysis; however, the use of Bayesian Networks (BN) has been proposed for modelling more complex systems. The ability of FT and BN to model safety risks in railway systems has been examined using SPAD examples (Mahboob & Straub, 2011). The classical method for identifying the critical components leading to SPAD and subsequent derailment is FT analysis, which allows the modelling and analysing of safety critical components in engineering systems. This method has been previously applied in railway systems to model errors made by train drivers (Dhillon, 2007, cited in (Mahboob & Straub, 2011)).

Fault tree analysis comprises a set of statistically independent basic events that lead to the final outcome or top event, while BN analysis comprises a set of dependent random variables. In the SPAD case study (Mahboob & Straub, 2011), the same probability was assigned to the FT basic events and the BN random variables; the resulting probability of derailment due to SPAD was identical. Therefore, they concluded that both methods are capable of handling the various dependencies arising in the safety analysis of railway systems.

The advantages of FT are that it provides a graphical representation of the logical relations between the basic events and the top event, and it is a well-known methodology that can be applied relatively easily by non-experts (Mahboob & Straub, 2011). By contrast, the application of BN in the railway industry is not common practice, and requires additional expertise and understanding. Moreover, the logical relationships between components of the system are not evident from the graphical representation. The main advantage of BN is that it can model dependencies with greater ease and its high flexibility enables it to be easily extended.

Considering that the majority of people who use risk modelling in the railway industry are not mathematical experts, FT analysis should be preferred over BN analysis, due to its wide application in the railway industry (enabling comparisons to be made among different studies) and its ease of use and interpretation (Mahboob & Straub, 2011).

2.9.3 Approaches to Safety Risk Modelling in the Railways Sector: RSSB's SRM vs. Evans' Statistical Model

2.9.3.1 Introduction

It is important to model safety risk not only to prevent incidents of a type that has already happened, but also to prevent other types of incidents that may happen in the future, i.e., to work to prevent potential rather than actual consequences. However, resources are limited, so we must aim to achieve an informed understanding of all the possible risks affecting operations – the better the understanding, the easier it is to effectively target finite resources for safety improvement (Muttram R. , 2002).

In railway systems, where accidents are less frequent than in highway systems and have variable outcomes, the precision of parameter estimation in statistical analysis is much lower, which is why risk models have been developed to estimate risks by modelling both the precursors and potential consequences of accidents in the system (Evans, 2003). Models represent simplified perspectives of complexity, in an attempt to strike a balance between over-simplification and over-elaboration (Bedford, French, & Quigley, 2004a). Two major categories of models are *black box models*, which model relationships without addressing the causality between variables, and *causal models* that attempt to model the relationships between variables explicitly. Black box models are based on empirical data and therefore must be calibrated, while causal models, such as risk analysis models, including fault and event tree models (e.g., the SRM) cannot be calibrated using statistical data because they are used to estimate the likelihood of low probability events. Evans' model is not an exclusively black box model because it aims to identify potential sets of accident precursors, SPADs, etc., thus it may be called a *semi-causal* model.

2.9.3.2 Railway Safety's Safety Risk Model (SRM)

The SRM developed by RSSB is a combination of fault tree (FT) and event tree (ET) models representing 110 hazardous events which collectively define the overall level of risk in the railway system (Dennis, Somaiya, Small, & Singh, 2002). This model has been designed to consider both high-frequency, low-consequence events (for which there are sufficient recorded data) and low-frequency, high-consequence events (for which there are few

recorded data). The results for each event are presented in terms of frequency of occurrence (events/year) and risk (equivalent fatalities/year). This model has been developed to provide a structural representation of the causes and consequences of potential accidents arising from railway operations and maintenance on the mainline railway (Muttram R. , 2002). Therefore, the primary objectives of the RSSB SRM are to obtain an understanding of the nature of the current risk on the mainline railway and to provide relevant risk information and risk profiles. The SRM is a system-wide model to support railway safety. It does not describe in detail the train operating companies, types of trains or different service intensities, each of which affects the estimates of risk. The SRM enables risk to be calculated in terms of collective risk, individual risk and societal risk (Dennis, Somaiya, Small, & Singh, 2002). The model is used to produce a risk profile bulletin which is used by operators to produce a safety case that includes the intended steps to ensure that risks are reduced to 'as low as reasonably practicable' (ALARP) and to plan for further safety improvements (Muttram R. , 2002).

2.9.3.3 Evan's statistical model

Evans' statistical approach (Evans, 2003) to estimating risk assumes that accidents occur randomly at a rate of λ per unit of activity (e.g., per vehicle-km), with a Poisson distribution. Once an accident occurs, the number of fatalities is also assumed to be random, having a probability distribution with mean, μ . The mean number of fatalities per unit of activity is then the product, $\lambda\mu$ – it is the primary measure of the risk of accidental death posed by the system. Evans' original analysis ((Evans, 2000) (Evans, 2001)) provided estimates for overall risk as well as for three mutually exclusive classes of fatal accidents – SPAD, ATP preventable, and ATP non-preventable – and made adjustments for changes in rolling stock.

2.9.3.4 Comparing the models

Evans compared the results of SRM version 2 with his own statistical analysis based on past accident data (Evans, Estimating transport fatality risk from past accident data, 2003). The overall risk estimate produced by his original analysis was 2.3 times lower than the overall risk estimate produced by the SRM. Evans concluded that this poses problems for practical purposes, such as appraising the benefits of new safety measures or assessing whether the objectives of safety measures have been met (Evans, 2003). Thus he tested the reliability and

validity of both risk estimates. Evans calculated confidence intervals (CI) based on the normal distribution, to test his own risk estimates, but claimed that it is difficult to test the estimates of the SRM because the models are complex and they incorporate various judgement assumptions. The SRM estimate fell outside of Evans' calculated CI, supporting his claim that the SRM is good for understanding risk structure, but not for calculating absolute risk. However, although a statistical difference was found between the models for the estimate of overall risk, when each of the three classes of fatal accidents was examined separately, a statistical significance was found only for non-ATP preventable accidents (Evans, 2003).

Bedford et al. ((Bedford, French, & Quigley, 2004a) (Bedford, Quigley, & French, 2004b)) compared the SRM modelling approach and Evans' statistical modelling approach to determine the differences between them. Evans' statistical model is a black-box statistical model, quantified by fairly sparse historical data. On the other hand, the SRM is a more detailed fault and event tree model quantified by a combination of expert judgement and historical data (Bedford, Quigley, & French, 2004b). The SRM model is considered a 'best estimate' model because it does not include uncertainty parameters (Bedford, French, & Quigley, 2004a). The great advantage of this model is that it provides an understanding of how the data arise. This understanding relies to a great extent on expert judgement and knowledge in determining a suitable structure, using the correct data for the model and using suitable risk metrics. Expert judgement may include determining data bounds, determining the length of the data collection period or pooling data across categories. In addition, when data is sparse, there will be a lot of noise in the parameter estimates; therefore, data need to be aggregated at a higher level. Expert judgement can be used to determine the parameters at the more detailed level (Bedford, French, & Quigley, 2004a).

In this comparison, the main critique of Evans' analysis (e.g., (Evans, 2000) (Evans, 2001) (Evans, 2002)) was that Evans does not provide clear objectives for his analysis, thus there are no clear criteria for choosing which data to use. Changes in the data chosen produce differences in results, affecting estimates and forecasts and the standard deviations used for calculating the CIs used for comparing his analysis with the SRM. Thus, Evans' CIs may be too narrow because he disregards uncertainties both in his own analysis and in the SRM. If we also

consider that the SRM does not provide any uncertainty interval for its own risk estimates, it is difficult to accept Evans' comparison.

In their detailed statistical comparison of the two approaches, Bedford et al. (Bedford, French, & Quigley, 2004a) (Bedford, Quigley, & French, 2004b)) reduced the rate of occurrence of each type of accident to include only fatal accidents. They modelled the probability of death with a Binomial distribution and approximated this distribution with the Poisson distribution for computational convenience. They used the likelihood method to generate CIs for the historical data, and bootstrapping (a random sampling method used to assign measures of accuracy to sample estimates) to generate CIs for the mean number of fatalities in a fatal accident. The number of fatal accidents estimated by Evans in 2002 due to SPAD, ATP preventable and ATP non-preventable were 0.45, 0.011 and 0.45, respectively (Evans, 2002). Those of the SRM were 0.38, 0.09 and 0.92, and lay within the CI for 2002. Bedford et al. (Bedford, French, & Quigley, 2004a) (Bedford, Quigley, & French, 2004b)) concluded that there was no statistical difference between the two methods in the estimation of risk. Importantly, with respect to the current study, the risk estimates for SPAD events produced by both approaches were similar, even within Evans' own comparison (Evans, 2003).

2.9.3.5 Summary and discussion

Both safety risk models and statistical methods have been used for modelling risks in railway systems. The statistical approach is a long-used, reliable approach for estimating probabilities in many fields of research. In contrast, the SRM approach is much more recent, having been developed and applied by the RSSB over the last two decades for the express purpose of improving safety on the railway system. For both approaches, a clear objective is required to ensure correct selection of data. Moreover, each approach is based on different assumptions and its estimates carry a degree of uncertainty which needs to be modelled to determine the reliability of those estimates. The two approaches have been shown to produce similar estimates of risk for the railway system, when the comparison between them is based on a common statistical foundation, as shown by Bedford et al. (Bedford, Quigley, & French, 2004b). In this light, it is safe to claim that the SRM approach can be used as a reliable safety improvement tool.

2.9.4 Applications of RSSB's SRM

2.9.4.1 SRM for the London Underground

Safety risk model techniques can be applied to other railways, by adjusting the ETs and FTs to the tested railway configuration, using input data from the particular railway's historical performance and applying control measures that reflect the local standards (Muttram R. , 2002). One example of a local application of the SRM approach was the development of an SRM for the London Underground (LU) (Taig & Hunt, 2012). The LU model is, by nature, more limited, as it applies only to one railway system, and concentrates primarily on fatality risk, covering lower order risks by extensive workplace risk assessments and customer risk assessments. By contrast, RSSB's SRM also considers non-fatal accidents and converts the output to fatalities and weighted injuries (FWI). Both models use the same FT/ET approach. Due to the differences in scope, the RSSB model includes a much larger number of top events (110) than the LU model (20). Overall, the risk in mainline SRM is higher due to the larger volume of more diverse operations. When calculating the number of estimated fatalities per year, the SRM result is much closer to the observed figure than the LU result (8 vs. 6.8 and 3.9 vs. 0.8, respectively). Taig and Hunt conclude that the discrepancy is probably due to the slow updating (each year different top events in the LU model are updated, while the entire RSSB model is updated every 18 months) and the longer time periods of statistical data used to quantify the model (Taig & Hunt, 2012). They state further that because of the piecemeal approach to updating the LU model, it may err on the side of pessimism and comparisons of risk across top events may be difficult. Nevertheless, they believe that the LU model offers a substantially richer and more valuable picture of safety risk than does a simple safety performance report based on a few years of recent actual data. Overall, Taig and Hunt consider both models to be reliable and credible for use in providing a picture of current railway risk. They are also considered a benchmark of railway risk modelling around the world. Thus, these models may provide the best available picture of current safety risk on the railway (Taig & Hunt, 2012). However, neither model includes any indication of the provenance of, or uncertainty in, the different risk estimates produced, although RSSB has the tools to address this issue.

2.9.5 Risk of Non-collision Injuries to Public Transport Passengers

Passengers in a moving vehicle are at risk of injury even when there are no impact events; such injuries are called non-collision injuries and occur relatively frequently. Non-collision injuries include both those occurring when falling inside the vehicle due to sudden braking (i.e., EJ), accelerating or turning, and those occurring when falling while boarding and alighting the vehicle. When falling, passengers may strike fixed parts of the vehicle, such as seat backs, bars for holding, doors or windows. A major objective of risk assessment in this context is to develop and evaluate the costs and benefits of measures to reduce the risk of falling on board public transport vehicles or make falls less serious. The general measure of the exposure to injury due to falls in a moving vehicle, i.e., as a result of EJ, is expressed as the number of events as a function of passenger kilometres produced:

$$\text{Risk of injury due to falls in a moving vehicle} = \frac{\text{Number of passengers injured in falls inside the vehicle}}{\text{Number of passenger kilometres}}$$

Equation 10: Risk of Injury Due to Falling in a Moving Vehicle (Elvik, 2019)

A recent study calculated estimates of exposure and risk for eleven previous studies on non-collision injuries in a range of different public transport vehicles (Elvik, 2019). Only one of these studies addressed trams. Based on this analysis, a typical level for the risk of falls inside a moving vehicle was determined to be about 0.3-0.5 per million passenger kilometres, i.e., 0.3-0.5 falls on board leading to injury for a public transport vehicle that produces 1 million passenger kilometres per year. However, this estimate has a wide range of variation (0.04–1.4 injuries per million passenger kilometres).

The development of options for reducing the probability of a fall and/or its severity requires an estimate of the frequency of occurrence of falls and their severity. Indeed, previous studies tried to estimate the distribution of non-collision injuries by severity; however, the methods of estimation and the subdivision of injury types by severity were not uniform, thus it is very difficult to give a general estimate for the distribution of injuries by severity. Nevertheless, a plausible range for the share of injuries that are severe is 4–15% (Elvik, 2019). Of course, all of these estimates must be used with utmost caution, due to the high degree of uncertainty

involved, which is to a large extent due to the lack of relevant data for quantifying exposure risk and determining the variation between different types of public transport (Elvik, 2019).

2.10 Tram Driver Behaviour

Driving a tram requires awareness of a complex environment populated by pedestrians, motor vehicles and other road users. As defined by Endsley (Endsley, 2011) cited in (Naweed, Rose, Singh, & Kook, 2017) a tram driver must be able to 'project ahead' the behaviour of other tram drivers, pedestrians and road users and to take action to avoid accidents. Experience may improve this skill, especially in tasks where there is an element of repetition, such as driving the same route, approaching stations, following other trams on a daily basis, etc. (Naweed, Rose, Singh, & Kook, 2017). Tram driving is affected by specific factors such as fatigue and shift work. Fatigue and distraction is a combination that may increase the risk of accidents; 10-23% of the causes of vehicle collisions are associated with driver distraction and this figure can also be attributed to tram collisions (Naweed, Rose, Singh, & Kook, 2017). Regan et al. (Regan, Hallett, & Gordon, 2011) developed a taxonomy which divides driver inattention into five categories based on different mechanisms causing inattention: 1) Driver Restricted Attention; 2) Driver Misprioritised Attention; 3) Driver Neglected Attention; 4) Driver Cursory Attention; and 5) Driver Diverted Attention. The purpose of the taxonomy is to provide a "common framework for coding different form of driver inattention as contributing factors in tram accidents so that comparable estimates of their role as contributing factors can be made across different studies". Naweed et al. (Naweed, Rose, Singh, & Kook, 2017) investigated whether the taxonomy can be a useful tool for determining risk reduction strategies, and came to the conclusions that the taxonomic categories in their current form may not be suited to the task of tram driving while adding clarifications to the codes and suggesting new codes that can make them more suitable.

In 2016, a study was conducted by Thomas et al. (Thomas, Rilea, Blomberg, Peck, & Korbela, 2016) to evaluate the safety benefits of a hazard awareness and hazard perception training program for young vehicle drivers, assuming that improvement in their hazard perception may reduce the rate of their involvement in accidents and traffic violations. The results showed that the crash rate of males who participated in this program was 23.7% lower than in the male control group and that the crash rate of participating females was 10.7% higher than in

the female control group, albeit not significantly. However, this study provided evidence that brief, computer-based training interventions can have a positive influence on driving safety for young drivers.

Following the study by Thomas et al. (Thomas, Rilea, Blomberg, Peck, & Korbela, 2016) a study was conducted to assess the hazard awareness skills of the JLRT drivers (Borowsky, Palacci, Itzhaki, & Shinar, 2019). One of the most interesting findings with respect to the differences between experienced tram drivers and young drivers was related to their awareness of hidden-potential hazards. The subjects were presented with nine situations in which the tram approaches a hidden hazard and, it was hypothesised, that experienced tram drivers will identify these types of hazards better than young tram drivers; however, it was found that the group of the young drivers was more likely than any other group to respond to hidden-potential hazards. This finding should be further investigated due to the low number of young drivers (4 drivers) who participated in this study. Out of the four young drivers, three were learner drivers. According to their instructors, during their training, drivers are taught what typical hazards exist when driving along the track and special emphasis is given to hidden hazards, implying that these drivers are relying on declarative knowledge rather than driving experience and that they are much more responsive to hazards that were emphasized during their training. This pattern of over-sensitivity to hazards after training was also reported by (Meir & Borowsky, 2014).

In summary, it is important for tram drivers to be able to 'project ahead' the possible behaviour of other tram drivers and road users and to take action to avoid accidents. Hazard awareness and hazard perception are skills that can be developed, and they benefit the safety of tram operation (Thomas, Rilea, Blomberg, Peck, & Korbela, 2016). Experience may improve this skill, especially in tasks where there is an element of repetition, such as driving the same route, approaching stations, following other trams on a daily basis (Naweed, Rose, Singh, & Kook, 2017) although, for explanatory reasons, this did not come up in the study by (Borowsky, Palacci, Itzhaki, & Shinar, 2019). Fatigue and distraction are a combination that may increase the risk of accident; however, the taxonomy that was developed by Regan et al. (Regan, Hallett, & Gordon, 2011) to provide a "common framework for coding different form of driver inattention as contributing factors in tram accidents" was found not to be a useful

tool for determining risk reduction strategies. Moreover, the taxonomy categories in their current form may not be suitable for the task of tram driving (Naweed, Rose, Singh, & Kook, 2017). Therefore, the conclusions are that the taxonomic model should be developed and adapted to tram driving; in addition, better route knowledge refresh, fatigue management and development of hazard perception skills can contribute to the safety of tram operation.

2.11 The Need for Injury Weighting

2.11.1 WTP-based Values for the Prevention of non-fatal Rail Injuries

People who use or have an interest in the railway system value the need to reduce the risks of injury as well as the risks of death. In addition, injuries have consequences for resources, whether those are needed to treat injuries, or as output lost due to those injuries. In the British railway industry, the weight attached to reducing the risk of any injury relative to the value of reducing the risk of death is based on a measure of the relative strengths of preference for reducing the risks of the personal pain, grief and suffering entailed by such injuries (Jones-Lee & Loomes, 2018). The guiding principle underlying the determination of the relevant indices for the strength of preference is based on willingness to pay (WTP). The issue with the weighting of the injury is: how much weight to give to the prevention of an injury relative to the value assigned to preventing a death. To answer this question, we must first determine how to estimate the WTP-based values for the prevention of non-fatal rail injuries.

The idea of non-fatal injury may be interpreted across a very wide range of undesirable consequences, from a minor cut or bruise, and rapid recovery, to severe and permanently disabling injury, or serious brain damage (Jones-Lee & Loomes, 2018). Even the classification of injuries into 'major' and 'minor' results in a wide range of injuries in each subcategory. The question is to what extent a breakdown of sub-categories of non-fatal train injury is possible. This question includes two important issues:

- a) The number of subcategories the public will be able to deal with when answering WTP-type questions;
- b) The number of subcategories that can sensibly be used by rail industry planners when evaluating proposed rail safety improvements.

Jones-Lee and Loomes (Jones-Lee & Loomes, 2018) have noted the number of sub-categories for which the public can provide WTP-based financial valuations by n_1 and the number that train planners could be expected to actually use as n_2 . They assume that since $n_1 > n_2$ the main tasks to be performed in estimating WTP-based values to prevent non-fatal statistical injuries are:

1. Divide non-fatal rail injuries into subcategories that span the spectrum of injury, and for which WTP-based values can be determined using an appropriate empirical estimation method;
2. Estimate the WTP-based value for each subcategory;
3. Define broader subcategories of non-fatal injuries that rail planners can feasibly use in cost-benefit analysis of proposed rail safety projects;
4. Estimate WTP-based values for each of the broader rail-planning subcategories, using the estimated values of the finer subcategories derived in (2), weighted by their respective frequencies.

Jones-Lee and Loomes have set out two different approaches that can be used for estimating WTP-based values (Jones-Lee & Loomes, 2018):

1. Contingent valuation (CV), which involves direct questioning about willingness to pay for small reductions in the risk of particular non-fatal road injury subcategories;
2. Standard gamble (SG), which estimates the utility loss from incurring a particular non-fatal road injury relative to the utility loss from premature death in a road accident.

Both approaches are based on exactly the same principles. However, the CV approach has been found to elicit many deficiencies and biases in the responses to direct questions, which have generally not been observed in SG question responses. Therefore, the RSSB decided to base its estimation on the SG approach.

2.11.2 Classification of Injuries, the 'Galasko' Breakdown

The simplest classification system is to divide rail injuries between major and minor injuries. A very detailed classification system for injury severity exists for road accidents – the Galasko descriptors, which consider hospitalization, recovery time and long-term disability, and their relative frequencies (see Table 10)

Table 10: The ‘Galasko’ Descriptions devised for Road Traffic Accident Injuries (Jones-Lee & Loomes, 2018)

Label	Injury Description	Percentage of all Serious Road Injuries	Valuation Relative to the Roads VPF*
F	No overnight stay in hospital: full recovery in 3–4 months	19%	0.02
W	Hospital 2–7 days: full recovery in 3–4 months	15%	0.02
X	Hospital 1–4 weeks: full recover in 1–3 years	31.5%	0.055
V	No overnight stay in hospital: mild permanent disability	6%	0.055
S	Hospital 1–4 weeks: mild permanent disability	13%	0.151
R	Hospital several weeks/months: some permanent disability or scarring	14%	0.233
N	Hospital several weeks/months: paraplegia/quadriplegia	1.5%	1.000
L	Hospital several weeks/months: severe permanent brain damage		1.000

* Value of a Prevented Fatality

However, we must ask whether this classification is applicable to rail accidents, and if so, what are the relative frequencies in the rail context? If the system is applicable to rail accidents and frequencies for the different subcategories can be established, weighted average values can be computed for minor and major non-fatal rail injuries. But is this simple two-level classification sufficient, or would a finer classification be more beneficial for the cost-benefit analysis of proposed rail projects? And would the classification be affected by the type of rail accident being considered?

The Galasko descriptions are very general as they do not consider specific body parts; they are also outdated with respect to medical knowledge and they contain certain gaps in recovery times (Jones-Lee & Loomes, 2018). Moreover, they do not consider the psychological dimension. The RSSB has a ‘Shock & Trauma’ category, used in its assessment of rail industry workers; however, it is not clear how this could be integrated into its classification of rail injuries since it reflects workers’ responses to witnessing rail accidents.

The Galasko classification has been applied to rail accidents by different organizations, using different databases (Jones-Lee & Loomes, 2018). The conclusion was that the Galasko classification can be used, but sometimes modification is needed, particularly with respect to data related to shock and trauma. The same authors also tackled the issue of how finely the major injury category should be subdivided for the purpose of conducting cost-benefit analysis of proposed safety investment programmes, and what are the appropriate average WTP-based values for each of the injury subcategories in the feasible planning breakdown (Jones-Lee & Loomes, 2018). Comparison of different types of accidents or of injuries sustained by workers vs. non-workers in the same rail system indicated differences in the frequency distributions of major injury types. Thus, it was not recommended to divide the major injury category into two or three finer categories (Jones-Lee & Loomes, 2018). However, the authors recommend a possible subdivision of the minor injury category into reportable vs. non-reportable (i.e., no hospitalisation).

An equivalence ratio of 10 major injuries to 1 fatality has been recommended (Jones-Lee & Loomes, 2018). Assuming that reportable minor injuries constitute 15% of all minor injuries, and that 20% of the reportable minor injuries are equivalent to the least severe major injuries, the recommended equivalence ratio is 200 reportable minor injuries to 1 fatality. The recommended equivalence ratio for non-reportable minor injuries (minor cuts/bruises) is 7000 non-reportable minor injuries to 1 fatality. If all minor injuries are included in one category, the recommended equivalence ratio is 1250 minor injuries to 1 fatality. There is no clear recommendation regarding the equivalence ratio for shock and trauma (Jones-Lee & Loomes, 2018). Finally, since current data are very limited, they add a strong recommendation for the rail industry to initiate a study to develop a classification and breakdown of non-fatal injuries, calculate WTP-based values, and establish reliable equivalence ratios for a finer breakdown of minor and major injuries.

2.11.3 Calculation of Injury Severity

In Britain, injury severity is categorised according to Fatality and Weighted Injury (FWI). All of the injury data is collected into a Safety Management Information System (SMIS) (RSSB, 2020), which thus includes a range of different injury severities. It is therefore useful to have a way of combining the different consequences occurring from a particular activity or event, in order

to prioritise activities and events in terms of their consequences. For example, few events with more serious consequences can be weighted against many events with less serious consequences, to inform a systematic decision of where to spend resources.

The accepted approach in Britain to combining injuries of different severity levels into one composite measure is based on weighting several less serious events as being equal to one fatality. The resulting index, the fatality weighted index (FWI), indicates the aggregate amount of safety harm for different degrees of injury (Table 11). The actual weightings are based on research and consultation using public focus groups.

Table 11: The Aggregate Amount of Safety Harm

Injury degree	Weighting	Number of injuries weighted as equal to a fatality
Fatality	1	1
Major injury	0.1	10
Minor injury (Class depends on seriousness of injury)	0.005 (Class 1)	200
	0.001 (Class 2)	1000
Shock/trauma (Class depends on seriousness of event resulting in shock/trauma)	0.005 (Class 1)	200
	0.001 (Class 2)	1000

The Annual Health and Safety Report 2019/20 for the British railway network (RSSB, 2020) emphasises that it is currently difficult to reasonably determine the classification of shock / trauma injuries into Class 1 or Class 2. Therefore, these injuries are not included in the calculation of FWI, but rather displayed as a total count.

2.11.4 Israeli Guidelines on Transport Projects Appraisal

2.11.4.1 Estimation of injury severity

The injury severity score (ISS) is a medical score that estimates the injury severity of the casualty, in accordance with the Transport Projects Appraisal (TPA) of the Israel Ministry of Finance and the Israel Ministry of Transport (Israel Ministry of Finance; Israel Ministry of

Transport, 2012). Estimation of the economic cost of accident casualties is based on categorisation of casualties among severity levels according to hospital data, where each hospital's categorisation is based on four severity levels in accordance with the international injury severity score (ISS) (Injury Severity Score, 2020). The ISS combines the injury severity for different body parts to provide an overall score of injury severity. All injuries are assigned an Abbreviated Injury Scale (AIS) code and score which ranges from 1) minor, 2) moderate, 3) serious, 4) severe, 5) critical, 6) an injury that is thought to be 'incompatible with life. Patients with multiple injuries are scored by adding together the squares of the three highest AIS scores in three predetermined regions of the body. This is the ISS which can range from 1 to 75 where 1 is a light injury and 75 is a very severe injury.

2.11.4.2 The cost of road accidents

The total economic cost to the national economy as a result of road accidents can be divided into two categories, the cost of casualties and the cost of damage to assets. A decrease in production, medical expenses and a decrease in welfare are attributed to the cost of casualties whereas the costs of road delays, property damage, and cost to institutions (insurance, police, courts, appraisers, attorneys and more) are attributed to the costs of asset damage. Table 12 shows the estimated costs of casualties for road accidents as presented in the TPA guidelines. The costs were converted from NIS (new Israeli shekels) to Euro using the exchange rate of 1 Euro = 4 NIS. The TPA does not show explicit costs for tram accidents; therefore, to conduct a CBA exercise the author will use the costs indicated in Table 12.

Table 12: Estimated Cost to the National Economy in 2012 k-Euro (Israel Ministry of Finance; Israel Ministry of Transport, 2012)

			Costs of casualties	Indirect costs	Total
Cost per casualty	Fatality		1500	125	1625
	Casualties who were hospitalised for at least two days	Critical	1000	90	1090
		Severe	380	40	420
		Moderate	260	20	280
		Minor	30	5	35

	Casualty who was not hospitalised		6	1	7
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2.12 Cost Benefit Analysis

TPA guidelines are based on economic analysis according to the CBA approach. This method is based on identifying and quantifying the costs and benefits of the project by determining monetary values for the tangible and intangible costs and benefits. Project feasibility is described using several profitability indicators; two of which are described below:

2.12.1 Net Present Value (NPV):

A profitability indicator that describes the net contribution of the project by calculating the total benefit to the economy less the costs to the economy from project execution, over the entire economic life cycle of the project, at current value (Equation 11). That is, all the costs and benefits are discounted at a present value to the reference point $t = 0$.

$$NPV(r, n) = \sum_{t=0}^n \frac{CF_t}{(1+r)^t}$$

Equation 11: Net Present Value Indicator

Where:

r = discounting rate per year

n = economic life cycle of the project

CF_t = cash flow in year t and;

$$\frac{1}{(1+r)^t} = \text{Present Value Coefficient}$$

When the future costs and benefits are fixed and recurring in each period / year, a serial present value coefficient would be (Equation 12):

$$\text{Serial Present Value Coefficient} = \frac{(1 + r)^n - 1}{r * (1 + r)^n}$$

Equation 12: Serial Present Value Coefficient

2.12.2 Benefit-cost Ratio

A profitability indicator that describes the ratio between the net present values of the project benefit divided by the net present value of the project costs.

$$B / C (r, n) = \frac{\sum_{t=0}^n \frac{B_t}{(1 + r)^t}}{\sum_{t=0}^n \frac{C_t}{(1 + r)^t}}$$

Equation 13: Benefit-cost Ratio

Where:

B_t = project benefit in year t

C_t = project costs in year t

r = discounting rate per year

n = economic life cycle of the project

The project is feasible / worthwhile if $B/C (r \& n) > 1$

2.13 The relative Frequency Definition of Probability

In the context of risk assessment based on past accident data the relative frequency of an event represents the number of events per unit of activity. In the case of this study, the main unit of activity is tram-km. If we look at the number of times a particular event, E1, occurs over N tram-km covered by the JLRT trams, we will find that E1 has occurred N1 times. We can then set up the ratio:

$$E1 = \frac{N1}{N}$$

If this ratio approaches a definite limit when N becomes very large, we call this limit the probability associated with $E1$, i.e., $P(E1)$ (Vesely & Goldberg, 1981). The term of probability is also used in Figure 9 as "*Probability of derailment / train mile travelled*" (Muttram R. I., Railway Safety's Safety Risk Model, 2002). Given the above and the fact that the number of tram-km which will be used in this study is very large, the author will use the term probability for relative frequency calculations. A frequency is the number of times a given datum occurs in a data set while a relative frequency is the fraction or proportion of times an event occurs.

3 Introduction to Safety Risk Modelling and Hazard Selection

3.1 Hazard Selection for the Study

The annual safety report for the JLRT system, which includes safety performance indicators, as shown in Table 13, *Table 13* was the base from which hazards were selected for this study. The list of performance indicators comprises a variety of accidents and incidents associated with operational hazards which are monitored by the tram operator and the author's department, and their yearly consequences are reported to the Ministry of Transport. Hazards which are associated with the safety indicators and comply with the criteria listed in Table 14 were chosen for the risk modelling study.

Table 13: JLRT 2014-2016 Safety Performance Indicators

2014-2016							
Events		Total Injuries					
Type Of Incident	Total Number	Passengers			3rd party		
		Light injury	Severe injury	Fatality	Light injury	Severe injury	Fatality
Collision with pedestrian	41	0	0	0	20	0	0
Collision with pedestrian in which EB was activated causing passenger injuries	6	9					
Collision with cyclist	13	0	0	0	4	0	0
Collision with cyclist in which EB was activated causing passenger injuries	2	6					
Collision with a car	60	0	0	0	12	0	0
Collision with car in which EB was activated causing passenger injuries	4	9					
Collision with object	5	0	0	0	0	0	0
Passenger or object trapped at the door	7	3	0	0	0	0	0
Passenger falling subsequent to EB	44	63	0	0	1	0	0
SPAD	39	0	0	0	0	0	0
SPAD (depot)	10	0	0	0	0	0	0
Total	231	90	0	0	37	0	0

Table 14: Hazard Selection Criteria

Criteria	Performance Indicator	Associated Hazard
Events that lead to major or minor injuries to passengers and staff on board the tram	Passengers falling subsequent to EB	EJ
Events that have potential to lead to tram collision and catastrophic consequence to passengers and staff on board the trams	SPAD	SPAD

In accordance with Table 13 and Table 14, two hazards were selected: EJ and SPAD. The third hazard, overturning of trams on sharp curves, does not appear in the performance indicators table as it was not monitored; however, it was chosen because of the accident that occurred in Croydon, England, in 2016, where a tram overturned on a curve with a radius of 30 m and the fact that the JLRT system also has tight radii.

There were 7 events of door trapping in the years 2014-2016 resulting in 3 light injuries, where passengers were trapped outside the trams. This hazard was eliminated by fixing the cameras outside the trams such that the drivers could see all of the tram doors before departing from the station. Figure 12 shows that in subsequent years there was no accident of this kind. Therefore, this hazard was not selected for the study.

The SPADs which occurred in the Depot cause no risk to passengers as there are no passengers on board the trams travelling in the Depot. Moreover, to avoid accidents, tram speed in the Depot is restricted to 10 km/h. During the years 2014-2016 SPADs occurred but they did not cause any accidents or near-miss accidents. Figure 12 shows that in subsequent years there were SPADs events, but with no accidents or near-miss accidents. Therefore, this hazard was not selected for the study.

With respect to hazards associated with collisions with a third party where passengers are injured, the cause of passenger injuries is attributed to EJ due to EB. It was revealed that, when the tram driver activated EB prior to the collision to avoid it, passengers fell in the tram and got injured. However, when the collision occurred with no activation of EB there were no injuries among the passengers in the tram. This can be explained by the large differences in the masses of the vehicles: LRT versus car, bicycle, or pedestrian. A collision between slow-moving vehicles whose masses are radically different may not create EJ that causes passengers

to fall and suffer injuries inside the vehicle, see also section 4.1. Therefore, in the calculation of the risk associated with EJ, in Chapter 4, 87 injuries as a result of emergency braking were taken into account, of which 24 injuries resulted from EB which was activated by the driver to avoid collision with a third party, but the collision was not avoided, and 63 injuries that resulted from other causes of EB. All the causes of EB are listed in Appendix A.

The main cause of collisions between trams and road vehicles and cyclists is violation of traffic rules, by vehicle drivers and cyclists. Figure 10 presents the distribution of causes of collisions based on five-year data (2014-2018). The main reason for collisions with pedestrians is also violation of traffic rules; pedestrian tend to enter the swept path unexpectedly, and they do not obey the traffic lights, as presented in Figure 11. A number of explanatory campaigns have been launched on social networks and passenger stations, but incidents still occur, mainly in the pedestrian mall of the city, which is a shopping area where a large public gathers, some of whom do not adhere to safety regulation.

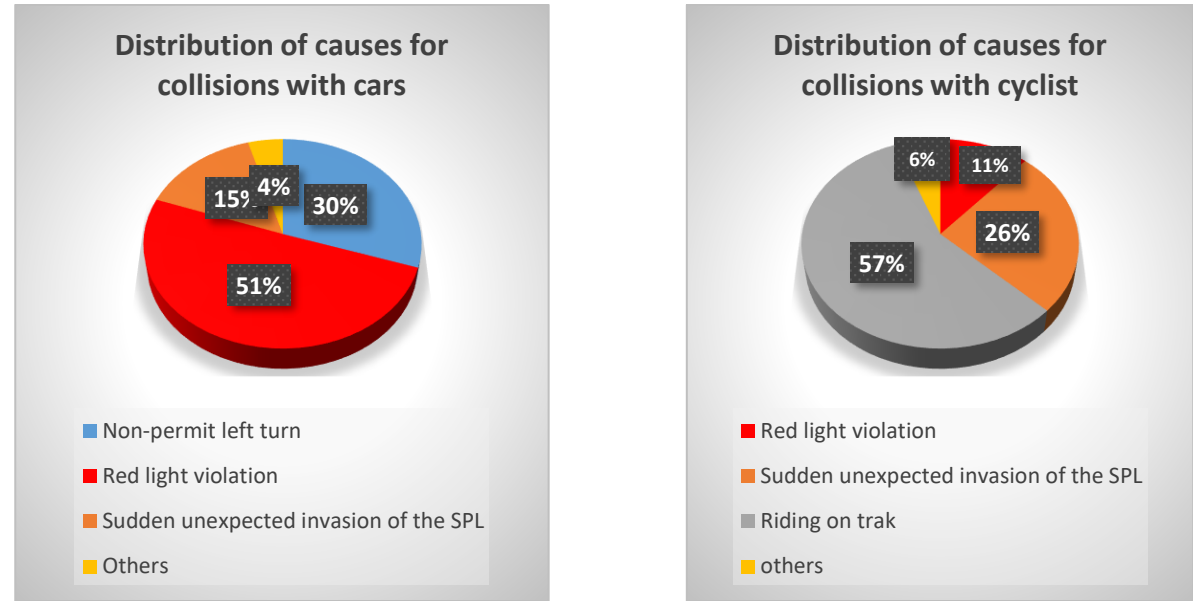


Figure 10: Distribution of Causes of Collisions with Cars and Cyclists

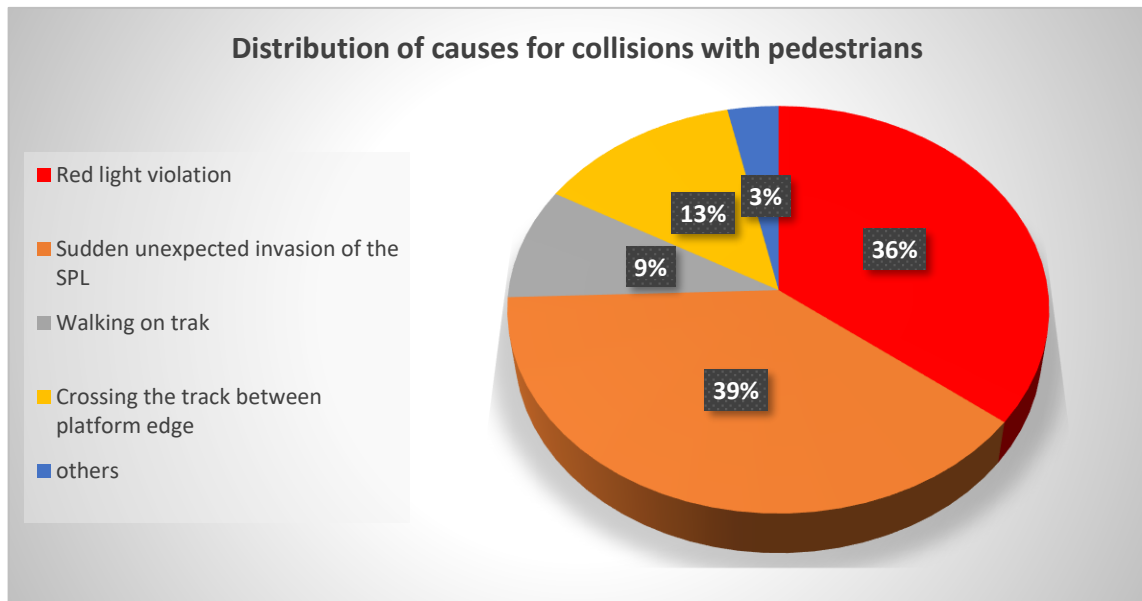


Figure 11: Distribution of Causes of Collisions with Pedestrians

Figure 12 shows the distribution of safety events on the JLRT system over five years: 2014-2018. As mentioned above, the event 'passengers trapped by the doors' has not been an issue since 2016. However, 'passenger falling subsequent to EB' and 'SPADs on the mainline' are events which constantly occur in the JLRT system.

The increase in the number of collisions with trams, according to the police reports (which are confidential), are part of a general growth in the number of accidents in the city. This increase has also been attributed to the annual growth in the number of road vehicles (of all kinds), as can be seen in the 2019 report of the Israeli Bureau of Statistics (Israel Bureau of Statistics, 2019). According to the accident investigation reports of the JLRT operator and the police, none of the causes of collisions were attributed to tram drivers' behaviour or lack of safety measures in the JLRT system. This issue is regularly discussed with the police and the Ministry of Transportation in order to promote technological and human enforcement. Therefore, the hazard 'collision with a third party' was not selected for the study.

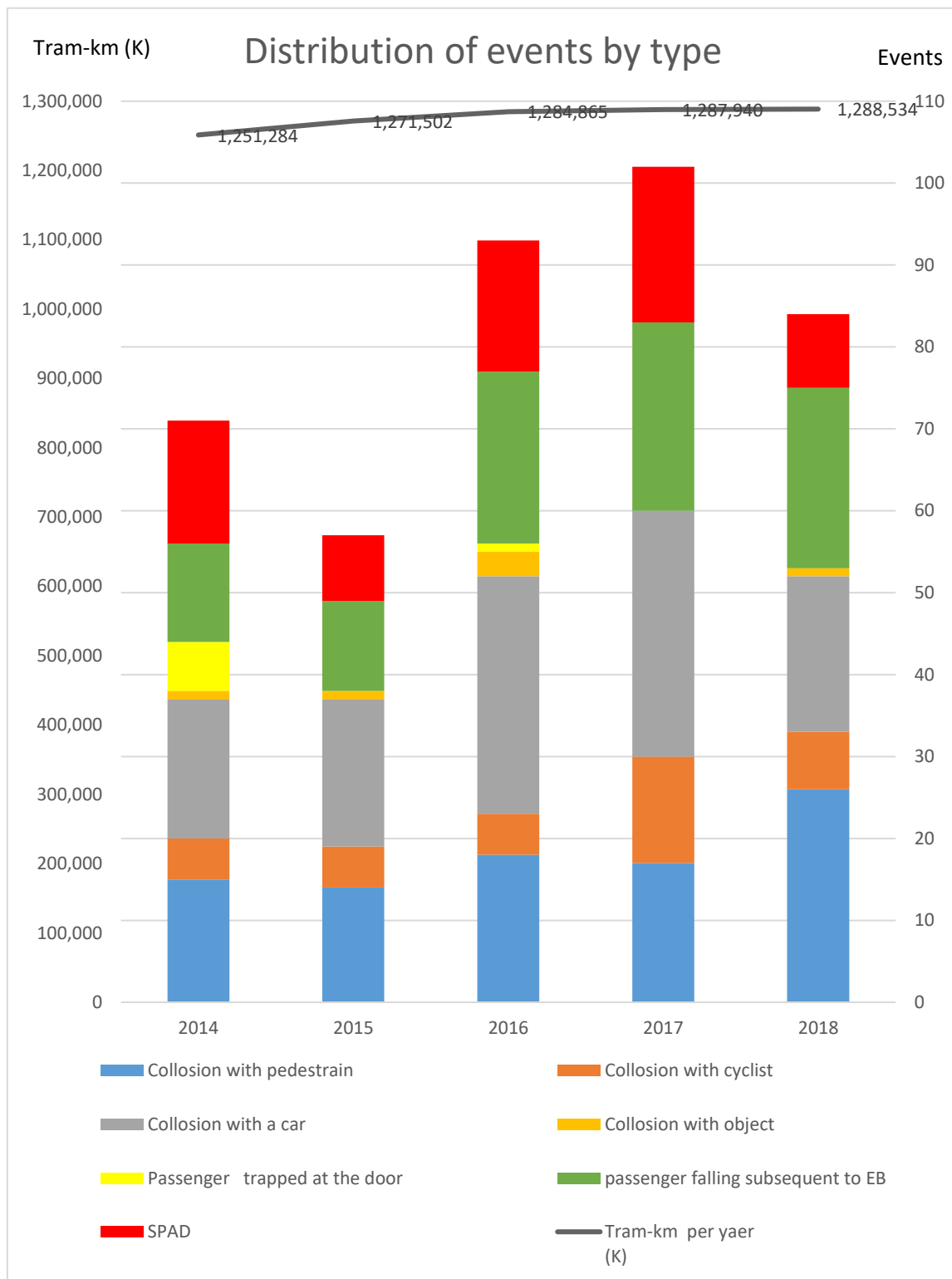


Figure 12: Distribution of Safety Events by Type and Year

3.2 Safety Risk Modelling

3.2.1 Modelling Approach

Following hazard selection and the literature review, the following modelling technique will be used to model the risks associated with the hazards EJ, SPAD and overturning of a tram on a sharp curve, as they can address the study objective and the model success criteria defined in Section 1.4:

- i. FTA and ETA are widely used in the UK SRM and they are suitable for modelling the risk of high-frequency, low-consequence events as well as for low-frequency, high-consequence events. Moreover, a FT provides a graphical representation of the logical relations between the basic events and the top event, and it is a well-known methodology that can be applied relatively easily; therefore, the risk associated with EJ and SPAD will be modelled by these modelling techniques.
- ii. Poisson distribution: this model is more suitable for the assessment of risk where accidents are more frequent and where past accident data exist; therefore, it will also be used to assess the risk of EJ. In addition, a comparison will be made between the outcomes of the FTA and ETA and those of the Poisson distribution.
- iii. NB: we are using the negative binomial model to develop a prediction model of EB events on a route Sections of the JLRT System
- iv. Since the sample data of tram velocity at the entrance to the sharp curve in the JLRT system are normally distributed, the normal distribution will be used to determine the probability of the tram entering the curve at an overturning speed.
- v. Due to the fact that a collision between trams due to SPAD and overturning of a tram on a sharp curve are considered rare events with sparse data, a qualitative risk assessment and evaluation using expert judgement will be carried out to validate the results of the risk associated with these hazards.
- vi. According to the article, “Risk of non-collision injuries to public transport passengers” (Elvik, 2019) the risk of falls inside a moving vehicle was determined to be about 0.3-0.5 per million passenger kilometres. This figure cannot serve as a benchmark in the study of EJ because it has wide dispersion around the mean, with a range of 0.04 to 1.4 injuries per million passenger kilometres.

3.2.2 Model Characteristics

The risk associated with each hazard will be quantified in terms of frequency, consequences and collective risk, where the latter is the product of the first two components. These components will be modelled and quantified as follows:

- i. The frequency of each hazard event will be modelled using FTA or through an adjusted statistical distribution as described above.
- ii. The possible outcomes from each hazard event will be estimated based on data obtained from the JLRT system, or accidents occurring elsewhere.
- iii. The annual collective risk (CR) associated with a particular hazard will be analysed using ETA and Equation 2, Section 2.2.16.

3.2.3 Risk Acceptance

The risk acceptance will be in accordance with the risk acceptance principle and criteria defined in Sections 2.6.2.4 and 2.6.2.5:

- i. The frequency level and the severity level of the quantitative safety risk models will be evaluated using Table 6 and Table 5, respectively.
- ii. The tolerability of the risk as a result of the combination of the frequency and severity levels will be evaluated using the risk matrix (Table 7).
- iii. Based on the risk evaluation results the acceptance of the risk will be in accordance with the risk acceptance criteria (Table 8).
- iv. Since the above risk modelling approach is in line with the explicit risk estimation and evaluation principle (Section 2.3.3.3 of the literature review), and according to RSSB “The ‘explicit risk estimation and evaluation’ principle is the only risk acceptance principle that explicitly invokes the ALARP principle” (RSSB, 2014), then for tolerable and undesirable risk, the ALARP principle and cost benefit analysis (CBA) will be applied (if necessary) in accordance with Sections 2.11.4.2 and 2.12.
- v. The results of the SPAD and Overturning safety risk models will be validated against expert judgement. The work format with the experts including the group discussion is detailed in Section 3.2.5.

3.2.4 Important Notes

- i. Since the author does not have access to data on the severity of injuries in casualties who were evacuated to hospitals after falling down inside the trams, the calculation of the risk in terms of FWI will be based on methods used in the UK, described in detail in the literature review, Section 2.11.
- ii. Coupled with the fact that “it is not acceptable to compare individual risk results for each hazard event with individual criteria” (RSSB, 2002) cited in Section 2.6.1.2 in the literature review, and the fact that this study models the risks associated with only three hazards inherent in the JLRT system, an evaluation of the individual risk for passengers will not be made.

3.2.5 Expert Judgement, Methodology

In accordance with Sections 2.4.2, 2.4.3 and 2.9.3, where the importance of expert opinion is raised, given that the events are rare, an expert judgement exercise was carried out to validate the results of the safety risk models of SPAD and overturning of a tram. Here are the main steps of the expert judgement exercise:

3.2.1.1 Preparing an exercise document

An exercise document was prepared for each hazard. The document contained a questionnaire according to which the experts were required to assess the likelihood of the hazard occurring and its severity should it occur. They were also asked to suggest measures to mitigate the risk and re-evaluate the likelihood and the severity. The experts were also asked to justify the assessments they made. The experts were asked to do their assessments based on Table 5 and Table 6 of Section 2.6.2.4, which were included in the exercise document.

3.2.1.2 Assembling a group of experts

A group of experts was assembled, as detailed in Table 15 and presented in Figure 13, a snapshot taken from the workshop with the experts.

Table 15: The Participants in the Expert Judgement Exercise

	Name	Role	Company
	Moshe Itzhaki	Head of Operations and Systems Division	JTMT
Facilitator	Steve Denniss	Expert, Technical director	WSP UK LTD
Expert B	Prasad Bhawe	Expert, Technical director	WSP UK LTD
Expert S	Eran Schechtman	Expert, CEO	Connect light rail Israel
Expert C	Alexandre Guillemin and Luc Clouet Alexandre: was not able to participate in the workshop	Alex: Expert, Safety manager Luc: Project manager (head of engineering desk of Egis Israel)	EGIS RAIL
Expert K	Shlomi Kahana	Expert, Quality and Safety manager	Ex- Connect JLRT Israel. Today Tevel Metro Israel



Figure 13 Expert Judgement Workshop (Author, 2021)

3.2.1.3 Selection of a facilitator

A facilitator was selected to lead the expert workshop where the experts' assessments and their assumptions would be discussed. The author did not take on this role in order to avoid biasing the experts towards the results of his safety risk models.

3.2.1.4 Consolidating the results of the questionnaires

The results of the questionnaire were consolidated on risk matrices, before and after implementation of risk mitigation measures. The matrices were presented and discussed in the workshop.

3.2.1.5 Workshop discussion

A workshop discussion was conducted to discuss the questionnaire results.

3.2.1.6 Comparison with the safety risk models

The last stage involved a comparison with the safety risk model results, author summary and discussion.

3.2.6 Assumptions Related to the Risk Modelling

- i. The signalling systems (RTSS & TSS), the tram system and the track system are maintained and operated appropriately and no significant change has been introduced since the commencement of operations of the JLRT system. All other subsystems operate under the same conditions.
- ii. The results from the risk models represent the residual risk currently predicted, assuming that all the safety mitigation measures exist with their current degree of effectiveness.
- iii. Safety related staff including drivers, operations managers, OCC personnel and maintenance staff are qualified and competent.
- iv. There is a flat operation plan with 6 min headway from 07:00-18:00.
- v. The round-trip time and the speed limits in every track section are constant and there has been no change since the commencement of operations of the JLRT system.
- vi. The total operation hours per year in the JLRT system are 66,295 hours and the annual change is negligible.
- vii. SPADs events occur randomly and independently along a given unit of distance, measured in tram-km.
- viii. EB events occur randomly and independently along a given unit of distance, measured in tram-km.

4 Modelling the Safety Risk Associated with Excessive Jerk in the Jerusalem Light Rail Transit System

4.1 Introduction

Jerk is the rate of change of acceleration (or deceleration). Excessive jerk (EJ) may result in an uncomfortable journey in a train or tram. It is a hazard that may cause passengers to lose their balance and to fall and injure themselves inside the vehicle.

The main cause of EJ in the JLRT system is emergency braking (EB). There are different reasons for tram drivers to apply EB; the most common reason is traffic disruption, when the LRT drivers take action to avoid collision with a third party. Others, defined under the category of tram failures, such as dead man failure or door failure, are not controlled by the driver and, when they occur, the tram brakes immediately. Between the years 2014-2016, 891 EB events occurred, of which 647 events, about 73%, occurred due to traffic disruption, 179 events, about 20%, occurred due to technical failures and the rest were due to operational failures. Figure 20 lists the EB causes associated with these categories.

The author visited France and Switzerland to assess the risk of EJ in other LRT systems, the causes of its occurrence and the measures taken to mitigate it. For reasons of confidentiality, the author was not given sufficient data to make a comparison of the risk levels in the different LRT systems. However, one of the important things learned from the visit, which reinforces the risk model presented in this study, is that the common cause of EJ is EB.

The purpose of this study is to quantify the risk of EJ in line-of-sight operations, where the tram drivers are solely responsible for acceleration and deceleration of the trams. This study presents two methods for modelling the risk associated with this hazard. The first method uses FTA and ETA, while the second method uses a Poisson distribution to quantify the risk. The results of risk quantification by each method are compared.

4.2 Modelling the Risk Associated with EJ Using FTA and ETA

4.2.1 Fault Tree Analysis

Excessive jerk is a hazard situation that can cause passengers to fall and suffer injuries inside the tram. The Preliminary Hazard Analysis (PHA) which was performed for the JLRT red line

indicated possible causes for EJ Figure 14, whereas the accident scenario analysis showed that the main cause of EJ is the application of EB, caused by different inherent operation situations, as described in the FTA (Figure 15, Figure 16 and Figure 17).

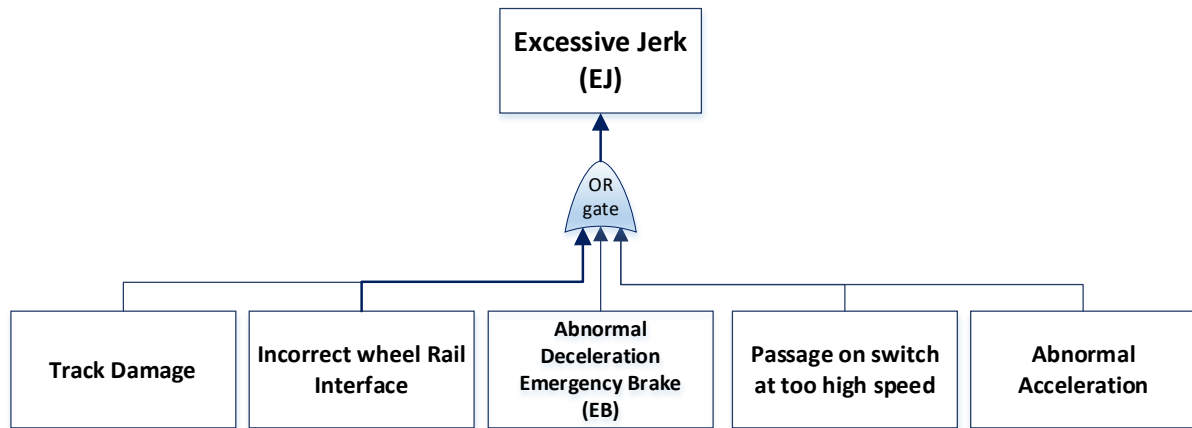


Figure 14: Possible Causes for EJ Based on JLRT PHA

The author assumes that the reason for this is that the JLRT system has been in operation for only a short time span of about six years and, therefore, failures such as track damage or incorrect rail wheel interface are relatively rare. This assumption was tested against other operators of light rail systems, as described in Section 4.10; it was noted that as in the JLRT system the main cause for EJ is EB. The common reason for applying the EB is pedestrians and vehicles crossing the swept path unexpectedly.

In the case of collisions as a cause for EJ, it was revealed that, when the tram driver activated EB prior to the collision, passengers were injured due to EJ. However, when the collision occurred with no activation of EB there were no injuries among the passengers in the tram. This can be explained by the large differences in the masses of the vehicles: LRT versus car, bicycle, or pedestrian. As already mentioned in section 3, a collision between slow-moving vehicles whose masses are radically different may not create EJ that causes passengers to fall and suffer injuries inside the vehicle. In cases where the driver activated EB before a collision, leading to passenger injury, EB was determined to be the cause of EJ.

The data table in Appendix A analyses the causes of EB events as recorded in the JLRT system during the years 2014-2016 (Appendix B) and the probability of occurrence of the events. Figure 15, Figure 16 and Figure 17 present a detailed FTA, which was performed with the data

in Appendix A. The FTA shows that there are only OR gates in the FT, meaning that every basic event (BEvn) can cause EB, i.e., each BEvn is a single point of failure. It can therefore be assumed that the events occur randomly and are independent.

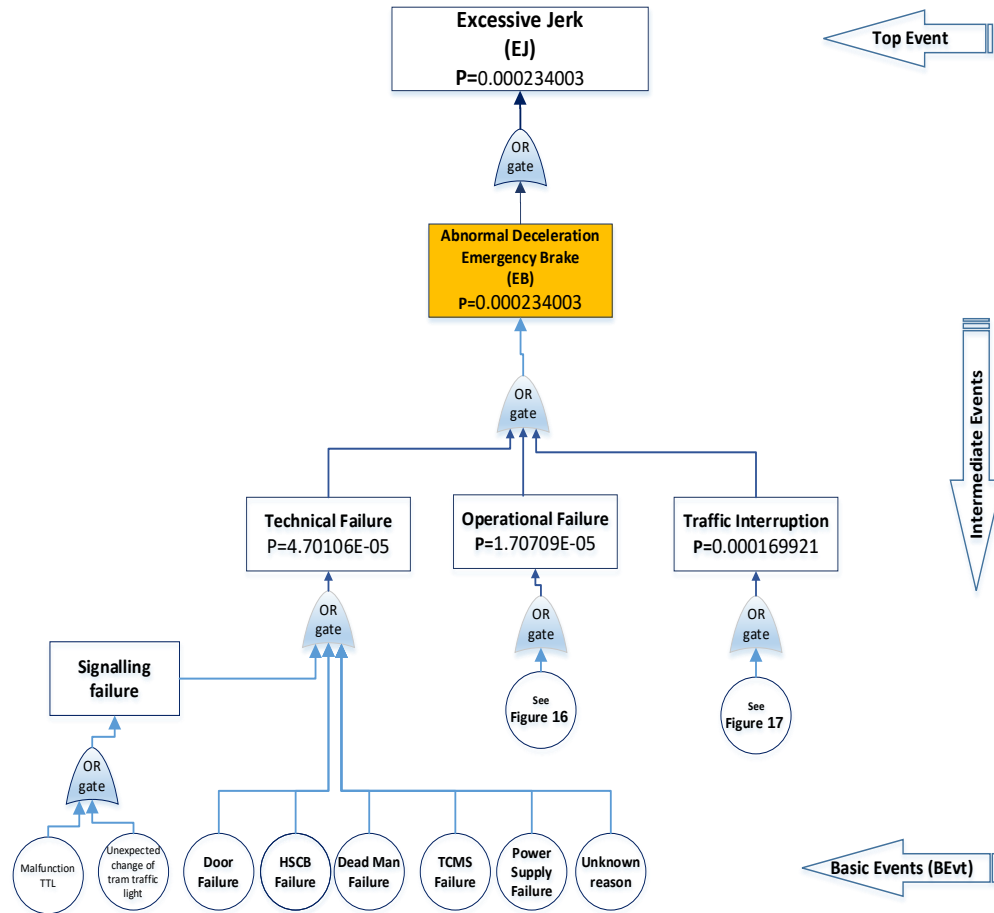


Figure 15: Partial Fault Tree of Excessive Jerk (Author)

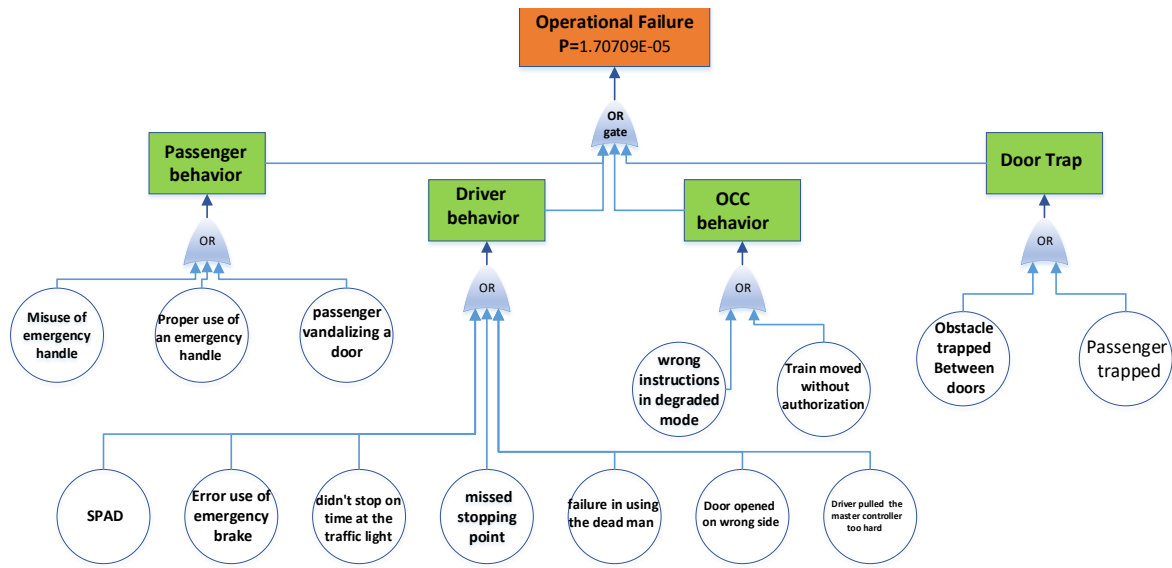


Figure 16: Continuation of Fault Tree – EB due to Operational Failure (Author)

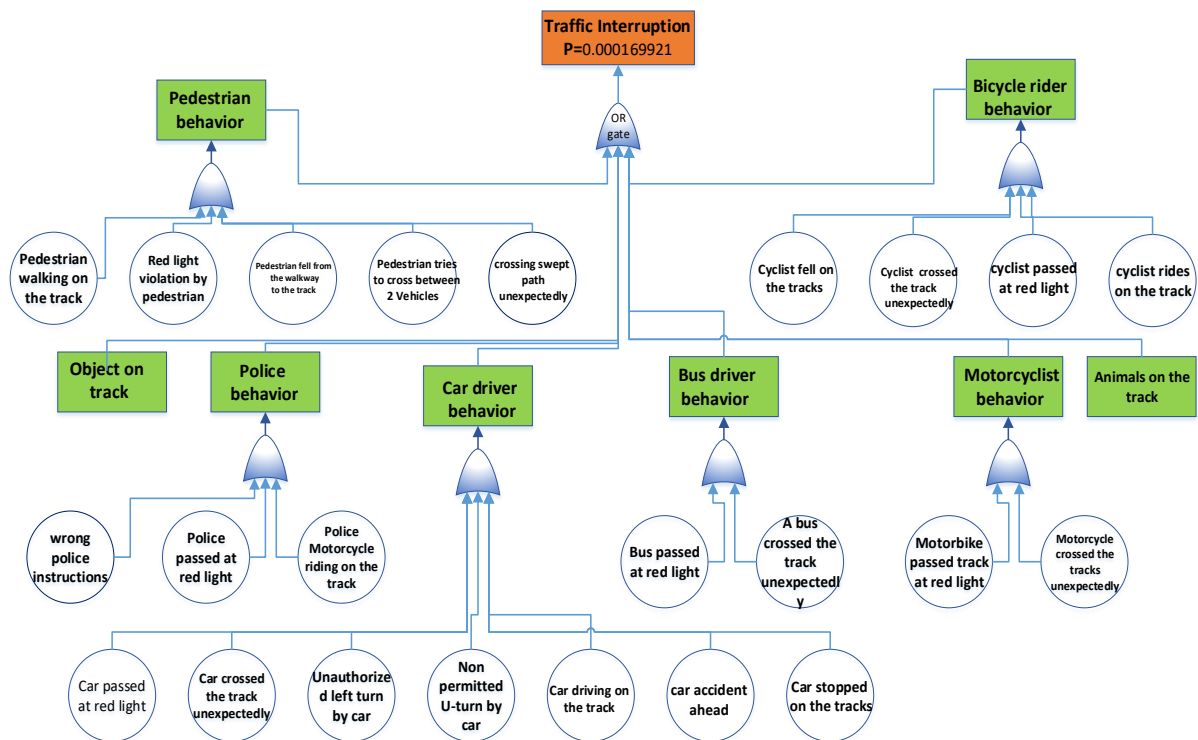


Figure 17: Continuation of Fault Tree – EB due to Traffic Disruption (Author)

Table 16 shows the aggregate number of EB events and injuries per year and per intermediate cause, as derived from the FTA. It can be seen that over 70% of EB events are caused by traffic interruption where the LRT drivers take action to avoid collision with a third party. These events are responsible for 69% of the incidents where passengers fall and injure themselves.

Table 16: Number of EB Events and Injuries per Year per Cause of EB

Intermediate causes of EB	2014				2015				2016			
	Total events	Events with injuries	Light injuries	Injuries that required first aid	Total events	Events with injuries	Light injuries	Injuries that required first aid	Total events	Events with injuries	Light injuries	Injuries that required first aid
Operational Failure	26	1	0	1	16	0	0	0	23	0	0	0
Traffic Interruption	140	9	7	8	226	8	3	11	281	22	16	15
Technical Failure	45	3	2	1	49	6	1	7	85	7	8	7
Total	211	13	9	10	291	14	4	18	389	29	24	22
Total Train-km per Year	1,251,284				1,271,502				1,284,865			

4.2.1.1 The probability of an EB event

Every BEvn can cause the occurrence of the top event EB, i.e., every BEvn is a single point of failure; thus, using Boolean logic, the probability of occurrence of an EB is a summation of the probabilities of each BEvn per tram-km. Therefore, based on the FTA and the data in Appendix A, the probability of occurrence of an EB is described by Equation 14:

$$P (EB \text{ Event per Tram} - km) = \sum_{i=1}^n P(BEvn_i) = 0.000234$$

Equation 14: Probability of an EB Event

where:

n= 891 BEvn causing EB during the years 2014-2016

The probability of an EB event is 0.000234 per tram-km, which represents a frequency of 1 EB event every 4,273 tram-km.

The total tram-km in the years 2014-2016 is 3,807,651.

In accordance with the statistics supported by the JLRT system the only cause for EJ is EB as described in the FTA; therefore, the probability of occurrence of EJ is equal to the probability of EB as described below (Equation 15) as well as the frequency of EJ.

$$P (EJ \text{ Event per Tram} - km) = P(EB \text{ Event per Tram} - km) = 0.000234$$

Equation 15: Probability of EJ

4.2.2 Event Tree Analysis (ETA)

4.2.2.1 Data used for the risk analysis

The data table in Appendix A lists all the types of EB events, some of which cause EJ, resulting in passenger injuries. The events and their consequences in the years 2014-2016 are summarised below in Table 17.

Table 17: Data Summary 2014-2016, and Calculation of the Consequences in Terms of Fatality and Weighted Injury

Measured parameter	Quantity	Notes
Total train-km	3,807,651	Total qty. Years 2014-2016
Total EB events	891	Total qty. Years 2014-2016
Total EB events with injuries	56	Total qty. Years 2014-2016
Total light injuries	37	Total qty. Years 2014-2016
Total injuries that required first aid	50	Total qty. Years 2014-2016
Fatality and Weighted Injury (FWI)	0.287	The weights for calculating FWI are given in Section 2.11.3
FWI per event with injuries	0.00513	FWI / Total EB with injuries
Probability of EB	0.000234	See Section 4.2.1.1
Probability of EB with injuries (once EB occurred)	0.06285	Total EB with injuries / Total EB

4.2.2.2 Forecast of the tram travel distance

Figure 18 presents the predicted number of train-km in the year 2017, which is gradually increasing. Generally, the total distance that the trams travel every year is a function of the operation plan agreed with the operator.

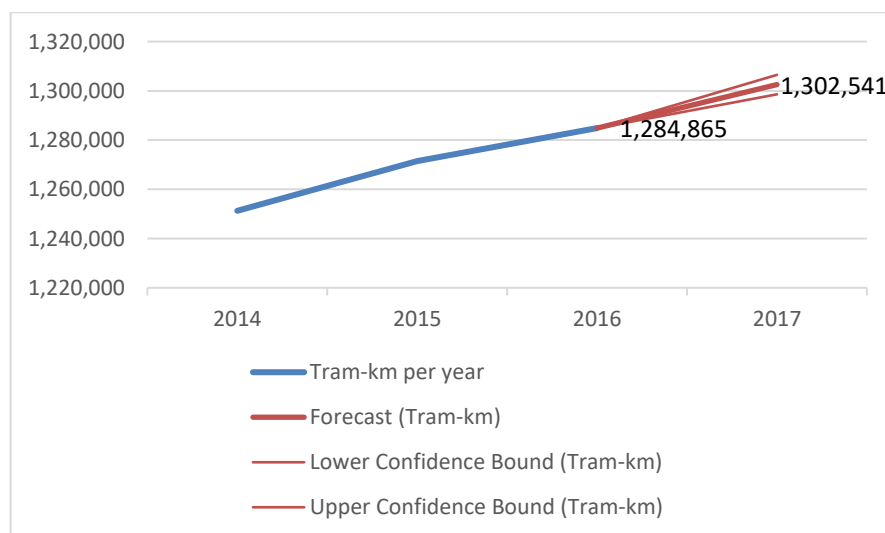


Figure 18: Forecast of Tram-km

4.2.2.3 Collective risk (CR)

The probability that an EB event will occur is 0.000234

This probability represents a frequency of one EB event every 4,273 tram-km.

In accordance with Table 17, the probability that an EB event will lead to EJ with injured passengers is:

$$P(EB \text{ with injuries}) = 56/891 = 0.06285$$

If: The aggregate amount of safety harm in terms of FWI is: $(37*0.001+50*0.005) = 0.287 \text{ FWI}$.

And: the number of EB events with injuries is: 56

Then: the FWI per EB Event is: $0.287 / 56 = 0.00513$

Given: the predicted travel distance for 2017 (Figure 18) is equal to: 1,302,541 tram-km

Therefore: in accordance with

Figure 19 the annual collective risk (CR) is:

$$\underline{CR = 0.0982 \text{ FWI per year}}$$

Total number of LRT tram-km / year	Probability EB / tram-km	Does EB lead to incident with injuries?	Fault sequence frequency (EB events / year)	Consequences equivalent FWI/ per event	Risk equivalent FWI / year
1,302,541	No		1,302,236	No EB. No injuries	
	0.999766				
	0.000234	No	286	EB incidents without injuries	
		0.93715			
Yes		0.06285	19	0.00513	0.0983
		Yes			
Collective Risk (CR)=					0.098

Figure 19: Calculation of the CR Resulting from EJ, Using the ETA Technique

4.3 The JLRT EJ Safety Risk Model

Let:

P: probability/relative frequency of occurrence of an EJ event with injuries

C: consequences FWI/Event

S: mileage accumulated by the tram fleet in year $j = 1, 2, 3, \dots$

Then:

$$\text{Annual CR} = S_j * P * C$$

Equation 16: Annual Collective Risk due to EJ

According to the ETA the probability and the consequences are:

$$P = 0.000234 * 0.06285 = 0.0000147$$

This probability represents the frequency of 1 event with injuries per 67,995 km

$$C = 0.00513$$

Therefore:

$$\text{Annual CR} = S_j * 7.54 * 10^{-8}$$

Equation 17: Annual Collective Risk to EJ Model equation

The EJ safety risk model (Equation 17) shows the dependence between the exposure and the risk. That is, the further the trams travel in a given year, the higher the risk of passenger injury as a result of EJ, provided that no significant change, such as a change in technology, is introduced to the system, which may influence the probability of occurrence of EJ events.

4.4 Evaluating CR Forecast Accuracy

The accuracy of the predicted annual CR was tested against the accident data from 2017. In that year there were 28 events of passengers falling inside the tram due to EJ: 15 passengers were slightly injured and 13 required first aid; accordingly, the CR for 2017 is:

$$\text{The actual CR} = 15 * 0.001 + 13 * 0.005 = 0.080 \text{ FWI}$$

$$\text{Knowing that the forecast value of the CR} = 0.0983$$

Then: the forecast accuracy will be calculated using

Equation 18:

$$\text{Percentage Error} = \left| \frac{\text{Actual value observed} - \text{Forecast value}}{\text{Actual value observed}} \right| * 100\%$$

Equation 18: Percentage Error

$$\text{Percentage Error} = \left| \frac{0.08 - 0.098}{0.08} \right| * 100\% = 22.8\%$$

This error can be explained in two ways: (1) The sample size is relatively small; and (2) The JLRT system is relatively immature and has not yet stabilised. There have been changes in drivers and a significant increase in passenger numbers during these years. Yet, the predicted CR provides a good approximation of the actual value of the annual CR.

4.5 Modelling the Risk Associated with EJ Using the Poisson Distribution

4.5.1 Estimating the Probability of Occurrence of an EB Event

4.5.1.1 Introduction

Assuming that EB events occur randomly and independently at a constant rate of λ per tram-km and the rate does not change through time or distance, it can be said that the variable EB has a Poisson distribution (Balka J, 2013); hence the author will use Evans' statistical approach (Evans, 2002) to predict the risk associated with EJ using the Poisson distribution and will compare the results with the risk prediction using FTA and ETA. In accordance with the comparison made between these two approaches by Bedford et al. (Bedford, Quigley, & French, 2004b) it is hypothesised that the results will be similar as the comparison between the approaches is based on a common statistical foundation.

The basic model of Evans (Evans, 2003) implies that, given any number of unit activity, say k tram-km, then the number of accidents in a specific year, t , is Poisson-distributed with a mean λk_t where k_t is the level of activity in year t . Assuming that the number of fatalities in an accident is another random variable, x , which is independent of the number of accidents and has a probability distribution with mean, μ , and standard deviation, σ , then the mean number

of fatalities would be $\lambda\mu$, where λ is the theoretical rate at which the events are occurring. $\lambda\mu$ is the primary measure of risk; therefore, the risk in any specific year would be $\lambda\mu k_t$ (Evans, 2003). The author will follow this paradigm and will calculate these sample statistics (λ and μ) where k_t is a known figure equal to 1,302,541 tram-km per year (see Section 4.2.2.2).

4.5.1.2 The Poisson distribution

The Poisson variable, x , is a count of the number of occurrences of a type of event. In this case x represents the number of EB events, which are the main cause for the risk arising from EJ in the JLRT system. EB events occur randomly and independently in a given unit of distance, measured in tram-km. Given this distance, k , the Poisson probability would be described by Equation 19:

$$P(x) = \frac{(\lambda k)^x * e^{-(\lambda k)}}{x!}$$

Equation 19: Probability of x Events over a Distance of k Tram-km

For any value of $x = 0, 1, 2, \dots, n$

where:

k = unit of distance in tram-km in the years 2014-2016

x = number of EB events occurring over a given unit of distance k

λ = rate at which EB events are occurring

e = the base of the natural logarithm, equal to 2.7183

therefore:

In accordance with the data presented in Table 17, the rate of EB per tram-km is described by Equation 20:

$$\lambda = \frac{\text{Total number of EB during 2014 – 2016}}{\text{Total tram – km during 2014 – 2016}} = \frac{891}{3,807,651} = 0.000234$$

Equation 20: The rate of EB per Tram-km

$\lambda = 0.000234$ EB per tram-km (when rounded to six decimal places) which represents a frequency of occurrence of one EB event every 4,273 km

In accordance with Equation 19 the probability that the random variable x takes the value 1 when k is equal to 1 tram-km is:

$$P(X = 1) = \frac{(0.000234 * 1)^1 e^{-0.000234 * 1}}{1!} = 0.000234$$

From these relationships we can conclude that when λ is small, then $P(X=1)$ is equal to λ .

The results show that the probability of X calculated by the Poisson equation is equal to the probability that resulted from the FTA as described in Section 4.2.1 .

4.5.1.3 The confidence interval around Lambda (λ):

The mean and the variance of a Poisson distribution are equal to λ :

$$E(x) = V(x) = 0.000234$$

This can also be written as:

$$\mu = \sigma^2 = 0.000234$$

and: The standard deviation is:

$$\sigma = \sqrt{\lambda} = 0.0153$$

The 95-percent confidence interval around λ is:

$$\lambda = \hat{\lambda} \pm 1.96 \sigma / \sqrt{n}$$

where:

$\hat{\lambda}$ = the maximum likelihood estimator of λ and it is equal to λ .

n = the number of tram-km in the years 2014-2016 (defined as k in paragraph 4.5.1.2)

$\sigma / \sqrt{n}$: is the standard error

1.96 = the Z-score

then:

The lower 95% λ is: 0.000219

The upper 95% λ is: 0.000249

We therefore say that the Poisson mean is 0.000234 with 95% confidence interval of (0.000219, 0.000249), i.e., we are 95% confident that the population mean falls within this range, it may not be 0.000234, but we are reasonably sure that it is not very different.

4.5.2 Estimating the Expectancy (μ) of the Injuries

4.5.2.1 Estimating the number of injuries caused by EB

EB causes EJ; the possible consequences of EJ are that passengers will fall and injure themselves inside the tram. The random variable Y, which represents the number of injuries, once an EB occurs, is an additional random variable, independent of the number of EB events, having a probability distribution with mean μ and standard deviation σ (Evans, 2002).

Based on the data in Table 17 the mean and standard deviation can be estimated as follows:

Let $\bar{y}$ be the estimated mean number of injuries per EB event:

Let n be the observed number of EB events

Let the observed number of injuries in an individual EB event i be y_i where ($i= 1, 2....n$)

Let S_n^2 be the estimated variance

Let S_n be the estimated standard deviation

then:

The estimated mean of injuries is:

$$\bar{y} = \frac{\sum_{i=1}^n y_i}{n} = \frac{87}{891} = 0.0976 \text{ injuries per EB}$$

and:

The estimated variance and standard deviation of the sample mean were calculated in accordance with appendix B using Excel functions VAR.S and STDEV.S respectively:

$$SD_{n-1}^2 = \frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1} = 0.219$$

$$SD_{n-1} = \sqrt{SD_{n-1}^2} = 0.467$$

4.5.2.2 Confidence interval of the mean number of injuries

According to the central limit theorem for large sample sizes, a sample mean is approximately normally distributed about the true mean with a standard deviation inversely proportional to the square root of the sample size. This is true regardless of the distribution from which we are sampling (Balka, 2021).

therefore:

$$SD_{\bar{y}} = \frac{SD}{\sqrt{n}} = 0.0156$$

where:

$SD_{\bar{y}}$ = the standard deviation of the mean sample

SD = the standard deviation of the original distribution

n = the sample size, equal to 891

and: The 95% confidence interval for the population mean is:

$$\mu = \bar{y} \pm 1.96 \frac{SD}{\sqrt{n}}$$

then:

The lower 95% mean is: 0.067

The upper 95% mean is: 0.128

We therefore say that the injuries estimated mean is 0.0976 injuries per EB with 95% confidence interval of (0.067, 0.128), i.e., we are 95% confident that the population mean falls within this range; it may not be 0.0976, but we are reasonably sure that it is not very different.

4.5.2.3 Hypothesis test for the population mean μ

Let: $H_0 : \mu = 0$ $H_1 : \mu > 0$

Let: the significance level $\alpha = 0.05$

Since σ is unknown we will use the t-distribution. This will be a one-tailed test. This can be learned from the signs of the hypotheses.

When:

$\alpha=0.05$ and $df = 890$

then:

The critical value t according to the t -distribution t table is:

$$t = TINV(0.05,890) = 1.962 \text{ (TINV is Excel function)}$$

and:

$$\text{The test statistic is: } t = \frac{\bar{y} - \mu_0}{SD_{\bar{y}}} = \frac{0.0976 - 0}{0.0156} = 6.256$$

therefore:

Since the test statistic is beyond the critical t -value, the null hypothesis is rejected and it can be said that the mean of the injuries per one EB event is greater than zero (0).

4.5.3 Estimating the Collective Risk Associated with EJ

4.5.3.1 The annual collective risk

Based on Sections 4.5.2.2 and 4.5.2.3, it can be said that the average sample, $\bar{y}$, estimates the expectancy, μ , of the number of injuries once the tram undergoes EB; therefore, the risk associated with the EB hazard event according to the Poisson model is:

$$CR = K_t * P * C$$

Equation 21: Annual Collective Risk due to EJ based Model Equation Based on the Poisson Distribution

Where:

CR = the collective risk, the estimated number of *injuries/year*

k_t = the number of tram-km in a specific year, t ; k_t is equal to 1,302,541 tram-km as per the prediction in Section 4.2.2.2 above

P = the probability / relative frequency at which the EB event occurs and is equal to λ

C = the consequences, the mean number of injuries per EB event, equal to $\bar{y}$

therefore:

$$\text{If: } \lambda = P(X = 1) = 0.000234$$

$$\text{and: } C = \bar{y} = 0.0976 \text{ injuries per EB}$$

then:

The estimated cumulative risk per year of operation is (Equation 22):

$$CR = 1,302,541 * 0.000234 * 0.0976 = 29.75 \text{ injuries per year}$$

Equation 22: The Annual Predicted Risk Due to EJ Based on the Poisson Distribution

Knowing that 42.5% are light injuries and the rest are injuries that require medical care we can calculate CR in terms of FWI (Equation 23):

$$CR = (29.75 * 0.425 * 0.001) + (29.75 * 0.575 * 0.005) = 0.09817 \text{ FWI per year}$$

Equation 23: The Annual Predicted Risk Due to EJ in Terms of FWI, Based on the Poisson Distribution

4.5.3.2 Discussion

The conclusion is that modelling the risk using the Poisson distribution leads to the same estimated risk as that calculated using the FTA and ETA modelling techniques, proving that the hypothesis defined in Section 4.5.1.1 cannot be rejected. The reason is that the two risk modelling methods are based on the same assumptions, namely, that emergency braking (EB) events are the only cause for EJ in the JLRT system and that these events are independent and occur randomly at a constant rate λ per unit of activity (tram-km). Both models also assume that the mean of injuries/fatalities per year, μ , has no trend over time. However, as noted by Evans (Evans, 2002) it may be unreasonable to assume that λ and μ are static over long periods of time, so it is necessary to extend the basic model to allow them to change over time; thus, the basic models of λ and μ as a function of time are shown in Equation 24 and Equation 25.

$$\lambda(t) = \alpha * e^{\beta t}$$

Equation 24: The mean of accident per unit of activity in year t (Evans, 2002)

Where:

α : represents the mean accident rate in year 0

β : represents the annual proportional change in the accident rate

$$\mu(t) = \gamma + \theta_t$$

Equation 25: The Mean Number of Injuries/Fatalities per Accident in Year t (Evans, 2002)

Where:

γ : represents the mean injuries/fatalities per accident in year 0

θ_t : represents the annual change in μ

Finally, the models clearly demonstrate the dependency of the risk in the amount of mileage the trams will accumulate in a certain year and the pros and cons of each of the risk modelling approaches. Evans' method is a 'black box' which models relationships without addressing the causality between variables and why a particular relationship exists (Bedford, French, & Quigley, 2004a), making it difficult to assign a particular risk mitigation means to a specific cause and review its contribution (see Section 4.7.2); however, since the approach uses a statistical distribution, it is possible to examine the sample statistics used in the model such as the mean fatalities, μ , and to determine to what extent they reflect the parameters of the population, i.e., how close they are to the true parameter (see Section 4.5.2.2.). FTA and ETA are causal models; they explicitly model the relationship between different variables, and the credibility of the model is therefore determined by understanding the causal relationships represented by the model (Bedford, French, & Quigley, 2004a).

4.5.4 The Role of Exposure in the Collective Risk

According to Evans' model "the product $\lambda\mu$ is the same whether or not the non-fatal accidents are included, its estimate is also the same whether or not the non-fatal accidents are included" (Evans, 2002). This is based on the assumption that λ and μ do not change over time. The following analysis will test this assertion by showing that the collective risk depends on the annual exposure, i.e., the risk depends on the distance travelled by the trams and does not explicitly involve the number of EB accidents.

Let the following be:

k = total exposure – the total number of tram-km in the years 2014-2016

k_t = annual exposure – the number of tram-km in a specific year t

$\lambda\mu$ = the mean number of injuries per tram-km (represents the measure of risk)

$k_t\lambda\mu$ = the mean number of injuries in any specific year t

n = the observed number of EB events

y_i = the observed number of injuries in an individual EB event i where $(i= 1.2....n)$

if:

The estimation of λ is $\left(\frac{n}{k}\right)$ which is the sample mean of the number of EB events for a given distance k

and:

The estimation of μ is $\frac{\sum_{i=1}^n y_i}{n}$, which is the sample mean of injuries per number of EB events

then:

The estimation of the risk ($\lambda\mu$) is: $\left(\frac{n}{k}\right) * \frac{\sum_{i=1}^n y_i}{n} = \frac{\sum_{i=1}^n y_i}{k}$

And the collective risk per year t is: $CR = k_t * \frac{\sum_{i=1}^n y_i}{k}$

thus:

$$CR = 1,302,541 * \frac{87}{3,807,651} = 29.76 \text{ Injuries per year}$$

Knowing that 42.5% are light injuries and the rest are injuries that require medical care we can calculate CR in terms of FWI:

$$CR = (29.76 * 0.425 * 0.001) + (29.76 * 0.575 * 0.005) = 0.982 \text{ FWI per year}$$

This is exactly the same value of CR as calculated in the previous sections.

4.5.5 Summary

The above analysis shows that the product $\sum_{i=1}^n y_i / k$, which represents the estimated risk ($\lambda*\mu$) per tram-km, does not explicitly involve the observed number of EB events, 'n'. Moreover $\sum_{i=1}^n y_i$ is the same regardless of whether EB accidents with no injuries are included, because, if the value of any y_i is zero, it adds nothing to the sum. Therefore, it makes no difference how many EB accidents with no injuries occurred, which proves Evans' assertion

(Evans, 2003). Yet, the analysis demonstrates that the annual collective risk depends on the total number of tram-km per year, represented by k_t .

4.6 Using the Negative Binomial Model to Develop a Prediction Model of EB Events on Route Sections of the JLRT System.

4.6.1 Introduction to Model Development

The literature review describes a statistical model called the random effects negative binomial (RENB) model which is based on the negative binomial distribution (Farhana, Graham, David, & Majid, 2016). Following this model, the author examined whether an explanatory model can be adapted to predict the EB events in the route sections at the JLRT system. The author hypothesised that length and the number of intersections between the tram stops will increase the frequency of the EB, i.e., a greater length and a higher number of intersections will increase the frequency of the EB events. The explanatory factors that were chosen are the length of each section and the density of the intersections within the sections, i.e., the number of intersections per km.

For this purpose, the author prepared a data table based on Appendix A, which included the incidents of EBs occurring in each route section (Table 18). The only EBs that were taken into consideration were those where the driver applied EB to avoid collisions with a third party. Technical causes of EB such as door failure were not taken into account, as it is assumed that they are not influenced by route section length or junction density.

According to the article (Farhana, Graham, David, & Majid, 2016) the data analysis was made by statistical software STATA version 13. Since the author does have access to the statistical software he submitted the data to the Statistics Laboratory at the Technion (Israel Institute of Technology) and asked the staff to identify whether the above factors affect the frequency of EB events along the route sections. ***It is important to mention that the aim of this exercise was not to quantify the risk of EJ but rather to identify factors that may increase the frequency of EB.***

Table 18: EB per Route Section

Section	Distance [m]	Number of intersections per km	Number of EB (2014-2016)	Number of EB with Injuries	Predicted EB Model 1
ID	Length (m)	Junction _ density	Events	Events_c	
S22 - S23	748	5.35	23	2	39
S21 - S22	523	7.65	29	4	24
S20 - S21	427	2.34	13	1	26
S19 - S20	810	4.94	29	0	43
S18 - S19	612	3.27	31	4	35
S17 - S18	437	6.86	34	3	21
S16 - S17	479	6.26	17	0	24
S15 - S16	400	5.00	32	3	21
S14 - S15	347	2.88	18	4	20
S13 - S14	659	1.52	63	5	41
S12 - S13	679	4.42	43	6	37
S11 - S12	447	4.47	22	1	24
S10 - S11	753	3.98	20	2	42
S09 - S10	876	3.42	30	0	50
S08 - S09	771	2.59	50	2	46
S07 - S08	668	2.99	22	0	39
S06 - S07	469	4.26	45	0	26
S05 - S06	697	4.30	87	2	38
S04 - S05	992	4.03	37	1	55
S03 - S04	658	6.08	47	0	33
S02 - S03	378	7.94	11	0	17
S01 - S02	447	6.71	5	0	21
Total	13.277 (km)		708	40	720

4.6.2 Results of the Data Analysis

4.6.2.1 The statistical distribution of the data

Appendix F presents the data analysis which was done using the function GENMOD in SAS. According to this, the dispersion parameter k (see Equation 5) is significantly different from zero (both confidence limits are above zero). Therefore, it can be said that this sample of EB is distributed according to the Negative Binomial Model. If k would have been equal to zero we would say that the Poisson model is more appropriate.

4.6.2.2 The prediction model of EB events in the route section

Following Equation 6: The Form of Negative Binomial Model , described in Section 2.9.1.2.4, two prediction models were adapted to predict the events in the route sections. The first relates to the prediction of the total EB events (with and without injuries) and the second of the EB events with injuries. Equation 26 describes the general form of the prediction models.

$$E = L \times \exp(\beta_0 + \beta_1 \times \text{junction_density})$$

Equation 26: Prediction Model of EB Events per Route Section

Where:

E : the number of events in 3 years

L : predictor (the length of the route section in meters)

Junction_density : predictor (intersections per km)

$\exp$: Exponential function

β_0 : Model constant

β_1 : Model coefficient

4.6.2.2.1 Model 1 - Prediction of the total EB events in the route sections

According to the analysis presented in Appendix F, $\beta_0 = -2.6887$ and $\beta_1 = -0.0516$. Therefore, the equation for Model 1 would be (Equation 27):

$$E (\text{total EB per route section}) = L \times \exp(-2.6887 - 0.0516 \times \text{junction_density})$$

Equation 27: Model 1 – Prediction of Total EB per Route Section (Technion & Author, 2021)

4.6.2.2.2 Model 2- prediction of the EB events with injuries in the route sections

According to the analysis presented in Appendix F, $\beta_0 = -5.3430$ $\beta_1 = -0.0912$. Therefore the equation for Model 2 would be (Equation 28):

$$E \text{ (EB with injuries per route section)} = L \times \exp (-5.3430 - 0.0912 \times \text{junction_density})$$

Equation 28: Model 2 – Prediction of EB with Injuries per Route Section (Technion & Author, 2021)

4.6.2.2.3 Results and discussion

To examine the goodness of fit of the model, the following tools were used to examine the differences between the observed values and the values predicted by the models:

- Pearson Chi-Square
- Pearson residuals, standardized to have unit asymptotic variance

Appendix F presents the results where the goodness of fit of the models represented by the Pearson Chi-Square and Deviance are close to 1, meaning that the model prediction fits the observed values. Appendix F also presents the dispersion of observations compared to the model line. When all points are within ± 3 limits the model is considered appropriate for the data. However, the effect of junction density is not significant, indicating a negative relationship with the total number of events, that is, the author's hypothesis is not supported by the evidence. If we were to assume that the more junctions we have in a section of track, the more emergency braking we will have, the two models show opposite results, as shown in Table 19. The emerging insight that may explain this result is that the number of route sections is small compared to the ones that were examined in Melbourne, Australia; the study by Farhana et al. (Farhana, Graham, Logan, & Majid, 2016) included crash data from 101 route sections vs. 23 in this study. However, the models do show that the length of the section does affect the number of events in the direction we would expect, meaning that the number of events will rise as route length increases. This finding corresponds to the findings of Farhana et al. (Farhana, Graham, Logan, & Majid, 2016), see Section 2.9.1.2.4. Model 2 shows the same pattern of results. Moreover, Model 1 shows that the total number of predicted EB events is very close to the total number of observed EB events, 720 vs. 708, see Table 18. In that case, it can be said that the NB model supports the models developed using FTA and ETA

and the Poisson model; the connecting thread between the three models developed for EJ is the exposure, meaning that the number of events is affected by the distance travelled.

Table 19: Model 1 Test Results

		Junction density (intersection per km)			
		2	3	4	5
Section Length (m)	500	30.652	1.785	0.099	0.005
	750	45.978	2.677	0.148	0.008
	1000	61.305	3.569	0.197	0.010
	2000	122.609	7.138	0.395	0.021

4.7 EJ Risk Evaluation and Acceptance

4.7.1 Risk Evaluation Following Risk Modelling

4.7.1.1 Data for risk evaluation

The EJ risk evaluation and acceptance will be made according to the process described in Chapter 3, Section 3.2.3 and the data in table below (Table 20). The data are based on the EJ risk modelling results of Sections 4.2 and 4.5 and the general assumptions defined in Section 3.2.6.

Table 20: Data for Risk Evaluation

Years 2014-2016				
Measured parameter	Total	EB due Dead man	EB due doors	Other EB
Total EB events	891	35	112	744
Total EB events with injuries	56	2	13	41
Total light injuries	37	0	11	26
Total injuries that required first aid	50	3	11	36
Total train-km	3,807,651			
Annual tram-km	1,302,541			
Annual operation hours	66,295			
Probability of EB event	0.000234			
Probability of EB event with injuries	0.0625			
The hazard consequence FWI/event with injuries	0.00513			

4.7.1.2 Severity level

Severity indicates the level of gravity of the consequence of the hazard. The consequence is 0.00513 FWI per EB event with injuries. This component can be related to Minor injuries as

per Table 11. Therefore, using Table 5, the severity level of 0.00513 FWI can be considered to be **Marginal**.

4.7.1.3 Frequency level

- a) The frequency indicates the frequency of a hazard turning into an accident, therefore, based on the ETA (Figure 19) the probability that an EJ event will end with injuries is:

$$P(EJ \text{ with injuries}) = 0.000234 \times 0.0625 = 0.000014625$$

Which represents a frequency of 1 event with injuries per 68,376 tram – km.

- b) In order to define the frequency level as per Table 6: Frequency of Occurrence of Hazard Events the frequency needs to be expressed in terms of event occurrence per hour and therefore:

$$P(EJ \text{ with injuries}) = 1/((68,376 / 1,302,541) \times 66,295) = 0.000287$$

Which represent a frequency of 1 event per 3,480 operation hours.

Using Table 7 the frequency level would be **Probable**.

4.7.1.4 Risk acceptance

- a) Using the risk matrix Table 7: Frequency – Consequence Matrix (Risk Evaluation and Acceptance)(Table 7), the combination of the above severity and frequency indicates that the risk is **Undesirable**.
- b) According to Table 8 the risk shall only be accepted with the agreement of the State/JTMT.

4.7.2 Action to be Taken

The residual risk associated with EJ is found to be Undesirable, and the decision made by JTMT experts is to limit the jerk rate by reducing the severity of emergency braking as applied by the safety loop. The automatically applied emergency brake (not initiated by the driver) will be reduced to emergency brake 1 standard EN 13452-1. The load category shall be EL 4 according to EN 13452-1, see Appendix G, tender requirement.

4.7.3 Cost-benefit Analysis

The purpose of the CBA is to compare the cost of implementing the risk control measures with the reduction in risk that these measures might achieve, and whether there is a lack of proportionality between them.

Pre-analysis assumption

The risk reduction measure will completely prevent passengers from falling as a result of emergency braking caused by failures in the doors and in the dead-man device.

4.7.3.1 Cost analysis

- a) The cost of upgrading the braking system is 2,281,000 NIS. Using an exchange rate of 1 Euro=4 NIS the upgrade cost will be 570,250 Euro. (Due to confidentiality the quotation cannot be presented in the study).
- b) This is the only cost related to the upgrade of the braking system, thus the net present value (NPV) of the cost is:

$$NPV (\text{costs of upgrading the braking system}) = \underline{570,250 \text{ Euro}}$$

4.7.3.2 Benefit analysis

- c) The annual risk was reduced from 0.098 FWI per year to 0.07 FWI per year (see section 4.7.4), meaning a saving of 0.028 FWI every year. This can be quantified in terms of monetary saving as follows:

According to Table 12, the cost of fatality to the national economy is 1625 K-Euro thus, the cost of 0.028 FWI would be: $1625\text{K-Euro}/\text{Fatality} \times 0.028 \text{ FWI} = \underline{45,500 \text{ Euro per year.}}$

- d) According to the Israeli TPA guidance the discounting rate per year is: $r=7\%$.
- e) Assuming that the life span of the vehicles is : $n=25$ years
- f) Then: the net present value (NPV) of the benefit using Equation 12 is:

$$NPV (\text{benefit}) = \frac{(1+0.07)^{25}-1}{0.07 \times (1+0.07)^{25}} \times 45,500 = 14.28 \times 45,500 = \underline{649,832 \text{ Euro}}$$

4.7.3.3 Conclusions

The cost-benefit analysis shows that the benefit of saving lives exceeds the cost of upgrading the braking system; therefore, the upgrade can be implemented as recommended by the JTMT experts. However, as the risk is still in the tolerable region, additional reduction measures should be reviewed on the basis of cost benefit analysis.

Note: The benefit analysis could have taken into account the saving from accident delays and other components (see Section 2.11.4.2); however, these were not included, since the

benefit of saving lives has already been shown to exceed the cost of investing in upgrading the braking system and it is clear that, if we add other savings resulting from other factors, the benefit will increase.

4.7.4 Risk Evaluation Following the Implementation of Mitigation Measures

4.7.4.1 Assumptions

Any failure caused by doors or dead-man will activate the EB and the tram will stop; however, passengers on board the tram will not be harmed, thanks to the change in the braking rate.

4.7.4.2 Severity level

- a) As per the assumption above, the number of injuries due to EB events caused by door and dead-man failure will be subtracted from the total number of injuries in the years 2014-2016. The result will represent the consequence of EJ following the mitigation measure.
- b) In addition, the total number of events with injuries due to door and dead-man failure shall be subtracted from the total number of events with injuries in the years 2014-2016.
- c) The consequence per EB event will be calculated by dividing the results of clause 'a' by the results of clause 'b'.
- d) The severity level of the consequence per EB event with injuries will be determined according to Table 5.
- e) The calculation of the consequence per EB event:
 - *Consequence (following the mitigation measure) = $((37-11) \times 0.001 + (50-14) \times 0.005) = 0.206 \text{ FWI}$*
 - *Event with injuries (following the mitigation measure) = $56-15 = 41$*
 - *Consequence (per EB event with injuries) = $0.260 / 41 = 0.00502 \text{ FWI}$*
- f) Determining the severity level

*The 0.00502 FWI can be related to Minor injuries as per Table 11; therefore, using Table 5, the severity level of 0.00502 FWI can be considered **Marginal**.*

4.7.4.3 Frequency level

As per the assumption above, the frequency per EB event will not change because the mitigation measure will not eliminate EB due to door and dead man failure; it will only reduce

the severity of the emergency brake impact when these failures occur. Therefore, the probability of an EB event remains 0.000234. However, the probability of an event with injuries due to emergency braking will change.

Therefore:

- a. The number of events with injuries as per Section 4.7.4.2 = 41
- b. $P(\text{event with injury}) = 41/891 = 0.046$
- c. $P(\text{EJ with injuries subsequent to EB event}) = 0.000234 \times 0.046 = 0.000010764$

Which represents a frequency of 1 event with injuries per 92,902 tram-km.

- d. The probability per operation hour would be:

$$P(\text{EJ with injuries}) = 1/((92,902/1,302,541) \times 66,295) = 0.0002115$$

Which represents a frequency of 1 event with injury per 4,728 operation hours

- e. Using Table 7 the frequency level would be **Probable**.

4.7.4.4 Risk calculation and evaluation

- a) Annual risk

Knowing the frequency of EJ with injuries and the consequences per event the annual risk can be calculated and evaluated as follows:

Annual risk = annual tram-km x P (EJ with injuries subsequent EB event) x Consequence (per EB event with injuries)

$$\text{Annual risk} = 1,302,541 \times 0.000010764 \times 0.00502 = 0.070 \text{ FWI}$$

- b) Risk acceptance

Using the risk matrix Table 7, the combination of the above severity and frequency indicates that the risk is **Undesirable**.

According to Table 8, the risk shall only be accepted with the agreement of the State / JTMT.

4.7.5 Results and Discussion

This result of the risk evaluation shows that applying a risk reduction measure did not change the classification of the risk; it remained Undesirable although closer to the Tolerable region rather than the Intolerable region as before. This is because of the reduction in the frequency

of events and the event consequences. This is expected, because the contribution of door and dead-man failure to the total consequences is approximately 28%. The other issue is that risks falling between these two regions are said to fall in the 'ALARP region'; this means the risk reduction measure should be applied if it is 'reasonably practicable' but the risk matrix cannot determine whether a risk reduction measure is reasonably practicable in such case. According to European common practice, estimated costs and benefits should be assessed. This practice is not required by the JTMT guidance (Section 2.6.2.4), nor by Israeli law; however, it has been done and it has shown that it is worthwhile to invest in measures to minimize the risk, but additional measures are required because the risk is still in the Undesirable region.

In fact, this evaluation process presents the practical side of the discussion in the literature review (Section 2.6.2.5) regarding the weakness of the risk matrix and the absence of risk acceptance criteria in Israeli law and their necessity in supporting decision making. This is why the author has recommended adoption of the European common practices to complement the JTMT guidelines for risk acceptance.

The models shall provide a basis for continuous safety improvement and confidence that the JLRT system can operate safely.

4.8 Adherence of the EJ SRM to the Study Objectives and the Success Criteria

The purpose of this section is to examine whether the EJ safety risk model complies with the study objectives and the success criteria defined in Section 1.4 and the model characteristics defined in Section 3.2.

- i. The EJ SRM justifies the hypothesis that it is possible to model and quantify the safety risk of EJ using the existing techniques, FTA and ETA, and statistical models such as the Poisson distribution; see Sections 4.2 and 4.5.
- ii. Comprehensiveness: the model enables the quantification of the annual collective risk, associated with the hazard, EJ, and determines the frequency and consequences associated with the hazards; see Section 4.2.2.
- iii. Practicality; the model enables easy determination of risk acceptability. Knowing the frequency of the hazard event and the consequences per event it shall be easy to

determine the tolerability level and the acceptability of the risk using the risk matrices, Table 7 and Table 8; see Section 4.7.

- iv. The fact that the model is based on an explicit risk assessment and evaluation enables the ALARP assessments as required by the study objectives, Section 3. In fact, Sections 4.7.2, 4.7.3 and 4.7.4 follow the ALARP process.
- v. Sections 4.7.2, 4.7.3 and 4.7.4 also demonstrate that the model enables the assessment of the change in risk that results from a change in technology, as required by the study objectives, Section 1.4.
- vi. Accuracy: the model results are reasonable. This can be seen from the CI analysis where the mean fatalities per accident, μ , falls within the range of the true mean, i.e., the population mean (see Section 4.5.2.2). The accuracy of the predicted annual CR was tested against the accident data from 2017 and the percentage error was found to be approximately 23%; this error can be explained by the fact that the sample size is relatively small and it is based on the first years of operating the system, when the system is still unstable. As noted by RSSB's Guidance on Risk Evaluation and Risk Acceptance "no analysis of risk can ever be completely accurate, but the uncertainty can generally be reduced by further data collection or analysis" (RSSB, 2014).
- vii. Usability: a safety manager or any other person can easily use the model. All that is required of him or her is to first estimate the mileage that the trams will cover in the following year and run Equation 17.
- viii. Maintainability: maintaining the model requires knowledge in reliability and the use of FTA and ETA.

In light of the above, the EJ model complies with the study objectives and the test criteria and provides a basis for continuous safety improvement and confidence that the JLRT system can operate safely.

4.9 Insights Arising from the Analysis of the Emergency Braking Data

4.9.1 The Main Causes of EB and Injury

Eight out of forty-five BEvn (Figure 15, Figure 16 and Figure 17), i.e., 18% of all BEvn, were responsible for 73% of all EB events, and for 89% of the injuries in the years 2014-2016, a classic case of the Pareto principle. The consequences of these BEvn are 77 injured passengers (Table 21, Figure 20).

Door failure is a major cause of injury, leading to 25% of all injuries. Fifty door failure events occurred in 2016, due to an increase in the number of passengers in that year without a parallel increase in services. Therefore, it can be assumed that more passengers were standing in the trams, and leaning on the doors, and the pressure they exerted on the doors broke the interlocking loop and brought the tram to an emergency stop. Figure 24 describes the increase in passenger demands vs. injuries due to door failure by year. It can be seen that, as the number of passengers rose, so did the number of door failures and the number of injuries.

The calculated r-squared shown in the graph explains how well the regression model fits the observed data. Values of r-squared close to one indicate that the observed data are best fitted to a linear regression model.

The correlation coefficient (r) between the number of passengers and the number of door failure events and the correlation coefficient between the number of door failure events and the number of injuries were calculated based on the data presented in Figure 24 and the CORREL function in Excel. The results were $r=0.93056$ and $r=0.8307$ respectively, representing fairly strong linear relationships between the above-mentioned variables, i.e., that an increase in the number of passengers leads to an increase in the number of doors failure events that leads to an increase in the number of passenger injuries. Approximately 40% of EB events were due to the problematic behaviour of pedestrians, which led to 25 injuries, about 30% of all injuries. There are two main reasons why pedestrians tend to behave abnormally, causing the tram driver to apply EB: (1) Thirty six percent of the incidents occurred in a pedestrian zone where the marking of the swept path is not highly visible, hence pedestrians are not aware that they are entering the trams' path; and (2) Some people use cell phones while walking. Their minds are distracted to the point that they cannot hear the tram approaching.

The proportion of EB events caused by cyclists is relatively low, at about 4%, but the proportion of injuries is almost triple, at about 11% of all injuries. This may be the result of cyclists moving faster into the danger and brake applications being stronger, therefore.

Table 21: The Main Causes of EB and Their Consequences

Cause Number	Cause of EB (BEvn)	Total EB events	Light injuries	Injuries requiring first aid	Total injuries
1	Pedestrian entered swept path unexpectedly	208	8	4	12
2	Red light violation by car	156	5	7	12
3	Door failure	112	11	11	22
4	Red light violation by pedestrian	73	0	8	8
5	Dead man failure	35	0	3	3
6	Pedestrian walking on the track	33	4	1	5
7	Inappropriate behaviour of cyclists (riding on the rail pathway against the law)	33	0	10	10
8	Non-permitted left turn by car	4	4	1	5
Total EB events and injuries due to the above causes (BEvn)		654	32	45	77
Total EB events and injuries due to all causes		891	37	50	87
Percentage out of all EB events and injuries		73%	86%	90%	89%

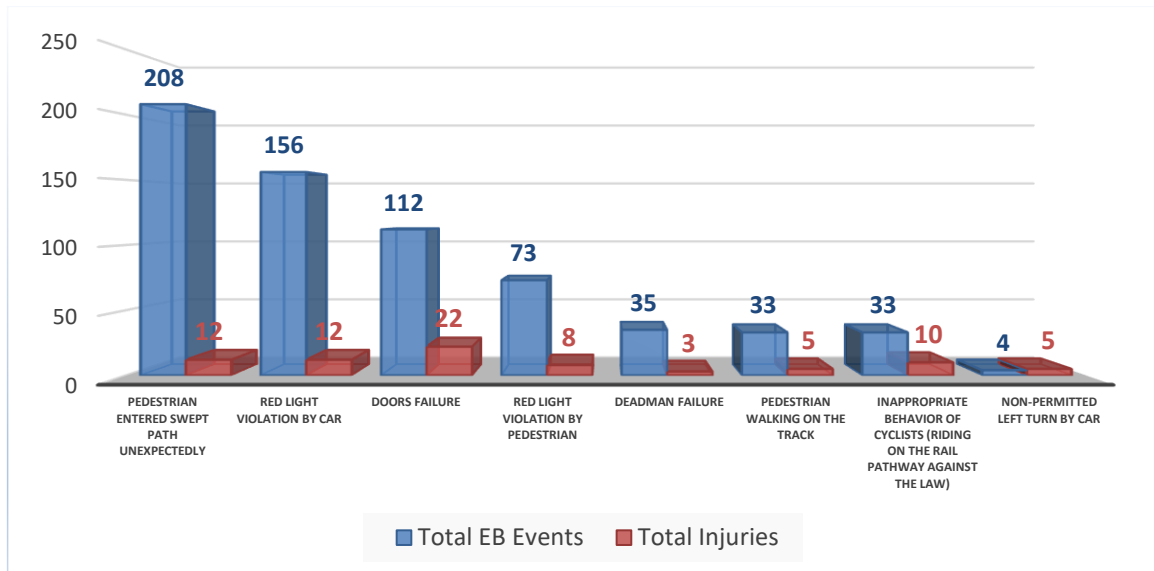


Figure 20: Major Causes of EB and their Consequences

4.9.2 The Effect of Exposure on EB

The increase in exposure is negligible, about 1% per year (Figure 21); nevertheless, there is still an increase in EB, and the question is why?

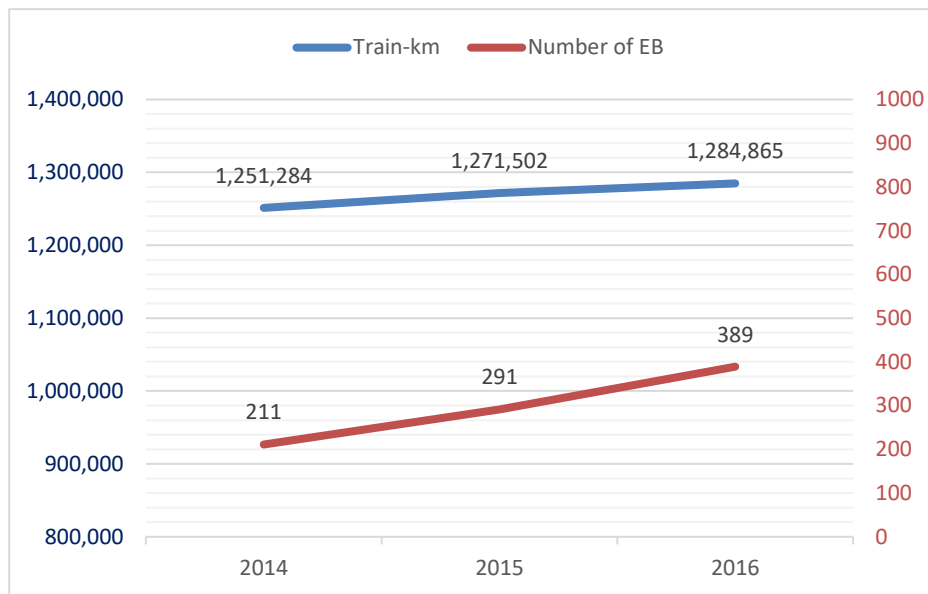


Figure 21: Exposure vs. Number of EB per Year

Why do we see an increasing trend in EB if the exposure (tram-km per year) is more or less the same every year? This can be explained by the fact that the operating conditions change from one year to the next. In 2016, new, inexperienced drivers entered the service, potentially contributing to an increase in EB. In addition, there was an increase of 10% in passenger demand in 2016, so probably more passengers were standing in the tram, some of whom did not hold the straps and hand-rails and fell when the tram was braking. Furthermore, traffic congestion increases every year and more traffic violations occur at the grade crossings.

4.9.3 The Effect of the Increasing Number of EB Events on the Number of Injuries

As the number of EB events increases, the number of events with injuries and the number of injuries also increases (Figure 22). It can be seen that in 2016 the number of EB events increased from 291 to 389 and the number of events with injuries increased from 14 to 29, while the number of injuries increased from 22 to 46 (light injuries and injuries that required first aid).

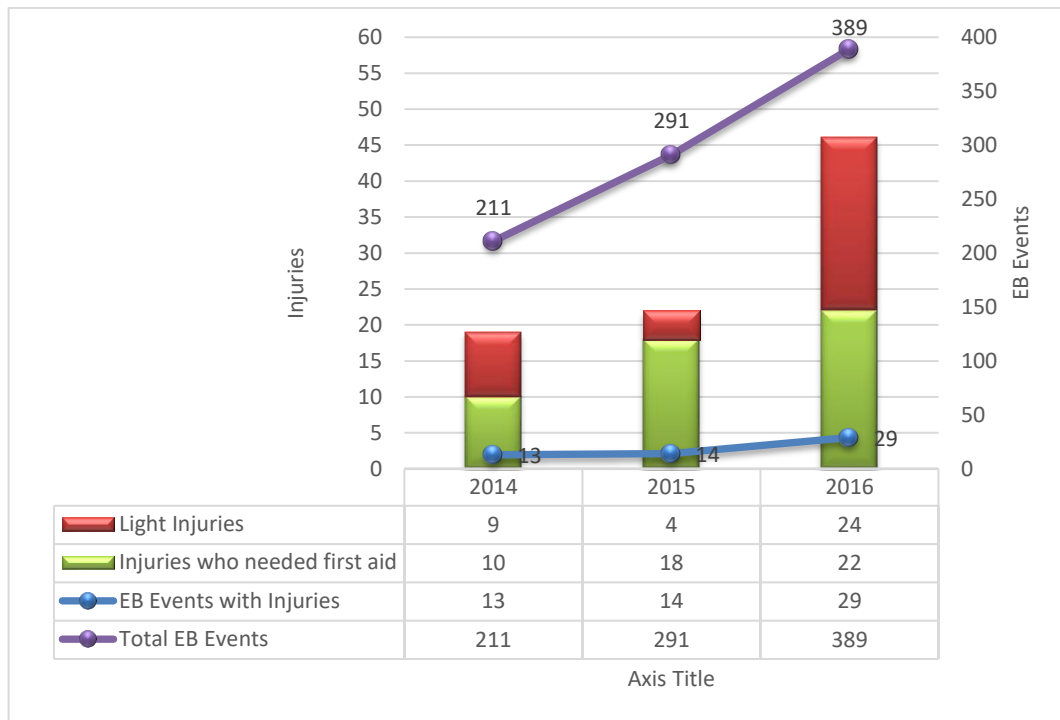


Figure 22: The Increase in Number of EB with Injuries vs. injured Passengers per Year

4.9.4 The Effect of the Increase in Passenger Demand on the Number of Injuries

The graph of total injuries by year (Figure 23) shows that R-square is low, meaning that there is large variability in the data which is reflected in strong deviations from the trend line. On the other hand, there is a clear upward trend in the number of passengers per year. The correlation coefficient (r) between these two variables, passenger number and the number of injuries, was calculated based on the data presented in Figure 23 and the CORREL function in Excel. The result was $r = 0.3395$, representing a weak linear relationship, meaning that an increase in the number of passengers over the years does not necessarily explain the increase in the number of injuries due to EB. However, although the correlation between the number of passengers and the number of injuries due to EB is rather weak, probably due to the small size of the data set, in general it can be seen that over the years more passengers were injured due to EB.

Neither the performance of EB nor the vehicles have changed over the period of time under consideration. The number of seats and possibilities of holding fast are still the same. Unless the willingness to report an injury has risen, and there is no clear indication of it, the rise must be connected to the only obvious change, the increasing number of passengers who are being

exposed to the risk. This is reasonable, as in crowded trains passengers either may not reach a good point to hold on to or they have a limited capability for evasive movements to absorb braking forces.

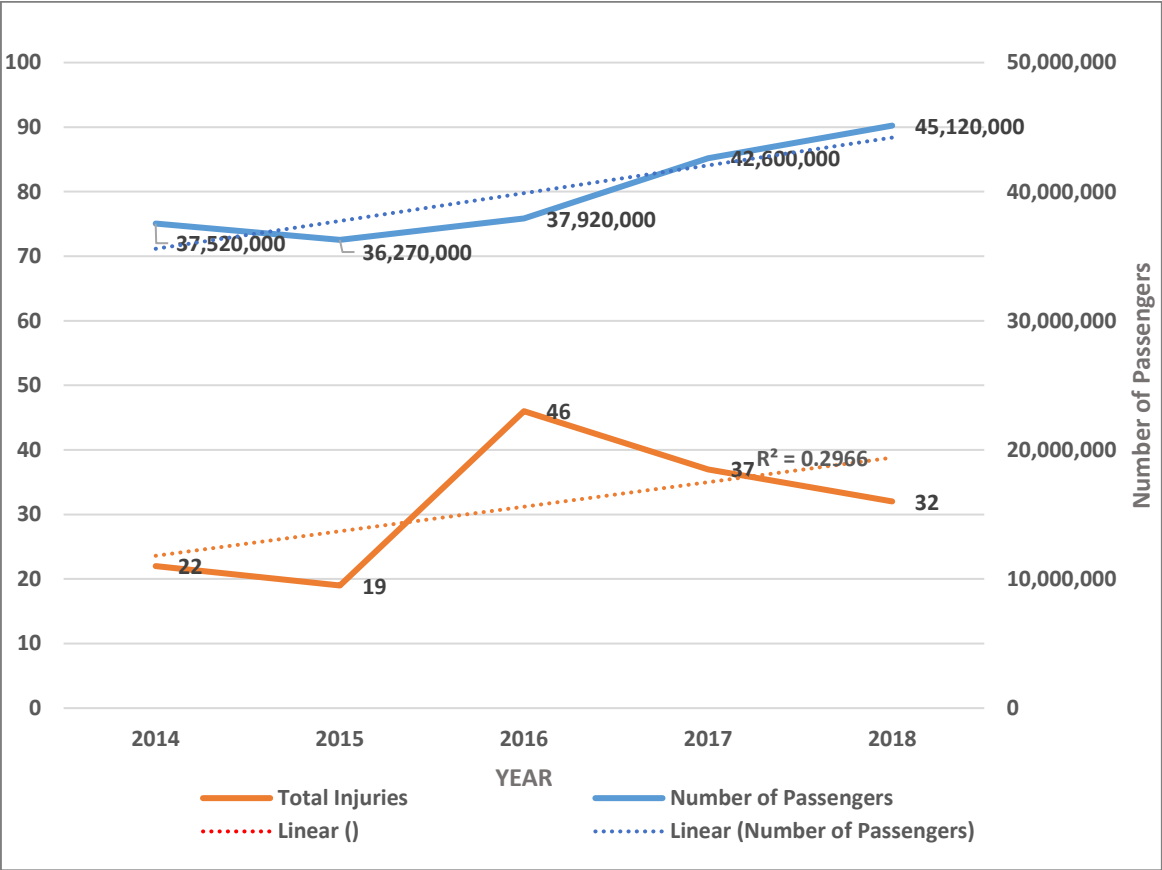


Figure 23: Increase in Passenger Demand vs. Injuries by Year

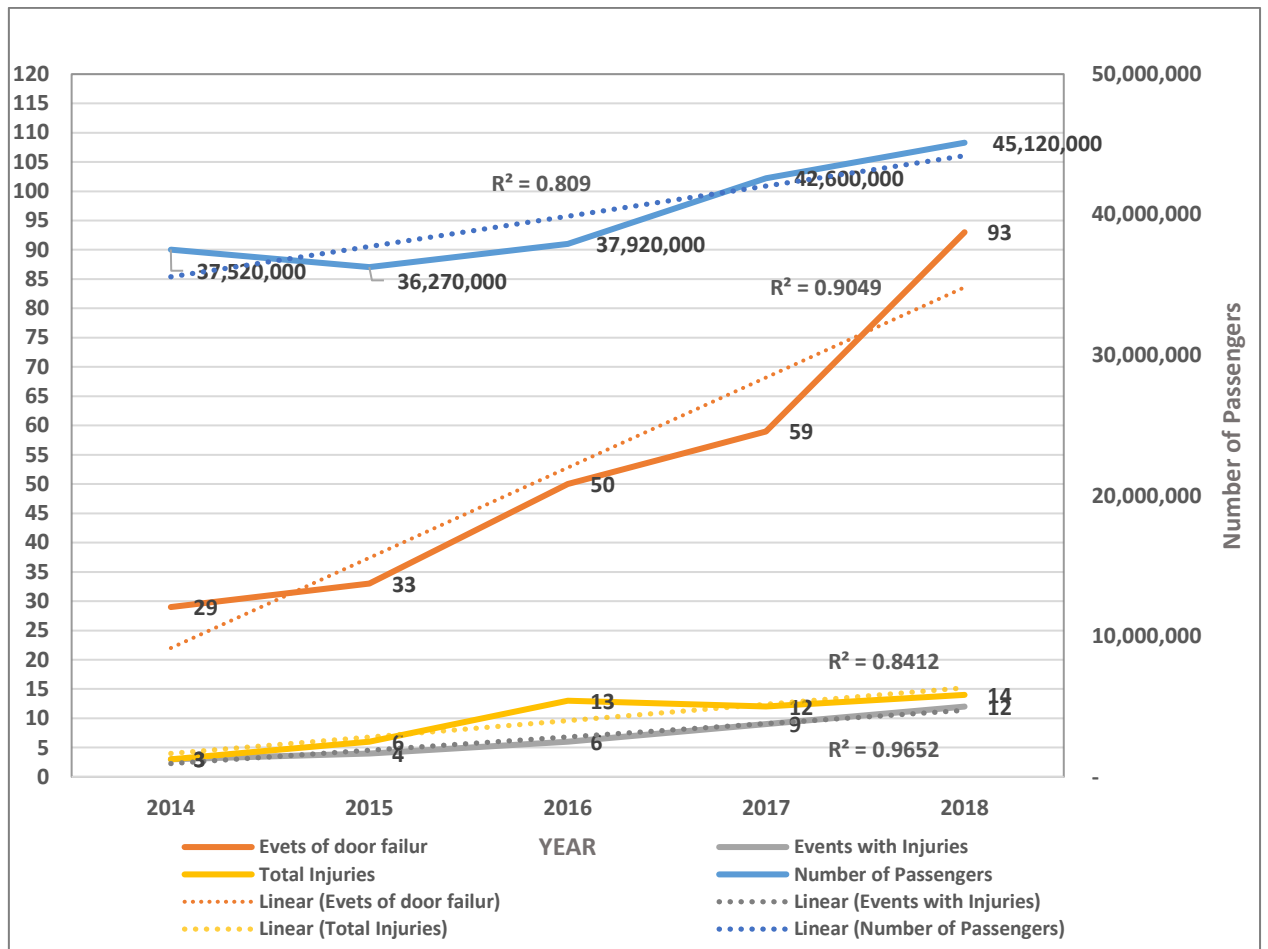


Figure 24: Increase in Passenger Demand vs. Injuries due to Door Failure by Year

4.10 Emergency Braking on foreign Tramway Networks

4.10.1 Background

The author met with a VBZ tram operator on 26 February 2018, in Zurich, Switzerland, and on 27 February 2018 with STRMTG, who are in charge of safety related issues in passenger transportation and act in the name of the French government. The author's main purpose in exploring other LRT networks was to compare the JLRT collective risk resulting from EB to that of some foreign LRT tramway networks, as well to learn how they deal with this hazard.

4.10.2 Zurich Public Transport (VBZ) Operator

4.10.2.1 About VBZ

Zurich Public Transport (VBZ) operator is the only public transport operator in the Swiss city of Zurich. VBZ owns and operates trams, trolleybuses, buses and funicular. VBZ owns the tram infrastructure and rolling stock. The tram network comprises 15 separate routes. The network operates on a 1 m-gauge track, electrified using overhead lines at 600 V DC.

The findings on EB events as detailed in Table 22 are related to the operation of line 11 which is one of the 15 tram lines in Zurich, during the years 2014-2016. The raw data are presented in Appendix C. Line 11 is 12.5 km long. Trams of various types operate on the line. The annual distance travelled by the trams is about 43 million kilometres, which is much greater than the distance travelled by the JLRT trams.

4.10.2.2 EB on Line 11

The EB events are monitored by the VBZ Zurich operator, but they only follow up on those resulting in injuries; therefore, it is not possible to calculate and compare the CR to that of the red line in Jerusalem. However, the causes of EB and their consequences can be compared, as shown in Table 21. It can be seen that 37 events occurred during the three years of operation and 40 passengers were injured. Six hazard situations caused the tram drivers to apply EB. Vehicles that entered the track path caused 48% of EB events, pedestrians walking on the track caused 28% of EB events and 20% were due to unknown causes.

Table 22: EB Events and Their Consequences per Year on Line 11 of VBZ Zurich

	2014		2015		2016	
The cause of EB	Number of events	Number of injuries	Number of events	Number of injuries	Number of events	Number of injuries
Pedestrians (woman with children in the track area)			1	1		
Pedestrians in the track area	4	5	2	2	3	3
Object in the track area	1	1				
Truck in the track area	1	2				
Car in the track area	6	7	6	6	4	4
Unknown	1	1	1	1	6	6
Cyclist in the track area	1	1				
	14	17	10	10	13	13

4.10.2.3 EB events on JLRT red line vs. those on Zurich Line 11

A comparison between the causes, the number of incidents and the number of injuries is to some extent problematic because of the environmental conditions, operating conditions, type of infrastructure and trams in each location, yet, it can be seen that in both systems, cars and pedestrians that enter the track path are the main causes of EB.

Door failure and dead man failure were not causes of EB events on Line 11; however, they were among the major causes on the JLRT red line system (see Table 21). The reason is that these are different types of trams with different protection mechanisms in the case of doors opening during the tram journey or dead-man failure.

4.10.3 French Tramway Network

4.10.3.1 Background

The meeting with STRMTG led to the understanding that out of the 62 light rail lines in France, the one in Reims is the most similar to that in Jerusalem, because the trams are of the same type, Citadis 302. The length of the line, the number of stations and the operating environment are almost the same. However, for confidentiality reasons the author received information only on the causes of EB without the consequences, thus the safety risk comparison could not be made.

In light of the above, the review in this chapter on EB events on the French tramway network will be based on the Accidentology of Tramways report for 2014 (STRMTG, March 2016), from which all the relevant citations, graphs and statistical tables were adapted for this report.

The Accidentology of Tramways report shows beyond any doubt that the main cause of injury to the tramway passengers is EB, the same as in the JLRT system and the Zurich tramway line. Similarly, the main cause of EB is driver action to avoid collisions with a third party, i.e., pedestrians, vehicles, and cyclists who violate the traffic laws or accidentally enter the track way.

4.10.3.2 EB events in the French tramway network

In 2014, the tram network in France comprised 68 lines, of which 62 on steel rails and 6 lines on rubber tyres. Figure 25 shows the distribution of safety events by type. Passenger accidents also refer to passengers falling in the tram, as a result of EB. As in the JLRT system, it can be seen that the number of passenger accidents increases as the exposure (tram-km) increases over the years (Figure 25).

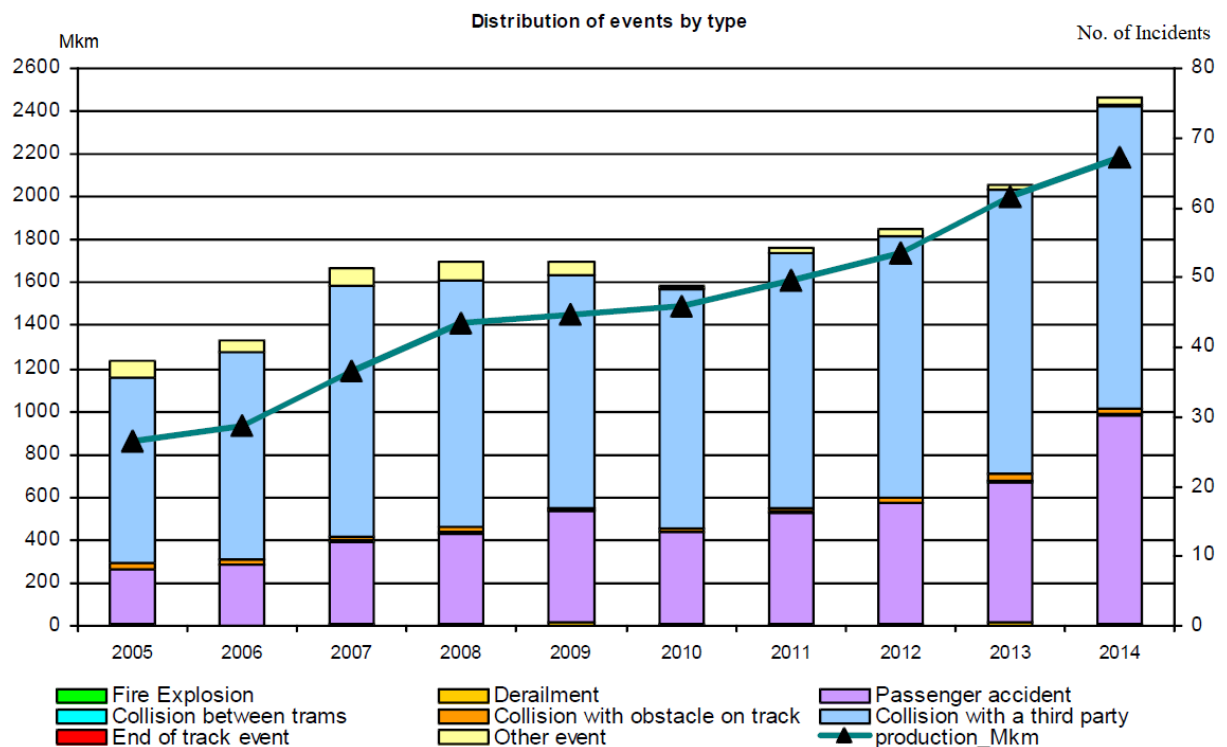


Figure 25: Distribution of Safety Events by Type (STRMTG, March 2016)

Table 23 shows the number of passenger injuries in 2014, including passengers who fall in the trams due to EB events. According to STRMTG, there were 330 passenger injuries out of 645 injuries, about 51%.

Table 23: Passenger Injuries (STRMTG, March 2016)

Passenger event subtype	No. of events	Passenger victims	Subtype victims/total passenger victims
Fall in the tram	712	645	78.37%
Fall from the tram on line	14	15	1.82%
Fall from the tram in station	54	46	5.59%
Fall from the platform	45	36	4.37%
Jamming in the tram	117	76	9.23%
Pulled along by the tram	7	5	0.61%
Total	949	823	100.00%

The distribution of injuries between 2005 and 2014 due to EB (Figure 26) identifies seven categories of EB causing passenger injuries. As in the JLRT system and the Zurich LRT Line, driver action to avoid accidents, in particular, collisions with third parties in an urban environment, is the main cause for EB. Driver action to avoid collisions is identified under the category 'Controller handle action'.

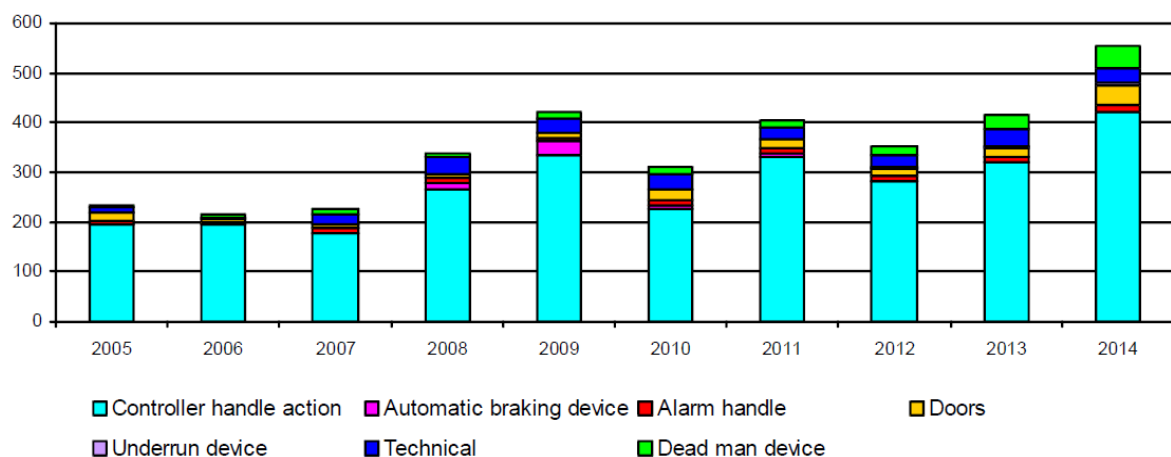


Figure 26: Distribution of Passenger Injuries by EB Cause (STRMTG, March 2016)

According to the STRMTG report, the share of severe injuries among passengers who were injured due to EB is low, between 0.2% and 2.6% over the period 2005-2014, where 'seriously

injured' means that the injured passenger was hospitalised for over 24 hours and 'fatal' means death within 30 days of the event.

The other categories presented in Figure 26 are described as follows: The 'Automatic braking device' (or Automatic Tram Protection - ATP) category is an automatic tram stopping system which can be found on a few networks with specific configurations, such as tunnels or single track, or whose operating speed exceeds 80 km/h. The 'Alarm handle' category is for the device available to passengers when the tram is leaving the station. The 'Doors' category corresponds to the EB being activated by detection of a door opening, either by passengers (forcing) or due to a setting adjustment. The 'Underrun device' category is for the device preventing bodies from being trapped under the tram or detecting obstacles on the tracks. The 'Technical' category denotes technical malfunctions encountered on the rolling stock. Declarations from operators do not enable their nature to be defined accurately. The 'Dead man device' category is EB following absence of activation of the vigilance device by the driver.

5 Modelling the Safety Risk Associated with SPADs on the Jerusalem Light Rail Transit System

5.1 Introduction

Most tramway and LRT systems (UITP, 2019) operate according to line-of-sight principles over part or all of their routes (BOStrab, 2007). Where the line-of-sight principles are not deemed safe enough, trackside signalling gives the drivers the authorization to proceed into and through so-called 'controlled sections'. The Jerusalem LRT network is no exception to this rule. Occasionally though, tram drivers may pass through tram signals that show restrictive aspects, an event called a SPAD (Signal Passed at Danger) (ORR, 2019). SPAD events create a risk of collision between trams or derailments at points that face the wrong direction, and they are frequently attributed to driver distraction and inattention (Naweed, 2013).

The trams of the JLRT system operate largely within the street network of the city, although its tracks are generally segregated from the road traffic. Tram movements conflicting with road traffic are confined to intersections and are regulated by a road traffic signalling system (RTSS). Conflicting movements between the trams themselves are regulated by a tram signalling system (TSS) (SII, 2002). The two signalling systems work independently of each other and are not coordinated. In contrast to metros and mainline railway systems, which commonly have a train-stop (TS) or an automatic train protection (ATP) system (Schmid & Connor, 2019), safeguarding against collisions in the event of conflicting movements between trams depends on tram drivers observing the restrictive signals.

Three sections of the JLRT line are controlled by a TSS. The signalled sections coincide geographically with intersections thus they incorporate both a TSS and an RTSS. Between 2014 and 2016, tram drivers passed a restrictive tram signal on 38 occasions. As a consequence, there were conflicting movements between trams which led to near-miss collision events. These potential collisions were avoided largely due to the speed restrictions imposed in the signalled zones. However, the fact that there were SPAD events without immediate consequences, raises the question of whether the risk of a collision between trams due to

SPAD can be quantified, since it is known that the risk is the product of the probability of occurrence of the safety event and its potential consequences.

The purpose of this study is to quantify the risk of SPAD in line-of-sight operations where the consequences of such risks are limited, mainly due to the speed restrictions in signalled zones. The risk assessment is based on the data obtained from SPAD investigation reports generated by the Jerusalem tram operator. The probability that a SPAD will lead to a collision was assessed using FTA (CENELEC, 2017). An assessment was made for each individual intersection within the signalled zones and the possible consequences were calculated based on the number of passengers travelling in the conflict areas. Knowing the probability and the consequences, the annual potential risk was calculated using ETA (IEC, 2010). The risk evaluation and acceptance were undertaken in accordance with the process defined in Section 0. The model results were validated against expert judgement. The work process with the experts is detailed in Section 3.2.5 while the results of the expert judgement and their analysis are detailed later in the present chapter.

5.1.1 General Description of the Controlled Sections

Three sections on the Jerusalem main line are controlled by a TSS: Heil Ha'Avir Terminus, Mount Herzl Terminus, and Depot Access. Each of the controlled sections has switch points that can change the direction of the tram (Figure 30, Figure 33 and Figure 38, respectively).

The signalled sections coincide geographically with road transport intersections, and consequently incorporate both a TSS and an RTSS (Figure 27). Consequently, tram drivers must follow instructions from two different signalling systems at the same location. They may proceed only when both signalling systems allow them to do so. Unlike railway systems, which commonly have an ATP system that stops the train in the event of a SPAD, the avoidance of a SPAD in the tram system depends principally on the tram driver's ability to immediately recognise that he/she is going to pass a restrictive signal, and to respond by stopping the tram before it enters an occupied controlled section.

Between 2014 and 2016, there were 38 SPADs in controlled sections of the JLRT. Approximately 70% of these SPADs were caused by conflicting information from the road traffic signal and the tram signal. Figure 27 presents the configuration of the two signalling

systems. The drivers accidentally ignored the restrictive aspect of the tram signal, proceeding into an occupied controlled section on receiving permission from the road traffic signal only.

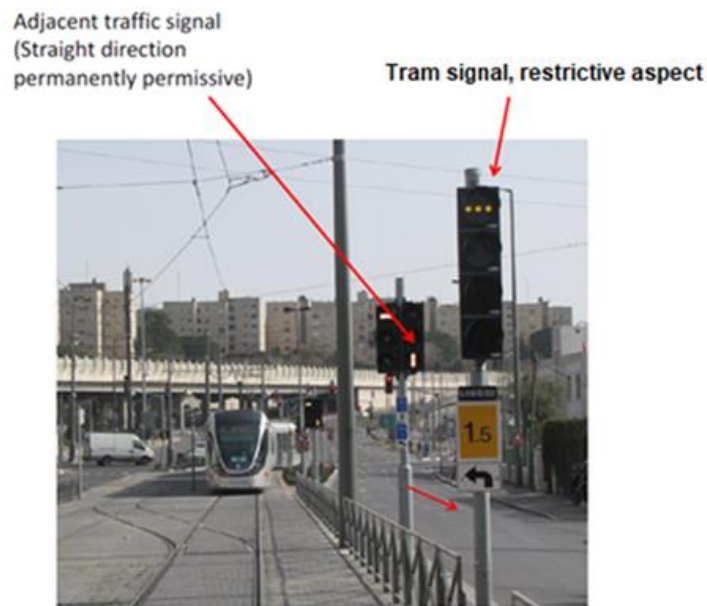


Figure 27: SPAD at Depot Access due to Conflict between Tram and Road Traffic Signals

5.1.2 Operation Principles within a Controlled Section

The main operational principles within a controlled section are shown below (Figure 28). The signal shows a restrictive aspect, and the command loop is placed at a distance sufficient for the system to provide a permissive aspect for the tram before it reaches the signal. The tram will be allowed to pass if: (a) the route is set; (b) the point is locked and detected in the correct position; and (c) the section is clear. When the interlocking controller detects that the tram has started the route, it again changes the signal to the restrictive aspect. When the tram completes the route and releases it, the interlocking controller clears the route.



Figure 28: Controlled Section (ALSTOM, 2008a)

5.2 Risk Quantification

5.2.1 Potential for Collisions between Trams

The consequences of SPADs in tram networks are limited, mainly due to the speed restrictions imposed in signalled zones. The JLRT is no exception; none of the 38 SPADs which occurred between 2014 and 2016 led to collisions between trams, nor to damage to the trams or injuries to the passengers.

The consequences of a specified event are an essential component in the development of a risk model. According to the RAMS standard EN 50126, risk is defined as the “combination of expected frequency of loss and the expected degree of severity of that loss” (CENELEC, 2017). In other words, risk is the probability of occurrence of a safety event, multiplied by its consequences. This poses an interesting hypothetical question: how can risk be modelled if there are no records of such consequences within a specified network?

A closer examination of the post-SPAD investigation reports, which were generated by the JLRT operator specifically the photographs of the locations, and a review of the investigations themselves, produced the evidence that there was indeed no actual accident as a result of a SPAD; however, there were several near-miss events (Figure 29). This led to the understanding that a risk model can be based on the risk of a Potential Collision, i.e., a near-miss collision between trams due to SPAD, rather than an actual collision. In the case of a near-miss, the SPADing tram continues its movement toward an occupied controlled section where another tram is already running or is about to enter. Further details regarding data availability on SPAD accidents outside the JLRT system are provided in Section 2.9.1.1.3.



Figure 29: Potential for Collision between Trams in Controlled Sections

5.2.2 Modelling the Risk of a Potential Collision

5.2.2.1 General method

The risk assessment is based on the data obtained from SPAD investigation reports generated by the Jerusalem tram operator. The probability that a SPAD will lead to a potential collision was assessed using FTA (CENELEC, 2017). An assessment was made for each individual TSS controlled section on the Jerusalem main line: Mount Herzl Terminus, Heil Ha'Avir Terminus, and Depot Access. The quantification of the possible consequences was based on a study that uses the consequences resulting from similar events occurring in recent years in Europe (Table 24). Knowing the probability and the consequences, the annual potential risk was calculated using ETA (IEC, 2010). The assessment and evaluation of the risk allows for the assessment of existing safety measures, to reduce the risk of collisions caused by a SPAD.

Table 24: Tram Collisions Occurring in Europe (RAIB, n.d.) (European Union Agency for Railways, n.d.)

Event No. and Country	Occurrence Type	Date	Description	Direct cause	Number of Passengers in the Trams	Impact Speed	Consequences / Harm to Passengers
NO-2426 Norway	Tram collision	17/5/2013	At 13:25, Tram No. 104 ran into tram no 114 at a tram stop in Oslo	Unauthorised train movement, driving too close to the tram in front	Was not defined	Was not defined	3 Passengers with serious injuries and 18 were slightly injured
RAIB - 17/2016 GB	Tram collision at Shalesmoor, Sheffield	22/10/2015	At 08:25, Tram No. 118, was stationary at the Shalesmoor tram stop, and was struck from behind by tram No. 120	Tram 120 did not brake as quickly as would be expected. Low adhesion conditions in autumn, due to contamination from leaves	Both trams were heavily loaded with passengers at the time of the accident	16 km/h	15 passengers and a member of staff sustained minor injuries
RAIB - 11/2006 GB	Tram collision at New Addington	23/11/2005	At 08:16, Tram 2538, passed KHD02 signal at danger. This signal protects the entry into the short single line section. The tram blocked the adjacent line to Croydon. At the same time tram 2533, on its way to Croydon entered the single track section and collided with tram 2538	The driver of tram 2533 did not react in a timely manner to the obstruction caused by tram 2538. Tram 2538 passed signal KHD02 whilst it displayed a stop aspect	Tram 2533 – 10 passengers Tram 2538 – 25 passengers	Tram 2533 was travelling at 26.1 km/h	Two whiplash injuries among the passengers were reported The severity of whiplash is range from a minor injury to a major injury (Tidy, 2021)

Event No. and Country	Occurrence Type	Date	Description	Direct cause	Number of Passengers in the Trams	Impact Speed	Consequences / Harm to Passengers
RAIB - 17/2007 GB	Tram collision at Soho Benson Road	19/12/2006	At 11:51, trams 09 and 10 collided near Soho Benson Road tram stop. Tram 10 had slowed to 24 km/h when it collided with stationary tram 09	Tram 10 did not stop short of tram 09, which was stationary due to a technical fault	Was not defined	24 km/h	12 passengers were taken to local hospitals. They sustained minor injuries
CZ-5491 Czech Republic	Tram collision Brno city	05/11/17	At 21:05, a frontal collision between tram 1 course 17 and tram 1 course 3. with consequent derailment	Tram No. 1 course 17 passed over switch No. 709, which was not switched for the required direction.	Was not defined	15 km/h	10 passengers and a member of staff sustained minor injuries

5.2.2.2 Mount Herzl Terminus

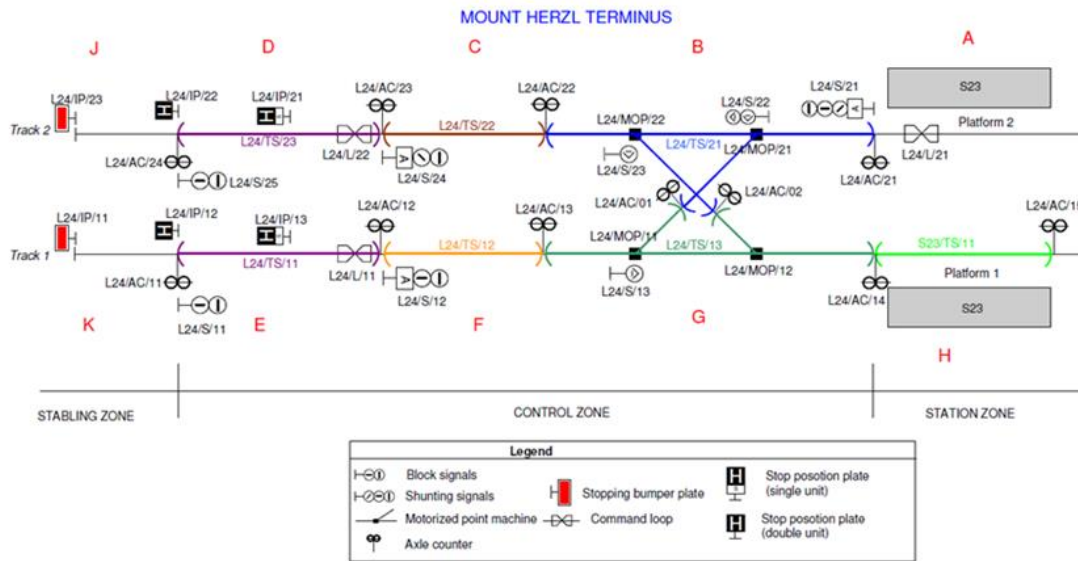


Figure 30: Controlled Section at Mount Herzl Terminus (ALSTOM, 2007)

This controlled section has three different zones (Figure 30):

- Station zone: Final station at the southern extremity of the line;
- Control zone: The zone where the switch points are located;
- Stabling zone: A zone where the trams park and turn around.

The potential for trams to collide exists in each of the zones.

5.2.2.2.1 Fault Tree Analysis

The frequency of a potential collision

The probability of the occurrence of a potential collision between trams due to a SPAD was calculated using the FTA technique (Figure 6, Figure 7). The left branch of the FT for the Mount Herzl Terminus (Figure 31) analyses the causes of the SPAD occurrence and calculates their probability based on the assumption that SPADs occur randomly and independently in a given unit of distance, measured in tram-km. Accordingly, the probability of occurrence of a SPAD is 0.00000315, representing a frequency of occurrence of 1 SPAD every 317,460 tram-km.

The right branch of the FT (Figure 31) analyses the conditions under which a collision or a potential collision between trams may occur, once a SPAD has happened. This analysis is in accordance with the controlled section diagram (Figure 30) and with the method used by Mahboob and Straub (Mahboob & Straub, 2011). The following presents an example of the

three conditions that must be satisfied simultaneously before a collision or potential collision occurs:

First condition: The SPADing tram passes a restrictive signal L24/S/21 and runs towards the stabling zone in Track 2.

Second condition: The SPADing tram does not stop and enters track section L24/TS/21.

Third condition: Track sections L24/TS/21 and L24/TS/22 are occupied, because a tram is coming from the stabling zone in Track 2 towards Platform 1.

If the second condition is not met and the driver stops the tram immediately upon passing signal L24/S/21, then there is no potential for a collision between trams even though a SPAD has occurred, and the track sections L24/TS/21 and L24/TS/22 are occupied. In this situation, the distance between the trams is large enough to avoid a collision or near-miss collision. Additional events where conditions for potential collision were not met are presented below (Table 25). We can see that 83% of the SPAD events occurred at the tram signal L24/S/21, where the driver failed to obey the restrictive aspect of this tram signal (Table 25).

The results of the FTA (Figure 31) are summarised as follows: Between 2014 and 2016, 12 SPAD events occurred in the controlled section at Mount Herzl. During that time period, the trams travelled an aggregate distance of 3.8 million km. The main cause of SPADs was the conflict between the tram signal and the road traffic signal, which served to confuse the drivers. There were no SPAD events following 'slip-sliding' of trams due to poor adhesion.

- *The probability of the occurrence of a SPAD is 0.00000315. This represents a frequency of occurrence of 1 SPAD every 317,460 tram-km.*
- *The probability that once a SPAD occurs, it will then lead to a potential collision or near-miss is 0.00000132.*

This represent a frequency of occurrence of 1 potential collision event due to SPAD every 757,600 tram-km at Mount Herzl Terminus

Table 25: SPAD Events at Controlled Sections – Mount Herzl Terminus

Event No.	SPAD on restrictive signal L24/S/21	The SPADing tram continued its movement towards the conflict area L24/TS/21	Track sections L24/TS/11 and L24/TS/12 are occupied (tram is approaching platform 1)	Track sections L24/TS/21 and L24/TS/22 are occupied (tram is approaching platform 1)	SPAD on restrictive signal L24/S/13	SPAD on restrictive signal L24/S/24	Track section L24/TS/21 is occupied by a tram that travels from platform 2 to the stabling zone	Conditions for potential collision
IL-20-2014	Y	The tram stopped immediately upon the SPAD	Y					N
IL-45-2014	Y	Y		Y				Y
IL-02-2015	Y	Y		Y				Y
IL-06-2015					Y		N	N
IL-26-2015	Y	The tram stopped immediately upon the SPAD		N				N
IL-12-2016	Y	The tram stopped immediately upon the SPAD	Y					N
IL-16-2016	Y	The tram stopped immediately upon the SPAD		Y				N

Event No.	SPAD on restrictive signal L24/S/21	The SPADing tram continued its movement towards the conflict area L24/TS/21	Track sections L24/TS/11 and L24/TS/12 are occupied (tram is approaching platform 1)	Track sections L24/TS/21 and L24/TS/22 are occupied (tram is approaching platform 1)	SPAD on restrictive signal L24/S/13	SPAD on restrictive signal L24/S/24	Track section L24/TS/21 is occupied by a tram that travels from platform 2 to the stabling zone	Conditions for potential collision
IL-18-2016	Y	Y		Y				Y
IL-21-2016	Y	The tram stopped immediately upon the SPAD		Y				N
IL-29-2016						Y	Y	Y
IL-30-2016	Y	Y		Y				Y
IL-74-2016	Y	Y		N				N
Number of SPAD events								12
Conditions for potential collision								5

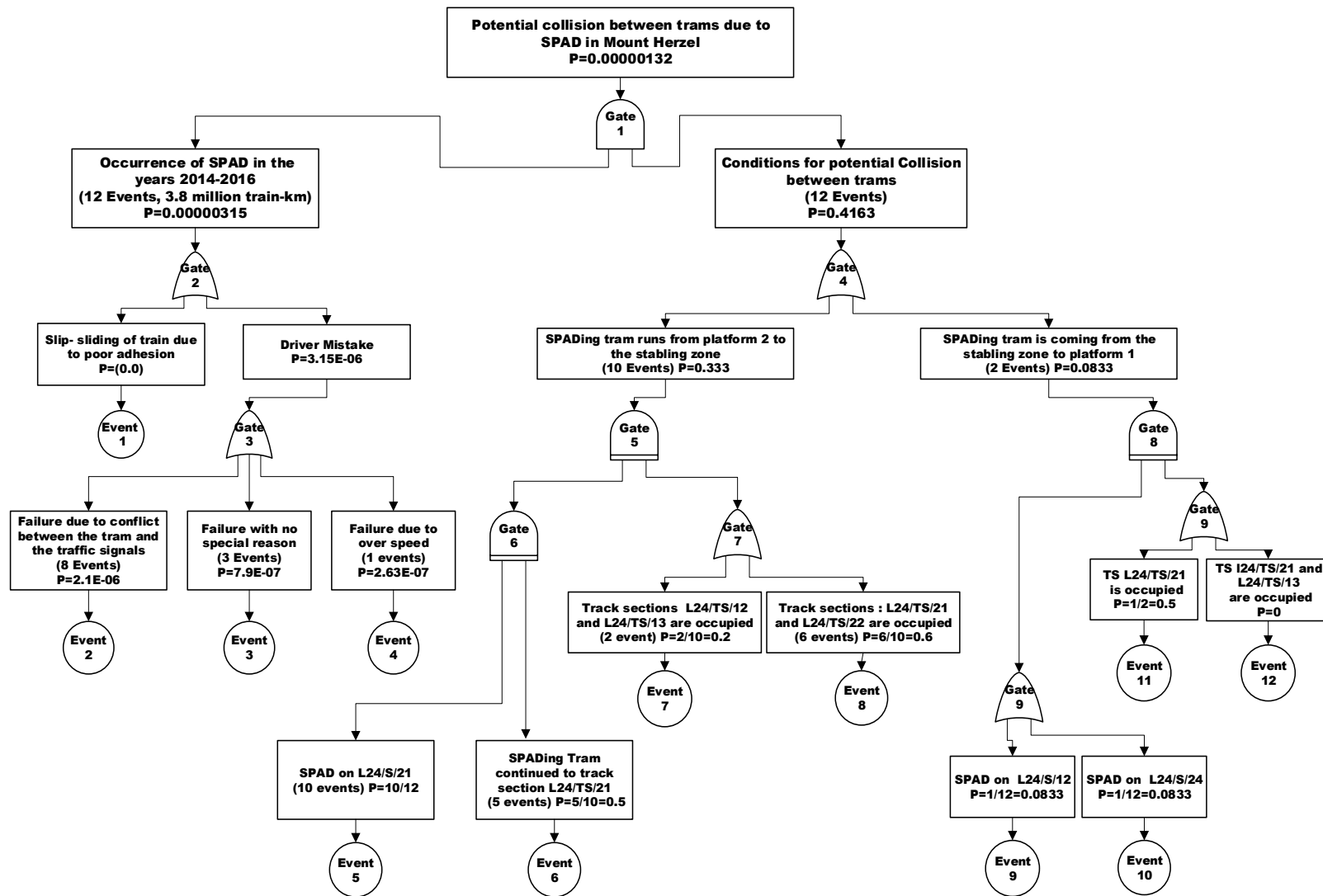


Figure 31: Fault Tree Analysis. Potential Collision between Trams due to SPAD at Mount Herzl Terminus

5.2.2.2.2 Event Tree Analysis

The potential consequences

Event tree analysis is an inductive approach, and thus suited to addressing hypothetical questions following a safety event, i.e., if there is a safety event, what are the likely consequences? In the current case, if a collision event between trams due to a SPAD occurs in this specific controlled section (Mount Herzl Terminus) then the only casualties will be the tram drivers. This is because there are no passengers on the trams in this area; whilst one tram would be travelling into the stabling zone after discharging its passengers the other will be emerging from that zone, to pick up passengers. There is the distinct possibility, however, that one or both drivers will be seriously injured. In terms of FWI, a serious injury is considered to be 0.1 fatalities. Therefore, assuming the worst case scenario that both drivers will be seriously injured the consequences per event in terms of FWI would be 0.2 fatalities.

The annual collective risk

Given the probability of a potential collision and its potential consequences, the annual potential risk can be modelled using ETA (Figure 32).

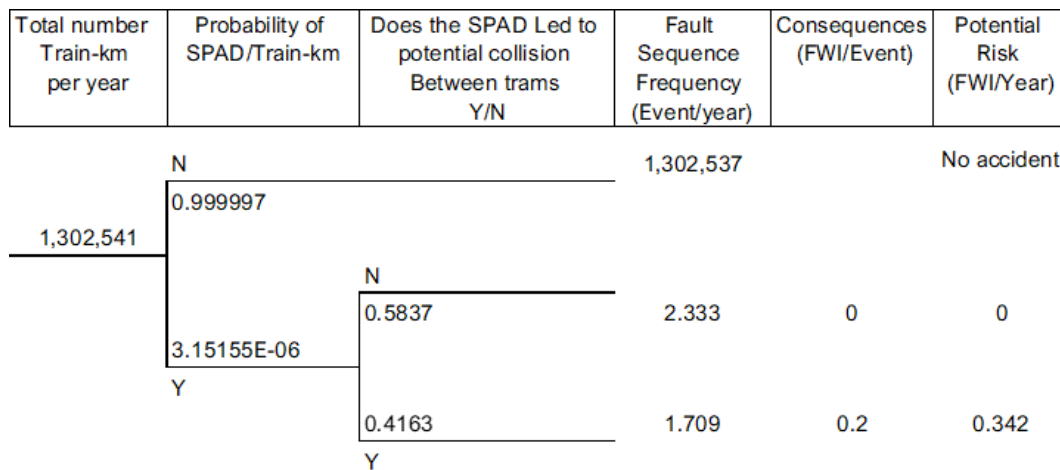


Figure 32: Event Tree Analysis. Potential Collision of Trams due to SPAD at Mount Herzl Terminus

The ETA shows that the annual potential collective risk of collisions between trams due to a SPAD at Mount Herzl Terminus is 0.342 FWI per year, and the mean of the potential collisions is 1.7 events per year.

5.2.2.3 Heil Ha'Avir Terminus

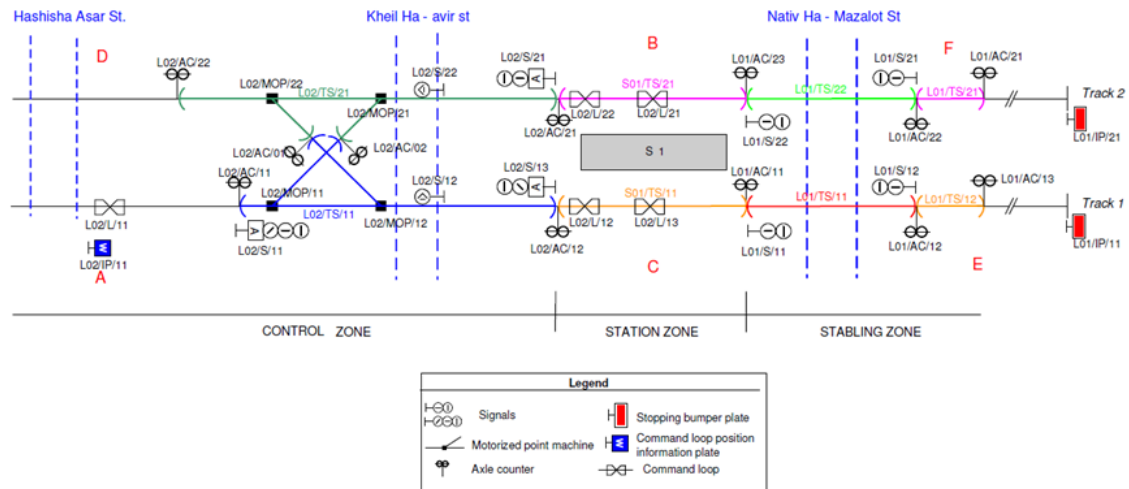


Figure 33: Controlled Section at Heil Ha'Avir Terminus

This controlled section has three different zones (Figure 33):

- Station zone: Final station at the North extremity of the line;
- Control zone: The zone where the switch points are located;
- Stabling zone: The zone where the trams park and turn around.

There are three types of movements: entering the station, exiting the station and movement between the stabling and station zones.

Entering the station: In this movement the tram goes from signal L02/S/11 to the station zone. The tram is able to move to platforms 1 and 2 of the station. The command loop placed in this area allows selection of the destination. If the driver does not push the on-board pushbutton when the tram passes over the detection loop, the system automatically sets an entrance route.

Movements between the stabling and station zones: Movement from stabling to station and movement from station to stabling are performed under the management of the OCC. Therefore, tram drivers must coordinate their movements with the OCC. The OCC has to request a route going from the station to the stabling area and vice versa.

Exiting the station: The driver must use an on-board pushbutton to start this movement. The interlocking controller waits until the safety conditions are met and afterwards establishes the routes, depending on the platform where the tram has stopped.

5.2.2.3.1 Fault Tree Analysis

The frequency of a potential collision

The probability of occurrence of a potential collision between trams due to a SPAD was quantified using FTA (Figure 6). The FT was constructed in the same manner as mentioned in Section 5.2.2.2.1, where the left branch analyses the causes of the SPAD event and calculates their probability and the right branch analyses the conditions under which a collision or a potential collision between trams may occur, once a SPAD has happened.

Based on the assumption that SPADs occur randomly and independently in a given unit of distance, measured in tram-km, the probability of SPAD occurrence at Heil Ha'Avir Terminus is: 0.000001313; this represents a frequency of occurrence of 1 SPAD every 761,614 tram-km. This is reflected in the left branch of the FT (Figure 34).

The right branch of the FT (Figure 34) describes three conditions according to which a potential collision between trams may occur given that the SPAD event occurred. These conditions were determined in accordance with Figure 33, the tram movement principles and the SPAD investigation reports for the years 2014-2016. The conditions for a potential collision event between trams are also summarised below (Table 26):

First condition: If the SPADing tram passes signal L02/S/11 which is in restrictive mode, on its way to platform 1 or 2, and tram sections L02/TS/11 or L02/TS/21 are occupied by other trams, then a potential collision can occur.

Second condition: If the SPADing tram passes signal L02/S/21 which is in restrictive mode, on its way out from platform 2, and tram section L02/TS/21 is occupied by another tram, then a potential collision can occur. During 2014-2016 there was one incident of a SPAD on signal L02/S/21 but the tram section L02/TS/21 was not occupied; therefore, the probability of occurrence of a potential collision under this condition is nil.

Third condition: If the SPADing tram passes signal L02/S/12 which is in restrictive mode, on its way out from platform 2, and tram section L02/TS/11 is occupied by another tram, then a potential collision can occur. The probability of a potential collision, in the event of this condition, is the highest, as shown in the FT (Figure 34).

The results of the FTA are summarised as follows: Between 2014 and 2016, five SPAD events occurred in the controlled section at Heil Ha'Avir Terminus. During that time period, the trams travelled an aggregate distance of 3.8 million km. The main cause of SPADs was the conflict between the tram signal and the road traffic signal, which served to confuse the drivers. There were no SPAD events following 'slip-sliding' of trams due to poor adhesion.

- *The probability of the occurrence of a SPAD is 0.000001313; this represents a frequency of occurrence of 1 SPAD every 761,614 tram-km.*
- *The probability that, once a SPAD occurs, it will lead to a potential collision is 0.000000788.*

This figure represents a frequency of occurrence of 1 potential collision event due to SPAD approximately every 1.3 million tram-km at Heil Ha'Avir Terminus

Table 26: SPAD at Heil Ha'Avir Terminus, Conditions for Potential Collision between Trams

Event No.	SPAD on signal L02/S/11. The SPADing tram is moving toward sections L02/TS/11 or L02/TS/21	Track section L02/TS/11 or L02/TS/21 is occupied	SPAD on signal L02/S/21. The SPADing train is moving toward L02/TS/21.	Track section L02/TS/21 is occupied	SPAD on signal L02/S/13 and L02/S/12. The SPADing train is moving toward section L02/TS/21	Track section L02/TS/11 or L02/TS/11 is occupied	Conditions for potential collision
IL-04-2014					Y	Y	Y
IL-15-2015	Y	N					N
IL-36-2015					Y	Y	Y
IL-65-2016	Y	Y					Y
IL-90-2016			Y	N			N
Number of SPAD events							5
Conditions for potential collision							3

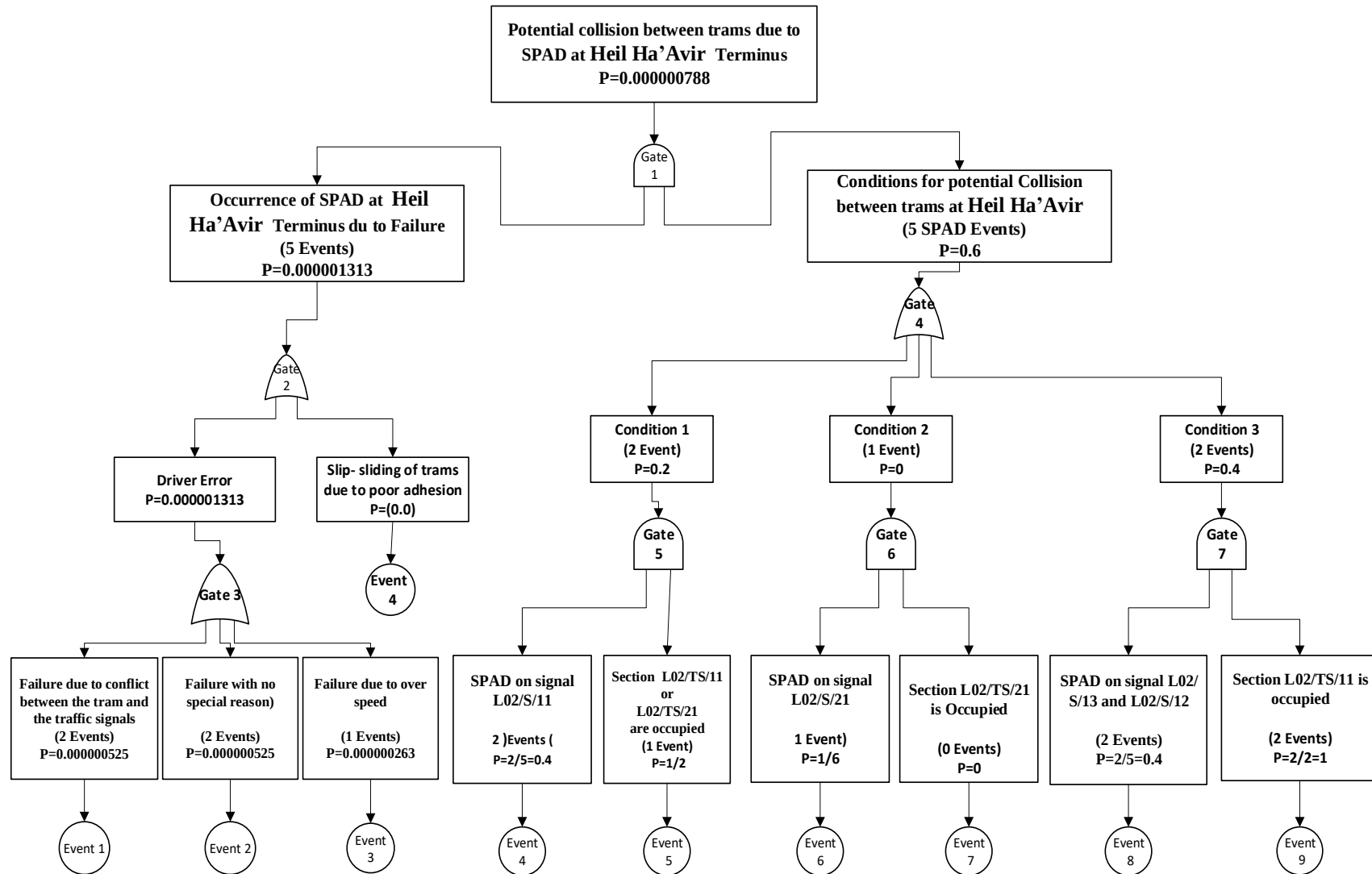


Figure 34: Fault Tree Analysis. Potential Collision between Trams due to SPAD at Heil Ha'Avir Terminus

5.2.2.3.2 Event Tree Analysis

The consequences of a potential collision

As mentioned in Section 2.9.1.3.2, ETA is an inductive approach that addresses hypothetical questions following a safety event, i.e., if a safety event of collision between trams will occur in Heil Ha'Avir Terminus what are the likely consequences? In order to answer this question, it should be known that at peak hour there are about 50 passengers on the tram departing from the station and about 30 passengers on the tram entering the station. It can be assumed that the passengers are uniformly distributed between the tram cars. In addition, the trams' speed in this section is approximately 15 km/h.

If an accident occurs at Heil Ha'Avir Terminus, it can be assumed (from Figure 36 Figure 37) that it may look like the one that happened in New Addington (event number 11/2006 in Table 24: Tram Collisions Occurring in Europe). Therefore, if the above data are scaled to the number of passengers in the trams and the trams' speed at the New Addington accident, the consequences of an accident in Heil Ha'Avir Terminus would be

$$\text{Potential consequences} = \left[\frac{15_{JRkph}}{26_{NAkph}} \times \frac{(80_{JR-pax})}{(35_{NA-pax})} \right] * 2_{NAC} = \sim 3$$

where:

JR: Jerusalem LRT;

pax: passengers

NA: New Addington; and

NAC: New Addington Consequences

However, the two collision situations are not really similar; in the case of New Addington one tram was stationary when the other tram collided with it and in the case of JLRT both trams are in motion. It is assumed that more passengers will get seriously injured on JLRT than in New Addington and that the driver of the SPADing tram will be seriously injured as well. Hence, the estimated consequences of an accident in Heil Ha'Avir Terminus would be 4 passengers and 1 staff member suffering from serious injuries; in terms of the aggregate amount of harm the potential consequences are:

$$\text{Potential Consequences per a Collision Event} = 0.1 * 5 = 0.5 \text{ FWI and};$$

The annual potential collective risk

Total number of LRT Train-km/Year	Probability of SPAD/Train-km	Does the SPAD Led to potential collision Between trains Y/N	Fault Sequence Frequency (Event/year)	Consequences (FWI/Event)	Potential Risk (FWI/Year)
1,302,541	N		1,302,539		No accident
	0.999999				
		N			
	1.31315E-06	0.4	0.684	0	0
		Y			
		0.6	1.026	0.5	0.513
		Y			

Figure 35: Event Tree Analysis. Potential Collision between Trams due to SPAD at Heil Ha'Avir Terminus

According to the ETA the annual potential CR = 0.513 FWI and the mean of the potential collisions is 1.026 events per year.

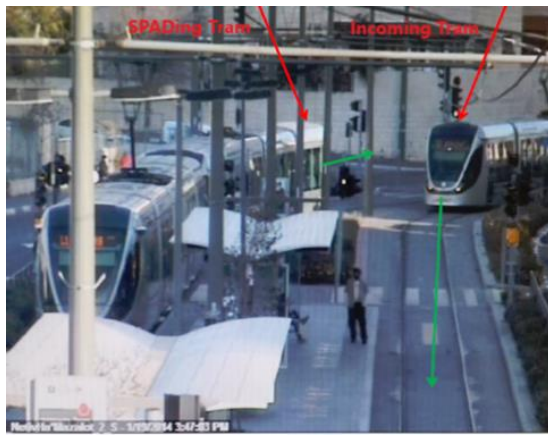


Figure 36: Potential Collision at Heil Ha'Avir Terminus (Author, 2016)



Figure 37: Tram Collision at New Addington (RAIB, 2005)

5.2.2.4 Depot Access

This controlled section is located between two stations, S7 and S8, (Figure 38). Trams usually remain on the main line when passing through this area. This is the default movement and just in case they have to enter or exit the depot the switches are changed. Trams moving between the main line and Depot take a bi-directional track, either Access Track Line 1 or

Access Track Line 2. Access Track Line 2 allows trams to enter the depot from Track 2 of the main line. Trams entering the depot from Track 1 or joining track 2 use Access Track Line 1.

Figure 38 describes the controlled section at the Depot Access; the notations and symbols in Table 27 demonstrate how to read the notations and symbols in Figure 38.

Table 27: Explanation of the Notations and Symbols in Figure 38

Notation	Symbol	Description
L08/TS/23		Track section No. 23 at Line control section 8
L08/AC/24		Axle Counter No. 24
L08/MOP/22		Motorized point machine No. 22
L08/L/11		Command loop number No. 11
L08/S/21		Block Signal No. 11
L08/S/11		Shunting signal No. 12
L08/S/12		Switching point can be locked and set for forward travel or right
DGN/TS/13		Track section No. 13 at the Depot Gate

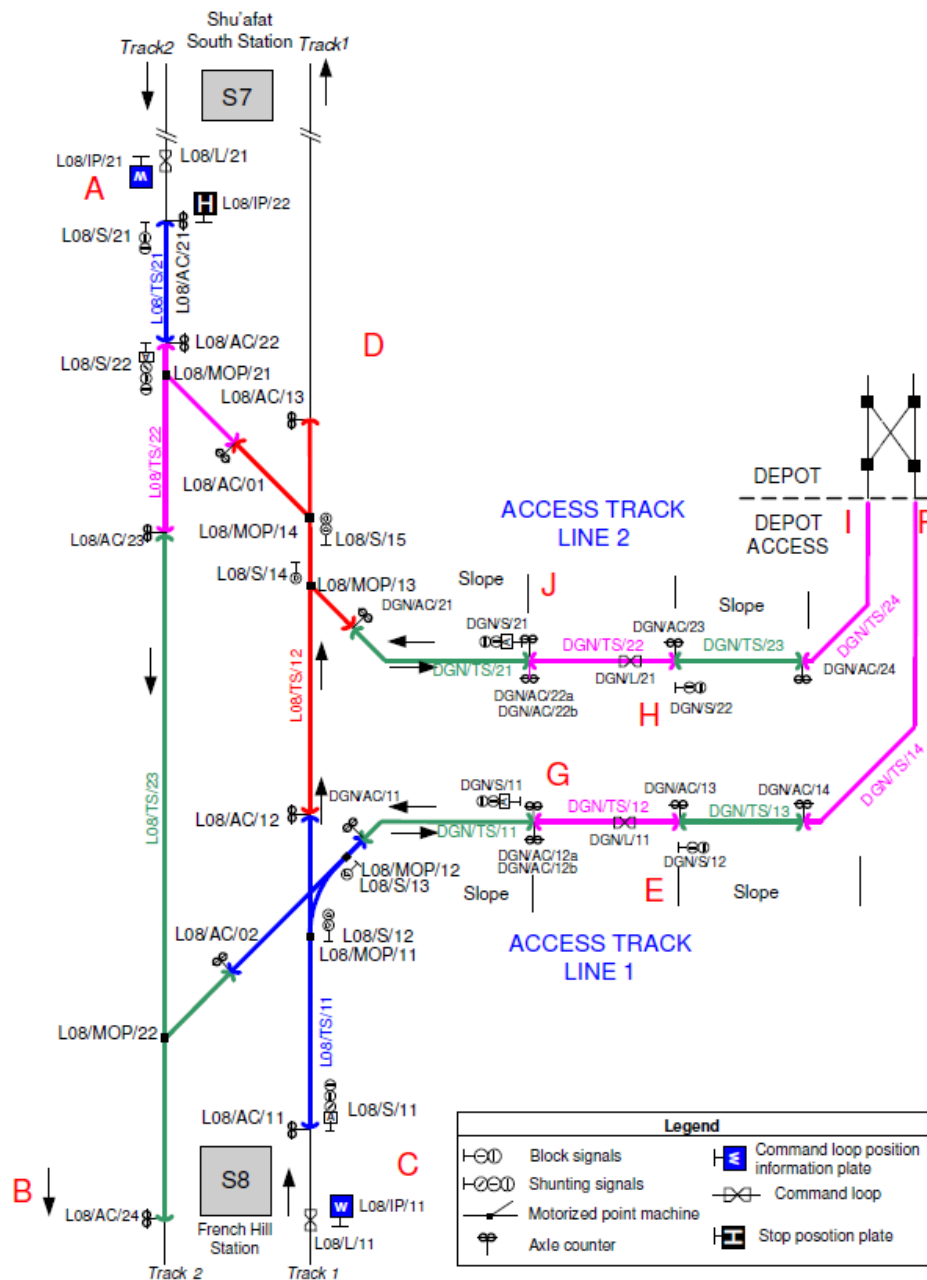


Figure 38: Controlled Section at Depot Access

Types of routes in this area

Main line routes

Passing route: This is the default route for trams moving along the main line. When trams approach the junction from either Track 1 or Track 2 they pass over a command loop. If the driver does not request entrance to the depot using the on-board pushbutton, the system automatically requests the default passing route and the tram remains on the main line.

Entrance routes to the depot

Entrance Route from Track 1: Trams moving along Track 1 access the depot using Access Track Line 1, following the route C-E-F (described in Figure 38). The driver requests access to the depot when the active antenna is over command loop L08/L/11. This command loop is right at the entrance to French Hill station.

Entrance Route from Track 2: Trams moving along Track 2 access the depot using Access Track Line 2, using the route A-H-I (described in Figure 38). The driver requests access to the depot when the active antenna is over command loop L08/L/21.

Block zone in entrance routes: In the access to the depot routes, line-of-sight principles are applied. Nevertheless, there are two areas that must be signalled, corresponding to a slope greater than 7%, in the downward direction. These areas are between points H and E. The general operational principles in this block section are:

- Block signals protect access to both depot tracks.
- The default aspect of the block signals is 'permissive aspect'.
- When the direction is set up as entrance by the OCC, the signals corresponding to the exit direction are switched off and vice versa.
- Wheel sensors (axle counters) define the track sections. The block area is locked when the tram is within it and clear when it leaves it.
- Only one tram is allowed to circulate through it at any given time.

Exiting routes from the depot

Exit route from depot to Track 1: Trams moving from the depot towards Track 1 take Access Track Line 2 following the route I-J-D.

Exit route from depot to Track 2: Trams exit the depot and head to Track 2 along Access Track Line 1, following the route F-G-B.

Block zone in exit routes: In the Access Depot routes, line-of-sight principles are applied. Nevertheless, there are two areas that must be signalled, corresponding to a slope greater than 7%, in the downward direction. These areas begin at points G and J (see Figure 38).

5.2.2.4.1 Fault Tree Analysis

In the years 2014-2016 there were 21 SPAD events in the Depot Access area. In view of the complexity of this controlled section and the multiple combinations of tram movement, the FTA was carried out in two parts. The first part covers the tram movements from S8 towards S7 and the second part covers the tram movements in the opposite direction.

The frequency of a potential collision - tram movements from S8 to S7

The tram movements from S8 to S7 are in conflict with road traffic at intersection 55 which is near the station. On his/her way out of S8 the tram driver will meet TSS L08/S/11, and an adjacent RTSS. The permissive aspect of the RTSS gives authorization for the tram to cross the intersection as the intersection is free of vehicles. The TSS indicates whether track section L08/TS/11 is occupied by another tram coming from the Depot toward S8 or track section L08/TS/12 is occupied by a tram coming from the Depot toward S7. These track sections are where conflicts between trams can occur, which can result in a potential collision.

Sometimes there are conflicts between the RTSS and the TSS signals. The TSS shows the restrictive aspect while the RTSS shows the permissive aspect, and drivers accidentally obey the RTSS. This is the most probable failure mode leading to SPAD; it is presented in the left branch of the corresponding FTA (Figure 39). The right branch presents the conditions for potential collision in the conflict areas, once a SPAD occurs. The same conditions are also presented below (Table 28). The data for the FTA were obtained from the SPAD investigation reports.

The results of the FTA show that between 2014 and 2016, 12 SPAD events occurred in the controlled section at the Depot Access where trams were moving from S8 to S7. During that time period, the trams travelled an aggregate distance of 3.8 million km. All the SPADs occurred due to conflict between the TSS and the RTSS, which served to confuse the drivers. There were no SPAD events following 'slip-sliding' of trams due to poor adhesion.

- *The probability of the occurrence of a SPAD is 0.00000315. This represents a frequency of occurrence of 1 SPAD every 317,460 tram-km.*

- *The probability that, once a SPAD occurs, it will lead to a potential collision 0.000001831.
This represents a frequency of occurrence of 1 potential collision event approximately every 546,448 tram-km at the Depot Access.*

Table 28: SPAD at Depot Access. Conditions for a Potential Collision between Trams. Tram Movement from S8 to S7

Event No.	Tram direction	SPAD on signal L08/S/11	The SPADing tram continued its movement towards the conflict area L08/TS/11 and L08/TS/12	Track section L08/TS/11 is occupied by another tram	Track section L08/TS/12 is occupied by another tram	Track sections L08/TS/21 and L08/12/201 are occupied by another tram. Tram is coming from Track 2	Conditions for potential collision
IL-09-2014	S8 to S7	Yes	The tram stopped immediately upon the SPAD	N	N	N	N
IL-64-2014	S8 to Depot	Yes	Y	N	N	N	N
IL-96-2014	S8 to S7	Yes	The tram stopped immediately upon the SPAD			Y	N
IL-104-2014	S8 to S7	Yes	Y		Y		Y
IL-112-2014	S8 to S7	Yes	Y	N			N
IL-55-2015	S8 to Depot	Yes	Y	Y			Y
IL-46-2016	S8 to S7	Yes	Y		Y		Y
IL-60-2016	S8 to S7	Yes	Y		Y		Y
IL-53-2016	S8 to S7	Yes	Y		Y		Y
IL-71-2016	S8 to S7	Yes	Y	N	N	N	N
IL-81-2016	S8 to S7	Yes	Y		Y		Y
IL-108-2016	S8 to S7	Yes	Y		Y		Y
Number of SPAD events							12
Conditions of potential collision							7

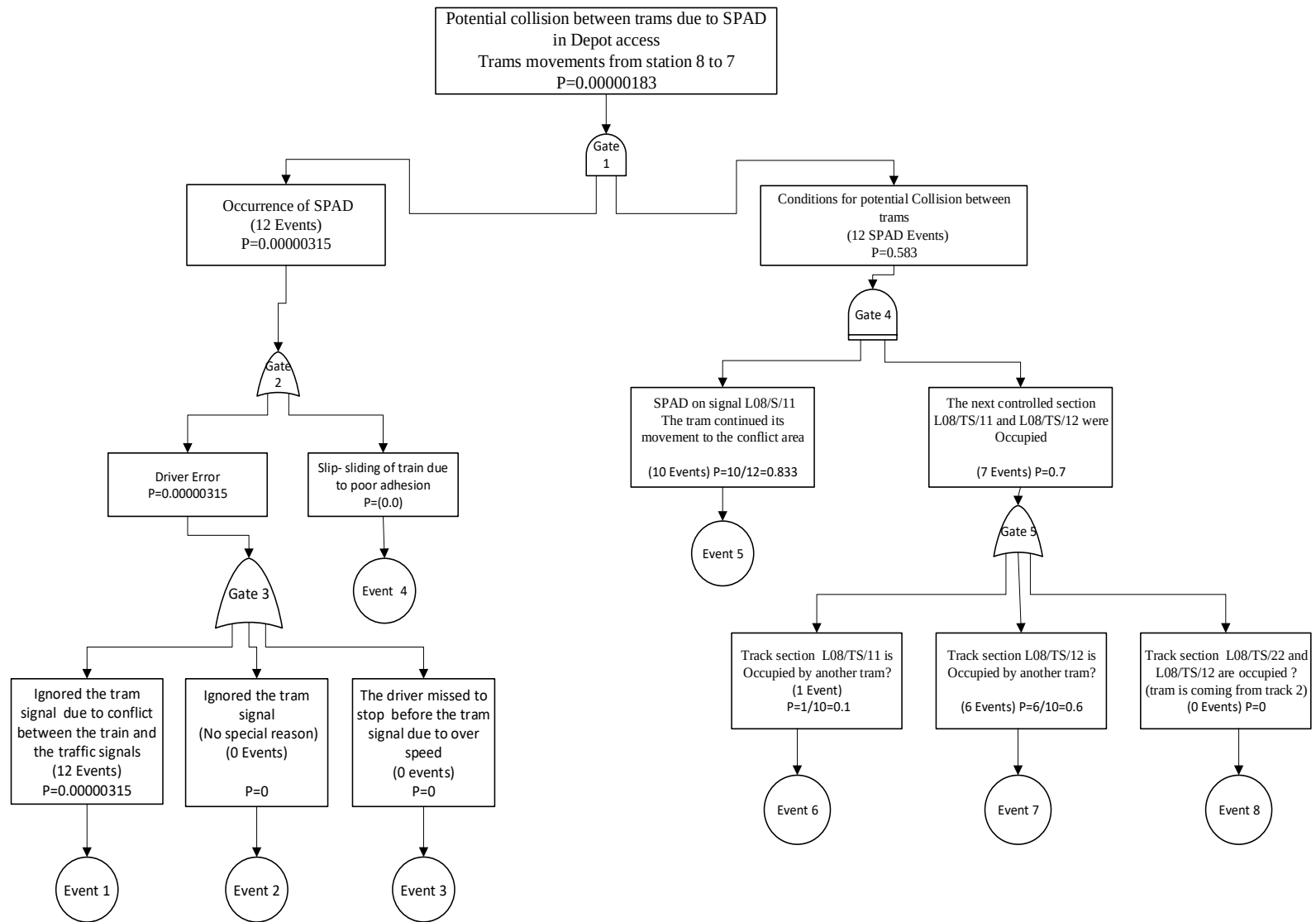


Figure 39: Fault Tree Analysis. Probability of a Potential Collision at the Depot Access. Tram Movement from S8 to S7

The frequency of a potential collision - tram movements from S7 to S8

In this direction the trams can continue their movement towards S8 through track section L08/TS/22 while passing TSS L08/S/22. The trams can also change direction, and return to the depot through track sections L08/TS/22 and L08/TS/12 while passing TSS L08/S/22. Conflicts between trams due to SPAD might occur in these track sections. Such a conflict can lead to potential collision between trams. Quantification of the probability of the said collision is done using the same paradigms as in the previous section (Tram movements from S8 to S7). The FTA – assessment of the probability of a potential collision (Figure 40) – and the conditions for the potential collision in the abovementioned track sections (Table 29) are presented below.

The results of the FTA show that between 2014 and 2016, 9 SPAD events occurred at the Depot Access controlled section, where trams were moving from S7 to S8. During that time period, the trams travelled an aggregate distance of 3.8 million km. In three cases the drivers failed to stop before the tram signal, yet, they stopped immediately upon the SPAD. There were no SPAD events following 'slip-sliding' of trams due to poor adhesion.

- *The probability of the occurrence of a SPAD is 0.000002363. This represents a frequency of occurrence of 1 SPAD every 423,190 tram-km.*
- *The probability that once a SPAD occurs, it will then lead to a potential collision is 0.00000105,*

This represents a frequency of occurrence of 1 potential collision event approximately every 952,380 tram-km.

Table 29: SPAD at Depot Access. Conditions for a Potential Collision between Trams. Tram Movement from S7 to S8

Event No.	Tram direction	SPAD on signal L08/S/21	SPAD on signal L08/S/22	The SPADing tram continued its movement to the conflict area	Track section L08/TS/23 is occupied due to tram at S8	Track section L08/TS/23 is occupied. Tram coming from the Depot to S8	Track section L08/TS/12 is occupied. Tram is coming from the Depot to S7	Track section L08/TS/12 is occupied. Tram is coming from S8	Conditions for potential collision
IL-08-2014	S7 to Depot		Y	Tram stopped immediately upon the SPAD			N	N	N
IL-25-2014	S7 to S8		Y	Y	N	N			N
IL-31-2014	S7 to S8		Y	Y	Y				Y
IL-75-2014	S7 to Depot		Y	Tram stopped immediately upon the SPAD			N	N	N
IL-76-2014	S7 to S8		Y	Y		Y			Y
IL-78-2014	S7 to S8		Y	Y		Y			Y
IL-109-2014	S7 to S8	Y		Tram stopped immediately upon the SPAD	N	N			N
IL-20-2015	S7 to S8		Y	Tram stopped immediately upon the SPAD	Y				N
IL-17-2016	S7 to S8		Y	Y	Y				Y
Number of SPAD events									9
Conditions of potential collision									4

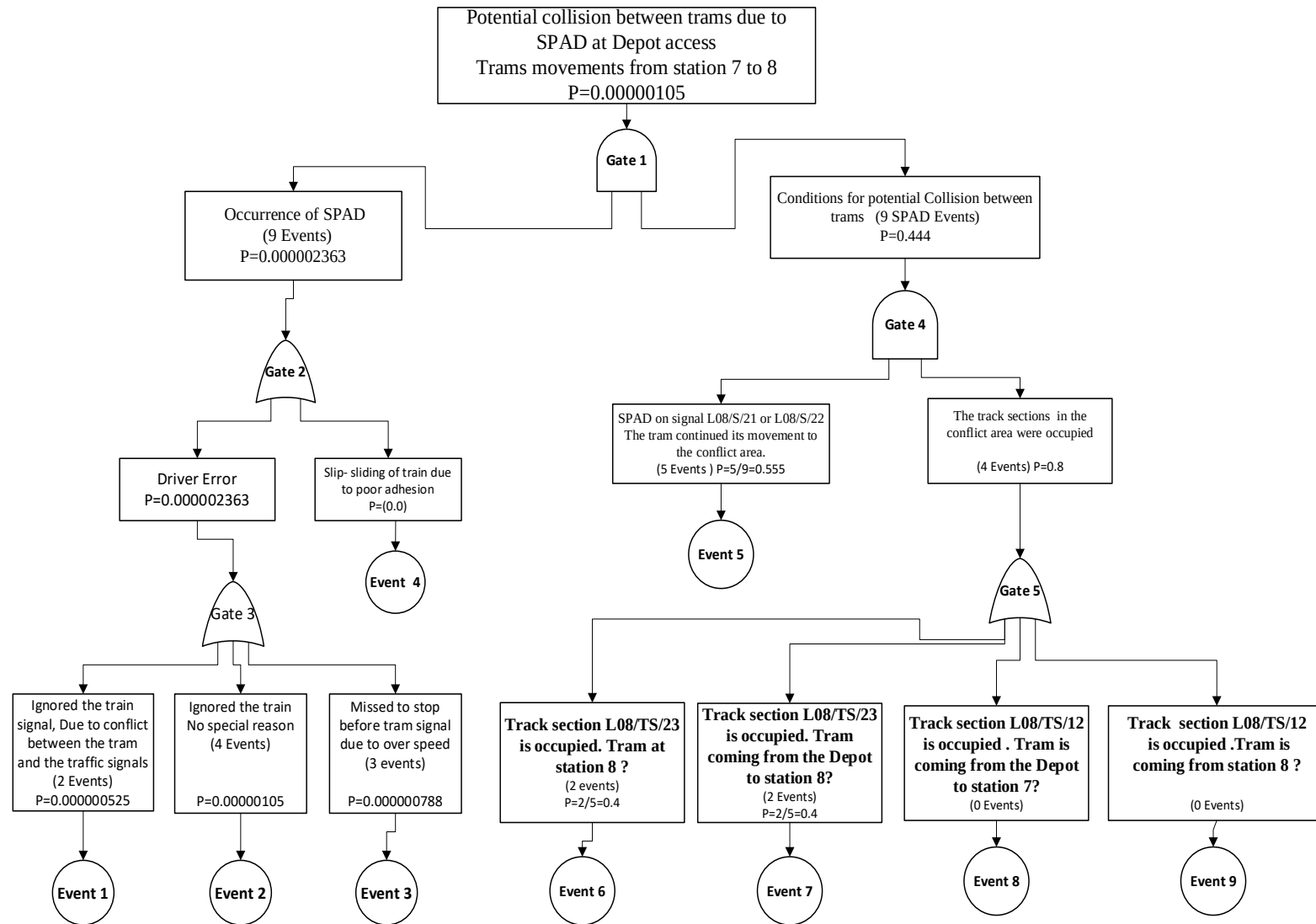


Figure 40: Fault Tree Analysis. Probability of a Potential Collision at the Depot Access. Tram Movement from S7 to S8

5.2.2.4.2 Event Tree Analysis

The consequences of a potential collision - tram movements from S8 to S7

If a collision between trams due to SPAD occurs in track section L08/TS/11 or in track section L08/TS/12, which are considered to be conflict sections, the tram that already entered the track section from the Depot will be struck from behind by the SPADing tram. According to frequency counts of passengers, during peak hours the SPADing tram might accommodate approximately 120 passengers, while the other tram is empty. It can also be assumed that their speed would be about 15 km/h, as this is the allowable speed in this section.

Event number 17/2007 in Table 24 gives an indication of the expected consequences of an accident in which one tram is struck from behind by another tram (see Figure 41). That event happened on 19/12/2006 at 11:51, near Soho Benson Road UK (RAIB, 2006); the impact speed was 24 km/h.



Figure 41: Trams 10 and 09 after the Collision (RAIB, 2006)

Twelve passengers were taken to local hospitals, suffering from minor injuries. Considering that this is a class 2 injury; the safety harm in terms FWI would be 0.06 FWI per event.

Although the impact speed was higher than what it might be if an accident occurred in track sections L08/TS/11 or L08/TS/12, there is no indication in RAIB's report regarding how many passengers were in the trams when the accident occurred; hence it is still reasonable to

assume that the FWI would be roughly the same, because this is the average number of injuries resulting from the accidents described in Table 24.

Hence; the estimated potential consequences in the direction S8-S7 is 0.06 FWI

The annual potential collective risk - tram movements from S8 to S7

Total number of LRT Train-km/Year	Probability of SPAD/Tram-km	Does the SPAD Led to potential collision Between trams Y/N	Fault Sequence Frequency (Event/year)	Consequences (FWI/Event)	Potential Risk (FWI/Year)
1,302,541	N		1,302,537		No accident
	0.999997				
		N			
		0.416666667	1.667	0	0
	3.15155E-06				
	Y				
		0.583	2.395	0.06	0.14
		Y			

Figure 42: Annual Potential Risk at Depot Access due to Conflicts at L08/TS/11 & L08/TS/12

According to the ETA the annual potential CR = 0.14 FWI and the mean of the potential collisions is 2.395 events per year.

The consequences of a potential collision - tram movements from S7 to S8

The FTA (Figure 39) suggests two possible accidents in this direction. The first accident is a collision between an empty tram exiting the depot and heading to Track 2 and a SPADing tram that runs on track section L08/TS/23. This accident may occur on the access to Track 2, near point machine L08/MOP/22. The second possible accident is a collision between a SPADing tram and a stationary tram at S8. This tram stop is located in the southern part of track section L08/TS/23. It is reasonable to assume that the harm to passengers would be roughly the same as that described in accidents number 11/2006 and number 17/2016, respectively (see Table 24), Figure 37 and Figure 43 respectively.



Figure 43: Event 17/2016. Position of Trams Immediately after the Accident at Tram Stop Shalesmoor (RAIB, 2016)

During peak hours the maximum number of passengers in the tram heading to S8 is 170 passengers. The maximum allowable speed in track sections L08/TS/23 and L08/TS/11 is 15 km/h. Therefore, the consequences of a potential collision at the access to Track 2 between a SPADing tram and the one that comes from the Depot can be estimated by scaling the consequences of the accident at New Addington, according to the number of passengers and the impact speed as calculated below:

$$\text{Numer of Injuries (Passengers)}_{\text{Jerusalem}} = \left[\frac{15_{JRkph}}{26_{NAkph}} \times \frac{(170_{JR-pax})}{(35_{NA-pax})} \right] * 2_{NAC} = \sim 6$$

where:

JR: Jerusalem LRT

NA: New Addington;

NAC: New Addington Consequences

pax: passengers

Therefore: In a situation where the SPADing tram is travelling at a speed of 15 km/h on track section L08/TC/23 and collides with an empty tram exiting the Depot and heading to Track 2, the estimated potential consequences are 6 major injuries among the passengers and it is assumed that the driver of the empty tram will suffer from major injuries as well; hence, in accordance with Table 11, the consequences on the access to Track 2 are:

Potential consequences per collision event = $0.1 * 7 = 0.7 \text{ FWI}$.

The consequences of a potential collision at S8 can be estimated in the same manner, using the data from the accident at Shalesmoor tram stop in Sheffield, event number 17/2016 (Figure 43). In this case the consequences would be the same, because the impact speed is more or less the same, as are the numbers of passengers in the trams, hence the estimated potential harm would be:

Potential consequence at S8 per collision event = $15_{PAX} * 0.005 = 0.075 \text{ FWI}$

And the total estimated potential consequences in the direction from S7 to S8:

Potential consequences in direction S7 – S8 = $0.7 + 0.075 = 0.775$

The annual potential collective risk - tram movements from S7 to S8

Total number of LRT Train-km/Year	Probability of SPAD/Tram-km	Does the SPAD Led to potential collision Between trams Y/N	Fault Sequence Frequency (Event/year)	Consequences (FWI/Event)	Potential Risk (FWI/Year)
1,302,541	N		1,302,538	No accident	
	0.999998				
	0.000002363	N	1.71	0	0
		Y	1.367	0.775	1.06

Figure 44: Annual Potential Risk at Depot Access Due to Tram Conflicts at L08/TS/23

According to the ETA the annual potential CR = 1.06 FWI and the mean of the potential collisions is 1.367 events per year.

5.2.2.4.3 The total Risk at the Depot Access

The annual collective risk at the Depot Access is the summation of the risks in both directions, hence:

$$\text{Annual potential } CR_{\text{Depot Access}} = 0.14 + 1.06 = 1.2 \text{ FWI / Year}$$

This is the highest residual risk, compared to the risks at the other controlled sections. The immediate insight is that there might be a lack of means to minimise the risk of collisions between trams in this area, and there is a need to re-examine the effectiveness of the existing means.

5.3 The JLRT SPAD Safety Risk Model

Let:

P_i : probability of a potential collision due to SPAD in control section i

C_i : potential consequences once a collision occurs in control section i

S_j : mileage accumulated by the tram fleet in year $j = 1, 2, 3, \dots$

i : the control section

where;

1-Mount Herzl Terminus

2-Heil Ha'Avir Terminus

3-Depot Access S8-S7

4-Depot Access S7-S8

Then:

Based on the FTA and ETA the estimated potential annual collective risk associated with a SPAD at the JLRT system would be:

$$\text{Annual CR} = S_j * [\sum_{i=1}^4 P_i * C_i]$$

Equation 29: Annual Collective Risk Due to SPADs

The SPAD safety risk model (Equation 29) clearly shows the dependence between the exposure and the risk, which means that the more the trams travel, the higher the risk of a collision. Parameter S is the product of the service plan, meaning that increasing/improving the service to the passengers comes at the cost of increased risk, and vice versa.

Table 30: Results Summary of the SPAD Risk Assessment

Control Section	[1]	Minor Injury	Major Injury	[2]	[1]*[2]
	Probability of a potential collision between trams due to SPAD			Consequences FWI/Event	
Mount Herzl Terminus	0.00000132		2	0.2	0.000000264
Heil Ha'Avir Terminus	0.000000788		5	0.5	0.000000394
Depot Access S8-S7	0.00000183	12		0.06	1.098E-07
Depot Access S7-S8	0.00000105		7	0.7	0.000000735
Total					1.5028E-06

In accordance with the risk assessment results (Table 30), the SPAD safety risk model equation is (Equation 30):

$$Annual\ CR = S_j * 1.503 * 10^{-6}$$

Equation 30: SPAD Risk at JLRT Controlled Sections, Model Equation

Given: the annual tram-km of the following year =1,302,541

Then: the total potential risk due to SPAD is: **CR=1.96 FWI**

Sensitivity analysis

The above annual potential CR is Unacceptable according to the risk evaluation in Section 5.4. Suppose this figure was obtained as a result of an underestimation of crashworthiness of the

JLRT trams and let's assume that over 50% of the injuries that were considered major injuries are now minor injuries class 1 (Table 31); then the annual $CR = S_i * 8.13 * 10^{-7} = 1.06 \text{ FWI}$.

This risk is still Unacceptable following the risk evaluation described in Section 5.4.

Table 31: Sensitivity Analysis

Control Section	[1]	Minor Injury (class 2)	Major Injury	[2]	[1]*[2]
	Probability of a potential collision between trams due to SPAD			Consequences FWI/Event	
Mount Herzl Terminus	0.00000132	1	1	0.15	1.98E-07
Heil Ha'Avir Terminus	0.000000788	3	2	0.215	1.69E-07
Depot Access S8-S7	0.00000183	2		0.06	1.1E-07
Depot Access S7-S8	0.00000105	4	3	0.32	3.36E-07
Total					8.13E-07

5.4 Risk Evaluation and Acceptance

5.4.1 Risk Evaluation Following Risk Modelling

5.4.1.1 Introduction to risk evaluation

The risk modelling as a result of SPAD was made separately for three controlled sections, and the risk assessment for the Depot Access was made separately for each direction, i.e., from station S7 towards station S8 and vice versa. It was found that the highest risk is in the direction from station S7 toward station S8 and this is also the highest risk of all the controlled sections. Therefore, the risk evaluation will refer solely to this section and will be validated based on expert judgement as per Sections 2.4.2, 0 and 2.9.3 from which the importance of expert opinion arises given that the event is rare. Of course, the risk evaluation should have been made for the overall risk arising from the SPAD, but inductive reasoning in this case would provide sufficient indication of the tolerability of the SPAD risk, as the risk in the direction S7 toward S8 is in the catastrophic range. The frequency level and the severity level of the risk will be evaluated in accordance with the process defined in Chapter 3, Section 3.2.1 and with the classification and acceptance of the risk.

5.4.1.2 Frequency level

According to the FTA (Figure 40) the probability of a potential collision at the Depot Access where the tram movement is from station S7 towards station S8 is $0.00000105 (1.05 * 10^{-6})$, representing a frequency of one event per 952,380 tram-km or, 1 event per 48,473 operation hours as calculated hereunder:

If : The annual tram-km is 1,302,541 and the equivalent amount of annual operation hours is 66,295 hours (see general assumptions, Section 3.2.6)

Then : 952,380 tram-km are equivalent to $\frac{952,380}{1,302,541} \times 66,295 = 48,473 \text{ hrs}$

Hence : The frequency of occurrence is: 1 event per 48,473 hours

And : The relative frequency /probability = $\frac{1}{48,473} = 2.06 * 10^{-5}$

Therefore : In accordance with Table 6: Frequency of Occurrence of Hazard Events, the frequency level can be classified as Remote.

5.4.1.3 Severity level

The potential consequence per event (see Section 5.2.2.4.2) is 0.775 FWI which can be considered Critical according to Table 5: Hazard Severity Level. If we were refer to the severity of the consequences following the sensitivity analysis (Table 31) the severity would still be Critical.

5.4.1.4 Risk acceptance

- Using the risk matrix (Table 7), the combination of the above severity and frequency indicates that the residual risk is Undesirable.
- According to Table 8 the risk shall only be accepted with the agreement of the State/JTMT.
- Another way to evaluate the risk acceptability is to use the ORR criterion defined in their CSM (ORR, 2018) and detailed in Section 2.3.3.3. Accordingly, considering the SPAD as an MMI failure, in this case, the frequency of the failure is higher than 10^{-7} per operation hour and the failure has a credible potential to lead directly to a critical accident, i.e., an accident that has adverse outcome on a small number of people and results in at least one fatality; therefore, the risk is not Acceptable and it needs to be further reduced.

5.4.1.5 Risk mitigation measure

As in the UK, the State of Israel, represented by JTMT, has decided to implement a speed supervision and enforcement system to mitigate the risk of SPADs and the risks arising from excessive speed, including overturning of trams on a sharp curve. This was a safety requirement in the recent tender, which stipulated that the current and new fleets should be equipped with this system, see Appendix H. The decision is also in line with the expert judgement, described in Section 5.4.2.

5.4.2 Risk Assessment and Evaluation by Expert Judgement

5.4.2.1 General process description

The approach for this exercise is based on Qualitative Risk Assessment (QRA). The exercise is meant to bring together the combined views of a group of suitably qualified experts (see Chapter 3, Section 3.2.5) with safety expertise, domain knowledge and experience. A questionnaire was generated which the experts were asked to complete; The results from the various experts' judgement were combined in risk matrices. A workshop was then held to understand some of differences of opinion and their underlying assumptions.

5.4.2.1.1 Phase A - Questions and Results

5.4.2.1.1.1 Questionnaire

- a. The experts were required to assess the potential risk of three potential accident scenarios in the direction from station S7 toward station S8. The scenarios are described hereunder and the routes sections indicated in each scenario appear in Figure 38 depicting the controlled section at the Depot Access.

Scenario 1

- The SPADing tram is a mainline tram continuing towards Station S8.
- The driver continues forward into track section L08/TS/23 after the SPAD has occurred.
- There is a tram approaching Station S8 in the same direction or at the station (S8) where passengers are alighting and boarding the tram.

In this scenario it should be assumed that both trams have a full load of 170 passengers.

Scenario 2

- The SPADing tram is a mainline tram continuing towards Station S8.
- The driver continues forward into track section L08/TS/23 after the SPAD has occurred.
- Track section L08/TS/23 is occupied by a tram exiting the depot towards Station S8.

This scenario is shown in Figure 29 on the right. In this scenario it should be assumed that the tram travelling from S7 to S8 on the mainline will have a full load of 170 passengers. The tram exiting the depot will have no passengers.

Scenario 3

- The SPADing tram is a non-passenger carrying tram going to the depot.
- The driver continues forward into track section L08/TS/12 after the SPAD has occurred.
- A passenger carrying tram is occupying L08/TS/12 going from S8 to S7.

In this scenario it should be assumed that the tram travelling from S8 to S7 on the mainline will have a full load of 170 passengers. The tram moving towards the depot will have no passengers.

- b. Following the given scenarios the experts were required to qualitatively assess the likelihood of a collision between trams and the severity of the collision event in accordance with Table 5: Hazard Severity Level and Table 6: Frequency of Occurrence of Hazard Events, respectively, and to record their results in the following Table 32 and Table 33.
- c. Once they completed this task they were asked to suggest mitigation measures to control the SPAD, repeat the qualitative assessment and record their results in new tables in the form of Table 32 and Table 33. The experts were also asked to present the assumptions on which they based their determination of the frequency and severity of the accident.
- d. Following the mitigation measures they were asked to reassess the likelihood and the severity of a collision between trams due to SPAD.

5.4.2.1.1.2 Questionnaire results - SPAD risk assessment before and after mitigation

a) Pre mitigation - questionnaire results

Table 32: Expert Judgement Likelihood before Mitigation

	Expert judgement		
	Scenario 1	Scenario 2	Scenario 3
Frequency			
Frequent			
Probable			B
Occasional	B, C, K	B, C, K	C, K
Remote	S	S	S
Improbable			
Incredible			

Table 33: Expert Judgement Severity Mitigation

Severity	Scenario 1	Scenario 2	Scenario 3
Catastrophic		B	B
Critical	C, K	C, K	C, k
Marginal	S, B	S	S
Negligible			

To evaluate the risk, the experts' assessments were combined on two risk matrices. The first matrix (Table 34) classifies the risk before the implementation of risk reduction measures and the second (Table 35) afterwards. The capital letters inside the matrix represent the names of the experts and their risk classifications of each scenario represented by the numbers next to the capital letters.

Table 34: SPAD Risk before Mitigation – Questionnaire Results

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable	B3			
	Occasional	B2	C (1,2,3) K (1,2,3)	B1	
	Remote			S(1,2,3)	
	Improbable				
	Incredible				
Intolerable Undesirable Tolerable Insignificant					

According to Table 34 the risk associated with Scenario 1 tends towards Undesirable while the other risks associated with Scenarios 2 and 3 are distributed between the intolerable and tolerable regions. All experts except for one recommended on ATP system or similar in addition to other means as set forth below:

Expert B: Speed supervision, train protection and warning system, driver retina scanning for microsleep and fatigue management of drivers

Expert S: Better positioning of the signals, synchronizing between the two signalling systems (RTSS and TSS) to avoided confusion of the driver, introducing an ATP system.

Expert K: Speed reduction to 10 km/h while passing over point machines, in order to avoid a tram collision following a SPAD occurrence, introducing an ATP system to avoid any SPAD.

Expert C: Operating rules and fines for drivers who induce SPAD, SPAD control system.

b) Post mitigation - questionnaire results

Table 35 describes the risk estimates following the implementation of mitigation measures. Accordingly, the risk associated with Scenarios 1 and 2 tends towards Insignificant. Regarding the risk associated with Scenario 3, some viewed it as still being Undesirable while others viewed it as Insignificant.

Table 35: SPAD Risk after Mitigation – Questionnaire Results

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable				
	Occasional				
	Remote	B3	C(1,2,3)		
	Improbable			K(1,2,3) S(1,2,3)	B(1,2)
	Incredible				
Intolerable Undesirable Tolerable Insignificant					

5.4.2.1.2 Phase B – workshop with the experts

a) Experts' qualitative assessment and assumptions

Following the introduction of the hazard and the risk assessment results (Table 35) by the facilitator, the experts were asked to present the assumptions underlying their assessments:

Expert C: Stated that the justification for the frequency was once the driver crosses a red signal there is still a possibility of a collision. From European experience, there is always a strict disciplinary process for any driver who has passed a red signal and it's an absolute no-no. Hence in his opinion the potential for a collision once SPAD occurs always exists; therefore, the frequency level is Occasional. The severity was determined as critical and not catastrophic based on his experience; however, following the discussion he noted that he did not consider the type of collision resulting from Scenario 2 where a tram hits the side of the other tram which may cause a fatality, hence he considered adjusting his assessment to catastrophic for Scenarios 2 and 3.

Expert S: The former CEO of the operator said that as there is no automatic system that can protect against SPADs and people tend to make mistakes once in a while, it should be assumed that it will happen; therefore, he set the likelihood as Remote for all scenarios. Regarding the severity he assessed it as marginal because the speed is very slow and it is assumed that the driver will reduce it even more, attempting to stop the tram; besides, the JLRT trams are designed to withhold a collision and most of the forces are absorbed within the tram itself. Injuries are more likely to happen as a result of the driver implementing a maximum service brake and creating more jerk. However, he cannot say for sure if there will be only minor injuries or also severe injuries, and in such a case the tendency is towards the worst case; therefore, his severity assessment was adjusted to critical for all three scenarios.

Expert K: The former safety manager of the JLRT operator said that he evaluated the frequency level as occasional since he assumes that if the rule that he set, that trams must reduce their speed to 10 km/h when approaching a point machine, will be revoked, then a collision is likely to occur several times in the system's lifecycle. He set the severity level to critical because he saw a collision between two trams in Dublin. They were traveling at 10 km/h when they collided and the damage to the tram was huge; however, there were no fatalities. Regarding

the mitigation measures, he recommended an ATP system since he now works as a safety manager for the tramway in Tel-Aviv where an ATP system is mandatory, and he understand better the importance of such system. Following the discussion Expert K did not adjust his assessment.

Expert B: Agreed with Expert C that the consequence does not matter, as once the train does SPAD there is the potential for a collision event to occur. Besides, the Jerusalem network is expanding with different lines and routes, multiple different rolling stocks and two additional depots; hence, an operational difficulty is to have drivers with similar or updated route knowledge of each line and curve and speed limits. So the likelihood is tends more towards Occasional for Scenario 2 in a wider network system. The likelihood of Scenario 3 is probable because the SPADing tram is now going across the points, and this is more complicated; it is at the end of the shift and the driver may be tired and might make more mistakes. Expert B was asked if he wanted to adjust any of his assessments to ‘Remote’ after hearing all other views. The answer was that he intends to retain his original assessment.

Table 36: SPAD Risk before Mitigation and after expert Discussion at the Workshop

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable	B3			
	Occasional	B2, C(2,3)	C (1) K (1,2,3)	B1	
	Remote		S(1,2,3)		
	Improbable				
	Incredible				
Intolerable Undesirable Tolerable Insignificant					

b) Post mitigation with ATP system as key system

For this scenario, some members of the group adjusted the frequency to insignificant. Expert C initially remained in the Undesirable area but stated that his post-mitigation assessment

was based solely on operational measures. However, if an ATP system is to be implemented he is willing to adjust his assessment from Remote to Improbable, hence the risk is Tolerable. Expert B said that for Scenario 3, due to underlying reasons such as fatigue etc. he will keep the frequency at Remote. The experts were asked why they adjusted their severity assessment from catastrophic to marginal and negligible. In this case there was a consensus that the speed will be reduced and hence the severity will be reduced.

In conclusion, it seems that except for Expert B whose risk assessment remains Undesirable for Scenario 3 (due to other underlying causes such as fatigue management, route knowledge, etc.) all experts adjusted the risk towards the Tolerable and Insignificant range. Hence the risk arising from Scenario 1 and 2, post-mitigation, is Tolerable in the worst case, but for Scenario 3 it remains Undesirable.

Table 37: SPAD Risk Post-mitigation after the Expert Discussion at the Workshop

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable				
	Occasional				
	Remote		B3		
	Improbable		C	S K	B 1, 2
	Incredible				

c) Summary and discussion of the expert judgement results

The emerging conclusion post-discussion on the frequency of the SPAD risk was that there is a difference of opinion, with some of the group tending to say the situation may happen occasionally and will lead to a collision whereas others tending to assess it as a Remote chance. As for the severity, it was a learning experience to understand the bias between the managerial viewpoint and the operational / systems safety viewpoint; this is reflected in what Expert C (the former CEO of the JLRT operator) said about the assessments he made

“managers need to move forward so they choose marginal severity or remote frequency”. This attitude is defined by Thomas R. Krause (Krause, 2008) as a cognitive bias that “can cause leaders to underestimate exposure risk and overestimate the capability of systems to mitigate hazards”. Scenarios 2 and 3 were assessed as intolerable by Expert B; his view of the relationship between fatigue and distraction is discussed in Naweed’s article (Naweed, Rose, Singh, & Kook, 2017) (Section 2.10). In contrast, his risk assessment also relied on the view of a wider JLRT network, whereas it was supposed to be based on the scenarios described at the defined geographical location. Therefore, the final results of the expert judgement exercise strengthen and validate the results of the quantitative safety risk model developed by the author. The risk is Undesirable and Not Acceptable and mitigation measures to reduce the residual risk of the SPAD are to be implemented. The post-mitigation assessment, with an ATP system in place and synchronisation of the two signalling systems as key risk mitigation measures, viewed the risk as having been reduced to the ALARP level; however, it was said that the risk should not be ignored and should continue to be monitored by the tram operator.

5.5 Adherence of the SPAD SRM to the Study Objectives and the Success Criteria

The purpose of this section is to examine whether the SPAD safety risk model complies with the study objectives and the success criteria defined in Section 1.4 and the model characteristics defined in Section 3.2.

- i. The SPAD SRM validates the hypothesis that it is possible to model and quantify the safety risk of SPAD using the existing techniques, FTA and ETA, and expert judgement qualitative risk assessment and evaluation (see Sections 5.2.2 and 5.4.2);
- ii. Comprehensiveness: the model enables the quantification of the annual collective risk associated with the hazard, SPAD, and determines the frequency and consequences associated with the hazard for any given control section (see Section 5.2.2);
- iii. Practicality: the model enables easy determination of the acceptability of the risk. Knowing the frequency of the hazard event and the consequences per event it shall be easy to determine the tolerability level and the acceptability of the risk using the risk matrices, Table 7 and Table 8, respectively (see Section 4.70);

- iv. The fact that the model is based on explicit risk assessment and evaluation enables the ALARP assessments as required by the study objectives, Section 1.4. This has been proven in the EJ model and it is also mentioned by RSSB (RSSB, 2014) that “the explicit risk estimation and evaluation principle is the only risk acceptance that explicitly invokes the ALARP principle”. Due the fact the SPAD risk was found to be Undesirable and in the worst case of the experts judgement as Intolerable, then applying an ATP system and synchronizing between the TSS and the RTSS as key mitigation measures will reduce the risk to ALARP (see Section 5.4.2.1.20);
- v. The SPAD model can allow assessment of the effect of technological change (ATP) on the risk, as required by the study objective in Section 4, and that is because the model is based on an explicit risk assessment. In the present case this is not required, because the assumption is that synchronization between the signalling systems and equipping the trams with an ATP system will prevent trams from reaching the conflict areas of the controlled sections when SPAD occurs; therefore, the assumption which is supported by the expert judgement is that the frequency level will drop to Improbable, meaning a collision event is unlikely to occur;
- vi. Accuracy: the SPAD model is an inductive model, based on an assessment of the potential risk of collision between trams. An assessment of potential risk does not make it possible to check the accuracy of the model because no collisions have occurred as a result of the SPADs. Therefore, the way to validate the results of the model was through expert judgement as detailed in Section 5.4.2. The expert judgement emphasised that the risk is Undesirable and at worst Intolerable (see Table 36); this result reinforces the risk assessment and evaluation made on the basis of the model. The results of the expert judgement and a discussion of results are presented in Section 5.4.2.1.20;
- vii. Usability: a safety manager or any other person can easily use the model. All that is required of him is to first estimate the mileage that the trams will cover in the following year and run Equation 30
- viii. Maintainability: maintaining the model requires knowledge in reliability and the use of FTA and ETA.

In light of the above, the SPAD model complies with the study objectives and the test criteria and provides a basis for continuous safety improvement and confidence that the JLRT system can operate safely.

6 Modelling the Safety Risk Associated with Overturning due to Excessive Speed on Curves on the Jerusalem Light Rail Transit System

6.1 Introduction

Overturning speed is defined as the speed at which a vehicle derails or overturns because reaction force by the track is insufficient to steer the train through a curve (National Academy of Sciences, 2012). The event of a tram overturning while negotiating a sharp curve is an accident that occurs mainly due to a driver disregarding a speed limit signal or restriction. The low rate of accidents of this type and, thus, of their serious consequences creates a challenge to quantifying the basic risk of such an event occurring; the paucity of historical data further impedes such calculations.

The safety risk model described in this section presents a method for modelling the risk of a tram overturning while accounting for the shortcomings of existing data. The model presumes that it is possible to model the potential risk on the basis of precursors indicating the risk of an accident occurring; in such a case the said precursor will be the number of events where a tram driver enters a sharp curve at a speed close to the threshold speed above which the tram may overturn. The probability will be that of the precursor, and the consequence will be based on similar events that have occurred elsewhere.

Between 2014 and 2016, there were no tram derailments or overturning events on the JLRT system, as a result of excessive speed on sharp curves. However, in view of the experience accumulated in the world, and the fact that there are locations on the JLRT line where the trams need to negotiate curves with a radius as sharp as 25 m, when running in city streets, it can be assumed that, in the longer run, a tram derailment or overturning may also occur in the JLRT system.

6.2 Overturning Speed

6.2.1 Cause of Overturning

The main cause of overturning of trams or trains, on sharp curves, is excessive speed. Table 38 provides an overview of some serious accidents, which occurred in recent years, showing the difference between the actual speed and the safely restricted speed. These accidents led to significant consequences including fatalities, severe injuries and serious damage to both the rolling stock and the infrastructure. Table 39 shows accidents on tramways where trams have overturned in the last three decades.

In their article, “Analysis of Train-Overturn Derailments Caused by Excessive Curving Speed” (Matsumoto, Michitsuji, & Tobita, 2016), the authors analysed the accidents described in Table 38 (items 2-5) and noted that the cause of the accidents is normally either driver delay in applying the brake on entry of the train into the curve or premature acceleration at the end of the curve. In the case of the Amagasaki derailment on West Japan Railway’s Fukuchiyama Line, the reason for the driver delaying the application of the brake was attributed to distraction of the driver’s attention from the driving task.

Table 38: Overview of Overturning Accidents (Matsumoto, Michitsuji, & Tobita, 2016)

Event No.	Accident	Rolling stock	Gauge (mm)	Curving radius (m)	Running speed (km/h)	Speed limit (km/h)
1	Croydon Tram (England)	Light rail	1435	30	73	20
2	Amagasaki (Fukuchiyama Line, Japan)	Commuter (EMUs)	1067	304	116	70
3	Santiago de Compostela high-speed train (Spain)	High speed	1668	380	153	80
4	Amtrak Philadelphia (USA)	(EL+PCs)	1435	437	163	80
5	NY Metro North Rail (USA)	Commuter (push-pull)	1435	291	131	48

Table 39: Accidents on Tramways in which Trams Have Overturned (RAIB, 2017)

Year	Location	Cause	Consequence
1993	Poznan, Poland	Overspeed on curve	5 fatalities, more than 60 injuries
1996	Kamianske, Ukraine	Runaway downhill due to brake failure subsequent impact with wall	34 fatalities, more than 100 injuries
2011	Rio de Janeiro, Brazil	Derailed on curve (heritage tram)	5 fatalities, at least 27 injuries
2013	Yuen Long, Hong Kong	Overspeed on curve	77 injuries
2014	Düsseldorf, Germany	Derailment at junction	Several injuries
2016	Croydon England	Overspeed on curve	7 fatalities and at least 61 injuries

6.2.2 The Sandilands Accident in Croydon, UK

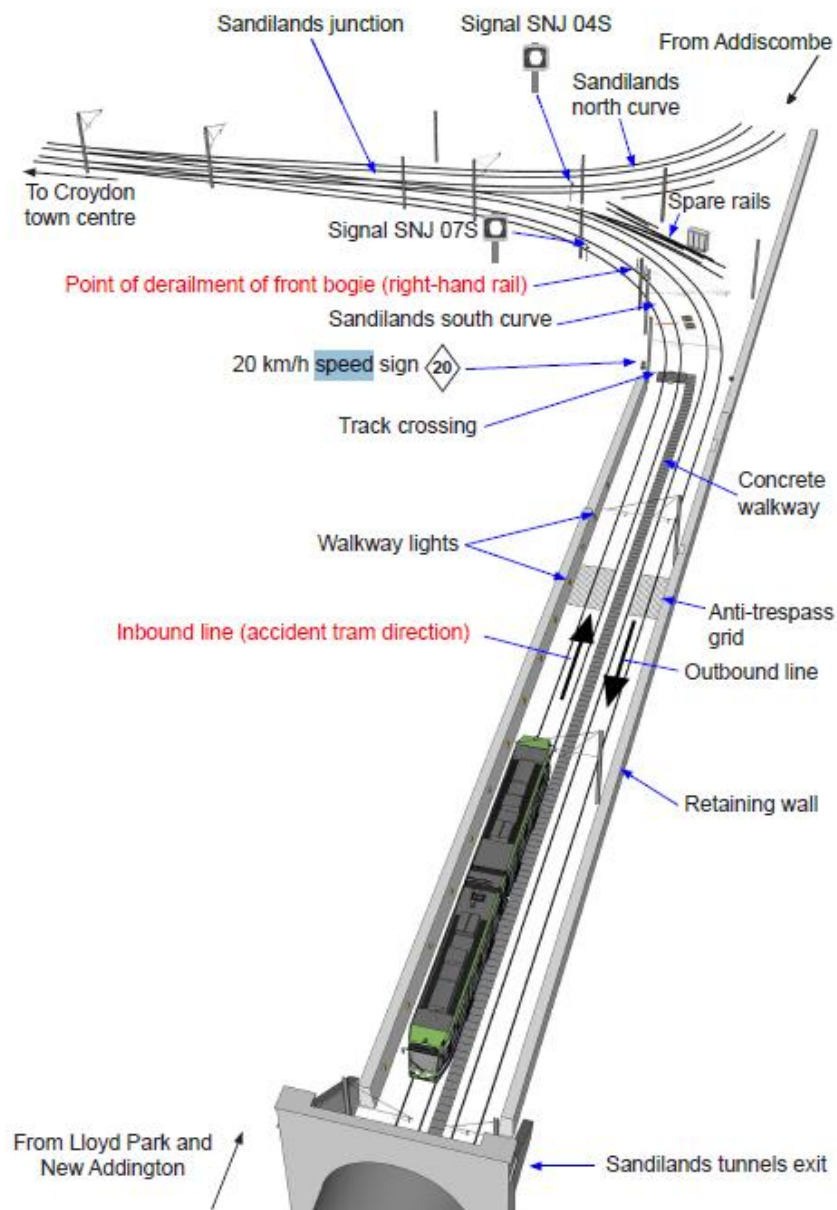


Figure 45: The Accident Site (RAIB, 2017)

The accident in Croydon, England (Figure 45) happened on 9 November 2016, around six o'clock in the morning. A tram approached the Sandilands south curve which has a radius of 30 m. "About 2.5 seconds before reaching a speed sign located at the start of the curve and denoting the start of a 20 km/h (12 mph) speed restriction, the tram's service brake was applied. The tram had slowed to approximately 73 km/h (45 mph) as it entered the curve and then travelled around part of this before overturning, sliding a short distance on its side and

then stopping close to the junction” (RAIB, 2017). The cause of the accident, according to the Rail Accident Investigation Branch (RAIB) is, “temporary loss of awareness of the driving task during a period of low workload, which possibly caused him to microsleep”.

To determine the circumstances under which derailment and/or overturning of the tram would have to be expected, a dynamic simulation of the tram approaching Sandilands south curve at various speeds was carried out by Bombardier Inc. The mass, centre of gravity and inertia of the tram were adjusted to account for the passenger loading. The track model was based on the design geometry in terms of alignment, curvature, gradient and cant, as described in the original construction drawings. The simulation demonstrated that the theoretical minimum speed at which a tram will overturn in Sandilands south curve in these conditions and with a friction coefficient of 0.2 is approximately 50 km/h.

The RAIB cross-checked the output of this simulation by carrying out a simple calculation to determine the overturning speed of a vehicle travelling around a 30-m-radius curve. This indicated an overturning speed of 49 km/h, comparable with the results of the simulation. Unfortunately, this simple calculation was not demonstrated in their report.

The main cause of accident indicated in the RAIB report, which aligns with Matsumoto's article and reinforces the author's risk model is:

“The tram did not slow down to a safe speed before entering Sandilands south curve because the driver did not apply sufficient braking”.

6.2.3 Effect of exceeding the centripetal Force provided by the Track

The overturning speed depends upon the height of the centre of gravity above the top of the rail (h) and the degree of lateral movement of the centre of gravity towards the high rail (National Academy of Sciences, 2012). When a tram is travelling on a curve, where the rails are at the same elevation, i.e., the plan of the track is horizontal, the combination of the reaction to the centripetal force (shown as centrifugal force ' F_c ' in Figure 46) and the weight of the tram ' W ' will yield a force ' F_r ' that does not coincide with the centre line of the track. In that case, the downward force on the outer rail is greater than the downward force on the

inner rail (Figure 46). As the velocity increases or the radius of the curve decreases, the resulting force 'Fr' moves further away from the centre line of the track. The tram is at risk of overturning (Figure 46) (Hook, 2017) If the resulting force 'Fr' approaches or crosses the outer rail, in this case the left hand rail.

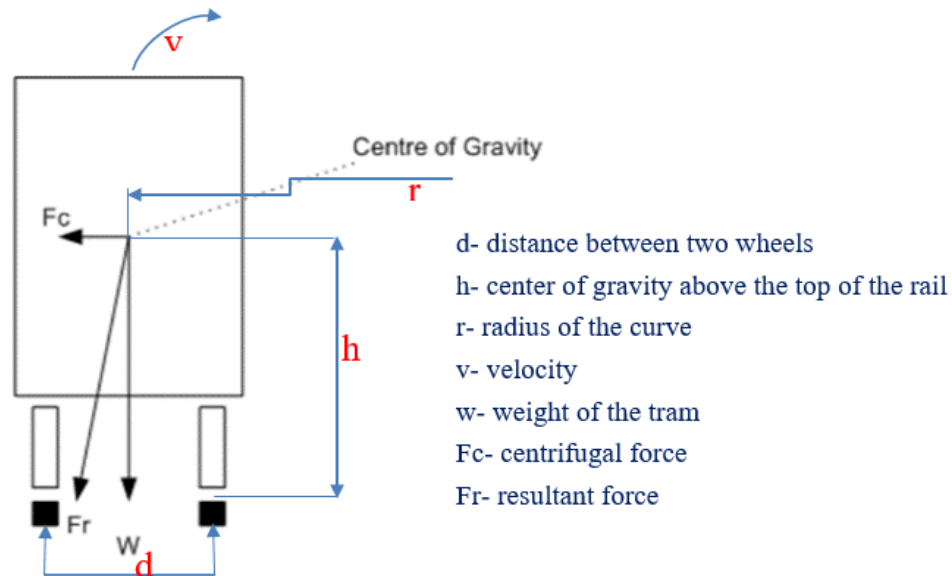


Figure 46: Forces when a Train rounds a Curve with the Rails at 0 Cant (Author, 2018)

6.3 Sharp Curves on the JLRT System

The JLRT line contains 89 curves, two of which are considered sharp curves with a radius of 25 m and 30 m as shown by the red arrows in Figure 47. However, the potential risk of a tram overturning as a result of excessive speed exists only in the curve with the radius of 25 m. This is because the speed allowed before entering this curve is 40 km/h, while the speed allowed within the curve is 15 km/h. Should the driver disregard the speed limit signal and continue at 40 km/h, the tram may overturn, as the theoretical speed threshold at which a tram can overturn on a 25-m curve without super-elevation (cant) is approximately 40 km/h (as detailed below in Section 6.4).

The 30-m curve is the one that connects the Depot Access to the main line and, therefore, there is a speed restriction of 15 km/h before the curve, even though the theoretical maximum speed is 30 km/h, and 15 km/h within the curve, as shown in Figure 47.

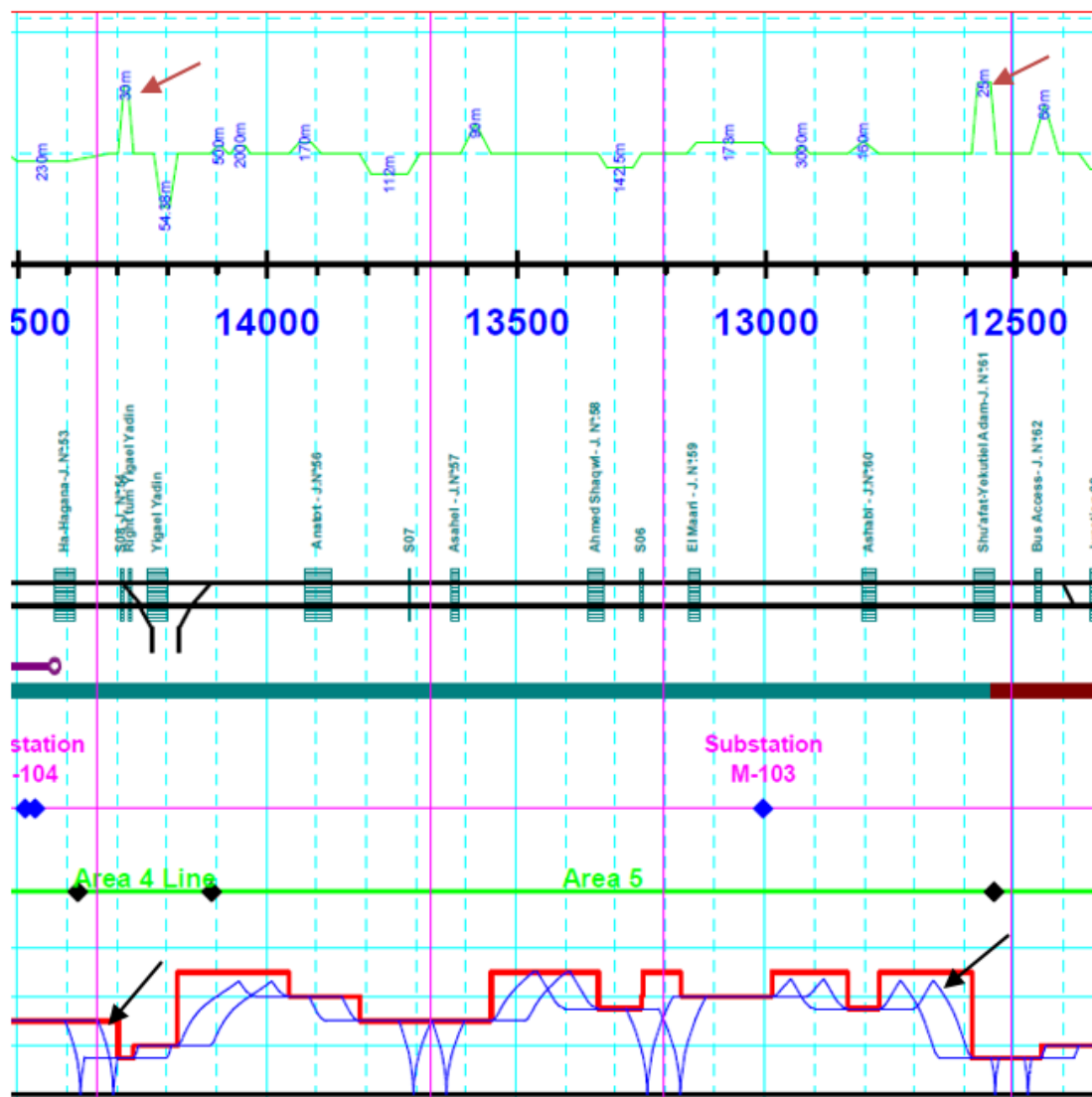


Figure 47: Sharp Curves and Allowable Speed along the JLRT Lines (ALSTOM, 2008b)

6.4 Risk Modelling and Quantification

6.4.1 Potential for Overturning of a Tram on a Sharp Curve

This risk quantification is related to the 25-m-radius curve described in Section 6.3. The curve comprises three main sections (Figure 48), the transition curves and the circular curve. The allowable speed along the straight section up to the following transition section is 40 km/h, as shown on the sign marked by the red circle in Figure 49.

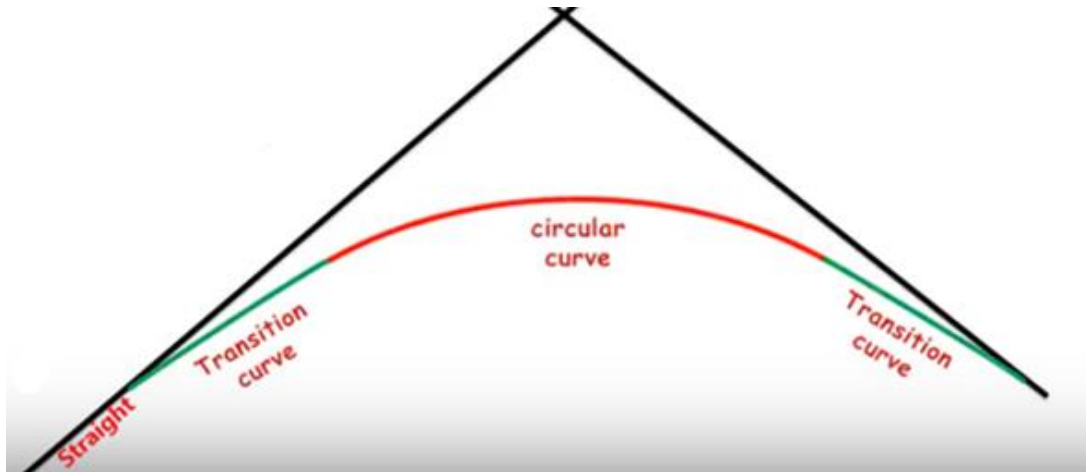


Figure 48: Curve with 25-m Radius (Khan, 2018)



Figure 49: Allowable Speed along the straight Line (Author, 2018)

The allowable speed on the circular curve is 15 km/h, as shown in the red circle in Figure 50. That is, the driver must reduce the speed from 40 km/h before the tram reaches the circular curve. The driver must start reducing speed as soon as he enters the transition curve.

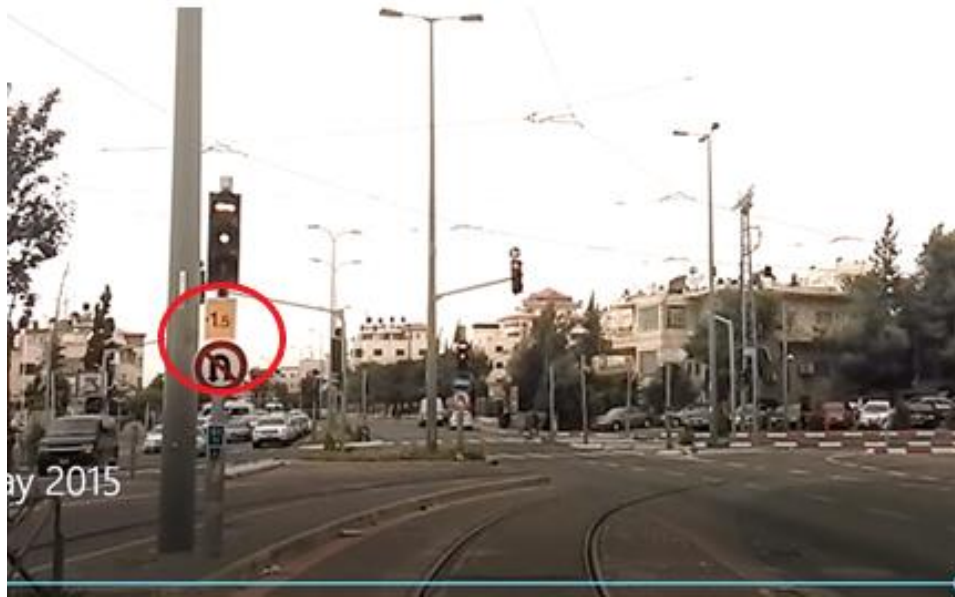


Figure 50: Allowable Speed along the circular Curve (Author, 2018)

The theoretical minimum speed at which a tram may overturn on the circular curve where the rails are at the same elevation (0 cant) and the plan of the track is horizontal is described by Equation 31:

$$V = \sqrt{dgr/2h}$$

Equation 31: Overturning Speed

where: d , r , and h are as described in Figure 46

If: $d = 1500\text{mm}$ $g = 9.81\text{ m/s}^2$, $r = 25\text{m}$ and $h \approx 1.5\text{ m}$

then: the overturning speed is: $11\text{ m/s} \approx 40\text{ km/h}$

The precursors indicating the risk of overturning of a tram in the circular curve will be the number of events in which a tram approaches the entry of the circular curve at a speed close to the overturning speed of 40 km/h. This reflects the potential risk of overturning.

6.4.2 Probability of the Potential Hazard / Precursor

To calculate the probability of the precursor, the author examined the tram speed for a sample of 814 trips. The speed measurement was made at the transition curve, near the entrance to the circular curve. The speed measurements were taken from the tachometers which are

installed in the trams. The speed measurement results, which were distilled from the recorded tachometer readings, are shown in Appendix D.

Tram speed	11	13	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
The number of times the tram traveled at that speed	1	1	2	3	5	8	5	18	30	45	82	126	127	120	95	54	37	32	12	3	3	1

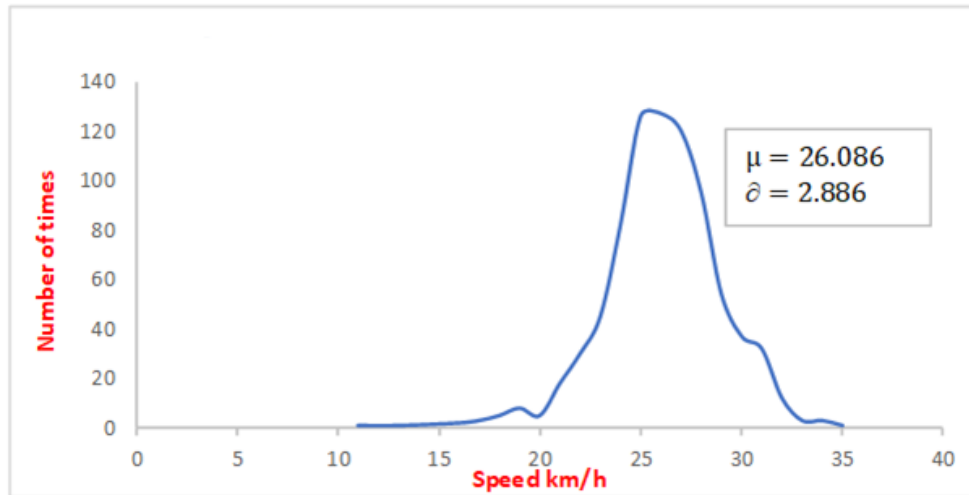


Figure 51: Speed Distribution at the Entry to the Circular Curve (Author, 2018)

The sample follows the normal distribution. It was found that the drivers reduce speed on the transition curve when approaching the circular curve. The speed distribution there is a normal distribution with a mean of 26.086 km/h and a standard deviation of 2.886 km/h (Figure 51).

The probability that the tram will enter the 25-m curve at a speed of 40 km/h or more can be calculated using the excel function NORM.DIST which is based on the Z-score function (Equation 9). Therefore, knowing the mean and standard deviation, the probability is (Equation 32):

$$P(v \geq 40) = 1 - \text{NORM.DIST}(40, 26.086, 2.886, \text{TRUE}) = 7.135 \times 10^{-7}$$

Equation 32: The Probability of Occurrence of a Speed of 40 km/h

The probability of 7.135×10^{-7} represents a frequency of occurrence of one theoretical event per 1,401,610 roundtrips, where the tram driver may be expected to approach the circular curve at a speed of 40 km/h at which a tram may overturn.

In terms of tram-km, this represents a frequency of one event per 38,684,439 km, because a tram reaches this curve once in every 27.6 km and this is actually the length of one roundtrip. Knowing that the annual tram-km is 1,302,541, the frequency would be 1 event per 29.7 years, or, a frequency of 1 event per 1,968,962 operation hours (based on 66,295 hours per year).

6.4.3 Hypothesis Test for the Proportion

The aim of the hypothesis test is to validate the calculated probability of a potential overturning of a tram in 25m curve in the JLRT system.

6.4.3.1 *The global probability of overturning of a tram*

In order to perform a hypothesis test for the proportion, the global probability of overturning of a tram should first be known, i.e., the probability of the population, denoted as P_0 . However, this statistic figure is not available; therefore, the global universe will be reduced to the tramway systems in the UK, for which the author received data on the mileage the trams accumulated since year 1992 (see Appendix H and the summary in Table 40).

Table 40: Accumulated Mileage of the Tramways in the UK

Tram system	London tram-link	Nottingham Express Transit	Midland Metro	Sheffield Supertram	Manchester Metrolink	Edinburgh Trams
Years	2001-2020	2004-2020	1999-2020	1994-2020	1992-2020	2014-2020
Million, tram-km	54.4	27.4	35.8	62.1	154.9	7.4
<i>Total tram-km = 342,000,000</i>						

The other statistical data required are the number of tram accidents in which trams overturned. This was obtained from the RAIB report (RAIB, 2017); accordingly, between 1983 and 2020 there were no overturning accidents other than the accident in Croydon. RAIB identified an accident in 1953 in Glasgow and two accidents in 1934: one in Liverpool and the other in Eltham. These accidents will not be counted in the probability calculation as the distance travelled is not available for these years.

Thus:

P_0 (Overturning of a tram in the UK tramway population) = $1/342,000,000 = 2.924 * 10^{-9}$

6.4.3.2 Sample probability

According to Section 6.4.2 the estimated frequency of overturning of a tram in the JLRT system is 1 event per 38,684,439 km, so the sample probability is:

$$\hat{p} = 1/38,684,439 = 2.585 * 10^{-8}$$

6.4.3.3 Sample size

The sample size n is equal to 38,684,439 as the first accident of overturning was estimated to be after 38,684,439 “trial” (trams-km).

$$n = 38,684,439 \text{ km}$$

6.4.3.4 Hypothesis test

$$H_0: P_0 = 2.924 * 10^{-9}$$

$$H_1: P_1 > 2.942 * 10^{-9} \text{ (As } \hat{p} \text{ is greater than the global probability } P_0)$$

$$\alpha = 0.05$$

$$Z_{\hat{p}} = \frac{\hat{p} - P_0}{\sqrt{\frac{P_0 * (1 - P_0)}{n}}}$$

Equation 33: Z score

$$Z_{\hat{p}} = \frac{2.585 * 10^{-8} - 2.924 * 10^{-9}}{\sqrt{\frac{2.924 * 10^{-9} * (1 - 2.924 * 10^{-9})}{38,684,439}}} = 2.639273$$

Look up 2.639273 in the z table = 0.995845

$$P \text{ Value} = 1 - 0.995845 = 0.004155$$

$$P \text{ Value} < \alpha$$

6.4.3.5 Conclusion

The null hypothesis is rejected and the alternative hypothesis is accepted. In other words, it can be said that the probability of an overturning of a tram in a sharp curve is greater than 2.942×10^{-9} and might be the same or close to the calculated probability shown in section 6.4.2.

6.4.4 Potential Consequences

The calculation of the potential consequences will be based on the consequences of the Croydon event, in which 7 passengers were killed, 19 were seriously injured and 42 suffered minor injuries, only one was reported as not having suffered an injury. The driver suffered minor injuries (RAIB, 2017) .

The aggregate amount of safety harm in terms of FWI, assuming that the minor injuries are class 1, is:

$$FWI = 7 + [(42 + 1) * 0.005 + (19 * 0.1)] = 9.115$$

The JLRT trams are also articulated trams, like the South London Tramlink vehicles. The average number of passengers travelling in each tram and passing the 25-m-radius curve is distributed as follows: 40 passengers early in the morning 05:30-07:00, 70 passengers during most of the day, and 40 passengers at night 21:00-24:00.

The potential consequences, if an overturning event were to occur on the JLRT system, can be estimated by scaling the consequences of the Croydon event according to the speed and the number of passengers on the tram, taking into account the maximum number of passengers traveling in the tram:

$$FWI_{Jerusalem} = \left[\frac{40_{JRkph}}{73_{CYkph}} \times \frac{(70_{JR-pax} + 1_{JR-driver})}{(69_{CY-pax} + 1_{CY-driver})} \right] * 9.115 = 5.065$$

where:

JR: Jerusalem LRT

CY: Croydon, and;

pax: passengers

Therefore: In a situation where the JLRT tram is travelling at a speed of 40 km/h on the 25-m curve, the estimated potential consequences would be 5.065 FWI per event of overturning.

6.4.5 The JLRT Overturning Safety Risk Model

Let:

P : probability of potential occurrence of a overturning event on a 25 – m curve

C : potential consequences once the overturning occurs

S_j : mileage accumulated by the tram fleet per year

Then:

$$\text{Annual CR} = S_j * P * C$$

Equation 34: Annual CR due to Overturning of a Tram

And:

$$\text{Annual CR} = S_j * 1.31 * 10^{-7}$$

Equation 35: Overturning Risk at JLRT, Model Equation

$$\text{Annual CR} = 1,302,541 \times 2.585 * 10^{-8} \times 5.065 = \underline{0.17 \text{ FWI per Year}}$$

The overturning safety risk model (Equation 34 and Equation 35) clearly shows again, as in the previous risk models, the dependence between the exposure and the risk, which means that the more the trams travel, the higher the risk of an overturning incident.

6.5 Risk Evaluation

6.5.1 Risk Evaluation Based on the Results of the Risk Modelling

The overturning risk evaluation and acceptance will be made according to the process described in Chapter 3, Section 3.2.1.

6.5.1.1 Severity level

The potential consequence, 5.065 FWI per event, is considered a catastrophic level according to Table 5: Hazard Severity Level.

6.5.1.2 Frequency level

According to Section 6.4.2, the frequency of overturning is 1 occurrence of a hazard event per 1,968,962 operation hours, which represents a relative frequency of 5.079×10^{-6} per hour. Therefore, in accordance with Table 6: Frequency of Occurrence of Hazard Events, the frequency level can be classified as remote.

6.5.1.3 Risk acceptance

- a) Using the risk matrix (Table 7), the combination of the above severity and frequency indicates that the risk is Undesirable.
- b) According to Table 8, the risk shall only be accepted with the agreement of the State/JTMT.
- c) If we consider the overturning of tram as an MMI failure, then according to the criterion defined by the ORR CSM (ORR, 2018) (see Section 2.3.3.3), if the frequency of the failure is greater than 10^{-7} per operation hour and the failure has a credible potential to lead directly to a critical accident, i.e., an accident that has an adverse outcome on a small number of people and results in at least one fatality, the risk is Not Acceptable and it needs to be further reduced. In this case the frequency is greater than 10^{-7} per operation hour and failure has the potential to lead to a catastrophic accident; therefore, the risk is Not Acceptable and must be reduced further.

6.5.1.4 Risk mitigation measures

As in the UK, the State, represented by JTMT, has decided to implement a speed supervision and enforcement system to mitigate the risk of SPAD and the risks that arise from excessive speed, including overturning of trams on a sharp curve. This was a safety requirement in the recent tender, which stipulated that the current and new fleets should be equipped with this type of system; see Appendix I. The decision is also in line with the expert judgement, described in Section 6.5.2.

6.5.2 Risk Assessment and Evaluation Using Expert Judgement

6.5.2.1 General process description

6.5.2.1.1 Introduction

The expert judgement process is detailed in Chapter 3, Section 3.2.5. The experts were asked to fill in a questionnaire based on their experience. A workshop was then held to understand some of the differences of opinion and understand their underlying assumptions. The answers were combined in risk matrices which are described in the following sections.

6.5.2.1.2 Phase A – questions and results

The experts were asked to qualitatively assess the likelihood and severity of the overturning of a tram on a 25 m curve in accordance with the matrices of hazard frequency (Table 6) and hazard severity (Table 7). Following their assessment, the experts were asked to suggest mitigation measures to reduce the risk and to then reassess the frequency and severity of the risk following implementation of the mitigation measures.

a) Pre mitigation - questionnaire results

To evaluate the risk, the experts' answers were combined on two risk matrices. The first matrix (Table 41) classifies the risk before the implementation (pre-mitigation) of risk reduction measures and the second (Table 42) classifies the risk after implementation (post-mitigation). The capital letters inside the matrix represent the names of the experts and their risk classifications.

Table 41: Overturning Risk before Mitigation – Questionnaire Results

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable	B			
	Occasional				
	Remote	C	K		
	Improbable	S			
	Incredible				
Intolerable Undesirable Tolerable Insignificant					

According to Table 41, the risk assessment pre-mitigation tends towards Undesirable, while the worst case is Intolerable. All experts except for one recommended an ATP or similar system in addition to other means as set forth below. Expert S, who classified the risk as tolerable, was satisfied with a system that only warns the driver that he or she is exceeding the speed limit.

Expert B: Speed supervision system; driver fatigue management and retina scanning technologies.

Expert S: More visible signage, periodical driver control to identify trends in behaviour and electronic speed measurement and alarms for the driver (not ATP).

Expert K: ATP system, adequate training and relocation of the 15 km/h speed sign.

Expert C: Speed supervision and enforcement system and fining drivers who drive at excessive speeds.

b) Post mitigation - questionnaire results

The risk assessment following the implementation of mitigation measures is described in Table 42. Accordingly, the risk tends towards Insignificant while the worst case is tolerable. It can be seen that the experts thought that the mitigation measures will reduce the likelihood of the risk up to the level of Incredible. As for the severity level there was no consensus; Expert C, who did not change the severity level, asserted that “Mitigation measure does not impact the severity of the risk”.

Table 42: Overturning Risk Post-mitigation – Questionnaire Results

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable				
	Occasional				
	Remote				
	Improbable	C		K	B
	Incredible	S			
Intolerable Undesirable Tolerable Insignificant					

6.5.2.1.3 Phase B – workshop with the experts

a) Experts' qualitative assessment and assumptions

Following the introduction of the hazard and the risk assessment results (Table 41) by the facilitator, the experts were asked to present the underlying assumptions of their assessments:

Expert S: The former CEO of the JLRT operator maintained his view that knowing the current driver complement, it seems unlikely that anyone will come close to the overturning speed; moreover, the trams are equipped with a dead-man device, which in the case of microsleep (as appears to have occurred in Croydon) will stop the tram ahead of the circular curve and thus the hazard occurrence is Improbable.

Expert B: The most pessimistic contributor, who assumed that there will be more 25 m curves in the future network; therefore, it is probable that such an event will happen. When he considered that there will be no further 25 m curves he changed the likelihood to Remote.

Expert C: said we cannot base our decisions solely on the experience gained in Jerusalem and must address what is happening in the world; therefore, we (he and his safety manager) have determined the likelihood to be Remote.

Expert K: the former safety manager of the operator said that he knows the JLRT drivers and to his best knowledge they slow down before entering the particular curve; however, driver mistake or driver fatigue may happen, so an overturning event is likely to occur sometime in the system's lifecycle, and thus the likelihood is Remote. He also noted that, if the event does occur the outcome will be catastrophic, so he changed his opinion on the severity level from Critical to Catastrophic.

Table 43: Overturning Risk before Mitigation and after the Expert Discussion at the Workshop

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable				
	Occasional				
	Remote	C, B, K			
	Improbable	S			
	Incredible				

Intolerable Undesirable Tolerable Insignificant

Table 44: Overturning Risk with Mitigation after the Discussion at the Workshop

Frequency		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent				
	Probable				
	Occasional				
	Remote				
	Improbable	C, S,B		K	
	Incredible				

b) Summary and discussion of the expert judgement results

It was noted that there was a general predisposition for Expert S and Expert K to assess the risk as lower than the other experts (see Table 41) due to their knowledge and experience and belief that the drivers and the procedures in place will tend to reduce the opportunity for human error. Experts B and C, with a more systems or safety perspective, took a worst-case viewpoint, thus estimating the risk to be higher (see Table 41). It can then be said that Experts S and K partly based their estimation on performance to date on the Jerusalem Red Line,

whereas the systems and safety experts took a wider viewpoint, anticipating changes in staff and operating procedures as the tram system expands. During this session Expert K realized that the consequences may not just be critical but possibly catastrophic, while Expert B realized that in an expanded network there will be no additional 25 m curves and thus reduced the likelihood of the hazard occurrence to Remote. However, Experts S and C did not change their assessment, maintaining that the risk is Undesirable; more experts supported this judgement.

In light of the above, the final pre-mitigation results and discussions (Table 43) of the expert judgement exercise strengthen and validate the results of the quantitative safety risk model developed by the author. The likelihood and the severity determined by the majority of the experts is Remote and Catastrophic, respectively, the same as the results of the quantitative model. Therefore, the risk must be deemed to be Undesirable and Not Acceptable and mitigation measures to reduce the residual risk of overturning are to be implemented.

Regarding speed limitation post-mitigation (Table 44), some members of the group were biased towards an Improbable or Negligible likelihood, while others tended towards Improbable, particularly in the degraded mode. In terms of severity, there was a consensus that the risk does not change if the tram overturns, and the consequence is Catastrophic.

The general outcome post-mitigation is that the risk could still be Tolerable, but not Negligible, and there are still some measures that State needs to employ. And the questions are: Could the system fail? How often will the degraded mode occur? What are the circumstances in which the system can avoid or get around it? The frequency will obviously depend on a number of these issues. Hence, we can say that if we have measures in place to control these extraneous factors the State can accept the risk as Tolerable.

6.6 Adherence of the Overturning SRM to the Study Objectives and the Model Success Criteria

The purpose of this section is to examine whether the overturning safety risk model complies with the study objectives and success criteria defined in Section 1.4 and the model characteristics defined in Section 3.2.

- i. The Overturning SRM validates the hypothesis that it is possible to model and quantify the safety risk of SPAD using existing statistical models and qualitative risk assessment and evaluation by expert judgement (see Sections 6.4 and 6.5.2);
- ii. Comprehensiveness: the model enables quantification of the annual collective risk associated with the hazard of overturning and determines the frequency and the consequences associated with the hazards (see Sections 5.2.26.4.1, 6.4.4 and 6.4.5);
- iii. Practicality: the model enables easy determination of the acceptability of the risk. Knowing the frequency of the hazard event and the consequences per event it will be easy to determine the tolerability level and the acceptability of the risk using the risk matrices, Table 7 and Table 8, respectively (see Section 6.5.1);
- iv. The fact that the model is based on explicit risk assessment and evaluation enables the ALARP assessments as required by the study objectives, Section 1.4. It has been proven in the EJ model and is also mention by RSSB (RSSB, 2014) that “the ‘explicit risk estimation and evaluation principle is the only risk acceptance that explicitly invokes the ALARP principle”. Since the overturning risk was found to be Undesirable in the worst case of the expert judgement, installing an ATP system as a key mitigation measure will reduce the risk ALARP (see Section 6.5.2.1.3);
- v. The overturning model can allow the assessment of the effect of technological change (ATP) on the risk as required by the study objectives, Section 4, because the model is based on an explicit risk assessment. In the present case this is not required, because the assumption is that equipping the trams with an ATP system will reduce the risk ALARP; therefore, the assumption, which is supported by the expert judgement, is that the risk is tolerable, subject to implementation of additional control measures;
- vi. Accuracy: similar to the SPAD model, the overturning model is also an inductive model, based on an assessment of the potential risk of overturning events. An assessment of the potential risk does not make it possible to check the accuracy of the model because, to date, no overturning of a tram has occurred as a result of overspeeding. Therefore, the way to validate the results of the model was through expert judgement, as detailed in Section 6.5.2. The expert judgement emphasised that the risk is Undesirable, and at worst, Intolerable (see Table 43); this result reinforces and

- validates the risk assessment and evaluation made with the model. The results of the expert judgement and discussion of the results are presented in Section 6.5.2.1.3b);
- vii. Usability: a safety manager or any other person can easily use the model. All that is required of him is to first estimate the mileage that the trams will cover in the following year and run Equation 35
 - viii. Maintainability: maintaining the model requires knowledge in reliability and statistics.

The overturning model complies with the study objectives and the test criteria and provides a basis for continuous safety improvement and confidence that the JLRT system operates safely.

7 Conclusions and Recommendations

7.1 Conclusions

- a. The safety risk models developed by the author of this study meet the success criteria defined in the study objectives, since they enable an understanding of the nature of the safety risks on the JLRT system and provide relevant risk information and risk profiles. They support the assessment of the impact of possible risk mitigation. Therefore, the hypothesis put forward at the start of this study has been shown to be true, i.e., it is possible to create a safety risk model for the JLRT system which operates in line-of-sight operation mode using the same techniques, models and methodologies that are used in the mainline railway sector. Moreover, it is possible to model and quantify rare events with sparse data by modelling the precursors that suggest the likelihood of a serious accident occurring in the future.
- b. The author of this study presents an original and pragmatic approach for modelling the risk of SPADs and the risk of overturning of trams on sharp curves that exist in the JLRT system and are considered rare events with sparse data. The paradigm presumes that it is possible to model the potential risk on the basis of precursors indicating the risk of an accident occurring. The SPAD risk model assesses the potential risk by evaluating the occurrence of conflicts between trams in controlled sections. Such conflicts can be considered precursors, suggesting the likelihood of a serious accident occurring in the future. In this way the model overcomes the lack of data on actual accidents. The risk model of overturning of a tram on a sharp curve due to excessive speed can also be considered a precursor model. In this case, the precursor indicating the risk of overturning is the number of events where trams approach a particular circular curve at an excessive speed, close to the overturning speed.
- c. The advantage of the quantitative risk models developed by the author of this study over the qualitative risk assessment done by expert judgement is that they provide a non-subjective understanding of the risks by assigning numerical values to their parameters, whereas qualitative risk assessments involve educated guesses that tend to use intuitive strategies that are not necessarily rational or optimal (Anthony

O'Hagan, 2006), as we witnessed in the expert workshop. Yet, when major decisions need to be taken in the presence of significant uncertainty, expert judgement is essential to minimize the uncertainty (Leung & Verga, 2007).

- d. The residual risk of SPADs is Not Acceptable. The experts judged that the post-mitigation outcome represented a reduction of the risk to ALARP, thanks to including an ATP system and synchronizing the two signalling systems, TSS and RTSS, as key risk mitigation measures. Nevertheless, the risk should not be ignored, and it should continue to be monitored by the tram operator, as tram driving is affected by specific factors such as fatigue and shift work. Fatigue and distraction are a combination that may increase the risk of accident; 10-23% of the causes of vehicle collisions are associated with driver distraction and this figure can also be applied to tram collisions (Naweed, Rose, Singh, & Kook, 2017).
- e. The residual risk of overturning of a tram on a sharp curve due to overspeeding is Unacceptable. The experts judged that the post-mitigation outcome maintained the risk a Tolerable, but not Negligible level and there were still some measures that the State needs to employ. The questions that remain are: Could the system fail? How often will the degraded mode occur? What are the circumstances in which the system can avoid or get around the hazard? The frequency will obviously depend on a number of these issues. Hence, we can say that, if we have measures in place to control these extraneous factors, the State can accept the risk as Tolerable.
- f. The residual risk of EJ is Unacceptable. The Experts judgment post mitigation outcome, after limiting the jerk rate by reducing the severity of the emergency brake applied by the safety loop, was that the risk was not reduced to ALARP. This was expected because the contribution of the automatically applied emergency braking to the total consequences is approximately 28%. Therefore, the State must consider additional mitigation measures to reduce the risk to ALARP.
- g. The key parameter of all the models developed by the author of this study is the exposure. The safety risk models clearly demonstrate the dependence between the exposure and the risk, which means that the further the trams travel, the higher the

- risk. The exposure is the product of the service/operation plan, meaning that increasing/improving the service to the passengers comes at the cost of increased risk.
- h. All the risk models developed by the author of this study are based on explicit risk assessment and evaluation and, as such, they enable the ALARP assessment and the assessment of the effect of technological change on the risk, as demonstrated in the EJ model. This is in line with RSSB's view, who noted that "The 'explicit risk estimation and evaluation' principle is the only risk acceptance principle that explicitly invokes the ALARP principle" (RSSB, 2014).
 - i. Evans' assertion (Evans, 2002) was shown by the author to be correct, in the current thesis, that is: "for systems in which accidents are frequent, the accepted method of estimating risk is by statistical analysis of past accident data, and for systems in which accidents are very rare, but may potentially be very serious, accident data are so sparse that direct statistical analysis of accident data is of little help in estimating the risk". The author had sufficient data on accidents related to EJ to model the risk using the Poisson distribution, while modelling the risk of collision due to SPAD could not be accomplished using statistical models because past accident data were limited.
 - j. As highlighted in the authors literature review, in Israel there is no explicit legislation for the tramway sector or any explicit law that defines safety risk targets and tolerability criteria. Moreover, there is no uniform governmental guidance on common safety methods for risk evaluation and risk acceptance. The State-owned entities are the ones who generate safety risk acceptance criteria. These criteria are very clear when referring to intolerable and insignificant risks classified by the risk matrix, but the risk matrix has very wide bands of acceptability, and many risks may fall into the Undesirable and Tolerable categories, as demonstrated in this study. For these risks there is no clear path to measure their acceptability. Hence, the author recommends that the State must determine explicit safety acceptance criteria for the tramway sector, including common safety methods for risk evaluation and risk acceptance.

7.2 Recommendations

- a. The EJ model based on the Poisson distribution assumes that EB events are independent and occur randomly at a constant rate, λ , per unit of activity (tram-km). The model also assumes that the mean fatalities per year, μ , has no trend over time. However, as noted by Evans (Evans A. W., 2002), it may be unreasonable to assume that λ and μ are static over long periods of time, so it is recommended to extend the EJ model to allow these parameters to change over time, in accordance with Equation 24 and Equation 25.
- b. It is recommended to further develop the EJ model on the basis of the Negative Binomial distribution (see Section 4.6) in order to identify factors that may increase the frequency of EB events.
- c. Since there is no explicit legislation for the tramway sector in Israel, nor safety risk targets and tolerability criteria or any uniform governmental guidance on common safety methods for risk evaluation and risk acceptance, it is recommended that such guidance and criteria be developed at a national level. This will support the tramway sector, which has gained momentum in recent years in Israel. For the time being, it is recommended to adopt the EU criteria identified in this study.
- d. Finally, it is recommended to model and quantify the risk resulting from the other hazards inherent in the operations of the JLRT systems and create a comprehensive Safety Risk Model (SRM) which will enhance the safety of the JLRT network and perhaps other similar tramway systems.

Appendix A – Data Table Representing the FTA

Fault Tree Notation	Fault Tree Sequences number	Top Hazard Event	Cause	Description	2014				2015				2016				Total				Probability of EB occurrence per Train-km
					Events	Events with injuries	Light injuries	Injuries who needed first aid	Events	Events with injuries	Light injuries	Injuries who needed first aid	Events	Events with injuries	Light injuries	Injuries who needed first aid	Events	Events with injuries	Light injuries	Injuries who needed first aid	
Top Event	1	EB		Emergency Braking																	
Intermediate Event Level 1	1.1		Operational Failure																		
Intermediate Event Level 2	1.1.1		Driver behavior																		
Basic Event (Best)	1.1.1.1			Driver failure in using the emergency brake					7				20				27	0	0	0	7.091E-06
Basic Event	1.1.1.2			Driver failure in using the dead man device	1												1	0	0	0	2.626E-07
Basic Event	1.1.1.3			Driver missed stopping point and braked emergency	4	1		1									4	1	0	1	1.051E-06
Basic Event	1.1.1.4			SPAD									3				3	0	0	0	7.879E-07
Intermediate Event Level 2	1.1.2		Passenger behavior														0	0	0	0	0.000E+00
Basic Event	1.1.2.1			Doors failure due to a passenger vandalizing a door													0	0	0	0	0.000E+00
Basic Event	1.1.2.2			Proper use of an emergency handle													0	0	0	0	0.000E+00
Basic Event	1.1.2.3			Emergency Handle misuse	20				8								28	0	0	0	7.354E-06
Intermediate Event Level 2	1.2.3		OCC behavior														0	0	0	0	0.000E+00
Basic Event	1.2.3.1			Train moved without authorization (insufficient coordination)													0	0	0	0	0.000E+00
Basic Event	1.2.3.2			OCC Operator wrong instruction to the wrong train (wrong instructions in degraded mode)													0	0	0	0	0.000E+00
Basic Event	1.2.4		Door Trap														0	0	0	0	0.000E+00
Basic Event	1.2.4.1			Passenger trapped													0	0	0	0	0.000E+00
Basic Event	1.2.4.2			Object trapped in door	1				1								2	0	0	0	5.253E-07
Intermediate Event Level 1	1.2		Traffic Interruption														0	0	0	0	0.000E+00
Intermediate Event Level 2	1.2.1		Bicycle rider behavior														0	0	0	0	0.000E+00
Basic Event	1.2.1.1			Cyclist rides on the track	1	1		5	1				3				5	1	0	5	1.313E-06
Basic Event	1.2.1.2			Cyclist entered the swept path unexpectedly					12	1		4					12	1	0	4	3.152E-06
Basic Event	1.2.1.3			Red light violation by Cyclist									9				9	0	0	0	2.364E-06
Basic Event	1.2.1.4			cyclist crossed the track unexpectedly	10												10	0	0	0	2.626E-06
Basic Event	1.2.1.4			Cyclist fell on the tracks					4	1		1	2				6	1	0	1	1.576E-06
Intermediate Event Level 2	1.2.2		Car driver behavior														0	0	0	0	0.000E+00
Basic Event	1.2.2.1			Car stopped on the tracks					6				1				7	0	0	0	1.836E-06
Basic Event	1.2.2.2			Car accident ahead					1								1	0	0	0	2.626E-07
Basic Event	1.2.2.3			Car driving on the track					2				1				3	0	0	0	7.879E-07
Basic Event	1.2.2.4			Non permitted U-turn by Car					5								5	0	0	0	1.313E-06
Basic Event	1.2.2.5			Non-permitted right turn by Car									1				1	0	0	0	2.626E-07
Basic Event	1.2.2.6			Non-permitted left turn by Car									4	2	4	1	4	2	4	1	1.051E-06
Basic Event	1.2.2.6			Car crossed the track unexpectedly	19	1	2										19	1	2	0	4.990E-06
Basic Event	1.2.2.7			Car entered swept path unexpectedly					47					24	1	1	71	1	0	1	1.865E-05
Basic Event	1.2.3		Bus driver behavior														156	9	5	7	4.097E-05
Basic Event	1.2.3.1			Red light violation by bus	30	1		1	27	3		5	99	5	5	1	0	0	0	0	0.000E+00
Basic Event	1.2.4		Motorcyclist behavior						2								2	0	0	0	5.253E-07
Basic Event	1.2.4.1			Motorbike crossed the tracks unexpectedly					1				2	1		1	3	1	0	1	7.879E-07
Basic Event	1.2.4.2			Motorbike driving on the track					1								1	0	0	0	2.626E-07
Basic Event	1.2.4.3			Red light violation by motorbike									3	1	1		4	1	1	0	1.051E-06
Intermediate Event Level 2	1.2.5		Pedestrian behavior														0	0	0	0	0.000E+00
Basic Event	1.2.5.1			Pedestrian walking on the track									33	5	4	1	33	5	4	1	8.667E-06
Basic Event	1.2.5.2			Pedestrian entered swept path unexpectedly	78	6	5	2	111	3	3	1	19	1	1		208	10	8	4	5.463E-05
Basic Event	1.2.5.3			Red light violation by Pedestrian	2								71	4		8	73	4	0	8	1.917E-05
Basic Event	1.2.5.4			Pedestrian caught the driver doors									1				1	0	0	0	2.626E-07
Basic Event	1.2.5.5			Pedestrian crossed the track dangerously					1				2	2	2	1	3	2	2	1	7.879E-07
Intermediate Event Level 2	1.2.6		Police behavior														0	0	0	0	0.000E+00
Basic Event	1.2.6.2			Police sudden stopped the train movement										1			1	0	0	0	2.626E-07
Basic Event	1.2.6.3			Wrong police instructions					2								2	0	0	0	5.253E-07
Intermediate Event Level 2	1.2.7		Animals on the track														0	0	0	0	0.000E+00
Basic Event	1.2.7.1			Animals entered to the swept path unexpectedly					2					4			6	0	0	0	1.576E-06
Basic Event	1.2.8		Object on track														0	0	0	0	0.000E+00
Basic Event	1.2.8.1			Object on the track					1								1	0	0	0	2.626E-07
Intermediate Event Level 1	1.3		Technical Failure														0	0	0	0	0.000E+00
Intermediate Event Level 2	1.3.1		Infrastructure Failure (Signaling failure)														0	0	0	0	0.000E+00
Basic Event	1.3.1.1			Malfunction of TTL	1												1	0	0	0	2.626E-07
Basic Event	1.3.1.2			Unexpected change of train traffic light													1	0	0	0	2.626E-07
Intermediate Event Level 2	1.3.2		Dead man failure						14	1		1	9	1		2	35	2	0	3	9.192E-06
Basic Event	1.3.3		Doors failure						33	4	1	5	50	6	8	5	112	13	11	11	2.941E-05
Basic Event	1.3.4		HSCB Failure						1								1	0	0	0	2.626E-07
Basic Event	1.3.5		Master control failure										2				2	0	0	0	5.253E-07
Intermediate Event Level 2	1.3.6		Speedometer failure														1	0	0	0	2.626E-07
Basic Event	1.3.7		Power supply failure						1	1		1					1	1	0	1	2.626E-07
Basic Event	1.3.8		Unknown reason						1				24				25	0	0	0	6.560E-06
Basic Event	1.3.8		Unknown reason																		
Total Emergency Braking and injuries per year					211	13	9	10	291	14	4	18	389	29	24	22	891	56	37	50	2.340E-04
Train-km per year					1,251,284				1,271,562				1,284,865				3,807,651				

Development of Generic Risk Models for Light Rail and Tramway Systems

Appendix B – A Database of EB Events that Occurred in 2014-2016

Year	Month	Count - Incidents per month	Date	Time	Incident Nr.	Type of Incident	Cause of EB with Injuries	Tram number	Destination	Incident Location	Station / Junction	Station / Junction Number	Driver number	EB with injuries	Light Injuries	Injuries needing First Aid	Total Injuries
2014	1	1	02/01/2014	0:31		EB	Emergency handle misuse	39-43	Heil HaAvir	Station 19- Kiryat Moshe	S	19	1021	No			0
2014	1	2	02/01/2014	9:13		EB	Pedestrian entered swept path unexpectedly	10-21	Mount Herzl	J28 - Cheshin	J	28	1046	No			0
2014	1	3	02/01/2014	15:52		EB	Pedestrian entered swept path unexpectedly	6-23	Mount Herzl	J10 - Denya square	J	10	1067	No			0
2014	1	4	06/01/2014	9:01		EB	Pedestrian entered swept path unexpectedly	4-25	Heil HaAvir	J28 - Cheshin	J	28	1019	No			0
2014	1	5	08/01/2014	11:56		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	STATION 14- JAFFA CENTER	S	14	1013	No			0
2014	1	6	16/01/2014	20:57		EB	Door failure	12-28	Heil HaAvir	J20 Jaffa / Sha'arei Tzedek	J	20	1011	No			0
2014	1	7	19/01/2014	15:54		EB	Pedestrian entered swept path unexpectedly	12-28	Heil HaAvir	J50 Road n° 1 / Shragai	J	50	1049	No			0
2014	1	8	20/01/2014	10:11		EB	Pedestrian entered swept path unexpectedly	5-26	Heil HaAvir	STATION 07- ES-SAHL	S	7	1035	No			0
2014	1	9	20/01/2014	14:50		EB	Doors failure	9-29	Mount Herzl	STATION 15 - DAVIDKA	S	15	1008	No			0
2014	1	10	21/01/2014	15:16		EB	Red light violation by car	17-41	Mount Herzl	J72 Moshe Dayan / Moshe Rachmilevich	J	72	1012	No			0
2014	1	11	21/01/2014	15:46		EB	Door failure	11-18	Mount Herzl	J20 Jaffa / Sha'arei Tzedek	J	20	1000	No			0
2014	1	12	23/01/2014	8:04		EB	Pedestrian entered swept path unexpectedly	24-40	Mount Herzl	J52 Road n° 1 / Shderot Eshkol	J	52	1062	No			0
2014	1	13	25/01/2014	22:52		EB	Emergency Handle misuse	10-21	Mount Herzl	STATION 08 - GIVAT HA' MIVTAR	S	8	1016	No			0
2014	1	14	27/01/2014	13:57		EB	Dead man failure	33-34	Mount Herzl	J13 Herzl / Rupin	J	13	1039	No			0
2014	1	15	28/01/2014	6:42		EB	Red light violation by car	17-41	Mount Herzl	J72 Moshe Dayan / Moshe Rachmilevich	J	72	1020	No			0
2014	1	16	29/01/2014	19:32		EB	Door failure	6-23	Mount Herzl	J20 Jaffa / Sha'arei Tzedek	J	20	1017	No			0
2014	1	17	30/01/2014	14:33		EB	Emergency handle misuse	24-40	Heil HaAvir	Station 13 - CityHall - Safra	S	13	1022	No			0
2014	1	18	31/01/2014	12:57		EB	Pedestrian entered swept path unexpectedly	9-29	Heil HaAvir	J28 - Cheshin	J	28	1031	No			0
2014	2	1	04/02/2014	12:31		EB	Red light violation by Pedestrian	19-36	Mount Herzl	J12 - Haft junction	J	12	1070	No			0
2014	2	2	06/02/2014	16:41		EB	Pedestrian entered swept path unexpectedly	3-45	Heil HaAvir	J92 Jaffa west Station	J	92	1041	No			0
2014	2	3	11/02/2014	8:45		EB	Pedestrian entered swept path unexpectedly	33-34	Heil HaAvir	J55 - GIVAT HA' MIVTAR	J	55	1030	No			0
2014	2	4	13/02/2014	15:20		EB	Pedestrian entered swept path unexpectedly	37-42	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1001	No			0
2014	2	5	16/02/2014	13:58		EB	Pedestrian entered swept path unexpectedly	9-29	Heil HaAvir	J59 Derech Shu'afat / El-Maari	J	59	1070	No			0
2014	2	6	18/02/2014	8:29		EB	Pedestrian entered swept path unexpectedly	13-14	Mount Herzl	J55 - GIVAT HA' MIVTAR	J	55	1063	No			0
2014	2	7	18/02/2014	19:28		EB	Pedestrian entered swept path unexpectedly	10-21	Mount Herzl	STATION 13 - SAFRA SQUARE	S	13	1011	No			0
2014	2	8	20/02/2014	15:15		EB	Red light violation by car	4-25	Mount Herzl	J60 Derech Shu'afat / A/Shabi	J	60	1002	No			0
2014	2	9	21/02/2014	12:10		EB	Red light violation by car	3-45	Mount Herzl	J61 Derech Shu'afat / Yekutieli Adam	J	61	1063	No			0
2014	2	10	22/02/2014	21:39		EB	Pedestrian entered swept path unexpectedly	15-27	Mount Herzl	J28 - Cheshin	J	28	1037	No			0
2014	2	11	25/02/2014	7:40		EB	Emergency handle misuse	13-14	Mount Herzl	STATION 05 - BEIT 'HANINA	S	5	1036	No			0
2014	2	12	25/02/2014	11:06		EB	Red light violation by car	32-46	Mount Herzl	J72 Moshe Dayan / Moshe Rachmilevich	J	72	1061	No			0
2014	2	13	25/02/2014	18:28		EB	Red light violation by car	7-22	Mount Herzl	J5 Herzel/Shmuel Bayth/Yeke Nof	J	5	1049	No			0
2014	2	14	27/02/2014	12:13		EB	Car crossed the track unexpectedly	6-23	Mount Herzl	J71 Moshe Dayan / Haim Toren	J	71	1034	No			0
2014	3	1	02/03/2014	8:18		EB	Red light violation by car	10-21	Mount Herzl	J66 Yekutieli Adam / Uzi Narkis East	J	66	1069	No			0
2014	3	#REF!	02/03/2014	12:38		EB	Object trapped in door	1-2	Mount Herzl	STATION 10 - SHIMON HATZADIK	S	10	1029	No			0
2014	3	#REF!	04/03/2014	0:50		EB	Dead man failure	10-21	Mount Herzl	DEPOT	D		1011	No			0
2014	3	#REF!	05/03/2014	7:55		EB	Pedestrian entered swept path unexpectedly	24-40	Mount Herzl	STATION 06 - SHUAFAT	S	6	1047	No			0
2014	3	#REF!	05/03/2014	18:56		EB	Door failure	38-44	Mount Herzl	STATION 18 - CBS	S	18	1064	No			0
2014	3	#REF!	06/03/2014	11:50		EB	Emergency handle misuse	5-26	Mount Herzl	STATION 14- JAFFA CENTER	S	14	1034	No			0
2014	3	#REF!	06/03/2014	19:19		EB	Door failure	11-18	Mount Herzl	J21 Jaffa / Eliyahu Mani	J	21	1042	No			0
2014	3	#REF!	09/03/2014	16:56		EB	Car crossed the track unexpectedly	37-42	Heil HaAvir	J70 - Y. Adam / M. Dayan	J	70	1011	No			0
2014	3	#REF!	09/03/2014	16:56		EB	Car crossed the track unexpectedly	24-40	Heil HaAvir	STATION 21 - DENYA SQUARE	S	21	1006	No			0
2014	3	#REF!	10/03/2014	17:44		EB	Door failure	24-40	Heil HaAvir	STATION 21 - DENYA SQUARE	S	21	1006	yes	1		1
2014	3	#REF!	11/03/2014	9:39		EB	Door failure	12-28	Mount Herzl	J91 Jaffa / Central Bus Station - West	J	91	1015	No			0
2014	3	#REF!	12/03/2014	8:08		EB	Driver failure in using the emergency brake	13-14	Mount Herzl	J55 Road n° 1 / Yigael Yadin	J	55	1031	No			0
2014	3	#REF!	13/03/2014	15:53		EB	Pedestrian entered swept path unexpectedly	1-2	Mount Herzl	STATION 21 - DENYA SQUARE	S	21	1051	No			0
2014	3	#REF!	14/03/2014	10:39		EB	Car crossed the track unexpectedly	39-43	Heil HaAvir	J52 Road n° 1 / Shderot Eshkol	J	52	1029	No			0
2014	3	#REF!	18/03/2014	7:49		EB	Red light violation by car	15-27	Mount Herzl	J65 Yekutieli Adam / Uzi Narkis west	J	65	1006	No			0
2014	3	#REF!	18/03/2014	19:13		EB	Car crossed the track unexpectedly	15-27	Heil HaAvir	J58 Derech Shu'afat / Hafez Ibrahim	J	58	1050	No			0
2014	3	#REF!	19/03/2014	10:35		EB	Emergency handle misuse	9-29	Heil HaAvir	STATION 11 - SHIVTEI ISRAEL	S	11	1068	No			0
2014	3	#REF!	20/03/2014	15:30		EB	Car crossed the track unexpectedly	4-25	Mount Herzl	STATION 06 - SHUAFAT	S	6	1016	No			0
2014	3	#REF!	20/03/2014	16:13		EB	Pedestrian entered swept path unexpectedly	8-31	Mount Herzl	STATION 16 - MAHANE YEHUDA	S	16	1017	No			0
2014	3	#REF!	23/03/2014	14:48		EB	Door failure	6-23	Mount Herzl	STATION 17 - HA' TURIM	S	17	1065	No			0
2014	3	#REF!	24/03/2014	20:14		EB	Red light violation by car	7-22	Mount Herzl	J60 Derech Shu'afat / A/Shabi	J	60	1047	No			0
2014	3	#REF!	25/03/2014	8:12		EB	Red light violation by car	3-45	Mount Herzl	J5 Herzel/Shmuel Bayth/Yeke Nof	J	5	1046	No			0
2014	3	#REF!	25/03/2014	11:27		EB	Door failure	30-35	Mount Herzl	STATION 16 - MAHANE YEHUDA	S	16	1003	No			0
2014	3	#REF!	25/03/2014	16:41		EB	Pedestrian entered swept path unexpectedly	10-21	Mount Herzl	J5 Herzel/Shmuel Bayth/Yeke Nof	J	5	1054	No			0
2014	3	#REF!	25/03/2014	20:14		EB	Speedometer failure	4-25	Heil HaAvir	J03 Herzel/Uziel	J	23	1065	No			0
2014	3	#REF!	26/03/2014	11:43		EB	Red light violation by car	17-41	Mount Herzl	J72 Moshe Dayan / Moshe Rachmilevich	J	72	1037	No			0
2014	3	#REF!	26/03/2014	13:16		EB	Pedestrian entered swept path unexpectedly	3-45	Mount Herzl	STATION 06 - SHUAFAT	S	6	1023	No			0
2014	3	#REF!	26/03/2014	14:14		EB	Car crossed the track unexpectedly	6-23	Mount Herzl	J52 Road n° 1 / Shderot Eshkol	J	52	1068	No			0
2014	3	#REF!	27/03/2014	5:20		EB	Red light violation by car	8-31	Track 4	J55 Road n° 1 / Yigael Yadin	J	55	1020	No			0
2014	3	#REF!	27/03/2014	18:10		EB	Emergency handle misuse	30-35	Mount Herzl	STATION 05 - BEIT 'HANINA	S	5	1051	No			0
2014	4	1	01/04/2014	13:23		EB	Pedestrian entered swept path unexpectedly	14/2448	Mount Herzl	J01 - Kiriat Ha'Yovel	J	1	1041	No			0
2014	4	2	01/04/2014	16:40		EB	Door failure	14/2455	Mount Herzl	STATION 18 - CBS	S	18	1070	No			0
2014	4	3	01/04/2014	19:35		EB	Red light violation by car	19-36	Heil HaAvir	STATION 15 - DAVIDKA	S	15	1017	yes		1	1
2014	4	4	04/04/2014	12:00		EB	Pedestrian entered swept path unexpectedly	14/2541	Mount Herzl	J53 Road n° 1 / Ha'hagana	J	53	1006	No			0
2014	4	5	04/04/2014	12:20		EB	Pedestrian entered swept path unexpectedly	14/2542	Heil HaAvir	J44 - Hanew'im	J	44	1047	No			0
2014	4	6	07/04/2014	12:33		EB	Dead man failure	14/2599	Mount Herzl	J15 Herzl / Kiryat Moshe	J	15	1070	No			0
2014	4	7	09/04/2014	17:45		EB	Pedestrian entered swept path unexpectedly	14/2652	Mount Herzl	J50 Road n° 1 / Shragai	J	50	1041	No			0
2014	4	8	16/04/2014	6:19		EB	Door failure	14/2753	Heil HaAvir	STATION 09 - AMMUNITION HILL	S	9	1013	No			0
2014	4	9	17/04/2014	14:09		EB	Car crossed the track unexpectedly	14/2780	Heil HaAvir	J41 - Tzanchanim - Shaar Hadash (New Gate)	J	41	1034	No			0
2014	4	10	18/04/2014	10:57		EB	Emergency handle misuse	11-18	Heil HaAvir	J50 Road n° 1 / Shragai	J	50	1006	No			0
2014	4	11	18/04/2014	15:00		EB	Pedestrian entered swept path unexpectedly	05-26	Mount Herzl	J28 - Cheshin	J	28	1002	yes	1		1
2014	4	12	25/04/2014	12:32		EB	Emergency handle misuse	24-40	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1013	No			0
2014	4	13	30/04/2014	15:24		EB	Door failure	30-35	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1070	No			0
2014	5	1	01/05/2014	18:42		EB	Car crossed the track unexpectedly	09-29	Heil HaAvir	J5 Herzel/Shmuel Bayth/Yeke Nof	J	5	1017	No			0
2014	5	2	05/05/2014	15:58		EB	Pedestrian entered swept path unexpectedly	12-28	Mount Herzl	STATION 21 - DENYA SQUARE	S	21	1062	yes	1		1
2014	5	3	12/05/2014	7:54		EB	Door failure	17-41	Heil HaAvir	STATION 09 - AMMUNITION HILL	S	9	1062	No			0
2014	5	4	12/05/2014	13:05		EB	Door failure	11-18	Heil HaAvir	STATION 11 - SHIVTEI ISRAEL	S	11	1022	No			0
2014	5	5	14/05/2014	7:59		EB	Malfunction of TTL	15-27	Heil HaAvir	J49 Road n° 1 / Shimon Hat'sadik	J	49	2003	No			0
2014	5	6	14/05/2014	14:56		EB	Door failure	09-29	Mount Herzl	J91 Jaffa / Central Bus Station - West	J	91	1068	No			0
2014	5	7	15/05/2014	18:21		EB	Emergency handle misuse	09-29	Mount Herzl	STATION 09 - AMMUNITION HILL	S	9	1013	No			0
2014	5	8	18/05/2014	14:52		EB	Pedestrian entered swept path unexpectedly	30-35	Heil HaAvir	STATION 21 - DENYA SQUARE	S	21	1010	No			0
2014	5	9	19/05/2014	13:18		EB											

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2014	6	3	02/06/2014	20:50		EB	Door failure	38-44	Heil HaAvir	J	18	1033	No			0
2014	6	4	05/06/2014	22:36		EB	Cyclist crossed the track unexpectedly	11-18	Mount Herzl	J	92	1040	No			0
2014	6	5	08/06/2014	9:19		EB	Car crossed the track unexpectedly	33-34	Mount Herzl	J	51	1003	No			0
2014	6	6	08/06/2014	9:27		EB	Car crossed the track unexpectedly	33-34	Mount Herzl	J	60	1003	No			0
2014	6	7	08/06/2014	22:21		EB	Dead man failure	04-25	Mount Herzl	S	13	1049	No			0
2014	6	8	09/06/2014	17:07		EB	Emergency handle misuse	13-14	Mount Herzl	S	18	1047	No			0
2014	6	9	15/06/2014	8:41		EB	Dead man failure	4-25	Heil HaAvir	S	16	1049	No			0
2014	6	10	15/06/2014	10:52		EB	Pedestrian entered swept path unexpectedly	12-28	Mount Herzl	S	16	1047	No			0
2014	6	11	16/06/2014	8:49		EB	Car crossed the track unexpectedly	15-27	Heil HaAvir	J	58	1057	No			0
2014	6	12	24/06/2014	7:25		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	S	4	1052	No			0
2014	6	13	24/06/2014	8:29		EB	Door failure	19-36	Heil HaAvir	J	40	1042	No			0
2014	6	14	29/06/2014	11:22		EB	Pedestrian entered swept path unexpectedly	15-27	Heil HaAvir	J	19	1026	No			0
2014	7	1	10/07/2014	13:01	67-2014	EB	Door failure	09-29	Heil HaAvir	J	20	1006	yes	1		1
2014	7	2	10/07/2014	22:05		EB	Pedestrian entered swept path unexpectedly	37-42	Mount Herzl	J	28	1066	No			0
2014	7	3	11/07/2014	9:30		EB	Pedestrian entered swept path unexpectedly	1-2	Mount Herzl	J	40	1069	No			0
2014	7	4	12/07/2014	22:52		EB	Door failure	16-20	Mount Herzl	J	52	1000	No			0
2014	7	5	12/07/2014	23:09		EB	Pedestrian entered swept path unexpectedly	32-46	Heil HaAvir	J	52	1028	No			0
2014	7	6	14/07/2014	17:01		EB	Door failure	30-35	Heil HaAvir	S	18	1033	No			0
2014	7	7	16/07/2014	15:08		EB	Door failure	09-29	Heil HaAvir	J	20	1013	No			0
2014	7	8	16/07/2014	19:42		EB	Red light violation by car	07-22	Mount Herzl	S	6	1054	No			0
2014	7	9	16/07/2014	21:39		EB	Pedestrian entered swept path unexpectedly	04-25	Heil HaAvir	S	6	1066	No			0
2014	7	10	17/07/2014	21:00		EB	Pedestrian entered swept path unexpectedly	17-41	Mount Herzl	J	28	1055	No			0
2014	7	11	20/07/2014	8:49		EB	Red light violation by car	24-40	Heil HaAvir	J	52	1019	No			0
2014	7	12	21/07/2014	18:56		EB	Cyclist crossed the track unexpectedly	24-40	Mount Herzl	J	19	1047	No			0
2014	7	13	27/07/2014	20:43	70-2014	EB	Door failure	10-21	Heil HaAvir	S	15	1009	yes		1	1
2014	7	14	25/07/2014	15:15		EB	Pedestrian entered swept path unexpectedly	32-46	Heil HaAvir	S	13	1022	No			0
2014	7	15	26/07/2014	23:37		EB	Door failure	19-36	Heil HaAvir	J	50	1016	No			0
2014	7	16	30/07/2014	7:10		EB	Dead man failure	15-27	Heil HaAvir	S	15	1024	No			0
2014	7	17	30/07/2014	14:34		EB	Pedestrian entered swept path unexpectedly	12-28	Heil HaAvir	J	72	1047	No			0
2014	7	18	30/07/2014	15:58		EB	Pedestrian entered swept path unexpectedly	37-42	Mount Herzl	J	25	1001	No			0
2014	7	19	31/07/2014	12:15		EB	Red light violation by car	10-21	Mount Herzl	J	28	1037	No			0
2014	7	20	31/07/2014	22:37		EB	Emergency handle misuse	01-02	Heil HaAvir	J	65	1019	No			0

Year	Month	Count - Incidents per month	Date	Time	Incident Nr.	Type of Incident	Cause of EB with Injuries	Tram number	Destination	Incident Location	Station / Junction	Station / Junction Number	Driver number	EB with Injuries	Light Injuries	Injuries needed First Aid	Total Injuries
2014	8	1	11/08/2014	17:00		EB	Red light violation by car	16-20	Mount Herzl	J66 Yekutiel Adam / Uzi Narkis East	J	66	1023	No			0
2014	8	2	12/08/2014	11:09		EB	Pedestrian entered swept path unexpectedly	30-35	Mount Herzl	J50 Road n° 1 / Shragai	J	50	1012	No			0
2014	8	3	13/08/2014	7:10		EB	Car crossed the track unexpectedly	13-14	Mount Herzl	J56 Derech Shu'afat / Derech Anatot (Ben Jabeli)	J	56	1049	No			0
2014	8	4	17/08/2014	9:40		EB	Pedestrian entered swept path unexpectedly	12-28	Mount Herzl	J50 Road n° 1 / Shragai	J	50	1063	No			0
2014	8	5	17/08/2014	12:01		EB	Pedestrian entered swept path unexpectedly	5-26	Mount Herzl	STATION 8 - GIVAT HA' MIVTAR	S	8	1066	No			0
2014	8	6	19/08/2014	17:11		EB	Emergency handle misuse	13-14	Mount Herzl	STATION 18 - CBS	S	18	1014	No			0
2014	8	7	21/08/2014	0:13		EB	Red light violation by car	39-43	Heil HaAvir	STATION 8 - GIVAT HA' MIVTAR	S	8	1028	No			0
2014	8	8	21/08/2014	15:30		EB	Red light violation by car	24-40	Track 1-2	J20 Jaffa / Sha'arei Tzedek	J	20	1034	No			0
2014	8	9	22/08/2014	17:36		EB	Emergency handle misuse	24-40	Mount Herzl	STATION 7 - ES- SAHL	S	7	1009	No			0
2014	8	10	22/08/2014	17:54		EB	Red light violation by car	32-46	Mount Herzl	J52 Road n° 1 / Shderot Eshkol	J	52	1005	No			0
2014	8	11	25/08/2014	18:00		EB	Emergency handle misuse	30-35	Heil HaAvir	STATION 9 - AMMUNITION HILL	S	9	1013	No			0
2014	8	12	25/08/2014	20:41		EB	Red light violation by car	17-41	Mount Herzl	J5 Herzel/Shmuel Bayth/Yeke Nof	J	5	1002	No			0
2014	8	13	28/08/2014	11:14		EB	Pedestrian entered swept path unexpectedly	38-44	Heil HaAvir	STATION 18 - CBS	S	18	1051	No			0
2014	8	14	29/08/2014	9:40		EB	Driver failure in using the emergency brake	16-20	Mount Herzl	J3 Herzel/Uziel	J	3	1022	No			0
2014	8	15	31/08/2014	16:06		EB	Emergency handle misuse	05-26	Heil HaAvir	STATION 13 - SAFRA SQUARE	S	13	1042	No			0
2014	9	1	07/09/2014	7:51		EB	Pedestrian entered swept path unexpectedly	24-40	Mount Herzl	J9 Herzel/Hameyasdim	J	9	1066	No			0
2014	9	2	07/09/2014	16:35		EB	Cyclist crossed the track unexpectedly	32-46	Heil HaAvir	J18 Jaffa / Sarei Israel / Nordau (Nordau Sq.)	J	18	1047	No			0
2014	9	3	07/09/2014	20:42		EB	Cyclist crossed the track unexpectedly	8-31	Track 1-2	J13 Herzel / Rupin	J	13	1051	No			0
2014	9	4	08/09/2014	11:22		EB	Pedestrian entered swept path unexpectedly	10-21	Mount Herzl	J28 Jaffa / Cheshin	J	28	1055	No			0
2014	9	5	09/09/2014	6:35		EB	Car crossed the track unexpectedly	13-14	Mount Herzl	J72 Moshe Dayan / Moshe Rachmievich	J	72	1035	No			0
2014	9	6	11/09/2014	9:11		EB	Red light violation by car	38-44	Mount Herzl	J53 Road n° 1 / Ha'hagana	J	53	1047	No			0
2014	9	7	12/09/2014	11:59		EB	Pedestrian entered swept path unexpectedly	11-18	Heil HaAvir	J7 Herzel/Tirza/Aharonov + Yefe Nof Station	J	7	1049	No			0
2014	9	8	14/09/2014	12:45		EB	Cyclist crossed the track unexpectedly	01-02(9)	Heil HaAvir	J13 Herzel / Rupin	J	13	1055	No			0
2014	9	9	14/09/2014	16:49		EB	Cyclist crossed the track unexpectedly	15-27	Mount Herzl	STATION 9 - AMMUNITION HILL	S	9	1051	No			0
2014	9	10	15/09/2014	8:35		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	J7 Herzel/Tirza/Aharonov + Yefe Nof Station	J	7	1066	No			0
2014	9	11	15/09/2014	12:02	89-2014	EB	Pedestrian entered swept path unexpectedly	38-44	Mount Herzl	STATION 15 - DAVIDKA	S	15	1047	yes		1	1
2014	9	12	18/09/2014	22:11		EB	Pedestrian entered swept path unexpectedly	06-23	Mount Herzl	J18 Jaffa / Sarei Israel / Nordau (Nordau Sq.)	J	18	1049	No			0
2014	9	13	18/09/2014	22:50		EB	Pedestrian entered swept path unexpectedly	07-22	Heil HaAvir	STATION 10 - SHIMON HATZADIK	S	10	1011	No			0
2014	9	14	19/09/2014	13:00		EB	Pedestrian entered swept path unexpectedly	01-02	Mount Herzl	STATION 8 - GIVAT HA' MIVTAR	S	8	1058	No			0
2014	9	15	22/09/2014	14:38	90-2014	EB	Car crossed the track unexpectedly	24-40	Mount Herzl	J10 Herzel/Ha'arazim / (Denia Sq)	J	10	1047	yes	2		2
2014	9	16	28/09/2014	12:14		EB	Dead man failure	10-21	Mount Herzl	J15 Herzel / Kiryat Moshe	J	15	2001	no			0
2014	9	17	28/09/2014	12:45		EB	Dead man failure	10-21	Mount Herzl	J61 Derech Shu'afat / Yekutiel Adam	J	61	2001	no			0
2014	9	18	28/09/2014	21:02	93-2014	EB	Pedestrian entered swept path unexpectedly	07-22	Heil HaAvir	J91 Jaffa / Central Bus Station - West	J	18	1037	yes	1		1
2014	9	19	29/09/2014	8:05		EB	Door failure	10-21	Mount Herzl	J4 Herzel/Military Cemetery	J	4	1065	No			0
2014	9	20	29/09/2014	14:19		EB	Red light violation by car	37-42	Heil HaAvir	J78 Moshe Dayan / Sayeret Duchifat	J	78	1023	No			0
2014	9	21	29/09/2014	18:48		EB	Door failure	39-43	Mount Herzl	STATION 5 - BEIT HANANIA	S	5	1016	No			0
2014	9	22	30/09/2014	10:52		EB	Pedestrian entered swept path unexpectedly	33-34	Heil HaAvir	STATION 9 - AMMUNITION HILL	S	9	1073	No			0
2014	10	1	01/10/2014	15:34		EB	Emergency handle misuse	11-18	Mount Herzl	STATION 17 - HA' TURIM	S	7	1063	No			0
2014	10	2	02/10/2014	7:58		EB	Pedestrian entered swept path unexpectedly	07-22	Heil HaAvir	STATION 22 - YEFE NOF	S	22	1059	No			0
2014	10	3	05/10/2014	17:33		EB	Car crossed the track unexpectedly	24-40	Heil HaAvir	J52 Road n° 1 / Shderot Eshkol	J	52	1055	No			0
2014	10	4	06/10/2014	9:04		EB	Pedestrian entered swept path unexpectedly	09-29	Heil HaAvir	STATION 17 - HA' TURIM	S	17	1074	No			0
2014	10	5	06/10/2014	19:45		EB	Cyclist crossed the track unexpectedly	09-29	Mount Herzl	J25 Jaffa / King George / Shtraus	J	25	1074	No			0
2014	10	6	07/10/2014	23:23		EB	Pedestrian entered swept path unexpectedly	33-34	Mount Herzl	J43 Road n°1/Sultan Suleiman	J	43	1066	No			0
2014	10	7	08/10/2014	11:30		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzl	J10 Herzel/Ha'arazim / (Denia Sq)	J	10	1010	No			0
2014	10	8	08/10/2014	12:26		EB	Dead man failure	10-21	Mount Herzl	STATION 9 - AMMUNITION HILL	S	9	1030	No			0
2014	10	9	12/10/2014	18:13		EB	Door failure	01-02	Heil HaAvir	J20 Jaffa / Sha'arei Tzedek	J	20	1016	No			0
2014	10	10	13/10/2014	11:31		EB	Pedestrian entered swept path unexpectedly	01-02	Mount Herzl	J28 Jaffa / Cheshin	J	28	1075	No			0
2014	10	11	13/10/2014	18:29		EB	Pedestrian entered swept path unexpectedly	12-28	Mount Herzl	J25 Jaffa / King George / Shtraus	J	25	1017	No			0
2014	10	12	14/10/2014	18:20		EB	Door failure	11-18	Heil HaAvir	J22 Jaffa / Beit Ya'akov	S	16	1036	No			0
							STATION 16 - MAHANE YEHUDA										
2014	10	13	15/10/2014	6:41		EB	Cyclist crossed the track unexpectedly	10-21	Mount Herzl	STATION 16 - MAHANE YEHUDA	S	16	1037	No			0
2014	10	14	17/10/2014	5:12		EB	Pedestrian entered swept path unexpectedly	17-41	Heil HaAvir	STATION 13 - SAFRA SQUARE	S	13	1037	No			0
2014	10	15	20/10/2014	8:19	101-2014	EB	Driver failure in using the emergency brake	01-02	Heil HaAvir	J16 Herzel / Ben Dor	J	16	1078	yes		1	1
2014	10	16	20/10/2014	16:21		EB	Pedestrian entered swept path unexpectedly	17-41	Heil HaAvir	J28 Jaffa / Cheshin	J	28	1051	no			0
2014	10	17	22/10/2014	8:14		EB	Pedestrian entered swept path unexpectedly	30-35	Mount Herzl	STATION 14- JAFFA CENTER	S	14	1017	no			0
2014	10	18	24/10/2014	12:36		EB	Pedestrian entered swept path unexpectedly	08-31	Heil HaAvir	STATION 18 - CBS	S	18	1055	no			0
2014	10	19	27/10/2014	17:04		EB	Door failure	04-25	Mount Herzl	STATION 22 - YEFE NOF	S	22	1068	no			0
2014	10	20	27/10/2014	17:49		EB	Pedestrian entered swept path unexpectedly	07-22	Mount Herzl	STATION 14- JAFFA CENTER	S	14	1075	no			0
2014	11	1	02/11/2014	13:57		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	STATION 6 - SHUAFAT	S	6	1017	no			0
2014	11	2	03/11/2014	17:06		EB	Pedestrian entered swept path unexpectedly	15-27	Mount Herzl	J22 Jaffa / Beit Ya'akov	J	22	1074	no			0
2014	11	3	04/11/2014	9:29		EB	Red light violation by Pedestrian	05-26	Mount Herzl	J43 Road n°1/Sultan Suleiman	J	43	1049	no			0
2014	11	4	04/11/2014	23:57		EB	Red light violation by car	01-02	Mount Herzl	J62 Derech Shu'afat North station	J	62	1073	no			0
2014	11	5	06/11/2014	13:19		EB	Pedestrian entered swept path unexpectedly	17-41	Mount Herzl	STATION 15 - DAVIDKA	S	15	1062	no			0
2014	11	6	09/11/2014	12:40		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzl	J20 Jaffa / Sha'arei Tzedek	J	20	1017	no			0
2014	11	7	11/11/2014	20:58		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1049	no			0
2014	11	8	13/11/2014	14:41		EB	Red light violation by car	04-25	Mount Herzl	STATION 6 - SHUAFAT	S	6	1063	no			0
2014	11	9	16/11/2014	9:06		EB	Pedestrian entered swept path unexpectedly	10-21	Heil HaAvir	J28 Jaffa / Cheshin	J	28	1075	no			0
2014	11	10	16/11/2014	11:03		EB	Dead man failure	15-27	Mount Herzl	J25 Jaffa / King George / Shtraus	J	25	1035	no			0
2014	11	11	16/11/2014	13:42		EB	Driver failure in using the emergency brake	15-27	Heil HaAvir	STATION 3 - PISGAT ZE'EV CTR.	S	3	1076	no			0
2014	11	12	17/11/2014	6:28		EB	Cyclist crossed the track unexpectedly	10-21	Mount Herzl	STATION 13 - SAFRA SQUARE	S	13	1071	no			0
2014	11	13	17/11/2014	13:39		EB	Red light violation by car	01-02	Mount Herzl	J61 Derech Shu'afat / Yekutiel Adam	J	61	1076	no			0
2014	11	14	18/11/2014	17:26		EB	Pedestrian entered swept path unexpectedly	39-43	Mount Herzl	J18 Jaffa / Sarei Israel / Nordau (Nordau Sq.)	J	18	1068	no			0
2014	11	15	19/11/2014	19:02		EB	Emergency handle misuse	08-31	Heil HaAvir	STATION 18 - CBS	S	18	1002	no			0

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2014	11	16	20/11/2014	8:22		EB	Dead man failure	12-28	Heil HaAvir	STATION 17 - HA' TURIM	S	17	1018	no			0
2014	11	17	23/11/2014	7:42		EB	Dead man failure	12-28	Heil HaAvir	STATION 12 - DAMASCUS GATE	S	12	1077	no			0
2014	11	18	24/11/2014	16:12		EB	Red light violation by car	39-43	Heil HaAvir	J41 Hatzanhanim/Notradam + New Gate	J	41	1030	no			0
2014	11	19	24/11/2014	22:33		EB	Cyclist crossed the track unexpectedly	06-23	Mount Herzl	J16 Herzl / Ben Dor	J	16	1060	no			0
2014	11	20	25/11/2014	13:25		EB	Emergency handle misuse	24-40	Heil HaAvir	J15 Herzl / Kiryat Moshe	J	15	1042	no			0
2014	11	21	26/11/2014	8:32		EB	Car crossed the track unexpectedly	38-44	Mount Herzl	J9 Herzl/Hameyasdim	J	19	1066	no			0
2014	11	22	26/11/2014	8:49		EB	Car crossed the track unexpectedly	13-14	Heil HaAvir	J65 Yekutiel Adam / Uzi Narkis west	J	65	1018	no			0
2014	11	23	26/11/2014	14:29		EB	Pedestrian entered swept path unexpectedly	10-21	Mount Herzl	STATION 23 - MOUNT HERZL	S	23	1011	no			0
2014	11	1	08/12/2014	8:31	114-2014	EB with Collision	Cyclist rides on the track	38-44	Mount Herzl	J41 - Ha Tzanhanim/NotRedam + New Gate	J	41	1032	yes	5	5	0
2015	1	1	01/01/2015	6:41		EB	Pedestrian entered swept path unexpectedly	39-43	Mount Herzl	STATION 10 - SHIMON HATZADIK	S	10	1047	no			0
2015	1	2	02/01/2015	7:52		EB	Red light violation by car	19-36	Mount Herzl	J9 Herzl/Hameyasdim	J	9	1077	no			0
2015	1	3	02/01/2015	13:18		EB	Pedestrian entered swept path unexpectedly	07-22	Mount Herzl	STATION 12 - DAMASCUS GATE	S	12	1047	no			0
2015	1	4	05/01/2015	14:40		EB	Cyclist entered the swept path unexpectedly	39-43	Heil HaAvir	STATION 9 - ADMUNITION HILL	S	9	1038	no			0
2015	1	5	05/01/2015	20:00		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	STATION 11 - SHIVTEI ISRAEL	S	11	1079	no			0
2015	1	6	06/01/2015	12:08		EB	Pedestrian entered swept path unexpectedly	24-40	Mount Herzl	J53 Road n° 1 / Ha'hagana	J	53	1018	no			0
2015	1	7	07/01/2015	22:16		EB	Red light violation by car	37-42	Mount Herzl	J66 Yekutiel Adam / Uzi Narkis East	J	66	1054	no			0
2015	1	8	09/01/2015	15:40		EB	Red light violation by car	19-36	Heil HaAvir	J66 Yekutiel Adam / Uzi Narkis East	J	66	1020	no			0
2015	1	9	10/01/2015	21:08		EB	Car entered swept path unexpectedly	05-26	Mount Herzl	STATION 22 - YEFE NOF	S	22	1051	no			0
2015	1	10	11/01/2015	8:06		EB	Car entered swept path unexpectedly	10-21	Heil HaAvir	J57 Derech Shu'afat / A'Sahel	J	57	1071	no			0
2015	1	11	11/01/2015	11:54		EB	Car entered swept path unexpectedly	09-29	Heil HaAvir	J58 Derech Shu'afat / Hafez Ibrahim	J	58	1077	no			0
2015	1	12	12/01/2015	11:02		EB	Red light violation by car	05-26	Mount Herzl	J15 Herzl / Kiryat Moshe	J	15	1058	no			0
2015	1	13	13/01/2015	8:59		EB	Pedestrian entered swept path unexpectedly	10-21	Mount Herzl	J22 Jaffa / Beit Ya'akov	J	22	1060	no			0
2015	1	14	13/01/2015	21:51		EB	Pedestrian entered swept path unexpectedly	33-34	Mount Herzl	J53 Road n° 1 / Ha'hagana	J	53	1076	no			0
2015	1	15	15/01/2015	10:06		EB	Car entered swept path unexpectedly	05-26	Heil HaAvir	J59 Derech Shu'afat / El-Maari	J	59	1016	no			0
2015	1	16	16/01/2015	14:19		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	J22 Jaffa / Beit Ya'akov	J	22	1073	no			0
2015	1	17	18/01/2015	19:13		EB	Red light violation by car	5-26	Mount Herzl	STATION 10 - SHIMON HATZADIK	S	10	1028	no			0
2015	1	18	19/01/2015	9:03		EB	Red light violation by bus	07-22	Heil HaAvir	J18Jaffa / Sarei Israel / Nordau (Nordau Sq.)	J	18	1026	no			0
2015	1	19	20/01/2015	7:01		EB	Pedestrian entered swept path unexpectedly	39-43	Mount Herzl	J53 Road n° 1 / Ha'hagana	J	53	1075	no			0
2015	1	20	20/01/2015	15:24		EB	Car entered swept path unexpectedly	12-28	Heil HaAvir	J56 Derech Shu'afat / Derech Anatot (Ben	J	56	1060	no			0
2015	1	21	21/01/2015	13:40		EB	Pedestrian entered swept path unexpectedly	33-34	Heil HaAvir	STATION 3 - PISGAT ZE'EV CTR.	S	3	1058	no			0
2015	1	22	22/01/2015	19:53		EB	Door failure	37-42	Mount Herzl	J91 Jaffa / Central Bus Station - West	J	91	1019	no			0
2015	1	23	25/01/2015	13:23		EB	Cyclist entered the swept path unexpectedly	37-42	Heil HaAvir	STATION 17 - HA' TURIM	S	17	1022	no			0
2015	1	24	26/01/2015	8:22		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	J57 Derech Shu'afat / A'Sahel	J	57	1029	no			0
2015	1	25	27/01/2015	16:34		EB	Pedestrian entered swept path unexpectedly	13-14	Mount Herzl	J28 Jaffa / Cheshin	J	28	1077	no			0
2015	1	26	28/01/2015	14:14		EB	Driver failure in using the emergency brake	06-23	Heil HaAvir	J58 Derech Shu'afat / Hafez Ibrahim	J	58	1022	no			0
2015	1	27	29/01/2015	9:22		EB	Red light violation by car	08-31	Heil HaAvir	J52 Road n° 1 / Shderot Eshkol	J	52	1077	no			0
2015	2	1	02/02/2015	13:30		EB	Car entered swept path unexpectedly	13-14	Mount Herzl	J58 Derech Shu'afat / Hafez Ibrahim	J	58	1026	no			0
2015	2	2	03/02/2015	18:06		EB	Car entered swept path unexpectedly	38-44	Mount Herzl	STATION 6 - SHUAFAF	S	6	1023	no			0
2015	2	3	04/02/2015	16:18		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	STATION 23 - MOUNT HERZL	S	23	1071	no			0
2015	2	4	05/02/2015	16:43		EB	Pedestrian entered swept path unexpectedly	03-45	Mount Herzl	STATION 8 - GIVAT HA' MIVTAR	S	8	1020	no			0
2015	2	5	06/02/2015	10:59		EB	Pedestrian entered swept path unexpectedly	11-18	Heil HaAvir	J71 Moshe Dayan / Haim Toren	J	71	1049	no			0
2015	2	6	08/02/2015	13:36		EB	Pedestrian entered swept path unexpectedly	38-44	Heil HaAvir	STATION 18 - CBS	S	18	1004	no			0
2015	2	7	08/02/2015	17:30		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzl	STATION 15 - DAVIDKA	S	15	1077	no			0
2015	2	8	09/02/2015	15:19		EB	Red light violation by car	07-22	Heil HaAvir	J47 Road n° 1 / Zacks	J	47	1016	no			0
2015	2	9	09/02/2015	23:40		EB	Red light violation by car	39-43	Mount Herzl	J66 Yekutiel Adam / Uzi Narkis East	J	66	1023	no			0
2015	2	10	10/02/2015	15:18		EB	Pedestrian entered swept path unexpectedly	10-21	Heil HaAvir	STATION 10 - SHIMON HATZADIK	S	10	1051	no			0
2015	2	11	13/02/2015	10:01		EB	Pedestrian entered swept path unexpectedly	33-34	Mount Herzl	STATION 16 - MAHANE YEHUDA	S	16	1037	no			0
2015	2	12	16/02/2015	21:57		EB	Emergency Handle misuse	5-26	Heil HaAvir	STATION 14 - JAFFA CENTER	S	14	1068	no			0
2015	2	13	18/02/2015	17:38		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	STATION 23 - MOUNT HERZL	S	23	1077	no			0
2015	2	14	19/02/2015	16:03		EB	Pedestrian entered swept path unexpectedly	11-18	Mount Herzl	STATION-04 YEKUTIEL ADAM	S	4	1066	no			0
2015	2	15	24/02/2015	7:52		EB	Car entered swept path unexpectedly	38-44	Heil HaAvir	Junction 57 - Shua'fat	J	57	1016	no			0
2015	2	16	26/02/2015	6:38		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzl	Junction 56 Derech Shu'afat	J	56	1066	no			0
2015	2	17	26/02/2015	9:44		EB	Pedestrian entered swept path unexpectedly	37-42	Heil HaAvir	Junction 44 - Hanevim	J	44	1034	no			0
2015	2	18	26/02/2015	16:20		EB	Car entered swept path unexpectedly	24-40	Mount Herzl	STATION 19 - KIRIAT MOSHE	S	19	1031	no			0
2015	3	1	01/03/2015	9:23		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	J15 Herzl / Kiryat Moshe	J	15	1031	no			0

Year	Month	Count - Incidents per month	Date	Time	Incident Nr.	Type of Incident	Cause of EB with Injuries	Tram number	Destination	Incident Location	Station / Junction	Station / Junction Number	Driver number	EB with Injuries	Light Injuries	Injuries needed First Aid	Total Injuries
2015	3	2	01/03/2015	12:02		EB	Pedestrian entered swept path unexpectedly	32-46	Heil HaAvir	J22 Jaffa / Beit Ya'akov	J	22	1037	no			0
2015	3	3	01/03/2015	13:43		EB	Pedestrian entered swept path unexpectedly	5-26	Mount Herzl	J20 Jaffa / Sha'arei Tzedek	J	20	1012	no			0
2015	3	4	02/03/2015	9:22		EB	Door failure	05-26	Heil HaAvir	STATION 13 - SAFRA SQUARE	S	13	1009	no			0
2015	3	5	02/03/2015	19:21		EB	Pedestrian entered swept path unexpectedly	37-42	Mount Herzl	STATION 21 - DENYA SQUARE	S	21	1058	no			0
2015	3	6	03/03/2015	13:50		EB	Pedestrian entered swept path unexpectedly	09-29	Mount Herzl	STATION 6 - SHUAFAT	S	6	1024	no			0
2015	3	7	05/03/2015	11:35		EB	Car entered swept path unexpectedly	9-29	Heil HaAvir	J70 Y. Adam / M. Dayan	J	70	1055	no			0
2015	3	8	05/03/2015	12:38		EB	Red light violation by car	15-22	Mount Herzl	J48 Shimon Hat'sadik Station	J	48	1016	no			0
2015	3	9	05/03/2015	12:57		EB	Car entered swept path unexpectedly	39-43	Heil HaAvir	J70 Y. Adam / M. Dayan	J	70	1047	no			0
2015	3	10	05/03/2015	19:35		EB	Pedestrian entered swept path unexpectedly	38-44	Heil HaAvir	STATION 14 - JAFFA CENTER	S	14	1040	no			0
2015	3	11	05/03/2015	21:19		EB	Car entered swept path unexpectedly	17-41	Mount Herzl	STATION 6 - SHUAFAT	S	6	1074	no			0
2015	3	12	05/03/2015	23:30		EB	Pedestrian entered swept path unexpectedly	16-20	Mount Herzl	J25 Jaffa / King George / Shtraus	J	25	1051	no			0
2015	3	13	08/03/2015	11:27		EB	Car entered swept path unexpectedly	8-31	Heil HaAvir	J28 Jaffa / Cheshin	J	28	1016	no			0
2015	3	14	08/03/2015	11:55		EB	Pedestrian entered swept path unexpectedly	38-44	Heil HaAvir	STATION 5 - BEIT HANINA	S	5	1015	no			0
2015	3	15	08/03/2015	19:12		EB	Car entered swept path unexpectedly	12-28	Mount Herzl	STATION 6 - SHUAFAT	S	6	1063	no			0
2015	3	16	09/03/2015	9:00		EB	Pedestrian entered swept path unexpectedly	04-25	Mount Herzl	J53 Road n° 1 / Ha'hagana	S	53	1067	no			0
2015	3	17	11/03/2015	14:39		EB	Dead man failure	12-28	Heil HaAvir	STATION 8 - GIVAT HA' MIVTAR	S	8	1039	no			0
2015	3	18	11/03/2015	20:07		EB	Cyclist entered the swept path unexpectedly	08-31	Heil HaAvir	STATION 21 - DENYA SQUARE	S	21	1028	no			0
2015	3	19	12/03/2015	12:15		EB	Red light violation by car	16-20	Mount Herzl	J66 Yekutiel Adam / Uzi Narkis East	J	66	1077	no			0
2015	3	20	17/03/2015	20:08		EB	Pedestrian entered swept path unexpectedly	17-41	Mount Herzl	J50 Road n° 1 / Shragal	J	50	1040	no			0
2015	3	21	17/03/2015	23:09		EB	Pedestrian entered swept path unexpectedly	17-41	Heil HaAvir	STATION 18 - CBS	S	18	1023	no			0
2015	3	22	18/03/2015	7:36		EB	Dead man failure	37-42	Mount Herzl	J70 Y. Adam / M. Dayan	J	70	1069	no			0
2015	3	23	19/03/2015	6:35		EB	Cyclist entered the swept path unexpectedly	17-41	Mount Herzl	J19 Jaffa west station	J	19	1072	no			0
2015	3	24	23/03/2015	5:42		EB	Car entered swept path unexpectedly	30-35	Heil HaAvir	J56 Derech Shu'afat / Derech Anatot (Ben	J	56	1049	no			0
2015	3	25	23/03/2015	11:49		EB	Car entered swept path unexpectedly	04-25	Mount Herzl	J72 Moshe Dayan / Moshe Rachmleivich	J	72	1020	no			0
2015	3	26	23/03/2015	16:08		EB	Pedestrian entered swept path unexpectedly	17-41	Heil HaAvir	STATION 3 - PISGAT ZE'EV CTR.	S	3	1077	no			0
2015	3	27	24/03/2015	17:33		EB	Dead man failure	01-02	Mount Herzl	J20 Jaffa / Sha'arei Tzedek	J	20	1057	no			0
2015	3	28	26/03/2015	21:42		EB	Pedestrian entered swept path unexpectedly	33-34	Heil HaAvir	STATION 19 - KIRIAT MOSHE	S	19	1049	no			0
2015	3	29	30/03/2015	13:47		EB	Pedestrian entered swept path unexpectedly	03-45	Mount Herzl	STATION 22 - YEFE NOF	S	22	1020	no			0
2015	4	1	03/04/2015	15:10		EB	Red light violation by car	05-26	Mount Herzl	J72 Moshe Dayan / Moshe Rachmleivich	J	72	1049	no			0
2015	4	2	08/04/2015	13:35		EB	Red light violation by car	08-31	Mount Herzl	J47 Road n° 1 / Zacks	J	47	1037	no			0
2015	4	3	08/04/2015	18:11		EB	Wrong police instructions	30-35	Heil HaAvir	J50 Road n° 1 / Shragal	J	50	1012	no			0
2015	4	4	08/04/2015	20:00		EB	Door failure	3-45	Mount Herzl	J65 Yekutiel Adam / Uzi Narkis west	J	65	1004	no			0
2015	4	5	12/04/2015	18:11		EB	Car entered swept path unexpectedly	3-45	Heil HaAvir	J57 Derech Shu'afat / A'Sahel	J	57	1024	no			0
2015	4	6	16/04/2015	7:17	24-2015	EB with Collision	Pedestrian entered swept path unexpectedly	16-20	Mount Herzl	Jaffa Street Pedestrian area near Mahne Yehuda	J	19	1051	yes	1	1	2
2015	4	7	16/04/2015	20:39		EB	Pedestrian entered swept path unexpectedly	13-14	Heil HaAvir	STATION 18 - CBS	S	18	1072	no			0
2015	4	8	17/04/2015	13:03		EB	Pedestrian entered swept path unexpectedly	16-20	Heil HaAvir	STATION 13 - SAFRA SQUARE	S	13	1019	no			0
2015	4	9	20/04/2015	10:48	25-2015	EB with Collision	Pedestrian entered swept path unexpectedly	32-42	Mount Herzl	J15 - Davidka	S	15	1031	yes	2		2
2015	4	10	20/04/2015	12:42		EB	Car entered swept path unexpectedly	10-21	Heil HaAvir	STATION 6 - SHUAFAT	S	6	1076	no			0
2015	4	11	20/04/2015	18:11		EB	Door failure	15-27	Heil HaAvir	J20 Jaffa / Sha'arei Tzedek	J	20	1047	no			0
2015	4	12	21/04/2015	7:42		EB	Car entered swept path unexpectedly	15-27	Mount Herzl	STATION 7 - ES-SAHL	S	7	1072	no			0
2015	4	13	22/04/2015	10:42		EB	Car entered swept path unexpectedly	39-43	Heil HaAvir	J15 Herzl / Kiryat Moshe	J	15	1047	no			0
2015	4	14	22/04/2015	22:01		EB	Pedestrian entered swept path unexpectedly	07-22	Mount Herzl	J28 Jaffa / Cheshin	J	28	1063	no			0
2015	4	15	22/04/2015	22:11		EB	Door failure	11-18	Mount Herzl	STATION 17 - HA' TURIM	S	17	1070	no			0
2015	4	16	24/04/2015	14:46		EB	Emergency handle misuse	07-22	Mount Herzl	STATION 7 - ES-SAHL	S	7	1063	no			0
2015	4	17	27/04/2015	8:21		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzl	J60 Derech Shu'afat / A'Shabi	J	60	1016	no			0
2015	4	18	27/04/2015	13:55		EB	Pedestrian entered swept path unexpectedly	01-02	Heil HaAvir	J46 Shvitey Israel station	J	46	1049	no			0
2015	4	19	28/04/2015	14:37	27-2015	EB	Door failure	17-41	Heil HaAvir	J17 - Ha Turim (Jaffa West)	S	17	1022	yes		1	1
2015	4	20	30/04/2015	9:15		EB	Dead man failure	38-44	Heil HaAvir	STATION 2 - SAYVET DUCHIFAT	S	2	1012	no			0

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2015	4	21	30/04/2015	16:45		EB	Pedestrian entered swept path unexpectedly	33-34	Heil HaAvir	STATION 9 - AMMUNITION HILL	S	9	1065	no			0
2015	5	1	03/05/2015	11:57		EB	Door failure	10-21	Mount Herzi	STATION 15 - DAVIDKA	S	15	1021	no			0
2015	5	2	03/05/2015	14:47		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	STATION 9 - AMMUNITION HILL	S	9	1049	no			0
2015	5	3	03/05/2015	17:29		EB	Pedestrian entered swept path unexpectedly	19-36	Mount Herzi	116 Herzl / Ben Dor	J	16	1026	no			0
2015	5	4	03/05/2015	18:44		EB	Red light violation by car	12-28	Mount Herzi	148 Shimon Ha'tsadik Station	J	48	1049	no			0
2015	5	5	04/05/2015	15:57		EB	Pedestrian entered swept path unexpectedly	09-29	Mount Herzi	140 Jaffa / Tzahal square	J	40	1031	no			0
2015	5	6	05/05/2015	13:25		EB	Pedestrian entered swept path unexpectedly	19-36	Mount Herzi	169 Y. Adam / M. Dayan station	J	69	1055	no			0
2015	5	7	05/05/2015	15:20		EB	Door failure	04-25	Mount Herzi	STATION 16 - MAHANE YEHUDA	S	16	1038	no			0
2015	5	8	05/05/2015	17:09		EB	Dead man failure	04-25	Heil HaAvir	STATION 18 - CBS	S	18	1079	no			0
2015	5	9	07/05/2015	12:07		EB	Pedestrian entered swept path unexpectedly	03-45	Heil HaAvir	128 Jaffa / Cheshin	J	28	1077	no			0
2015	5	10	07/05/2015	19:10		EB	Pedestrian entered swept path unexpectedly	15-27	Heil HaAvir	141 Hatzanhanim/Notradam + New Gate	J	41	1006	no			0
2015	5	11	11/05/2015	7:00		EB	Car entered swept path unexpectedly	12-28	Mount Herzi	160 Derech Shu'afat / A'Shabi	J	60	1047	no			0
2015	5	12	11/05/2015	12:37		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzi	STATION 19 - KIRIAT MOSHE	S	19	1027	no			0
2015	5	13	11/05/2015	15:32		EB	Door failure	06-23	Mount Herzi	192 Jaffa west Station	J	92	1070	no			0
2015	5	14	11/05/2015	17:38		EB	Dead man failure	39-43	Mount Herzi	156 Derech Shu'afat / Derech Anatot	J	56	1018	no			0
2015	5	15	12/05/2015	5:50		EB	Dead man failure	19-36	Heil HaAvir	156 Derech Shu'afat / Derech Anatot	J	56	1049	no			0
2015	5	16	12/05/2015	20:56		EB	Driver failure in using the emergency brake	8-31	Heil HaAvir	144 Road n°1/Hanev'im	J	44	1055	no			0
2015	5	17	13/05/2015	8:04		EB	Pedestrian entered swept path unexpectedly	*	Mount Herzi	STATION 9 - AMMUNITION HILL	S	9	1072	no			0
2015	5	18	13/05/2015	16:40		EB	Red light violation by car	33-34	Heil HaAvir	165 Yekutieli Adam / Uzi Narkis west	J	65	1033	no			0
2015	5	19	14/05/2015	15:20		EB	Door failure	15-27	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1054	no			0
2015	5	20	15/05/2015	12:53		EB	Emergency handle misuse	11-18	Heil HaAvir	STATION 6 - SHUAFAT	S	6	1031	no			0
2015	5	21	15/05/2015	14:10		EB	Dead man failure	38-44	Mount Herzi	STATION 22 - YEFE NOF	S	22	1012	no			0
2015	5	22	17/05/2015	14:48		EB	Pedestrian entered swept path unexpectedly	17-41	Mount Herzi	150 Road n° 1 / Shragai	J	50	1030	no			0
2015	5	23	17/05/2015	16:10		EB	Cyclist entered the swept path unexpectedly	07-22	Heil HaAvir	STATION 17 - HA' TURIM	S	17	1018	no			0
2015	5	24	18/05/2015	16:32	38-2015	EB	Door failure	05-26	Heil HaAvir	113 City Hall (Safra Square)	S	13	1019	yes	1		1
2015	5	25	20/05/2015	8:14		EB	Door failure	32-46	Mount Herzi	STATION 18 - CBS	S	18	1068	no			0
2015	5	26	20/05/2015	16:32		EB	Pedestrian entered swept path unexpectedly	19-36	Heil HaAvir	160 Derech Shu'afat / A'Shabi	J	60	1077	no			0
2015	5	27	20/05/2015	21:04		EB	Pedestrian entered swept path unexpectedly	9-29	Mount Herzi	STATION 19 - KIRIAT MOSHE	S	19	1077	no			0
2015	5	28	25/05/2015	11:33		EB	Car entered swept path unexpectedly	01-02	Mount Herzi	STATION 6 - SHUAFAT	S	6	1068	no			0
2015	5	29	25/05/2015	17:39		EB	Car entered swept path unexpectedly	04-25	Heil HaAvir	170 Y. Adam / M. Dayan	J	70	1002	no			0
2015	5	30	28/05/2015	23:15		EB	Red light violation by car	33-34	Heil HaAvir	166 Yekutieli Adam / Uzi Narkis East	J	66	1003	no			0
2015	6	1	08/06/2015	13:39		EB	Cyclist entered the swept path unexpectedly	15-27	Heil HaAvir	112 Herzl/Hapsagah/Ein karem (Holand sq)	J	2	1077	no			0
2015	6	2	11/06/2015	8:30		EB	Pedestrian entered swept path unexpectedly	08-31	Mount Herzi	STATION 8 - GIVAT HA' MIVTAR	S	8	1077	no			0
2015	6	3	11/06/2015	16:26		EB	Pedestrian entered swept path unexpectedly	07-22	Mount Herzi	111 Haft Station	J	11	1077	no			0
2015	6	4	11/06/2015	21:14	40-2015	EB	Door failure	24-40	Mount Herzi	115 - Davidka	S	15	1070	yes		1	1
2015	6	5	11/06/2015	21:56		EB	Car entered swept path unexpectedly	17-41	Heil HaAvir	128 Jaffa / Cheshin	J	28	1068	no			0
2015	6	6	12/06/2015	17:30		EB	Cyclist entered the swept path unexpectedly	17-41	Mount Herzi	150 Road n° 1 / Shragai	J	50	1017	no			0
2015	6	7	14/06/2015	13:56		EB	Door failure	24-40	Heil HaAvir	120 Jaffa / Sha'arei Tzedek	J	20	1079	no			0
2015	6	8	15/06/2015	14:07		EB	Door failure	38-44	Mount Herzi	STATION 12 - DAMASCUS GATE	S	12	1036	no			0
2015	6	9	18/06/2015	18:00		EB	Car entered swept path unexpectedly	33-34	Mount Herzi	165 Yekutieli Adam / Uzi Narkis west	J	65	1063	no			0
2015	6	10	18/06/2015	18:55		EB	Door failure	33-34	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1033	no			0
2015	6	11	21/06/2015	12:47		EB	Car accident ahead	39-43	Heil HaAvir	115 Herzl/Shmuel Bayth/Yeke Nof	J	5	1016	no			0
2015	6	12	21/06/2015	20:24		EB	Pedestrian entered swept path unexpectedly	24-40	Heil HaAvir	STATION 16 - MAHANE YEHUDA	S	16	1079	no			0
2015	6	13	21/06/2015	22:27		EB	Pedestrian entered swept path unexpectedly	07-22	Heil HaAvir	STATION 6 - SHUAFAT	S	6	1073	no			0
2015	6	14	24/06/2015	15:45		EB	Red light violation by car	32-46	Mount Herzi	165 Yekutieli Adam / Uzi Narkis west	J	65	1071	no			0
2015	6	15	24/06/2015	15:56		EB	Car entered swept path unexpectedly	04-25	Heil HaAvir	STATION 5 - BEIT HANINA	S	5	1039	no			0
2015	6	16	24/06/2015	18:10		EB	Door failure	12-28	Mount Herzi	STATION 8 - GIVAT HA' MIVTAR	S	8	1072	no			0
2015	6	17	25/06/2015	7:27		EB	Pedestrian entered swept path unexpectedly	32-46	Mount Herzi	128 Jaffa / Cheshin	J	28	1047	no			0
2015	6	18	26/06/2015	9:54		EB	Red light violation by car	24-40	Heil HaAvir	172 Moshe Dayan / Moshe Rachmilevich	J	72	1047	no			0
2015	6	19	28/06/2015	7:55		EB	Door failure	01-02	Mount Herzi	113 Herzl/Uziel	J	3	1036	no			0
2015	6	20	28/06/2015	9:07		EB	Car entered swept path unexpectedly	17-41	Heil HaAvir	120 Jaffa / Sha'arei Tzedek	J	20	1069	no			0
2015	6	21	28/06/2015	15:23		EB	Cyclist entered the swept path unexpectedly	07-22	Heil HaAvir	STATION 18 - CBS	S	18	1033	no			0
2015	6	22	28/06/2015	18:27		EB	Wrong police instructions	32-46	Mount Herzi	171 Moshe Dayan / Haim Toren	J	71	1063	no			0
2015	6	23	29/06/2015	15:28		EB	Door failure	12-28	Heil HaAvir	120 Jaffa / Sha'arei Tzedek	J	20	1058	no			0
2015	6	24	30/06/2015	7:49		EB	Dead man failure	19-36	Heil HaAvir	141 Hatzanhanim/Notradam + New Gate	J	41	1014	no			0
2015	7	1	02/07/2015	12:35		EB	Door failure	30-35	Mount Herzi	112 Herzl/Ha'chaluz/Dgania/Haft Sq)	J	12	1020	no			0
2015	7	2	02/07/2015	14:26		EB	Cyclist fell on tracks	01-02	Heil HaAvir	112 Herzl/Ha'chaluz/Dgania/Haft Sq)	J	12	1037	no			0
2015	7	3	02/07/2015	10:00	47-2015	EB	Red light violation by car	15-27	Heil HaAvir	110 - Shimon Ha-Tzadik	S	10	1054	yes		2	2
2015	7	4	02/07/2015	14:58		EB	Driver failure in using the emergency brake	24-40	Heil HaAvir	152 Road n° 1 / Shderot Eshkol	J	52	1049	no			0
2015	7	5	04/07/2015	23:29		EB	Pedestrian entered swept path unexpectedly	07-22	Heil HaAvir	128 Jaffa / Cheshin	J	28	1037	no			0
2015	7	6	05/07/2015	13:56		EB	Pedestrian entered swept path unexpectedly	06-23	Mount Herzi	116 Herzl / Ben Dor	J	16	1071	no			0
2015	7	7	07/07/2015	10:48	72-2015	EB with Collision	Red light violation by car	37-42	Mount Herzi	109 - Tomer- Hameyasdim	J-9	9	105	YES		2	2
2015	7	8	07/07/2015	21:15		EB	Pedestrian entered swept path unexpectedly	01-02	Mount Herzi	STATION 14- JAFFA CENTER	S	14	1082	no			0
2015	7	9	08/07/2015	11:35	49-2015	EB	Cyclist fell on tracks	06-23	Mount Herzi	153 - Road n° 1 / Ha'hagana	J	53	1051	yes		1	1
2015	7	10	09/07/2015	11:38		EB	Pedestrian entered swept path unexpectedly	30-35	Mount Herzi	STATION 14- JAFFA CENTER	S	14	1034	no			0
2015	7	11	09/07/2015	17:45		EB	Pedestrian entered swept path unexpectedly	24-40	Heil HaAvir	114 Herzl / Peak	J	14	2003	no			0
2015	7	12	10/07/2015	16:40		EB	Car entered swept path unexpectedly	39-43	Heil HaAvir	Private access 7 - Near junction 70	J	70	1051	no			0
2015	7	13	11/07/2015	0:10		EB	Pedestrian entered swept path unexpectedly	04-25	Heil HaAvir	STATION 14- JAFFA CENTER	S	14	1018	no			0
2015	7	14	12/07/2015	13:12		EB	Door failure	33-34	Heil HaAvir	STATION 18 - CBS	S	18	1001	no			0
2015	7	15	12/07/2015	21:20		EB	Pedestrian crossed the track dangerously	13-14	Mount Herzi	STATION 6 - SHUAFAT	S	6	1071	no			0
2015	7	16	13/07/2015	14:11		EB	Unknown reason	05-26	Mount Herzi	176 Moshe Dayan / Shmuel Eden (road)	J	76	1027	no			0
2015	7	17	13/07/2015	17:43		EB	Motorbike crossed the tracks unexpectedly	17-41	Mount Herzi	123 Jaffa / Haneveem / Chiah (Davidka Sq.)	J	23	1077	no			0
2015	7	18	13/07/2015	20:27	51-2015	EB	Door failure	11-18	Heil HaAvir	116 - Makhane Yehuda	S	16	1073	yes		3	3
2015	7	19	15/07/2015	14:58		EB	Pedestrian entered swept path unexpectedly	01-02	Heil HaAvir	STATION 22 - YEFE NOF	S	22	1084	no			0
2015	7	20	15/07/2015	18:22	53-2015	EB	Power supply failure	17-41	Heil HaAvir	112 - Ha-Halutz (Haft junction)	J	12	1011	yes		1	1
2015	7	21	15/07/2015	20:00		EB	Animal entered swept path unexpectedly	37-42	Heil HaAvir	160 Derech Shu'afat / A'Shabi	J	60	1063	no			0
2015	7	22	16/07/2015	12:38		EB	Pedestrian entered swept path unexpectedly	15-27	Mount Herzi	STATION 13 - SAFRA SQUARE	S	13	1077	no			0
2015	7	23	21/07/2015	12:40		EB	Door failure	37-42	Heil HaAvir	111 Haft Station	J	11	1032	no			0

Appendix C – EB in Lines 7 and 11, Zurich Public Transport (VBZ)

Jahr	Fall	Schadennummer	Datum	Unfallart	Notstopp	Ursache	Detail zur Ursache	Bemerkung	Linie
2014	1	14-2962	19/12/2014	Stoppunfall	Notstopp	LKW in Gleisbereich			11
2014	2	14-2972	17/12/2014	Stoppunfall		Fussgänger in Gleisbereich		Scheibe defect	11
2014	3	14-2943	15/12/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW überholt Tram und hält an (Baustelle)		11
2014	4	14-2804	25/11/2014	Stoppunfall		unbekannt			11
2014	5	14-2797	19/11/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW fährt ohne Halt über Kreuzung	2 Personen gestürzt	11
2014	6	14-2623	25/10/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW fährt plötzlich an		11
2014	7	14-2424	12/09/2014	Stoppunfall		Gegenstand von im Gleisbereich	Werkzeugkasten von Baustelle	Baustellenbereich	11
2014	8	14-2381	06/09/2014	Stoppunfall	Notstopp	Velofahrerin fuhr vor den Bus	Velofahrerin machte plötzlich einen Schwenker vor Bus		11
2014	9	14-2195	08/08/2014	Stoppunfall	Notstopp	Fussgänger in Gleisbereich	wartender Fahrgast bückt sich und kommt dadurch in Gleisbereich		11
2014	10	14-1709	15/05/2014	Stoppunfall		PW in Gleisbereich	PW überquert Tramgeleise und sieht Tram zu spät		11
2014	11	14-1708	15/05/2014	Stoppunfall	Notstopp	Fussgänger in Gleisbereich	mehrer Fussgänger kommen hinter einem Container hervor und wollen Tramgeleise überqueren		11
2014	12	14-1450	02/04/2014	Stoppunfall	Notstopp	Fussgänger in Gleisbereich	ein Fussgänger rennt über Geleise		11
2014	13	14-1375	22/03/2014	Stoppunfall	Notstopp	PW in Gleisbereich	ein PW kommt hinter einem Gegenkurs über die Geleise		11
2014	14	14-1135	31/01/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW schwenkt in Gleisbereich aus		11
2014	15	14-3031	31/12/2014	Stoppunfall	Notstopp	LKW in Gleisbereich	LKW hält plötzlich im Gleisbereich an		7
2014	16	14-3011	30/12/2014	Stoppunfall		PW in Gleisbereich	unbekannt		7
2014	17	14-2948	17/12/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW biegt plötzlich links ab	Kinderwagen beschädigt?	7
2014	18	14-2954	17/12/2014	Stoppunfall	Notstopp	Fussgänger in Gleisbereich	Fussgänger läuft in Gleisbereich		7
2014	19	14-2666	28/10/2014	Stoppunfall		unbekannt	unbekannt		7
2014	20	14-2644	20/04/2014	Ruckunfall		Tram fuhr an	Kindergruppe halten sich ungenügend		7
2014	21	14-2067	08/07/2014	Stoppunfall	Notstopp	Weichenstörung	Fahrgast fällt über Fahrgast		7
2014	22	14-1760	25/05/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW biegt plötzlich links ab		7
2014	23	14-1154	04/02/2014	Stoppunfall	Notstopp	PW in Gleisbereich	PW biegt plötzlich links ab		7
2014	24	14-1119	29/01/2014	Stoppunfall	Notstopp	Fussgänger in Gleisbereich	Fussgänger läuft in Gleisbereich		7
2014	25	14-1049	15/01/2014	Stoppunfall	Notstopp	Fussgänger in Gleisbereich	Fussgänger läuft in Gleisbereich		7

Jahr	Fall	Schadennummer	Datum	Unfallart	Notstopp	Ursache	Detail zur Ursache	Bemerkung	Linie
2015	1	15-1761	02/06/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW setzte trotz rasseln des Trams die Fahrt fort		11
2015	2	15-1627	06/05/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW will li abbiegen		11
2015	3	15-1124	26/01/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW will li abbiegen		11
2015	4	15-2982	14/12/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW kommt in Gleisbereich		11
2015	5	15-2880	26/11/2015	Stoppunfall	Notstopp	Frau mit Kinderw. Im Gleisbereich	Frau mit. KW überquert Geleise		11
2015	6	15-2831	20/11/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW kreuzt rasant und stoppt im Gleisbereich		11
2015	7	15-2727	07/11/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW kreuzt und stoppt im Gleisbereich		11
2015	8	15-2578	10/10/2015	Stoppunfall	Notstopp	unbekannt	unbekannt		11
2015	9	15-2533	03/10/2015	Stoppunfall		Fussgänger im Gleisbereich	Fussgänger überquert Gleisbereich	FG (Kind) Kopf angeschlagen	11
2015	10	15-2508	02/10/2015	Stoppunfall	Notstopp	Fussgänger im Gleisbereich	Fussgänger stürzt vors Tram		11
2015	11	15-3064	26/12/2015	Stoppunfall		unbekannt	unbekannt		7
2015	12	15-3011	17/12/2015	Stoppunfall	Notstopp	LKW in Gleisbereich	LKW misachtet Vortrittsrecht		7
2015	13	15-2830	20/11/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW biegt plötzlich links ab		7
2015	14	15-2704	29/01/1900	Stoppunfall		unbekannt	unbekannt		7
2015	15	15-2088	27/07/2015	Stoppunfall	Notstopp	Velofahrerin im Gleisbereich	Velofahrerin fährt in den Gleisbereich		7
2015	16	15-1583	30/04/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW hält plötzlich im Gleisbereich an		7
2015	17	15-1619	24/03/2015	Stoppunfall		unbekannt	unbekannt		7
2015	18	15-1379	14/03/2015	Stoppunfall	Notstopp	PW in Gleisbereich	PW fährt in Gleisbereich		7

Jahr	Fall	Schadennummer	Datum	Unfallart	Notstopp	Ursache	Detail zur Ursache	Bemerkung	Linie
2016	1	16-3041	19/11/2016	Stoppunfall		PW in Gleisbereich	PW überquerte schnell noch die Kreuzung	Kindderwagen umgkippt	11
2016	2	16-2932	03/11/2016	Stoppunfall		unbekannt	unbekannt		11
2016	3	16-3327	09/09/2016	Stoppunfall	Notstopp	unbekannt	unbekannt		
2016	4	16-2686	09/08/2016	Stoppunfall		unbekannt	unbekannt		11
2016	5	16-3332	05/08/2016	Stoppunfall		unbekannt	unbekannt		11
2016	6	16-2274	22/07/2016	Stoppunfall	Notstopp	Fussgänger im Gleisbereich	Fussgänger läuft vors Tram	FG abgelenkt durch Natel	11
2016	7	16-2207	03/06/2016	Stoppunfall		unbekannt	unbekannt		11
2016	8	16-1845	24/05/2016	Stoppunfall	Notstopp	PW in Gleisbereich	PW überquerte Gleisbereich ohne Blinker		11
2016	9	16-1694	18/04/2016	Stoppunfall		unbekannt	unbekannt		11
2016	10	16-1377	10/03/2016	Stoppunfall		Fussgänger im Gleisbereich	Fussgänger überquert Tramegeise		11
2016	11	16-1256	15/02/2016	Stoppunfall	Notstopp	Fussgänger im Gleisbereich	Fussgänger überquert Tramegeise		11
2016	12	16-1116	27/01/2016	Stoppunfall	Notstopp	PW in Gleisbereich	PW biegt in Gleisbreich ab		11
2016	13	16-1113	26/01/2016	Stoppunfall	Notstopp	PW in Gleisbereich	PW will wenden und überquert Gleisbereich		11
2016	14	16-2977	10/11/2016	Stoppunfall	Notstopp	PW in Gleisbereich	PW will abbiegen		7
2016	15	16-2949	06/11/2016	Stoppunfall		unbekannt	unbekannt	1 ältere Dame schlägt die Schulter an	7
2016	16	16-2783	13/10/2016	Stoppunfall		Fussgänger im Gleisbereich/Notstopp	Fussgängerin bemerkte das herannahende Tram nicht		7
2016	17	16-2270	25/07/2016	Stoppunfall		unbekannt	unbekannt	1 Frau schlägt den Kopf an Scheibe an	7
2016	18	16-2237	04/07/2016	Stoppunfall		unbekannt	unbekannt		7
2016	19	16-1785	13/05/2016	Stoppunfall	Notstopp	Fussgänger im Gleisbereich			7
2016	20	16-1576	07/04/2016	Stoppunfall	Notstopp	PW in Gleisbereich	PW halt plötzlich im Gleisbereich an		7
2016	21	16-1198	03/02/2016	Stoppunfall		PW in Gleisbereich	PW fährt schnell über die Geleise		7

Appendix D – Tram Speed at Different Distances from Station 5 where It Stops after Completing the 25 m Curve

Vehicle number	Date and time	0 m	20 m	30 m	80 m	90 m	170 m	250 m
1	09/04/2017 09:43	0	16	16	25	26	31	35
1	09/04/2017 11:37	2	16	16	25	26	31	35
1	09/04/2017 13:31	0	19	19	25	26	30	35
1	09/04/2017 15:25	2	19	19	29	30	33	33
1	09/04/2017 17:29	1	17	17	29	31	33	35
1	09/04/2017 18:12	0	17	17	31	30	31	25
1	09/04/2017 19:01	2	12	12	28	29	34	35
1	09/04/2017 19:55	1	21	21	27	28	30	34
1	09/04/2017 21:52	2	15	15	23	25	27	34
1	09/04/2017 23:47	1	19	19	23	23	24	27
1	11/04/2017 20:41	1	13	13	25	25	30	33
1	11/04/2017 22:26	2	17	17	27	28	33	34
1	12/04/2017 00:23	1	16	16	27	27	27	32
1	12/04/2017 06:46	2	21	21	29	30	30	34
1	12/04/2017 08:35	2	17	17	27	29	33	34
1	12/04/2017 10:27	2	17	17	19	20	31	30
1	12/04/2017 12:22	1	17	17	25	25	32	37
1	12/04/2017 14:16	2	12	12	24	24	29	33
1	12/04/2017 16:15	2	17	17	33	34	35	35
1	12/04/2017 18:07	2	21	21	25	28	35	38
1	12/04/2017 20:31	2	20	20	31	33	28	32
1	13/04/2017 06:01	2	17	17	25	28	31	31
1	13/04/2017 08:00	0	16	16	24	24	28	35
1	13/04/2017 09:55	1	19	19	26	27	30	32
1	13/04/2017 11:46	2	19	19	17	15	31	33
1	13/04/2017 13:41	2	18	18	25	26	32	36
1	13/04/2017 15:56	2	19	19	27	29	33	33
1	13/04/2017 18:58	1	17	17	28	28	29	33
1	14/04/2017 05:56	2	19	19	25	25	28	32
1	14/04/2017 07:46	3	22	22	27	28	32	34
1	14/04/2017 09:39	2	16	16	27	27	27	32
1	14/04/2017 11:34	2	18	18	27	30	33	34
1	14/04/2017 14:42	2	16	16	27	27	32	32
1	14/04/2017 16:23	0	17	17	27	29	32	35
1	15/04/2017 21:06	1	16	16	27	27	30	29
1	15/04/2017 22:58	1	18	18	26	26	30	34
1	16/04/2017 06:58	0	20	20	29	30	38	36
1	16/04/2017 08:51	2	14	14	24	25	27	32
1	16/04/2017 10:40	2	16	16	26	27	33	34
1	16/04/2017 12:37	0	20	20	30	31	36	36
1	16/04/2017 14:27	0	20	20	27	27	29	33
1	16/04/2017 16:18	2	16	16	26	26	31	32
1	17/04/2017 21:31	1	17	17	25	25	25	30
1	17/04/2017 23:28	2	13	13	20	21	25	28
1	12/04/2018 13:32	2	19	19	32	32		31
1	12/04/2018 15:32	2	18	18	28	28	24	36
1	12/04/2018 17:23	2	16	16	27	29	33	35
1	12/04/2018 19:12	3	17	17	25	26	32	37
1	12/04/2018 21:08	2	19	19	30	31	33	31
1	12/04/2018 23:00	1	16	16	27	27	34	34
1	13/04/2018 05:52	0	14	14	28	29	29	30
1	13/04/2018 07:39	2	19	19	28	28	33	33
1	13/04/2018 09:32	0	20	20	30	31	33	33
1	13/04/2018 11:24	2	18	18	24	24	30	35
1	13/04/2018 13:15	1	19	19	31	31	32	34
1	13/04/2018 15:10	2	15	15	28	29	33	35
1	13/04/2018 17:00	1	16	16	27	28	33	32
1	15/04/2018 06:11	1	17	17	24	25	29	29
1	15/04/2018 08:07	0	23	23	30	32	35	35
1	15/04/2018 10:01	2	21	21	27	27	31	34
1	15/04/2018 11:52	0	15	15	25	25	29	28
1	15/04/2018 13:44	1	17	17	25	25	33	32
1	15/04/2018 15:39	1	18	18	32	31	32	37
1	15/04/2018 17:48	1	20	20	27	28	32	36
1	16/04/2018 06:02	1	17	17	27	29	32	34

1	16/04/2018 08:03	2	16	16	27	29	35	28
1	16/04/2018 09:57	2	19	19	28	28	33	36
1	16/04/2018 11:49	2	14	14	27	27	31	33
1	16/04/2018 13:37	2	15	15	22	23	30	37
1	16/04/2018 15:38	0	15	15	11	13	20	25
1	16/04/2018 17:30	2	17	17	24	26	34	32
1	16/04/2018 19:19	3	17	17	24	25	28	32
1	16/04/2018 21:28	1	15	15	28	27	32	36
1	16/04/2018 23:25	2	19	19	31	31	33	33
1	17/04/2018 08:22	0	14	14	26	28	30	33
1	17/04/2018 10:13	0	15	15	26	26	26	27
1	17/04/2018 12:07	1	19	19	25	26	31	35
1	17/04/2018 14:05	1	17	17	22	23	29	29
1	17/04/2018 15:54	2	15	15	31	30	31	31
1	17/04/2018 17:48	1	17	17	27	29	31	34
1	17/04/2018 19:51	1	18	18	26	27	33	39
1	17/04/2018 23:43	1	17	17	29	31	31	32
1	18/04/2018 05:37	1	20	20	27	27	29	33
1	18/04/2018 07:32	2	19	19	17	16	27	30
1	18/04/2018 09:32	1	16	16	24	25	32	38
1	18/04/2018 11:53	1	16	16	28	28	31	31
1	18/04/2018 13:55	1	13	13	25	24	32	28
1	18/10/2017 17:19	2	19	19	29	30	34	35
1	19/10/2017 06:18	0	15	15	26	27	32	34
1	19/10/2017 08:15	1	16	16	28	30	27	37
1	19/10/2017 10:11	2	14	14	23	25	27	34
1	19/10/2017 12:03	1	20	20	30	30	32	31
1	19/10/2017 13:57	2	18	18	25	25	34	37
1	19/10/2017 18:46	1	13	13	21	22	25	24
1	19/10/2017 21:10	1	15	15	25	26	31	33
1	19/10/2017 22:13	3	17	17	26	26	31	38
1	20/10/2017 00:24	1	17	17	23	24	26	35
1	20/10/2017 06:58	1	20	20	25	25	35	38
1	20/10/2017 08:50	2	16	16	24	24	27	31
1	20/10/2017 10:43	2	18	18	28	29	33	38
1	20/10/2017 12:39	1	16	16	24	27	35	37
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39	15/04/2017 20:38	2	18	18	22	23	26	27
39	15/04/2017 22:30	2	18	18	27	27	31	33
39	16/04/2017 00:23	1	13	13	23	24	28	30
39	16/04/2017 07:27	1	15	15	24	25	30	36
39	16/04/2017 09:19	2	15	15	24	25	33	37
39	16/04/2017 13:08	2	17	17	28	30	30	33

39	16/04/2017 14:54	0	16	16	28	29	32	32
39	16/04/2017 17:05	2	18	18	26	26	35	33
39	17/04/2017 21:27	2	13	13	25	28	32	38
39	17/04/2017 23:16	2	13	13	25	26	29	36
42	26/07/2017 08:25	2	19	19	28	29	35	37
42	26/07/2017 10:20	2	15	15	24	26	30	37
42	26/07/2017 12:14	1	16	16	27	28	35	36
42	26/07/2017 14:06	0	21	21	31	33	33	33
42	26/07/2017 17:32	2	20	20	26	29	33	37
42	26/07/2017 19:18	1	18	18	26	26	30	32
42	26/07/2017 21:16	2	19	19	28	27	29	32
42	26/07/2017 23:12	2	18	18	28	29	31	32
42	27/07/2017 06:53	2	13	13	16	18	25	34
42	27/07/2017 09:06	2	18	18	28	28	30	37
42	27/07/2017 11:04	0	17	17	25	26	34	38
42	27/07/2017 12:56	3	20	20	31	32	39	39
42	27/07/2017 19:38	1	17	17	29	30	31	38
42	27/07/2017 21:30	1	16	16	22	22	25	25
42	27/07/2017 23:31	2	15	15	22	23	28	31
42	28/07/2017 06:55	3	17	17	28	28	31	36
42	28/07/2017 08:52	0	13	13	23	25	25	29
42	28/07/2017 12:37	1	18	18	28	30	32	35
42	28/07/2017 14:29	3	16	16	26	27	32	38
42	28/07/2017 16:17	0	18	18	27	28	31	39
42	29/07/2017 21:40	1	13	13	24	24	29	31
42	29/07/2017 23:37	1	15	15	26	27	32	32
42	30/07/2017 05:56	2	16	16	25	26	28	28
42	30/07/2017 07:46	0	18	18	28	30	32	35
42	30/07/2017 09:39	2	23	23	27	28	33	34
42	30/07/2017 11:31	2	17	17	28	30	36	37
42	30/07/2017 13:25	1	15	15	26	27	34	32
42	30/07/2017 15:19	2	18	18	28	28	28	33
42	30/07/2017 17:34	2	17	17	30	31	33	34
42	30/07/2017 21:30	0	16	16	25	26	30	35
42	30/07/2017 23:27	1	17	17	27	29	36	39
42	31/07/2017 07:14	0	15	15	19	21	30	31
42	31/07/2017 09:06	0	17	17	25	26	33	33
42	31/07/2017 11:02	1	16	16	25	26	30	34
42	31/07/2017 12:59	1	18	18	30	32	37	40
42	31/07/2017 16:46	1	15	15	28	29	28	31
42	31/07/2017 18:41	2	14	14	23	24	31	39
42	31/07/2017 20:35	1	16	16	25	26	27	32
42	31/07/2017 22:28	0	17	17	26	27	29	30
42	01/08/2017 00:29	0	14	14	22	25	35	35
44	09/04/2017 09:04	1	18	18	29	30	30	36
44	09/04/2017 10:54	1	19	19	26	27	29	34
44	09/04/2017 12:50	2	18	18	22	23	29	30
44	09/04/2017 14:45	1	13	13	27	28	34	34
44	09/04/2017 16:40	2	18	18	24	24	26	32
44	09/04/2017 21:05	0	17	17	25	26	29	32
44	09/04/2017 23:17	1	18	18	28	28	29	34
44	11/04/2017 20:58	2	18	18	26	26	30	31
44	11/04/2017 22:46	0	18	18	26	27	32	33
44	12/04/2017 07:53	0	20	20	25	25	25	41
44	12/04/2017 09:45	1	19	19	28	28	32	33
44	12/04/2017 11:43	1	19	19	26	26	27	31
44	12/04/2017 13:37	2	19	19	25	25	37	31
44	12/04/2017 15:30	3	20	20	27	27	29	33
44	12/04/2017 17:23	2	22	22	29	30	32	34
44	12/04/2017 19:16	1	17	17	25	24	14	31
44	13/04/2017 05:35	0	17	17	24	25	28	33
44	13/04/2017 07:37	2	20	20	27	28	31	34
44	13/04/2017 09:26	1	20	20	29	30	34	34
44	13/04/2017 11:22	1	16	16	25	26	30	37
44	13/04/2017 13:20	2	16	16	24	26	34	31
44	13/04/2017 15:47	1	17	17	24	25	29	32
44	13/04/2017 17:35	1	19	19	28	28	28	32
44	13/04/2017 19:36	2	16	16	25	26	28	30
44	14/04/2017 06:09	1	14	14	24	24	27	28
44	14/04/2017 08:00	2	22	22	27	27	31	31
44	14/04/2017 09:53	1	17	17	23	25	26	29
44	14/04/2017 11:47	2	17	17	30	31	33	33
44	14/04/2017 15:58	2	21	21	25	25	32	39
44	15/04/2017 22:21	2	15	15	23	23	28	31

44	16/04/2017 00:11	1	21	21	26	27	28	29
44	16/04/2017 06:08	1	20	20	28	29	34	33
44	16/04/2017 08:01	1	21	21	26	27	28	30
44	16/04/2017 09:52	0	16	16	25	25	26	31
44	16/04/2017 11:47	3	19	19	27	28	29	31
44	16/04/2017 13:40	1	14	14	18	23	32	30
44	16/04/2017 15:32	1	23	23	31	31	34	34
44	17/04/2017 21:18	2	17	17	23	25	30	34
44	17/04/2017 23:06	1	20	20	27	27	31	32

Appendix E – Documents Showing Status of Publications

Moshe Itzhaki

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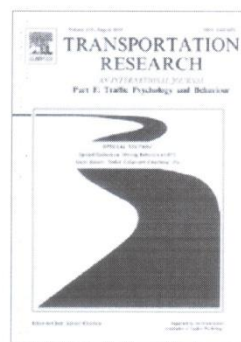
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Dear Mr Itzhaki,

As co-author of the article *The assessment of hazard awareness skills among light rail drivers*, we are pleased to let you know that the final version – containing full bibliographic details – is now available online.

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10/30/2019

Mail – MXI513@student.bham.ac.uk

TRB 2020 Annual Meeting Session 1149

Claire Randall <MyTRB@updates.nas.edu>

Mon 28/10/2019 13:40

To: Moshe Itzhaki (PhD Dept of Civil Eng FT) <MXI513@student.bham.ac.uk>;

Dear Colleague,

On behalf of the standing committees of the TRB Technical Activities Division, we are pleased to inform you of your scheduled participation in the TRB 99th Annual Meeting, to be held January 12-16, 2020, in Washington, D.C.

Event Title: Current Research in Transit Safety and Security
Event Number: 1149
Event Type: Poster Session
Your Role: Presenter

Presentation Number: 20-01848

Presentation Title: Assessing the Risk of Collisions Between Trams due to SPADs in Conflict Areas of an LRT Network

NOTE: The standard poster session at the TRB Annual Meeting will be one hour and 45 minutes (1.75 hours) in duration - the same as lectern sessions. Poster session presenters and attendees are urged to pay close attention to the starting and ending times for each poster session.

The specific poster board assignment will be sent to you later.

IMPORTANT ACTION ITEMS

ASAP: Register for the TRB Annual Meeting and make your hotel reservation. **Meeting registration is required for all participants** (presenters, moderators, discussants, etc.) in lectern sessions, poster sessions, and workshops. Register at <http://www.trb.org/AnnualMeeting/Registration.aspx>. Once you've done so, you'll be able to book your hotel room at the discounted TRB rate.

BEFORE DECEMBER 15: Review your event details and complete the Annual Meeting participant confirmation form on the Annual Meeting participant information page described below. If necessary, submit an updated version of your paper to the paper submission website.

Please be sure to complete the Annual Meeting Participant Confirmation Form. It is your responsibility to inform TRB of your participation in the Annual Meeting. **Failure to complete the Annual Meeting participant confirmation form may result in TRB dropping you from the program.** Conversely, if for some reason your plans have changed and you or a designee on your behalf will NOT be able to present your paper at the TRB Annual Meeting, you MUST inform TRB by returning this form. Otherwise, your presentation may be included in the final TRB Annual Meeting program, and your paper may be included in AM Online if you have given TRB the permission to do so when you originally submitted your paper.

NOTE that completing the participant confirmation form does NOT automatically register you for the Annual Meeting.

ANNUAL MEETING PARTICIPANT INFORMATION

<https://annualmeeting.mytrb.org/EventParticipation>

Please visit your Annual Meeting participant information page to review your event details, to complete the Annual Meeting participant confirmation form, and to find important information about how to register for the Annual Meeting and make your hotel reservations. Please note that users of older web browsers may experience problems with the system. Please update to the latest version of your browser or use a different browser (such as Google Chrome) for best results.

The deadline to submit an updated electronic version of your paper to the paper submission website (<https://trr.editorialmanager.com/>) is November 15. Authors should go to <http://www.trb.org/Contact/Pages/910.aspx> for more information on how to submit papers.

GENERAL INFORMATION

General information about the Annual Meeting can be found on our website at:
<http://www.trb.org/AnnualMeeting/AnnualMeeting.aspx>

VISAS - If you will require a visa to enter the United States to attend the Annual Meeting you should apply now. See details and instructions at www.TRB.org/AnnualMeeting.

<https://mail.bham.ac.uk/owa/#path=/mail>

1/2

Appendix F – NB, DATA Analysis

1. Model 1

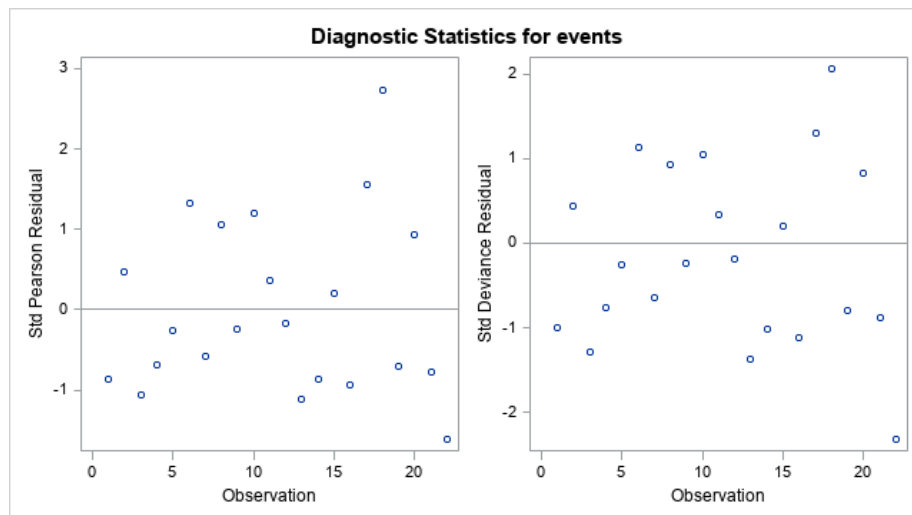
1.1. Analysis of Maximum Likelihood Parameter Estimates – Model 1

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept β_0	1	-2.6887	0.3034	-3.2834	-2.0940	78.52	<.0001
junction_density β_1	1	-0.0516	0.0624	-0.1739	0.0707	0.68	0.4082
Dispersion k	1	0.2083	0.0718	0.1060	0.4093		

1.2. Goodness of fit of Model 1

Criterion	DF	Value	Value/DF
Deviance	20	22.7440	1.1372
Pearson Chi-Square	20	22.8860	1.1443

1.3. Dispersion of observations compared to the model line (Technion & Author, 2021)



2. Model 2

2.1. Analysis of Maximum Likelihood Parameter Estimates – Model 2

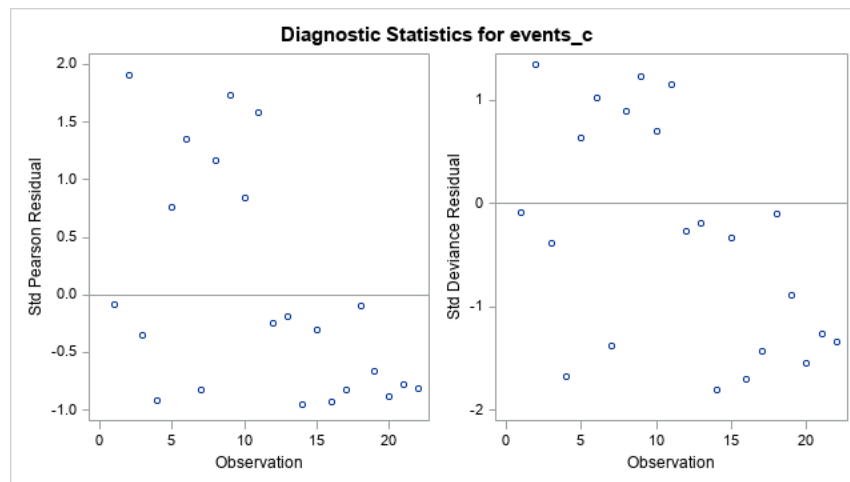
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-5.3430	0.6870	-6.6895	-3.9965	60.49	<.0001
junction_density	1	-0.0912	0.1436	-0.3726	0.1903	0.40	0.5254
Dispersion (k)	1	0.8537	0.5174	0.2602	2.8005		

2.2. Goodness of fit of Model 2

Criterion	DF	Value	Value/DF
Deviance	20	24.7635	1.2382

Pearson Chi-Square	20	18.3359	0.9168
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2.3. Dispersion of observations compared to the model line (Technion & Author, 2021)



Appendix G – JTMT Tender Requirement for Upgrading Emergency Braking System

J – Net Tender Documents

Volume 3 – Part 2 - Section 2.2.1

Chapter 24.1 - Upgrades of the Existing Red Line – Rolling Stock

T8000_TP_01.00X000_ERA_TS_01589_A-01C_03



JERUSALEM TRANSPORTATION
MASTER PLAN TEAM

3.2.4 The upgraded Vehicles shall be capable of delivering Train-to-Track data (line and destination code) as required for the automatic route request in the J-Net System.

3.3 Emergency Brake:

3.3.1 The emergency brake controlled by the control handle shall be cancellable by the driver.

3.3.2 The automatic applied emergency brake (not initiated by the driver) shall be reduced to emergency brake 1 standard EN 13452-1. The load category shall be EL4 according to EN 13452-1.1.

3.4 Communication Equipment:

3.4.1 Voice and data radio:

3.4.2 The radio system shall be changed to be compatible with the radio system to be installed on the J-Net System.

3.4.3 WI-FI for passengers

Wi-Fi and Internet access shall be provided for passengers.
Refer to Volume 3 Part 2 Section 2.2.1 Chapter 7 (Wireless
Communication System (Radio)) for technical requirements.

There shall be signage in each Vehicle informing passengers of
the availability of open WI-FI.

3.5 Image transmission/CCTV:

T8000_TP_01.00X000_ERA_TS_01589_C_03

Appendix H – Light Rail and Tram Systems, UK

Financial year	Docklands Light Railway			London Tramlink			Nottingham Express Transit			Midland Metro		
	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)
1983/84	.	.		.	.		.	.		.	.	
1984/85	.	.		.	.		.	.		.	.	
1985/86	.	.		.	.		.	.		.	.	
1986/87	.	.		.	.		.	.		.	.	
1987/88	.	.		.	.		.	.		.	.	
1988/89	0.8	11	72.7	.	.		.	.		.	.	
1989/90	0.7	11	63.6	.	.		.	.		.	.	
1990/91	0.8	21	38.1	.	.		.	.		.	.	
1991/92	1.0	40	25.0	.	.		.	.		.	.	
1992/93	1.1	38	28.9	.	.		.	.		.	.	
1993/94	1.1	86	12.8	.	.		.	.		.	.	
1994/95	1.5	86	17.4	.	.		.	.		.	.	
1995/96	2.0	70	28.6	.	.		.	.		.	.	
1996/97	2.2	70	31.4	.	.		.	.		.	.	
1997/98	2.4	70	34.3	.	.		.	.		.	.	
1998/99	2.6	70	37.1	.	.		.	.		.	.	
1999/00	2.9	70	41.4	.	.		.	.		1.7	16	106,250.0
2000/01	2.9	79	36.7	2.1	24	87,500.0	.	.		1.9	16	118,750.0
2001/02	2.9	74	39.2	2.4	24	100,000.0	.	.		1.6	16	100,000.0
2002/03	3.2	94	34.0	2.5	24	104,166.7	.	.		1.7	16	106,250.0
2003/04	3.4	94	36.2	2.5	24	104,166.7	.	15		1.7	16	106,250.0
2004/05	3.3	94	35.1	2.4	24	100,000.0	1.0	15	66,666.7	1.6	16	100,000.0
2005/06	3.4	94	36.2	2.4	24	100,000.0	1.2	15	80,000.0	1.7	16	106,250.0
2006/07	4.4	94	46.8	2.5	24	104,166.7	1.2	15	80,000.0	1.6	16	100,000.0
2007/08	4.4	94	46.8	2.2	24	91,666.7	1.2	15	80,000.0	1.5	16	93,750.0
2008/09	4.0	110	36.4	2.2	24	91,666.7	1.1	15	73,333.3	1.7	16	106,250.0
2009/10	4.6	149	30.9	2.6	24	108,333.3	1.1	15	73,333.3	1.6	16	100,000.0
2010/11	4.7	149	31.5	2.6	24	108,333.3	1.1	15	73,333.3	1.7	16	106,250.0
2011/12	4.9	149	32.9	2.7	24	112,500.0	1.1	15	73,333.3	1.7	16	106,250.0
2012/13	5.7	149	38.3	2.9	30	96,666.7	1.1	15	73,333.3	1.7	16	106,250.0
2013/14	5.8	149	38.9	3.1	30	103,333.3	1.1	15	73,333.3	1.6	16	100,000.0
2014/15	5.8	149	38.9	3.2	30	106,666.7	1.3	20	65,000.0	1.6	16	100,000.0
2015/16	6.0	149	40.3	3.2	34	94,117.6	2.6	37	70,270.3	1.7	21	80,952.4
2016/17	6.0	149	40.3	3.2	36	88,888.9	3.1	37	83,783.8	1.9	21	90,476.2
2017/18	6.1	149	40.9	3.3	35	94,285.7	3.0	37	81,081.1	1.8	21	85,714.3
2018/19	6.1	149	40.9	3.2	35	91,428.6	3.1	37	83,783.8	1.8	21	85,714.3
2019/20	6.1	149	40.9	3.2	35	91,428.6	3.1	37	83,783.8	2.0	21	95,238.1

Financial year	Sheffield Supertram			Tyne and Wear Metro			Manchester Metrolink			Blackpool Tramway			Edinburgh Trams		
	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)	Fleet KM PA (m)	Fleet	Tram km PA (k)
1983/84	.	.		5.1	88	57,954.5	.	.		1.2	75	16,000.0	.	.	
1984/85	.	.		6.3	88	71,590.9	.	.		1.2	75	16,000.0	.	.	
1985/86	.	.		5.8	88	65,909.1	.	.		1.2	75	16,000.0	.	.	
1986/87	.	.		5.9	88	67,045.5	.	.		1.2	75	16,000.0	.	.	
1987/88	.	.		5.6	90	62,222.2	.	.		1.2	76	15,789.5	.	.	
1988/89	.	.		5.4	90	60,000.0	.	.		1.3	79	16,455.7	.	.	
1989/90	.	.		5.8	90	64,444.4	.	.		1.2	79	15,189.9	.	.	
1990/91	.	.		5.9	90	65,555.6	.	.		1.3	81	16,049.4	.	.	
1991/92	.	.		5.9	90	65,555.6	.	.		1.3	79	16,455.7	.	.	
1992/93	.	.		5.6	90	62,222.2	2.0	26	76,923.1	1.4	81	17,284.0	.	.	
1993/94	.	.		5.5	90	61,111.1	1.9	26	73,076.9	1.4	81	17,284.0	.	.	
1994/95	1.1	25	44,000.0	5.6	90	62,222.2	2.1	26	80,769.2	1.4	81	17,284.0	.	.	
1995/96	2.5	25	100,000.0	5.4	90	60,000.0	2.1	26	80,769.2	1.3	76	17,105.3	.	.	
1996/97	2.8	25	112,000.0	5.0	90	55,555.6	2.3	26	88,461.5	1.3	76	17,105.3	.	.	
1997/98	2.7	25	108,000.0	4.8	90	53,333.3	3.2	26	123,076.9	1.2	76	15,789.5	.	.	
1998/99	2.4	25	96,000.0	4.8	90	53,333.3	3.4	26	130,769.2	1.2	76	15,789.5	.	.	
1999/00	2.4	25	96,000.0	4.8	90	53,333.3	3.6	32	112,500.0	1.2	75	16,000.0	.	.	
2000/01	2.4	25	96,000.0	4.7	90	52,222.2	4.4	32	137,500.0	1.2	81	14,814.8	.	.	
2001/02	2.4	25	96,000.0	4.7	90	52,222.2	4.6	32	143,750.0	1.3	75	17,333.3	.	.	
2002/03	2.5	25	100,000.0	6.3	90	70,000.0	4.6	32	143,750.0	1.1	76	14,473.7	.	.	
2003/04	2.5	25	100,000.0	5.8	90	64,444.4	4.6	32	143,750.0	0.9	76	11,842.1	.	.	
2004/05	2.4	25	96,000.0	5.6	90	62,222.2	4.4	32	137,500.0	0.8	76	10,526.3	.	.	
2005/06	2.4	25	96,000.0	5.5	90	61,111.1	4.4	32	137,500.0	0.8	76	10,526.3	.	.	
2006/07	2.4	25	96,000.0	5.8	90	64,444.4	3.8	32	118,750.0	0.9	75	12,000.0	.	.	
2007/08	2.4	25	96,000.0	6.2	90	68,888.9	4.0	32	125,000.0	0.7	74	9,459.5	.	.	
2008/09	2.5	25	100,000.0	5.6	90	62,222.2	3.9	32	121,875.0	0.7	73	9,589.0	.	.	
2009/10	2.4	25	96,000.0	5.6	90	62,222.2	3.4	44	77,272.7	0.6	73	8,219.2	.	.	
2010/11	2.4	25	96,000.0	5.6	90	62,222.2	3.8	47	80,851.1	0.5	31	16,129.0	.	.	
2011/12	2.4	25	96,000.0	5.7	90	63,333.3	4.6	56	82,142.9	0.2	31	6,451.6	.	.	
2012/13	2.5	25	100,000.0	5.5	90	61,111.1	5.9	70	84,285.7	0.8	26	30,769.2	.	.	
2013/14	2.2	25	88,000.0	5.5	90	61,111.1	8.4	81	103,703.7	0.9	26	34,615.4	.	.	
2014/15	2.2	25	88,000.0	5.6	90	62,222.2	9.1	98	92,857.1	0.9	26	34,615.4	0.9	27	33,333.3
2015/16	2.3	26	88,461.5	5.6	90	62,222.2	11.5	111	103,603.6	1.0	26	38,461.5	1.1	27	40,740.7
2016/17	2.4	32	75,000.0	5.6	90	62,222.2	11.6	120	96,666.7	1.0	26	38,461.5	1.2	27	44,444.4
2017/18	2.4	32	75,000.0	5.5	90	61,111.1	11.6	120	96,666.7	1.0	28	35,714.3	1.4	27	51,851.9
2018/19	2.6	32	81,250.0	5.5	90	61,111.1	12.9	120	107,500.0	1.0	28	35,714.3	1.4	27	51,851.9
2019/20	2.5	32	78,125.0	5.2	89	58,427.0	12.8	120	106,666.7	1.1	28	39,285.7	1.4	27	51,851.9

Appendix I – Tender Requirement for Speed Supervision and Enforcement System

J – Net Tender Documents

Volume 3 – Part 2 – Section 2.2.1

Chapter 1 – RSS

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- 4.3.2 All new J-Net Trains shall operate in tunnels (in compliance with IS 5350 and EN 45545-2 - Fire Test to railway components), having speed supervision and enforcement and keeping a safety interval between two trains.
- 4.3.3 All new J-Net trains shall be able to stop at pre-determined locations with the required accuracy in order to comply with a platform screen doors specification for the underground stations.
- 4.3.4 SPADs mitigation and speed supervision and enforcement measures shall be in accordance with Volume 3, Part 4 - Preliminary Hazard Analysis - and shall also be addressed in the Safety Case.
- 4.3.5 All on-board speed supervision and enforcement measures shall be upgradable via a “universal” interface (such as ATO system upgrade) using common and standard equipment and communication protocols for supplier independency.
- 4.3.6 Sections of the line with gradient equal or steeper than 7% shall have either a Block Zone or speed supervision and enforcement which shall maintain a safe distance between two consecutive Trains.
- 4.3.7 Special attention shall be paid to the following situations:
 - 4.3.7.1 Trains shall obey speed limit signs and shall be stopped automatically ahead of a restrictive signal.
 - 4.3.7.2 Where a Train approaches a restrictive signal, and brakes using the service brake before the signal, then, provided the Train's speed does not exceed the maximum allowed speed at that point, in the event of the signal changing to permissive, the Train shall be able to continue on the Route without stopping.

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