Report

Crossrail Safety Risk Model Update

Prepared for – Crossrail

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EXECUTIVE SUMMARY

Crossrail (CRL) developed the Crossrail Safety Risk Model (CSRM) [1], initially named the Train Accident Risk Model (TARM), to understand the nature of the risk profile associated with the planned operation of the railway. The railway is now operational as the Elizabeth Line with:

- Rail for London Infrastructure (RFLI) as the infrastructure manager;
- MTREL as the operator, referred to as the Crossrail Train Operating Company (CTOC) in this report; and
- London Underground as operators for some stations.

This model provides a structured representation to assess the risk from seven major hazardous events on the railway that could lead to injuries and/or fatalities, and identifies the dominant contributors to the risk. These seven were selected by Crossrail as they were considered to be the hazards with the most system interfaces that might need assessment to inform designs and future operations. RFLI have developed their own risk model to cover all hazards and assess the full risk profile for the Elizabeth Line.

The CSRM provides a structured means for considering any proposed options for mitigating risk. In order to support the top level safety justification for the Central Operating Section (COS), the risk models for the following seven hazardous top events have been updated to Issue 6.0 using Crossrail-specific data, and upon an improved understanding of how the railway operates:

- Collision between trains (Appendix A);
- Derailment (Appendix B);
- Train fire (Appendix C);
- Flooding (Appendix D);
- Train held in section (Appendix E);
- Station fire (Appendix F);
- Platform Train Interface (PTI) (Appendix H).

The CSRM was developed to cover both the COS and the Mainline (i.e. Western, Heathrow and Eastern) Sections of Crossrail. Only the risk models for the COS have been updated to version 6.0 as it was updated to support the Top Level Safety Justification for the COS, for which the Western, Heathrow and Eastern Sections are out of scope.

For Western, Heathrow and Eastern sections, the Crossrail Safety Risk Model version 4.0 [1] should be viewed. Note that this only includes the route up to Maidenhead on the Western Section as this was the scope of the route at the time of development and it has not since been updated.

The model was developed for a number of potential uses for both the design and operation of the Elizabeth Line as follows:

- The model provided a design risk baseline against which significant changes to the design basis or operating concept could be evaluated. It allowed the model to be used as a tool to inform decisions on the proposed changes as part of design, and it can be used to assess changes going forward in operation;
- The model provides a means for assessing risk reduction associated with implementing proposed control measures. The model results can be input into Cost Benefit Analysis (CBA) studies and then used to demonstrate that the risk of railway operation has been reduced so far as is reasonably practicable (SFAIRP);
- The model enabled the CRL design team to influence and assess the implications of detailed risk assessments undertaken by the suppliers of key systems such as the signalling system or rolling stock;
- It can identify the risk to the railway system from human errors; thus allowing dominant human errors to be targeted for specific task analysis and mitigation where required;

- It can be used to support the safety case for the operation of the railway in accordance with Regulation 19 of the Railways and Other Guided Transport Systems (Safety) Regulations 2006 (ROGS).

The model consists of a set of Fault Tree and Event Tree Analyses, which are used to quantify the frequency, consequences and risk associated with each of the seven hazards. Risk is measured in Fatalities and Weighted Injuries (FWI) which is a composite measure of the level of harm, taking into account both (major and minor) injuries and fatalities. It equates major and minor injuries to fatalities by applying weighting factors. The industry standard[i] weighting factors for major and minor injuries which are used are as follows:

- 1 fatality = 10 major injuries;
- 1 fatality = 200 minor injuries (RIDDOR Reportable);
- 1 fatality = 1000 minor (non-RIDDOR reportable) injuries; NB: given most of the CSRM modelled events have the potential to result in multiple fatalities, the CSRM consequences conservatively weight all minor injuries as reportable minor injuries and therefore, this weighting has not been used.

This safety risk model has been based on industry recognised risk models (the mainline railway Safety Risk Model (SRM) and the London Underground Model (LU Model)) and has been modified to model the specifics of the Elizabeth Line COS Operation. Factors such as route kilometres, train kilometres and passenger loadings were used to ensure the CSRM reflects the risk associated with the Elizabeth Line COS Operation.

Collective Risk Results

The overall, collective risk (from all seven hazards) was found to be 6.30E-01 FWI per year.

The table below ranks the seven hazards in order of their contribution to the overall, collective risk. The frequencies of the seven major hazards are expressed in terms of the number of expected events per year. The average consequence shows a best estimate of the number of FWIs that result from one realisation of the hazard i.e. in one accident event. This gives an indication of how severe each hazard is and allows a comparison of the hazard severities. The risk, measured in FWI per year, is the product of frequency (events per year) and consequence (FWI per event).

Collective Risk Results (Ranked)

Top Event Hazard	Frequency (events/yr.)	Average period between events (years)	Average Consequence (FWI/event)	Risk (FWI/yr.)	% Total Risk
PTI	4.48E+01	0.022	1.32E-02	5.91E-01	93.8%
Derailment	4.01E-02	24.93	4.12E-01	1.65E-02	2.6%
Train held in section	2.09E+01	0.048	6.55E-04	1.37E-02	2.2%
Flooding	2.55E-02	39.27	1.92E-01	4.88E-03	0.78%
Train Fire	1.75E-01	5.728	1.28E-02	2.24E-03	0.36%
Station Fire	2.67E-01	3.751	4.40E-03	1.17E-03	0.19%
Collision	8.46E-04	1182.52	8.44E-01	7.14E-04	0.11%
Total	**6.62E+01**	**1.51E-02**	**9.52E-03**	**6.30E-01**	**100%**

Collective Risk by Exposed Group

The CSRM defines four different exposed groups of people who are expected to interact with the CRL system in different ways and hence have a different risk exposure:

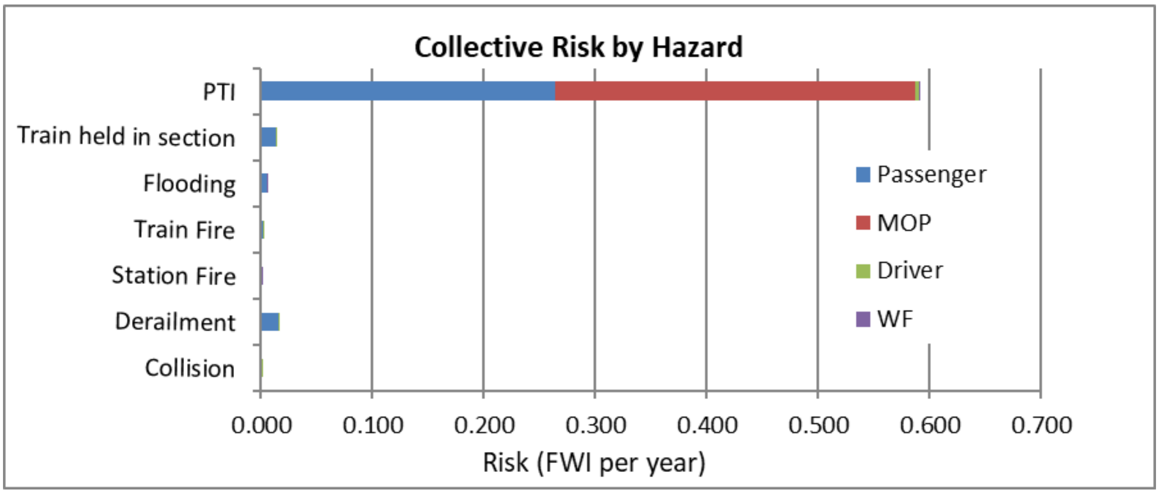
- Passengers: defined as CRL passengers within all the paid areas and on the train;

[i] Note that RSSB have recently updated their weighting factors but the data used from SRM v8.5 retains the listed weightings and thus no updates have been made to the CSRM on this basis. It is also aligned with the weightings used by the TfL Risk Team in their QRA models [29].

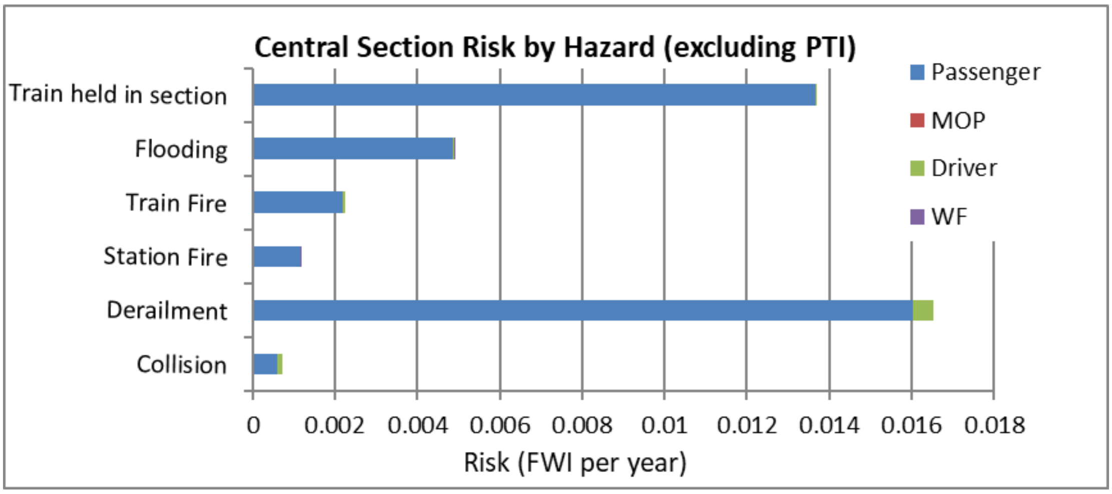
- Drivers: defined as employed drivers who are in control of a CRL train at the time of the event;
- Workforce: defined as Elizabeth Line staff who are not drivers i.e. staff located at stations (note this does not include track workers);
- Member of Public (MOP): defined as persons other than passengers, drivers or workforce (with the exception of track workers who are completely outside the scope of this study).

The different risk exposure experienced by these groups is reflected in the figure below:

Risk (FWI per year) by hazard and by exposed group



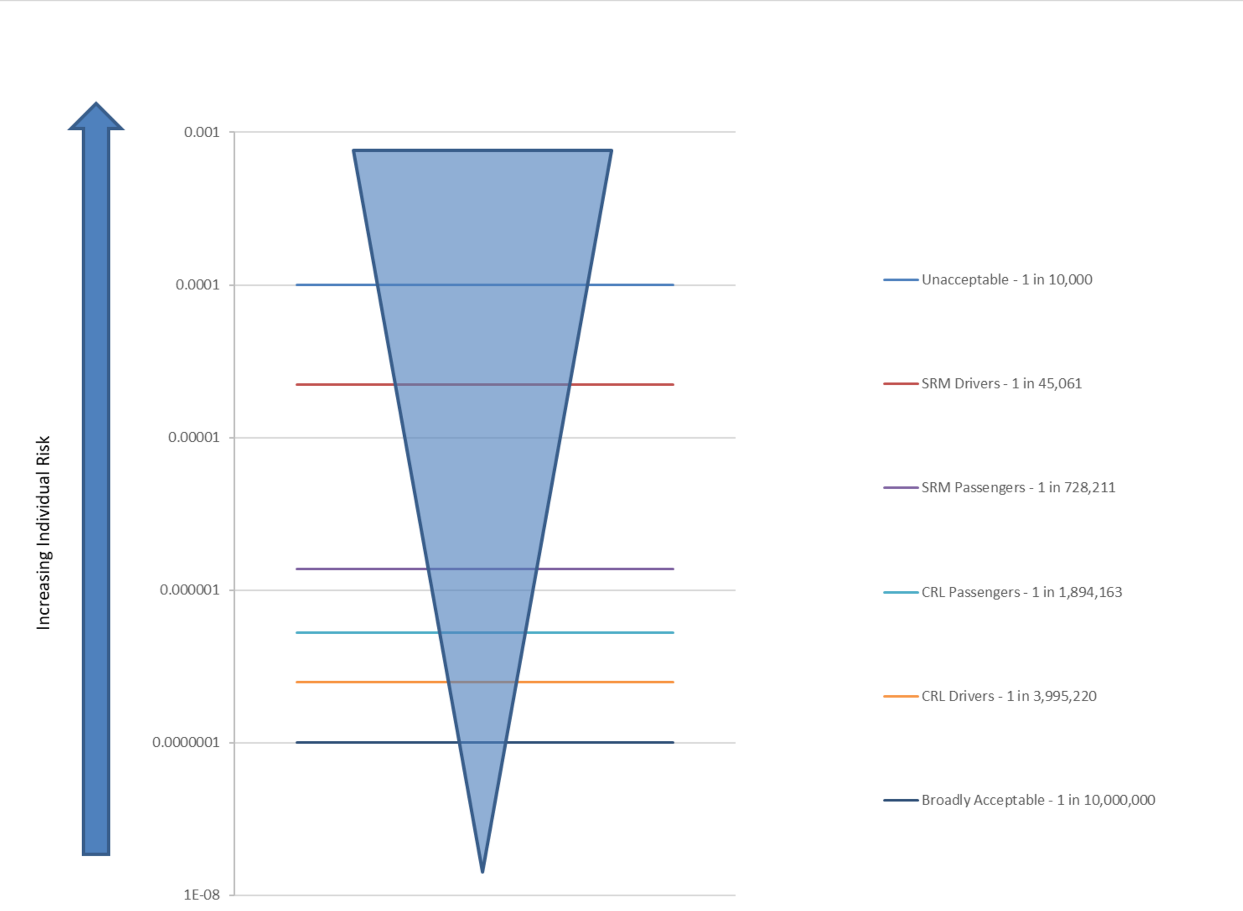
Risk (FWI per year) by hazard and by exposed group (excluding PTI)



Individual Risk

Individual risk is defined as the probability of a fatality per year (note this excludes any contribution from major or minor injuries) to which a type of individual is exposed. Individual risk for the COS for Elizabeth Line passengers and drivers is presented below with a comparison to the equivalent GB Mainline figures. Note this is only the contribution from five of the seven hazards modelled for Crossrail, Flooding, and Train Held in Section (THIS) are excluded as there is no like for like comparison data for these.

Individual risk (Fatality Probability per year per Person) with Comparison to National Figures



The results of this CSRM indicate that individual risk falls into the "tolerable region" (as is the case for most population groups in the UK railway industry). For the 5 hazards used in the comparison, the levels of passenger and driver individual risk are lower than the National average for mainline trains. This is partly because the average length of each passenger journey travelled on the Elizabeth Line is lower than that for the GB Mainline network. The remainder of the reduction in individual risk is due to the improvements within the rolling stock, infrastructure and signalling system in the central section.

The development of this CSRM has been achieved through discussions, meetings and workshops with competent people to ensure that the fault sequences contained in the models are comprehensive [1]. The fault sequences developed in the model were based on industry recognised risk models i.e. the mainline railway Safety Risk Model (SRM) [3] and the London Underground Model (LU Model) [2], which have been modified to model the specifics of the Elizabeth Line COS Operation (see Section 3.1).

Technical failures which have the direct potential for a catastrophic consequence for the seven hazardous events under consideration have been modelled and take into account design reliability targets and requirements specified in the relevant CRL technical specifications as well as improved supplier data where available. The baseline failure data used in the model was, again, from the industry accepted SRM and LU models (see data tables in Appendices A to H) and was modified and scaled appropriately (based on the meetings with CRL engineers) to model the Elizabeth Line Operation.

The CSRM version 4 [1] has been formally reviewed and accepted by an Independent Peer Review by Crossrail Engineering Safety.

ISSUE RECORD

Issue	Date	Author Name	Reviewer Name	Approver Name	Revision History
4.0	21-Mar-12	Jackie Beaton Steven Burke Yan Chan Robert McTaggart Gary White	Gordon Dixon	Gordon Dixon	Final issue of the Risk Model at design stage, accepted by Crossrail and ISA in March 2012
5.0	29-Apr-22	Rachael Johnson/Jasmine Gill	Anna Holloway	Gordon Dixon	Update of the models to reflect final Crossrail System. Formal issue to support Revenue Service.
5.1	09-May-22	Rachael Johnson/Jasmine Gill	Anna Holloway	Gordon Dixon	Minor correction made to table in Executive Summary. No updates made to any of the appendices.
6.0	30-Sept-22	Anna Holloway	Rachael Johnson	Gordon Dixon	Updates to Issue 6, including normalisers and updates to address CRL and RFLI comments.

DISTRIBUTION

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TABLES

FIGURES

ABBREVIATIONS

Abbreviation	Description	Abbreviation	Description
ALARP	As Low As Reasonably Practicable	OHLE	Overhead Line Equipment
ATO	Automatic Train Operation	PSD	Platform Screen Doors
ATP	Automatic Train Protection	QRA	Quantitative Risk Assessment
CBA	Cost-Benefit Analysis	RAM	Reliability, Availability and Maintainability
COS	Central Operating Section	RCC	Route Control Centre
CRL	Crossrail	RFLI	Rail for London (Infrastructure)
CSM	Common Safety Methods	RM	Restricted Manual
CSRM	Crossrail Safety Risk Model	ROGS	Railways and Other Guided Transport Systems (Safety) Regulations 2006
CTRL	Channel Tunnel Rail Link	RSSB	Railway Safety and Standard Board
DOO	Driver Only Operation		
ECS	Empty Coaching Stock	SPAD	Signal Passed at Danger
EMU	Electrical Multiple Unit	SRM	Safety Risk Model (published by RSSB)
FWI	Fatalities and Weighted Injuries	SM	Supervised Manual
GPH	General Purpose Hand Portables Mobiles	TBTC	Transmission Based Train Control
GSM-R	Global System for Mobile Communications for Railways	TOC	Train Operating Company
HEART	Human Error Assessment and Reduction Technique	TPH	Trains per Hour
HSE	Health and Safety Executive	TPWS	Train Protection and Warning System
LU	London Underground	TSI	Technical Specifications for Interoperability
MOP	Member of Public	UPS	Uninterrupted Power Supply
NR	Network Rail	WSP	Wheel Slide Protection

1 INTRODUCTION

1.1 Overview

Crossrail (CRL) developed the Crossrail Safety Risk Model (CSRM) [1], initially named the Train Accident Risk Model (TARM), to understand the nature of the risk profile associated with the planned operation of the railway. The railway is now operational as the Elizabeth Line with:

- Rail for London Infrastructure (RFLI) as the infrastructure manager;
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This model provides a structured representation to assess the risk from seven major hazardous events on the railway that could lead to injuries and/or fatalities, and identifies the dominant contributors to the risk. These seven were selected by Crossrail as they were considered to be the hazards with the most system interfaces that might need assessment to inform designs and future operations. RFLI have developed their own risk model to cover all hazards and assess the full risk profile for the Elizabeth Line.

The CSRM provides a structured means for considering any proposed options for mitigating risk. In order to support the top level safety justification for the Central Operating Section (COS), the risk models for the following seven hazardous top events have been updated to Issue 6.0 using Crossrail-specific data, and based on an improved understanding of how the railway will operate:

- Collision between trains (Appendix A);
- Derailment (Appendix B);
- Train fire (Appendix C);
- Flooding (Appendix D).
- Train held in section (THIS) (Appendix E);
- Station fire (Appendix F);
- Platform Train Interface (PTI) (Appendix H);

The CSRM was initially developed to cover both the COS and the Mainline (i.e. Western, Heathrow and Eastern) Sections of Crossrail. Only the risk models for the COS have been updated to version 6.0 as it was updated to support the Top Level Safety Justification for the COS, for which the Western, Heathrow and Eastern Sections are out of scope.

For Western, Heathrow and Eastern sections, the CSRM version 4.0 [1] should be viewed. Note that this only includes the route up to Maidenhead on the Western Section as this was the scope of the route at the time of development and it has not since been updated.

The operating environment between the COS and the Mainline is clearly different and therefore the model is based on a combination of two relevant industry standard risk models. These are:

- The London Underground (LU) Quantitative Risk Assessment (QRA) Model [2]; and
- The Rail Safety and Standards Board (RSSB) Safety Risk Model (SRM) [3].

In general, the LU QRA was used as the basis for most of the risk modelling in the COS and the SRM was used for the mainline sections of the model, however some hazards do use a combination of both. Modifications were then made to capture the characteristics of the Crossrail line and operating environment. Each section of Crossrail, i.e. Western, Heathrow, Central and Eastern, was modelled separately to capture the different passenger loadings, timetabling and characteristics of each. A series of workshops were held for the CSRM v4.0 [1] to review a preliminary version of each of the six top event models (excluding PTI) with the relevant stakeholders from Crossrail to ensure that the model was developed to provide a complete and accurate assessment of the risk associated with the operation of the Crossrail railway. The briefing packs and records of these workshops are given in the References for the CSRM version 4 [1]. Following a recommendation raised by Risktec that PTI is a significant risk, a PTI was developed at a later stage using the LU Risk Model as a basis. This can also be found in reference [1].

1.2 Purpose

The CSRM provides an assessment of the risk to Elizabeth Line passengers, drivers, members of the public (MOP) and staff present at stations arising from the seven hazards identified, noting areas of exclusion as listed in section 1.3.

The model was developed for a number of potential uses for both the design and operation of the Elizabeth Line as follows:

- The model provided a design risk baseline against which significant changes to the design basis or operating concept could be evaluated. It allowed the model to be used as a tool to inform decisions on the proposed changes as part of design, and it can be used to assess changes going forward in operation;
- The model provides a means for assessing risk reduction associated with implementing proposed control measures. The model results can be input into Cost Benefit Analysis (CBA) studies and then used to demonstrate that the risk of railway operation has been reduced so far as is reasonably practicable (SFAIRP);
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- It can be used to support the safety case for the operation of the railway in accordance with Regulation 19 of the Railways and Other Guided Transport Systems (Safety) Regulations 2006 (ROGS).

1.3 Scope

The CSRM is designed to model the risk due to the seven top event hazards in Section 1.1; the risk arising due to hazards other than these seven is explicitly outside the scope of the model as per the original request from Crossrail. As detailed in Section 1.1, these hazards were selected by Crossrail as they were considered to be the hazards with the most system interfaces that might need assessment to inform designs and future operations. RFLI have developed their own risk model to cover all hazards and assess the full risk profile for the Elizabeth Line.

Other items that are outside the current scope of the model are:

- Events within depots or sidings – these were specifically agreed to be outside the scope of the model at Issue 4. This was aligned with the approach of RSSB's SRM at the time of development (SRM v6), and is aligned with the TFL QRA which models only passenger operations;
- Terrorism – No account is taken of acts of terrorism in the model.

Furthermore, the table below shows which fault scenarios are within, or outside, the scope of the CSRM.

	In scope	Out of scope
Collision between trains	• Head on Collision • Forward Collision • Side-on Collision • Slow Collision • Auto-reverse (AR)	• Terrorism • Depots/sidings • Unplanned AR
Derailment	• Over-speed • Points related derailment • Track/Rolling Stock Faults • Running into Obstructions • Other causes (e.g. extreme weather) • AR	• Terrorism • Depots/sidings • Unplanned AR
Train fires	• Inside car • Outside car	• Terrorism • Depots/sidings • Unplanned AR
Station fires	• Public area (e.g. platforms, lifts, escalators) • Non-public area (e.g. machine rooms)	• Terrorism • Fire in retail outlets
Train held in section	• Overheating train • Injuries during evacuation • Loss of power or traction • Localised failures	• Terrorism • Depots/sidings • Unplanned AR
Flooding	• Seepage of Groundwater • Firewater Main Burst • Tidal Flooding • Extreme Weather (e.g. high rainfall)	• Terrorism • Depots/siding • Unplanned AR
Platform Train Interface	• Fall into gap between stationary train and platform • Fall from platform • STF while boarding/alighting • Struck by train door or PSD • Entrapment between train door and PSD • Dragged along platform • Trespass • Suicide/attempted suicide • AR at Paddington and Abbey Wood	• Terrorism • Depots/siding • Unplanned AR • Trespass and suicide not accessed from platform

1.4 Software

All Fault Tree and Event Tree models in this analysis were constructed using Reliability Workbench software (from Isograph) v15.

1.5 Document Structure

The document is laid out as follows:

- Section 1 – Introduction.
- Section 2 – Description of the system.
- Section 3 – Methodology adopted in developing the model.
- Section 4 – Results, together with a discussion of the key findings of the analysis.
- Section 5 – Conclusions.

The structure of the model, calculations and references are presented in more detail in Appendices A to H:

- Appendix A – Collision Between Trains;
- Appendix B – Derailment;
- Appendix C – Train Fires;
- Appendix D – Flooding;
- Appendix E – Train Held in Section;
- Appendix F – Station Fire;
- Appendix H – Platform Train Interface.

Appendix G presents the derivation of general normalisers and scaling factors used in all the models.

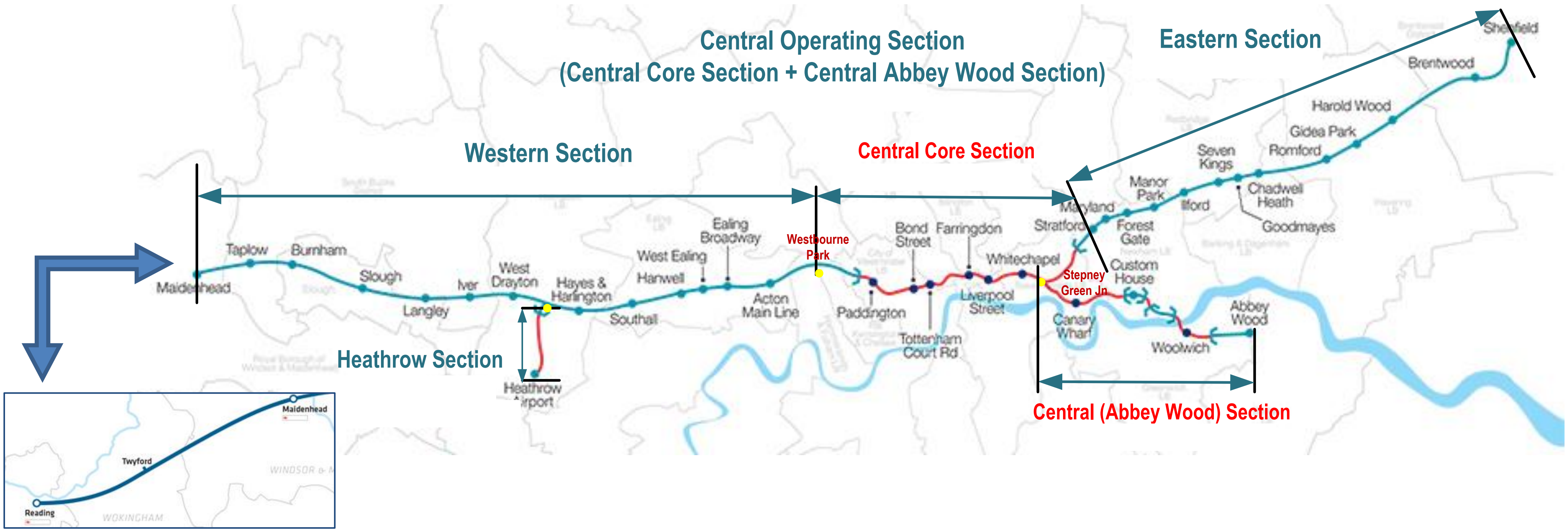
2 SYSTEM DESCRIPTION

2.1 Crossrail Sections

For the purposes of the CSRM, Crossrail has been split into four sections as illustrated in Figure 1. Only the COS has been updated from Issue 5.

- Western: Maidenhead[2] to Westbourne Park;
- Heathrow: Heathrow Airport to Airport Junction;
- Central Operating Section: Westbourne Park to Stratford (Central Core Section) and Stepney Green Junction to Abbey Wood (Abbey Wood Section);
- Eastern: Stratford to Shenfield.

Figure 1 Map of Crossrail Route Sections



[2] The Elizabeth Line operates out to Reading. However, the Western Section of the CSRM only includes the route up to Maidenhead as this was the scope of the route at the time of development and it has not since been updated.

The boundaries from West/Central and Central/East sections are drawn at locations where the Signalling System switches from Conventional Signalling to Automatic Train Operation (ATO) and vice versa. This takes place on the move at Westbourne Park and whilst the train is stationary in the platform at Stratford. Specific boundaries are defined as:

- Boundary with Western Section EB – At the COS Rule Book and GE/RT8000 Mainline Rule Book interface. This is 20 chains west of the CCOS Datum 0 kilometres marker, MLN1 00 1612 [11]
- Boundary with Western Section WB – At the COS Rule Book and GE/RT8000 Mainline Rule Book interface. This is 11 chains west of the CCOS Datum 0 kilometres marker, MLN1 00 1847 [11]
- Boundary with Eastern Section EB – Eastern end of Stratford Station Crossrail platforms, ELR LTN 3mi, 70ch [13] i.e. 40 chains east of the CCOS-NR Anglia Network Boundary.
- Boundary with Eastern Section WB - Eastern end of Stratford Station Crossrail platforms, ELR LTN 3mi, 70ch [13] i.e. 40 chains east of the CCOS-NR Anglia Network Boundary.

As described in Section 1.1, only the risk models for the COS have been updated to this version 6.0 in order to support the Top Level Safety Justification for the COS for which the Western, Heathrow and Eastern sections are out of scope. For Western, Heathrow and Eastern sections, the CSRM version 4.0 [1] should be viewed. Note that this only includes the route up to Maidenhead on the Western Section as this was the scope of the route at the time of development and it has not since been updated.

2.2 Key Data

Key information on Crossrail used within the risk model is given in this section. The calculation of this data is given in Appendix G.

To provide best value to the project, a pragmatic approach was taken to updating the model at Issue 5 and 6. Key assumptions were reviewed and updated where applicable, and data was updated with supplier data where available. Historic references used in Issue 4 are retained as they still form a basis for development of the model structure.

Note that numbers within tables have been rounded for presentation purposes. In certain cases, this might make it appear that totals in tables are incorrect.

2.2.1 *Route Km*

Route distances (in km) for the COS are presented in Table 1. Distances are calculated from the Sectional Appendices [11, 13, 14].

Table 1 Route km in Each Section

Section	Section Description	Km
CENTRAL	Westbourne Park –Stratford	15.9
CENTRAL – AW	Stepney Green Junction - Abbey Wood	13.2
	Total	**29.1**

Table 2 contains the data used in the risk model for the lengths of route in tunnels, stations and in the open for the COS. These are derived from the Crossrail Sectional Appendix [11] and Anglia Sectional Appendix [13].

Table 2 Route km Data Used in Risk Model for Central Section

Location	Route km	Total
Tunnel (including stations)	24.2	**29.1**
Open (including stations)	4.9	
All Stations	2.4	**2.4**
Open (minus stations)	4.4	**29.1**
Twin bore (minus stations)	21.0	
Single bore (minus stations)	1.3	
Station Surface	0.5	
Station Subsurface	1.9	

2.2.2 *Train Distances (km)*

In order to scale the data in the risk model it was necessary to derive the total distance travelled (in km) by the entire Crossrail fleet of trains across the Central Section in one year. This was done using the trains per hour (TPH) data as presented in Section 2.3.3.2 of the Crossrail Programme Functional Requirements [6]. As explained in Appendix G, current timetables for the Elizabeth Line are not used as it is currently operating a phased opening service. The final model represents the full service, as initially specified in the Crossrail Programme Functional Requirements [6] which have not fundamentally changed. The results for the COS are shown in Table 3. See Appendix G for the derivation.

Table 3 Train km Data

Type	Train distance per year (km)
Open	602,346
Single track, twin bore tunnel	3,574,657
Subsurface station	384,222
Surface station	63,302
Twin track, single bore tunnel	176,071
COS Total	**4,800,599**

2.2.3 *Passenger Loadings*

This is defined as the average number of passengers on each CRL train during the peak and off-peak periods. Appendix G describes the calculation of these figures, which is based on the Crossrail Rolling Stock Energy Consumption Targets & Carbon Footprint [7]. For Issues 5 and 6 of the models, these values were revisited with reference to the latest estimates within the Station Demand Matrices [15] and were determined to still be representative of the system, and thus no updates made. See Appendix G for more details on this.

Table 4 Number of Passengers per Train

Section	Crush Peak	Peak time	Off-peak time
Central Operating Section	1500	499	325

2.2.4 *Loading Bands*

There are three loading band categories (Peak, Off-peak and Night) and two different calculations of these loading bands for the COS; one is based on the proportion of trains, for train accident-related risks, while the other is related to the proportion of time spent in each band based on the operational day to account for events that may be independent of train operations e.g. within stations.

Note: for all but THIS, each of the hazards uses *either* the proportion of trains *or* the proportion of time loading bands; nowhere are these used together. The exception of this is THIS. This is because the loss of power frequency could occur at times that trains are not running so the proportion of time in each band is used for the LOGTCENTRAL tree which considered power failure. These are displayed in Table 5, along with a list of the models they are used for.

Table 5 Loading Bands (By Proportion of Trains)

	Proportion of trains in the COS	Proportion of time in each Band
Peak	0.299*	0.179
Off-Peak	0.701	0.577
Night	0.000	0.245
Models used for:	Collision between trains; Derailment; Train fire; Train Held In Section (excluding LOGTCENTRAL);	Station fire; Flooding; Train Held in Section (LOGTCENTRAL)

* Note that, as discussed in Appendix G, crush loading is assumed to occur for 10% of the peak period.

As shown in Table 5, the model assumes that no Elizabeth Line passenger trains operate at night (i.e. between close and start of service) and so no hazards that depend on train movement e.g. collision between trains, may be initiated at this time. However, during the 0.245 proportion of time that night operations occur (as a proportion of 24 hours), hazards that do not require train operations may still occur e.g. flooding. The loading bands are calculated as discussed in Appendix G based on the TPH data [6].

2.3 Signalling and Train Protection

2.3.1 *Overview of Signalling and Train Protection*

In the COS the trains normally operate under ATO from Westbourne Park to Stratford and down to Abbey Wood. Bi-directional operation is permitted by the ATO/ATP system, though this will be a rare occurrence. ATP provides train protection in the COS as part of the ATO/ATP signalling system.

Management of hazards associated with the Signalling System is presented in the Signalling Safety Case [21].

2.3.2 *Transfer from ATO to Conventional Signalling*

The switch from the conventional signalling to ATO signalling (for eastbound trains) occurs on the move at Westbourne Park where ATP is automatically enforced and the driver manually selects whether or not to enable ATO (i.e. choose between entering in full Automatic Mode (AM) or Protected Manual (PM)).

The switch back to conventional signalling on leaving the COS takes place while the train is stationary in the platform at Stratford as part of the timetabled station stop.

For westbound trains, these two switchovers are the reverse processes to that described above.

An interface/transition risk report [10] was produced post Issue 4 of the CSRM to determine if additional work was required to account for transitional risks in the models. It was concluded that the failures of either TPWS or CBTC (depending on the side of the transition) to protect the train passing signals or exceeding Movement Authority are already captured in the COS and Mainline risk models and remain in place through the interface area. Therefore, risks associated with the transition are already inherently included within the CSRM and no specific interface area events were required to be added into the models.

2.3.3 *Features of ATO and ATP*

The ATO/ATP signalling system allows trains to proceed on the basis of their relative positions and speeds, which govern their movement based on a "distance to target" method; allowing the speed to be regulated in order to maintain safe separation between trains.

Emergency braking is designed into the system to allow individual or all trains to be stopped under failure or in an emergency, whilst still maintaining safe train separation and control.

The ATO system is integrated with the opening and closing of the train doors and Platform Screen Doors (PSD) at stations.

2.3.4 *Summary of the Operating Modes in the COS*

The system has the following operating modes [30]:

Automatic Mode (AM): In AM the train drives automatically according to the train movement authority, with the driver present in the cab authorising the start from each station and with train protection and speed supervision provided by ATP. The on-board subsystem supervises the vital and non-vital constraints and has control over all train movements. This is the normal method of operation in the Central Operating Section.

Protected Manual (PM): In PM mode, the driver operates the unit within the limits displayed to them on the DMI and is supervised by the ATC on-board system, which is fully responsible for the unit's protection. The ATP system is active but the ATO system is either not operational or the driver has elected not to use it (e.g. for route learning purposes at non-peak times). The driver has control of the train within the safe speed profile imposed by the ATP, which takes account of speed restrictions and conflicting trains. In order to drive in this mode, authorisation will be required from the Route Control Centre (RCC) for each individual train.

On-Sight Mode (OM): OM is a sub mode of PM, with a maximum speed limit of 40kph. OM is applied to enter a station, where no PED closed and locked information is available for the relevant platform due to a failure. A pre-requisite for activating OM is an appropriate OM Movement Authority either In Possession Movement Authority (IPMA) or Proceed on Sight Movement Authority (PSMA) issued by the signaller.

Staff Accountable Mode (SA): In SA mode the train will be manually operated by the driver under dedicated operational procedures with limited ATP supervising a configured SA mode speed (<40kph). The driver must respect all existing wayside signals and the signaller instructions, and is fully responsible for the unit movement. The on-board ATC subsystem displays the speed to the driver via the DMI screen.

SA Mode is used for a delocalised unit to localise by passing two Signalling & Control System balises and to sieve to obtain valid movement authority; to allow unit movements under limited ATC supervision or into territories not equipped with ATC supervision or when a relevant on-board system has failed; for coupling purposes or to approach buffer stops closer than is allowed in other driving modes which consider buffer stops as vital movement authority limit.

Auto Reverse Mode (AR): AR is a special driving mode for shortening turnaround times at predefined turnback locations and in emergency situations. The ATO has control over the train, with the driver on the train but not necessarily in the cab. This is for use on empty stock trains travelling between Abbey Wood station and sidings and between Paddington Low Level station and Westbourne Park. Also an Automatic Reverse option i.e. in ATO mode (with ATP) driver may reverse train (e.g. at the turn back sidings at Westbourne Park or anywhere over crossovers) where driver may walk back through the train but these moves will normally be undertaken without passengers and the ATP system will protect other CRL trains in the area. Passengers will only be present when used in emergency scenarios as part of Unplanned AR.

Restricted Manual Mode (RM): RM Mode is not a standard selectable driving mode of the ATC on-board subsystem. It will not be realised within the ATC on-board subsystem but by an STM isolation switch of the RST; the ATC on-board subsystem is powered off. It corresponds to the STM state Power Off. The train is within an ATO area but the ATO and ATP are not active, or have been overridden due to a fault or emergency situation. The driver has control but the train is limited to a low maximum speed (35 kph [21]). This is a function of last resort used to remove defective trains from the system. Trains running in such a mode will de-train passengers at the first available station. Communication with RCC will be required for each individual train operating in this mode. The driver operates the train under on-sight procedures being fully responsible for train movement and train safety, getting verbal movement authority from the signaller while observing the trackside signs.

2.4 Rolling Stock

The Crossrail Rolling Stock is a class 345, electrical multiple unit (EMU), built by Bombardier and is equipped to operate from a 25kV AC overhead line equipment system. The length of train is 205m (9 car formation), with a maximum speed of 145km/h (90mph). Note the line speed in the COS is limited to 100km/h.

Train braking is a hybrid of electric and pneumatic systems for brakes. Normal regenerative braking (using disc brakes) is in place with adhesion management (sanding). Moreover, emergency friction braking (with a braking performance of 12% g) is provided and the trains are fitted with wheel slide protection (WSP).

The train has an open gangway. There are no interior doors between carriages apart from one fire barrier (20 minute fire rated) in the middle of the train, between car 4 and 5, which can be positioned open or closed in normal running.

The train car has train-borne ventilation installed. In the event of a fire inside the car, the train-borne ventilation is activated by the driver to extract smoke from the car and prevent smoke spreading to the full length of the train. The train-borne ventilation system also has an external fire sensor. This allows for a switch to re-circulation mode in the event of an external train car fire, which prevents smoke ingress into the car and re-circulates the air inside the car. The drivers can also close the dampers to minimise smoke ingress.

2.5 Tunnelling and Infrastructure

2.5.1 *Overview of Tunnels*

The features of each of the main tunnels on Crossrail [25] are documented in Table 6 with distances taken form the Crossrail Sectional Appendix [11]:

Table 6 Crossrail COS Tunnels

Tunnel	Locations	Length (km)	Features
Royal Oak to Pudding Mill	Royal Oak Portal (Paddington) to Pudding Mill Lane Portal (Stratford)	14.35	Single track, twin bore with cross passages and side walkways
Stepney Green to Abbey Wood	Stepney Green Junction to Victoria Dock Portal (Custom House)	5.22	Single track, twin bore with cross passages and side walkways
Connaught Tunnel	South east of Custom House	1.35	Twin track, single bore with no side walkways. The 4 foot is for both derailment containment and an evacuation walkway.
Thames Tunnel	North Woolwich Portal to Plumstead Portal	3.312	Single track, twin bore with cross passages and side walkways

Evacuation walkways are installed in the tunnel sections (with the exception of the Connaught tunnel), which can accommodate a wheelchair, and persons with reduced mobility will be assisted by volunteers. Note that tunnel lighting will be switched on in the event of evacuation. An Uninterrupted Power Supply (UPS) will supply three hours of emergency tunnel lighting.

Cross-passages connect the two tunnel bores in the COS, which are alarmed enabling the RCC to stop trains in the event that they are opened.

Note that the Connaught Tunnel is different in nature (twin track, single bore) to the rest of the Crossrail tunnels and was considered as such in the risk model. There are no side evacuation walkways due to the restricted space in this tunnel. Instead, the 4 foot is the designated evacuation walkway.

2.5.2 *Tunnel Ventilation*

Tunnel ventilation is provided on Crossrail, which provides mitigation to the hazards of train fires (to extract smoke from the tunnels) as well as in the event of a train being held in a tunnel section (controls tunnel temperature and humidity). Note that because of the larger trains, and therefore tunnels on Crossrail, as compared to LU, greater heat is generated in the tunnel.

In the event of fire in the Central tunnels (Central Core tunnels and Thames), as a general principal, tunnel ventilation pushes smoke in the direction of travel and passengers evacuate in the opposite direction.

There is significant redundancy designed into the tunnel ventilation system, including a dual power feed. The tunnel ventilation is designed such that single equipment failure does not compromise the performance. The system is more likely to be in a degraded state in the event of an equipment fault rather than being completely failed. The fans are sized such that they more than meet the design requirements. If a shaft is taken out of service the system is automatically reconfigured for an extended ventilation section. This is discussed in Appendix C, Train Fires.

2.5.3 *Overview of Infrastructure*

Permanent Way

Crossrail is slab track in the COS (with floating slab track under the Barbican, at Tottenham Court Road and a small amount at Bond Street [28]) with steel tie bars between sleepers (similar to the Channel Tunnel Rail Link, CTRL).

The rails in the COS are continuously welded (with no fishplates or insulated joints).

All Switches and Crossings (S&C) are fixed nose centre-block crossings manufactured from manganese steel with weldable legs [23].

Derailment containment is implemented in areas of large negative consequence [21], specifically at:

- Approaches to station platforms – to minimise the risk of a derailed vehicle sweeping the platform
- Approaches to underground junction areas – to minimise the risk of a derailed vehicle impacting a head wall
- Approaches to portals headwalls – to minimise the risk of a derailed vehicle impacting a tunnel head wall.
- Connaught tunnel – to minimise the risk of a passenger train on the opposite track colliding with the derailing train.

Stations

Liverpool Street (which is taken as a reference station for the model) has two separate exits for evacuation, which like all Crossrail stations, meets the 4 to 6 minute time to evacuate criteria.

Full height (floor to ceiling) PSDs are installed at all subsurface stations, i.e. 8 of the 10 stations in the COS. Thus the PSDs and tunnel ventilation system will act to seal the tunnel bore in the event of a fire. Places of refuge are designed into the stations and manual call points are provided for passengers to alert staff of a fire.

Heavy duty escalators (with built in cleaning brushes to remove debris) are used in Crossrail stations.

The lifts used on Crossrail do not require machine rooms and have separate risers to house wiring for other services. These will not therefore be an ignition source in the lift shaft. Designated lifts are provided for firefighting personnel.

2.6 Operations (including Communications)

2.6.1 *Operations Overview*

Bi-directional signalling capability is designed into the system in the COS, though it is not used as a regular mode of operation. This is to provide the capability to move a train out of a tunnel if required. If the signalling system has failed, the driver can proceed at line of sight (in RM mode) to take passengers to the nearest station.

Although not part of normal operation, there is a level of driver familiarity regarding the override of the system in the event of a failure, achieved through simulator training. Screen messages are displayed in the cab to instruct the driver on how to move the train out of a section when required.

There are no train dispatch staff, but MTREL have confirmed [16] that customer experience staff will be present on platforms including at all times during passenger service at non-PSD stations, Custom House and Abbey Wood. Staff are trained to undertaken the train sweep procedure as per the station teams competence management system requirements. Staff at non-PSD stations are also trained in use of the Emergency Stop Plungers (ESPs).

In the event of a train fire, the operational principle is for the traction power supply (i.e. the Overhead Line Equipment (OHLE)) to remain operational such that trains can always be moved to the nearest station for evacuation. A decision might be taken by Operations to isolate this as part of a dynamic risk assessment and there is also potential for the traction system to fail.

If train air conditioning is known not to be working, the train will not be allowed to enter a tunnel section.

2.6.2 *Communication System*

The trains operate under Driver Only Operation (DOO) with revenue protection staff only on-board intermittently. As required by DOO Railway Group Standards, a secure train-to-shore radio system is provided via the Global System for Mobile Communications for Railways (GSM-R) system, which is installed throughout the route [22]. General purpose hand portables (GPH) mobiles (mobile phones restricted to use on GSM-R system and unable to connect to the public networks) are available for general purpose communication along the route. There is an "all trains stop" functionality that ensures the adjacent line can be protected in the event of an incident.

2.7 Power

2.7.1 *Traction Power*

The entire Crossrail route (including tunnels) is electrified using a 25-0-25KV AC auto-transformer system delivered by the overhead line equipment (OHLE) system [27]. Adjacent lines between Plumstead Portal and Abbey Wood are electrified at 750V DC. Crossrail does not have DC traction power.

Rigid Overhead Conductor beam used in tunnels and an overhead contact system (wires) is used in open section.

3 METHODOLOGY

3.1 Overview

As discussed in Section 1.1, the SRM and LU QRA models have been used as the basis for the CSRM. These industry standard models give great detail as to the numerous initiating causes (contained within the fault trees) that can lead to an accident and also to the combinations of escalation scenarios and mitigating factors (in the event trees) that apply if the top event is realised.

The CSRM update to version 5.0 for the COS mostly consisted of data updates using new information available from Crossrail suppliers, as well as updated values from the LU QRA and SRM. Some models, such as Train and Station Fires, required some modelling changes, which are explained in more detail in their respective appendices. Additional updates to normalisers were made in version 6.0.

The steps undertaken to update the models can be summarised as:

- Where available, new and/or improved information from Crossrail suppliers was sourced and used to update a number of base events that were previously based on expert judgement or LU QRA/SRM models.
- Where Crossrail specific data was not available, the latest industry standard Jubilee Line QRA [2] and RSSB SRM [3] risk models were reviewed to update the corresponding base events within the CSRM; these models were taken as the basis for the CSRM as these have been developed and accepted for use to calculate the risk on LU and GB Mainline, respectively; depending on the top event either the LU QRA alone, or a combination of the LU QRA and SRM may have been required;
- Recommendations for each model from CSRM version 4.0 [1] were reviewed and closed out where possible.
- The final risk results were then produced for each top event hazard and combined to calculate the overall, collective risk and individual (passenger and driver) risk for Crossrail as detailed in Section 4.

3.2 Fault and Event Tree Modelling

3.2.1 *Frequency, Consequence and Risk*

Firstly, a definition of terms must be given:

- Frequency: the number of (hazardous) events of a given type that occur in one period of time; for the CSRM, frequency is measured per year and is therefore calculated as events per year.
- Consequence: the (average) number of combined fatalities and weighted injuries (FWI) that occur given that a (hazardous) event has occurred. This is measured in FWI per event.
- FWI: the aggregate amount of safety harm, which equate injuries of differing degrees with a fatality allowing all risk on the railway to be compared[3]. One FWI is equivalent to:
    - 1 fatality, or
    - 10 major injuries i.e. 0.1 of a fatality per major injury, or
    - 200 minor injuries, i.e. 0.005 of a fatality per minor injury (RIDDOR reportable); or
    - 1000 minor (non-RIDDOR reportable) injuries; NB: given most of the CSRM modelled events have the potential to result in multiple fatalities, the CSRM consequences conservatively weight all minor injuries as reportable minor injuries and therefore, this weighting has not been used.
- Risk: Using the above information, risk is defined as:

  Risk (FWI per year) = frequency (events per year) x consequence (FWI per event)

- Normalised Risk: when comparing the risk between different Crossrail sections or against equivalent LU or National rail figures, a measure of risk expressed in units of FWI per million train km was used, defined as:

  Risk (FWI per million train km) for section = risk (FWI per year) for that section ÷ (10^6 x number of train km operated per year in that section)

3.2.2 *Overview of Fault and Event Trees*

Fault and event tree models were used to quantify the frequency, consequences and risk associated with all the possible hazardous scenarios that could give rise to each of the top event hazards in the risk model.

Fault Tree

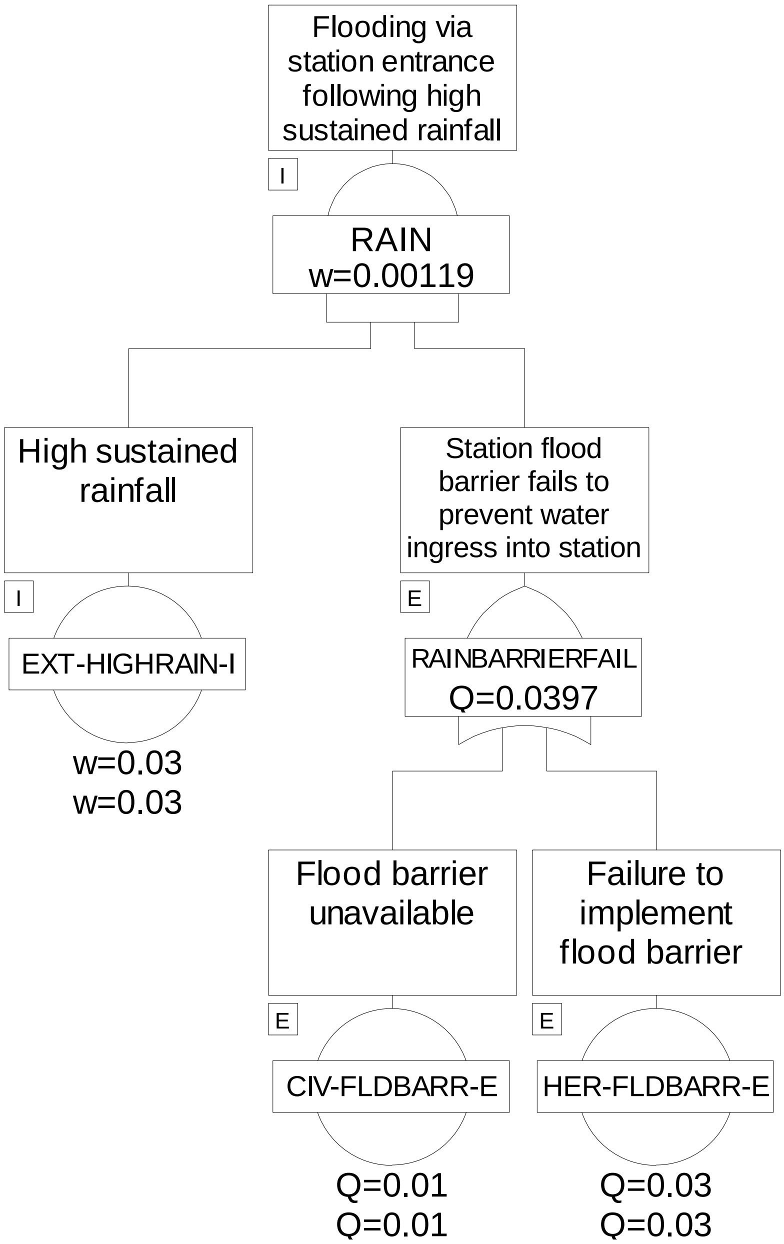
Figure 2 shows an example fault tree model for flooding via a station entrance following heavy rainfall. The fault tree models the possible initiating causes and failed control measures and how these must logically combine such that the top event (in this case flooding due to rainfall) is realised. The different aspects of a fault tree are:

- Base event: either a potential initiating cause of the top event or a failed control measure or other scaling factor that affects the likelihood of the top event occurring (e.g. EXT-HIGHRAIN-I). Note that the model uses two different types of these based on whether the base event is representing a:
    - Frequency (events per year), w: number of initiating events that occur in a year (e.g. EXT-HIGHRAIN-I occurs 0.03 times per year i.e. once every 33.3 years); or an
    - Unavailability (probability), Q: the probability that an event occurs, a control measure fails or simply a scaling factor (e.g. SCA-FLDBARR-E occurs with probability 0.01 i.e. there is a 10% chance the flood barrier will fail when it is required to mitigate a flood).
- Top event: the ultimate event that may occur should the cause(s) occur in combination with the corresponding failed control measure(s) i.e. the realisation of the hazard that may lead to an accident (e.g. Flooding due to high sustained rainfall).

[3] Note that RSSB have recently updated their weighting factors but the data used retains the listed weightings and thus no updates have been made to the CSRM on this basis. It is also aligned with the weightings used by the TfL Risk Team in their QRA models [29].

- OR gate: the event described in the gate will occur should any one or all of the base events occur (e.g. RAINBARRIERFAIL).
- AND gate: the event described in the gate will occur only if all the base events below occur together (e.g. RAIN).

Figure 2 Example Fault Tree



Event Tree

An event tree models the chain of events that could occur following the realisation of a top event i.e. all potential escalation factors that could occur and mitigation measures that might fail. Figure 3 shows the possible event sequences, given that a flood via a station entrance has occurred due to high, sustained rainfall as modelled in the fault tree in Figure 2, from the top event frequency on the left to the consequences of each sequence of events on the right. The different aspects of an event tree are as follows:

- Column: each column represents a step in the escalation of the initiating event (e.g. injury during station evacuation) that ultimately leads to an accident.
- Success/failure branch: a yes or no decision based on the event probability (e.g. a Q=0.1 conditional probability that a peak loaded train is crush loaded).

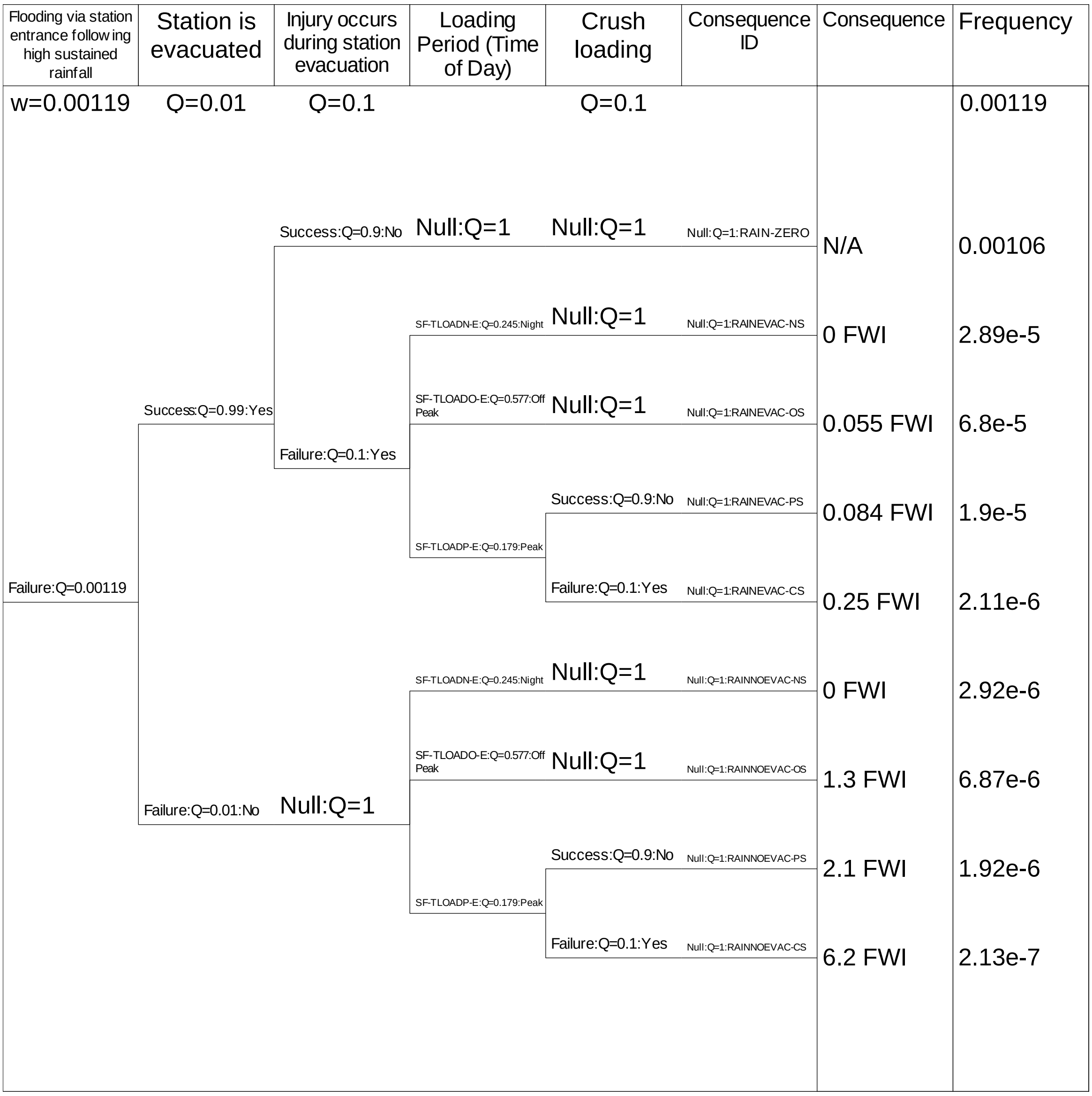
- Partial failure: where there are more than two possible scenarios (e.g. under the passenger loading column the train may be any one of peak, off-peak or night loading).
- Consequence: this is attached to each end state and allocates the FWI for that event e.g. 6.2 FWI casualties for the bottom sequence.

The frequencies calculated for the end of each branch sequence are simply the initiating frequency fed into the event tree from the top event (e.g. w=0.00119 events per year) multiplied by the probability of each branch occurring to the endpoint. The consequences (FWI per event) are then attached to each of these endpoints.

As defined, the combination of each frequency and consequence gives the risk of that particular combination occurring. The sum of all the endpoint risk figures for a given fault and event tree sequence gives the overall risk associated with that particular top event hazard. For the Figure 3 example, consider the following:

- For the bottom sequence the frequency of the endpoint is 2.13E-07 events per year i.e. the initiating frequency multiplied by the relevant probabilities w = 0.00119 x 0.01 x 1 x 0.179 x 0.1 x 1 = 2.13E-07 events per year.
- The consequence is 6.2 FWI per event i.e. 1 x (5.05 fatalities) + 0.1 x (10.1 major injuries) + 0.005 x (25.25 minor injuries) = 6.2 FWI per event.
- Therefore, the risk associated with this endpoint is the frequency (events/year) multiplied by consequence (FWI per event) i.e. 2.13E-07 x 6.2 = 1.32E-06 FWI per year.

Figure 3 Example Event Tree



3.2.3 *Data and Data Sources*

As CRL is a new railway operation there is no historic data from the system with which to populate the model, however, supplier data has been used wherever possible. Where this is not possible, and CRL is comparable in nature, data has been used from established data sources (i.e. LU QRAs and the SRM) scaled or adapted appropriately for CRL. These data sources are considered to provide the most appropriate data for incorporation into the CRL model where Crossrail specific failure rates were unavailable.

A number of documents were also used to populate the model:

- Supplier RAM data/failure rates (various sources; see Appendices for specific sources for each model).
- Programme Functional Requirements [6].
- Rolling Stock Energy Consumption Target & Carbon Footprint [7].

Where there was no data available expert judgement has been used.

3.2.4 *Consequences*

The Crossrail requirement was for each fault sequence to be assigned the number of fatalities, major injuries and minor injuries occurring to passengers, drivers, staff and MOPs i.e. the end of every event tree branch has an assigned FWI value. These have been based on the consequence data from the SRM and the LU Model. This is further discussed in the Appendices.

The definition of injuries are as defined in RIDDOR 1995. It is noted that RIDDOR 2013 updated these categories, however, the previous definitions were retained as this is how historic data used was coded, and how RSSB continued to code it for their Risk Model v8.5 [3]:

- Major Injury – includes consciousness, most fractures, major dislocations and hospital stays of 24 hours or more;
- Minor Injury - physical injuries that are not major, but which result in more than three days' absence from work (for members of the workforce) or require hospital treatment (for passengers and members of the public).

Note that two additional categories of consequences were excluded from the model that are in the GB Mainline SRM i.e. differentiation between reportable and non-reportable minor injuries and class 1 and 2 shock/trauma. This is aligned with the approach taken by London Underground [29].

In addition, the consequences were specified to allow for passenger loadings during peak, off-peak, night and crush loaded conditions.

3.3 Development of the Model: Hazard by Hazard

3.3.1 *Collision between Trains and Derailment (see Appendices A and B)*

At design stage, the LU models developed for the TBTC signalling and train control system introduced on the Jubilee Line were considered to be the most appropriate to use for modelling the ATO/ATP signalled COS of Crossrail as they correctly identify the failure modes and protection available with this type of moving block system that can lead to a collision or derailment. Specific parts of these were then updated in Issue 5.0 and 6.0 to align with the Siemens Fault Trees [17] to make sure that the model correctly reflected the procured Siemens signalling system.

For a derailment caused by a failure of infrastructure (e.g. track faults) or rolling stock faults within the COS, the model takes account of the improvements in design of Crossrail, when compared to the national failure data. The SRM initiating causes were therefore used as the basis for these parts of the model, which were then scaled to take account of the Crossrail specific improvements. This also ensured a consistent basis for the modelling in all parts of the Crossrail network.

Any updates in the values within the SRM and LU QRA were taken account of in the CSRM models update, as well as new signalling failure rate data now available from Siemens [17].

3.3.2 *Train Fires (see Appendix C)*

In the absence of data from Bombardier, the SRM and LU models were reviewed for causal information, and the frequency was taken from the SRM and scaled for the COS. This approach at Issue 5 was reviewed and agreed by RFL Rolling Stock Engineers. Vandalism was adjusted to reflect the COS operation as agreed in workshops. Consequences were taken for open track, single track, twin bore tunnels and twin track, single bore tunnels as well as stations from the SRM. However, these were adjusted to model the characteristics of the COS, e.g. walkways, tunnel ventilation, sub surface stations, code red, train borne ventilation etc.

The Train Fire version 5.0 update took account of any changes in the frequency and consequence information within the reference models. This update also included implementing changes to be made as part of the Optimum Train Fire Evacuation Risk Assessment [8] including adding a number of new factors within the event trees.

At Issue 6.0, normalisers were updated and the risk as a result of an extended ventilation section was added to the model [18].

3.3.3 *Flooding (see Appendix D)*

The Crossrail flooding model is based on the LU QRA model. This was reviewed to model the specific flooding mechanisms, flood warning and protection, and evacuation procedures on the Crossrail network. The SRM was not used for the flooding model.

The version 5.0 update also took account of updates to base data, and version 6.0 accounted for updated normalisers.

3.3.4 *Train held in Section (see Appendix E)*

For the Central tunnels, the fault trees were based on the LU QRA model. For all other parts of Crossrail outside these Central tunnels, i.e. open sections of the Central section, the fault and event trees were based on the SRM.

The most recent LU model is a very detailed assessment of all causes that could potentially lead to a train being held in a tunnel section. This was then scaled to account for the proportion of events that would lead to different length delays. The different causes of trains being stuck in tunnels were reviewed, including consideration of the reliability, availability and maintainability (RAM) data that was made available by Crossrail.

When creating the models, the event tree modelling and consequences from a number of existing models, both the LU models for ventilation hazard and loss of power, as well as the SRM for equivalent NR contributions, were reviewed.

The SRM was used as the basis for the consequences of Train Held in Section for everything except the Central tunnels e.g. for passengers fainting due to overheating or passengers injured due to evacuation for the non-tunnel sections.

For the Central tunnels the consequences were based on the LU QRA but updated with a number of assumptions to add injuries (major and minor) to the consequences (as the LU models only look at fatalities). These Central tunnel consequences were then generally reviewed to more accurately model the specific issues on Crossrail.

The version 5.0 update also took account of RAM and failure data related to the signalling and ventilation systems and version 6.0 accounted for updated normalisers.

3.3.5 *Station Fires (see Appendix F)*

The LU models provided the initial basis for the structure of the station fires model as the issues relating to underground fires and their mitigations are well developed and understood for LU. The LU approach also considers the risks associated with evacuation.

The LU model has more detailed information on the root causes of fires and the combination of events that result in fires.

The Station Fire version 5.0 update required a complete restructure of the model and style of frequencies used (from frequency per asset per year to overall frequency per year for all assets) due to a restructure in the LU QRA models. There were no updates to the model at Issue 6.0 as is was not impacted by the updated normalisers.

3.3.6 *Platform-Train Interface (see Appendix H)*

The Platform-Train Interface (PTI) fault and event trees were developed to cover the 10 stations within the COS. Both the LU QRA and SRM were used as the basis for various events within the model, adapted for the operations on CRL. The COS stations include both stations with PSDs and stations without; the LU data was used to determine injuries related to PSD stations, whereas at non-PSD stations the models were used in combination.

The update for the CSRM version 5.0 took account of recent LU QRA and SRM updates, as well as, new information related to the gap between the PSDs and train doors related to entrapment risk. Version 6.0 accounted for updated normalisers.

4 RESULTS

4.1 Collective Risk (From All Hazards)

4.1.1 *Collective FWI Risk*

Collective Risk is the total risk from the seven hazards within the CSRM for the COS, experienced by all the exposed groups and expressed in FWI per year. The collective risk associated with Elizabeth Line COS operations is **6.30E-01 FWI per year**.

Table 7 presents the key risk results by hazard. It ranks the seven hazards in order of their contribution to the overall, collective risk. The consequence shows, on average, the number of FWIs that result from one realisation of the hazard i.e. in one accident event. This shows how severe each hazard is and allows a comparison of the hazard severities.

Table 7 Collective Risk Results (Ranked)

Top Event Hazard	Frequency (events/yr.)	Average period between events (years)	Average Consequence (FWI/event)	Risk (FWI/yr.)	% Total Risk
PTI	4.48E+01	0.022	1.32E-02	5.91E-01	93.8%
Derailment	4.01E-02	24.93	4.12E-01	1.65E-02	2.6%
Train held in section	2.09E+01	0.048	6.55E-04	1.37E-02	2.2%
Flooding	2.55E-02	39.27	1.92E-01	4.88E-03	0.78%
Train Fire	1.75E-01	5.728	1.28E-02	2.24E-03	0.36%
Station Fire	2.67E-01	3.751	4.40E-03	1.17E-03	0.19%
Collision	8.46E-04	1182.52	8.44E-01	7.14E-04	0.11%
Total	**6.62E+01**	**1.51E-02**	**9.52E-03**	**6.30E-01**	**100%**

4.1.2 *Collective FWI Risk by Exposed Group*

Different affected groups will have different exposures to each hazard. For example, the safety of staff located at stations is unlikely to be affected by a Train Held in Section. Table 8 and Figure 4 show the risk for each hazard, broken down by the four exposed person groups.

Table 8 Collective Risk by Hazard and Exposed Group (Ranked) including suicide

Hazard	Collective Risk (FWI/yr.)				
	Passenger	MOP	Driver	Workforce	Total
PTI	2.64E-01	3.23E-01	3.54E-03	2.19E-04	5.91E-01
Derailment	1.60E-02	9.66E-07	5.04E-04	0.00E+00	1.65E-02
Train held in section	1.37E-02	0.00E+00	3.40E-05	0.00E+00	1.37E-02
Flooding	4.87E-03	0.00E+00	1.09E-05	1.98E-06	4.88E-03
Train Fire	2.20E-03	0.00E+00	4.40E-05	0.00E+00	2.24E-03
Station Fire	1.17E-03	0.00E+00	0.00E+00	6.18E-06	1.17E-03
Collision	6.08E-04	0.00E+00	1.06E-04	0.00E+00	7.14E-04
Total	**3.03E-01**	**3.23E-01**	**4.24E-03**	**2.27E-04**	**6.30E-01**

Figure 4 Collective Risk by Hazard and Exposed Group

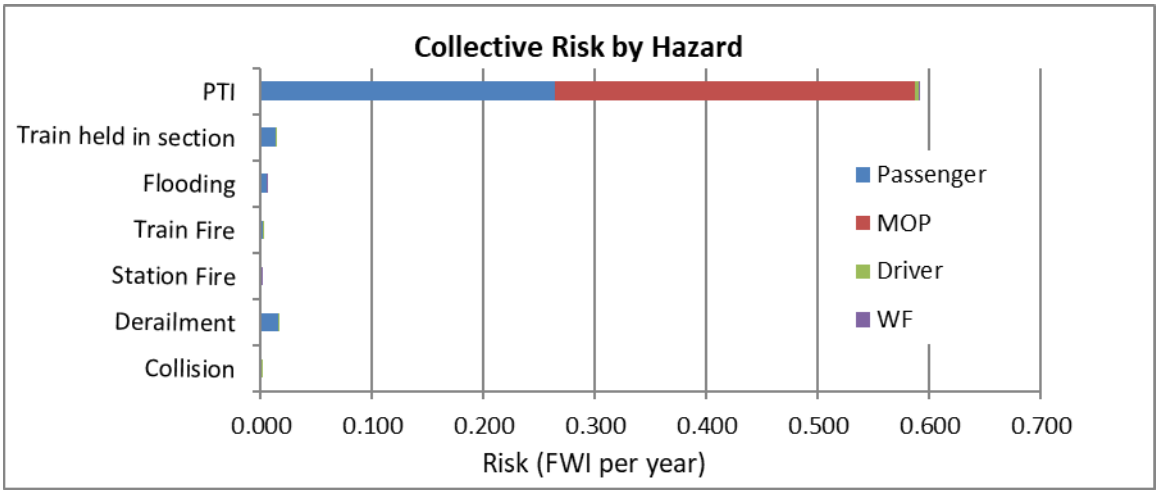
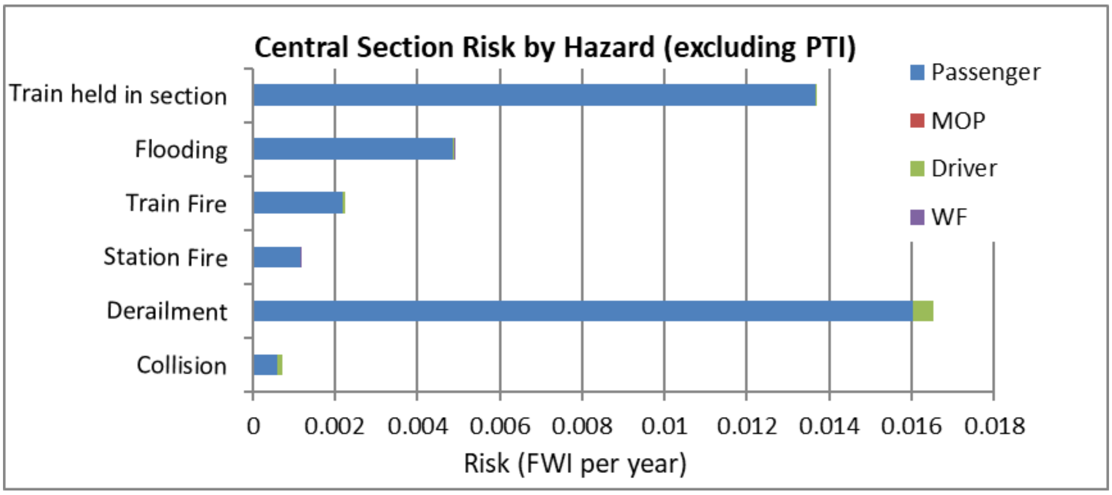


Figure 5 Collective Risk by Hazard and Exposed Group (excluding PTI)



Excluding suicide risk, the collective risk is dominated by the risk to passengers (63.4%), followed by MOP (35.8%), which is largely PTI trespass risk, with a small contribution from drivers (0.7%). The risk to the workforce (staff located at stations) is much smaller (0.05%). Most hazards, as shown, follow a similar risk pattern in terms of the split by exposed groups i.e. passenger risk is the primary affected group, with drivers and MOP each having a small contribution.

Although PTI dominates, this is lower than the LU due to the presence of platform screen doors at 8 of 10 of the stations. A direct comparison cannot be made to the GB Mainline but it is also expected to be lower for the same reasons.

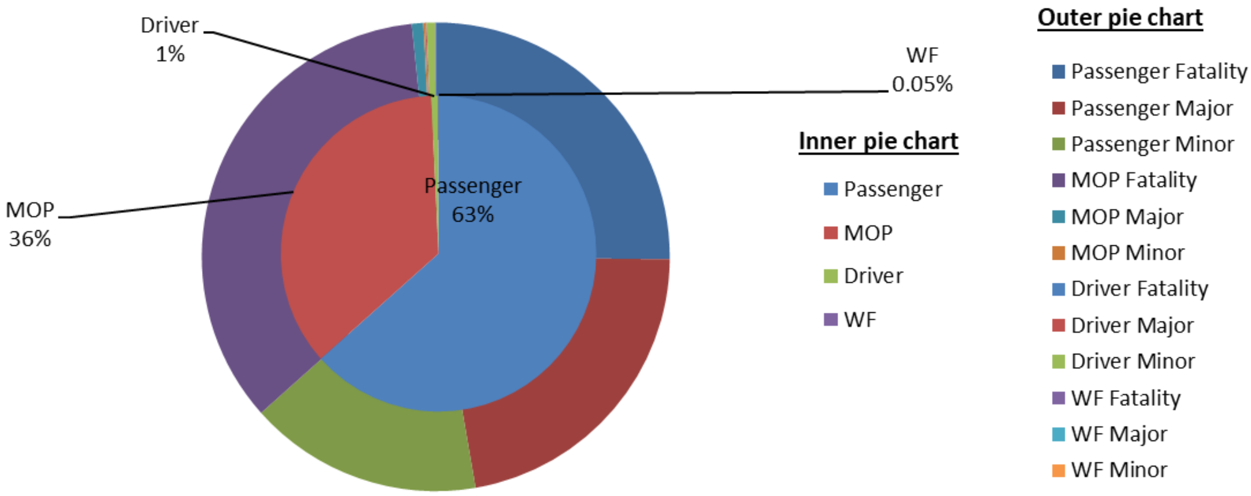
Driver risk is found to be mostly from PTI, Derailments and Collisions with some contribution from Train Fire, Train Held in Section and Flooding. For derailment and collisions, this is because of the position of the driver in the train and the role of the driver in implementing evacuations in emergency situations. MOP risk is zero in most hazards, except in PTI, and a very small proportion in Derailment.

Since risk (in FWI) is a composite measure made up of contributions from fatalities, major injuries and minor injuries, it is instructive to break down the risk contribution by different casualty types. Table 9 and Figure 6 show the risk contribution broken down for each affected group (passengers, drivers, MOP and workers) and in terms of the casualties (fatality, major or minor injury). The inner pie chart of Figure 6 shows the FWI breakdown by exposed group and the outer pie chart presents a further breakdown by the casualty contributions within each exposed group.

Table 9 Affected Group Casualty Breakdown (excluding MOP suicide)

Affected Group	Casualty	FWI per year	Percentage of total risk
Passenger	Fatality	1.20E-01	25.2%
	Major	1.06E-01	22.1%
	Minor	7.70E-02	16.1%
MOP	Fatality	1.67E-01	34.9%
	Major	3.78E-03	0.791%
	Minor	5.10E-04	0.107%
Driver	Fatality	1.57E-04	0.033%
	Major	3.86E-04	0.081%
	Minor	2.78E-03	0.583%
Workforce	Fatality	1.63E-04	0.034%
	Major	5.76E-05	0.012%
	Minor	7.14E-06	0.001%

Figure 6 Affected Group Casualty Breakdown (excluding MOP suicide)



4.1.3 *Collective Fatality Risk by Exposed Group*

A different and useful way to look at the risk is by considering the contribution to the risk from fatalities *only*. Table 10 shows the fatality risk for each hazard (ranked), to which each group is exposed. Figure 7 shows this same information in a bar chart.

Table 10 Fatality Risk (Per Year) by Hazard and Exposed Group (Ranked and Including Suicide)

	Fatality risk (per year)					
Top Event Hazard	Passenger	MOP	Driver	Workforce	Total	% Total
PTI	1.01E-01	1.67E-01	0.00E+00	1.57E-04	2.68E-01	93.36%
Derailment	8.51E-03	0.00E+00	9.60E-05	0.00E+00	8.61E-03	3.00%
Flooding	4.73E-03	0.00E+00	1.09E-05	6.08E-07	4.74E-03	1.65%
Train held in section	3.01E-03	0.00E+00	1.02E-05	0.00E+00	3.02E-03	1.05%

	Fatality risk (per year)					
Top Event Hazard	**Passenger**	**MOP**	**Driver**	**Workforce**	**Total**	**% Total**
Train Fire	1.41E-03	0.00E+00	2.03E-05	0.00E+00	1.43E-03	0.50%
Station Fire	1.01E-03	0.00E+00	0.00E+00	5.35E-06	1.01E-03	0.35%
Collision	2.35E-04	0.00E+00	1.89E-05	0.00E+00	2.54E-04	0.09%
Total	1.20E-01	1.67E-01	1.56E-04	1.63E-04	2.87E-01	100.00%

Figure 7 Fatality Risk (Per Year) by Hazard

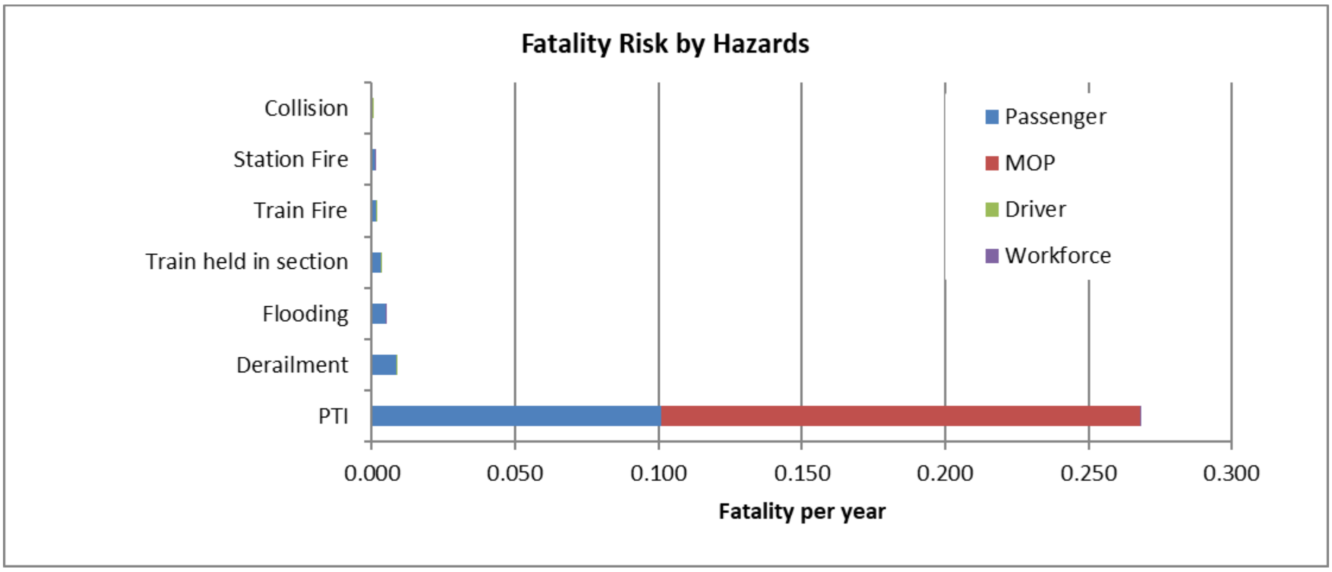
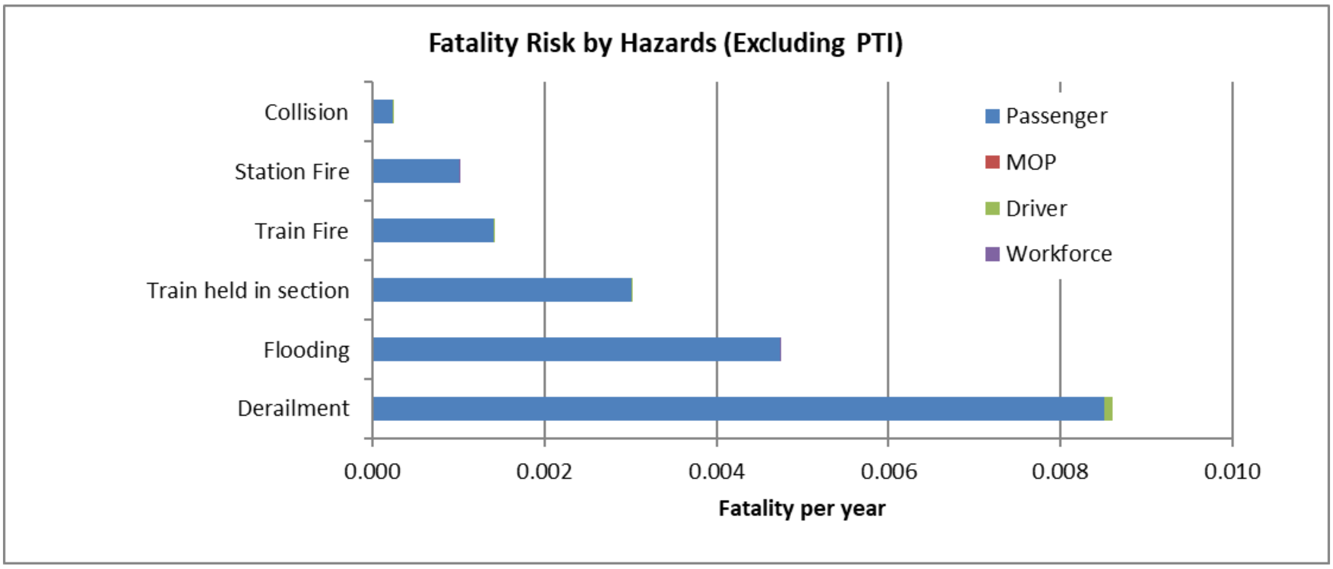


Figure 8 Fatality Risk (Per Year) by Hazard (Excluding PTI)



After PTI, Derailment is the most significant fatality risk contributors (accounting for 45% of the remaining fatality risk) i.e. they are most severe events and can cause multiple fatalities in one event. Flooding is another major hazard that can cause numerous fatalities. However, because of its low initiating frequency of occurrence, the fatality risk contribution is much less than for Derailment. It should be noted that Train Held in Section, which is the third highest FWI/yr. risk contributor, has a low fatality risk per year as it would be rare for such an event to result in a fatality. Collision is the lowest risk contributor in terms of fatality risk; though it can result in multiple fatality events, the frequency is so low such that it is the lowest contributor of fatality risk.

4.1.4 *Comparison to Issue 5*

Table 11 provides a comparison of the updated risk in Issue 6 to Issue 5 of the CSRM. Overall there is a 3% increase in risk. This is predominately due to inclusion of the risk from auto-reverse at the PTI which had been excluded from the total risk profile in Issue 5.

Table 11 Risk Comparison to CSRM Version 5

Top Event Hazard	Risk (FWI/yr.)	% Total Risk	% change from Issue 5	Reason
PTI	5.91E-01	93.8%	4%	0% change for main model, however, AR risk has now been included in this summary report to align with the approach taken for collisions and derailments. The 4% increase is fully attributed to inclusion of the AR risk.
Derailment	1.65E-02	2.6%	-4%	The normalisers were reviewed in line with the sectional appendix. This has led to an increase in single track tunnel train km vs train km in the open. The main change is that the Thames Tunnel is approximately 1km longer than previously estimated in the Operational Concept on which the normalisers were previously determined. In addition to this, multiple track has now been assessed for all open sections of the Central Section (West, East and SE spur), and not just the Abbey Wood area. This has resulted in a reduction in the proportion of multiple track in the open when compared to dual track. This results in lower secondary collision probability for derailment events and lower resultant consequences.
Train held in section	1.37E-02	2.2%	0%	Update to normalisers has had negligible impact.
Flooding	4.88E-03	0.8%	0%	Update to normalisers has had negligible impact.
Train Fire	2.24E-03	0.4%	20%	The update to normalisers has had negligible impact, however, the model now includes a conservative estimate of risk from a fire within an extended ventilation section, in line with risk assessment CRL1-XRL-O7-RGN-CR001-50133, which has increased the risk by 20%.
Station Fire	1.17E-03	0.2%	0%	No updates have been made to this model since Issue 5.

Top Event Hazard	Risk (FWI/yr.)	% Total Risk	% change from Issue 5	Reason
Collision	7.14E-04	0.1%	-44%	The event relating to error in applying TSRs was reduced to be in line with the Siemens signalling model for consistency purposes. This resulted in a large reduction in risk as it is a dominant event within the cutsets. This change was also applied to the derailment model but had less of an impact due to the derailment risk being driven by other factors, such as collision with objects. In addition to this, the normalisers were reviewed in line with the sectional appendix. This has led to an increase in single track tunnel train km vs train km in the open. The main change is that the Thames Tunnel is approximately 1km longer than previously estimated in the Operational Concept on which the normalisers were previously determined. In addition to this, multiple track has now been assessed for all open sections of the Central Section (West, East and SE spur), and not just the Abbey Wood area. This has resulted in a reduction in the proportion of multiple track in the open when compared to dual track. This results in lower secondary collision probability for collision events and lower resultant consequences.
Total	**6.30E-01**	**100%**	**3%**	

4.2 Individual Risk

Individual risk is the probability of fatality per year for a particular person interacting with the Crossrail network. In this report, there are four identified exposed group of people: passengers, drivers, other members of the workforce (staff located at stations) and MOPs. The fatality risk for these groups of people (as shown in Table 10) will differ because of the different way they interact with the Crossrail system.

Individual risk is calculated by dividing the collective fatality risk for the exposed group by the total number of individual people in the group using Crossrail per year. The collective risk is as shown in Section 4.1, Table 9. The total number of individual passengers, as calculated in Appendix G, is estimated to be 212,660 per year. The number of full time drivers is 540 in accordance with discussions with MTREL [16]. Individual risk on the COS is only calculated for Elizabeth Line passengers and MTREL drivers and not for staff located at stations or MOPs:

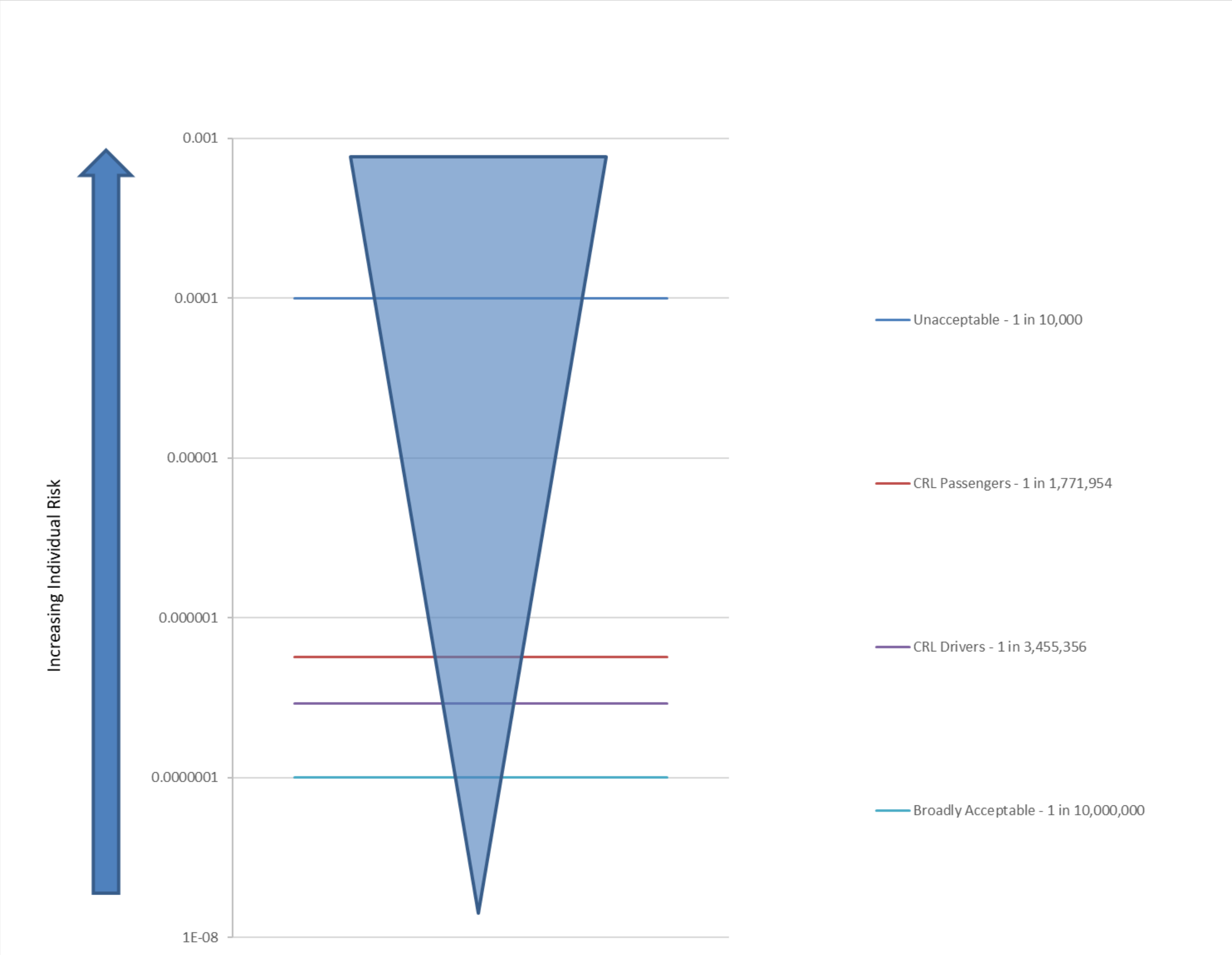
- Staff: these are only considered to be exposed to three of the seven hazards modelled: station fire, flooding and PTI. As well as this is not considered to cover a large enough proportion to present the individual risk, this could be a mix of staff: station operational staff or maintainers which would make it difficult to estimate the numbers to use.
- MOPs: As explained in the RSSB Risk Model [3], in hazardous industries where all operations occur within a discrete, clearly-defined, geographical location, the numbers of exposed members of the public, and therefore individual fatality risk to the public, can be determined. For the GB railway, however, it is only possible to discuss fatality risk to the public population as a whole.

Table 12 and Figure 9 show the individual risk results for both passengers and drivers. Individual risk is expressed as the likelihood of fatality per year per person. The tolerability criteria shown in the plot are based on the limits as defined in the HSE's guidance on Reducing Risks, Protecting People [9].

Table 12 Individual Risk to Passengers and Drivers

	Passenger	Driver
Collective risk (fatalities per year)	1.20E-01	1.56E-04
No. of people in exposed group	2.13E+05	5.40E+02
Individual Risk		
Individual risk per year	5.64E-07	2.89E-07
Probability of fatality per year	1 in 1,771,954	1 in 3,455,356

Figure 9 Individual Risk to Passengers and Drivers



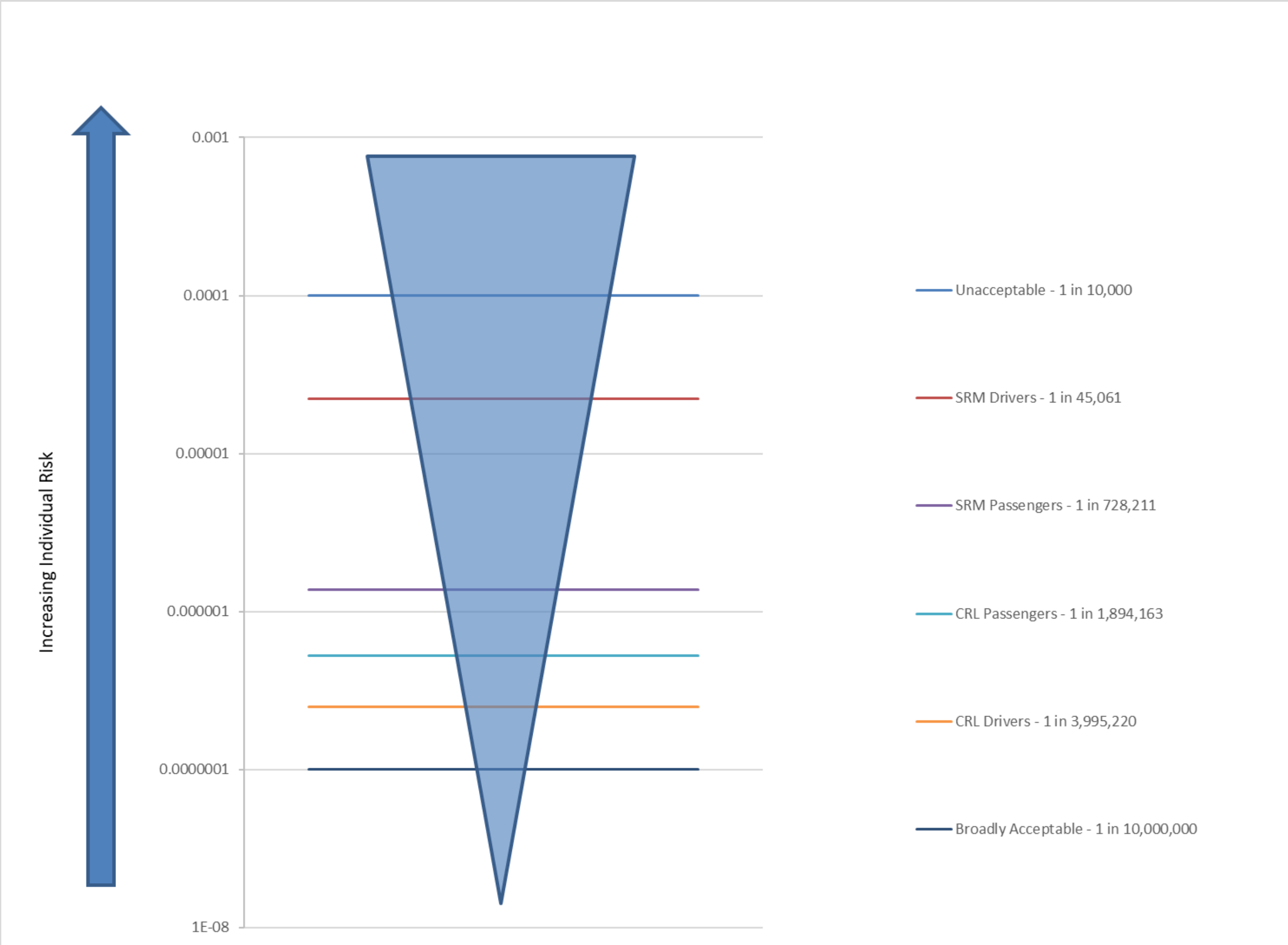
4.2.1 *Individual Risk Comparisons with Other Models*

Table 13 shows the individual risk to Elizabeth Line passengers and drivers on the COS as compared with the corresponding individual risk figures in the SRM. On a logarithmic scale, Figure 10 gives a graphical representation showing the benchmarking of the individual risk against this model. Note that, in order for this to be a like for like comparison, Train Held in Section and Flooding are not included as there is no data available to compare with the National data for individual risk.

Table 13 Individual Risk Comparison to SRM

	Chance of fatality per year	
Individual Risk from Models	**Passenger**	**Driver**
Crossrail (excluding Train Held in Section and Flooding)	1 in 1,894,163	1 in 3,995,220
SRM (RPBv8) for equivalent 5 hazards	1 in 728,211	1 in 45,061

Figure 10 Individual Risk Comparison to SRM



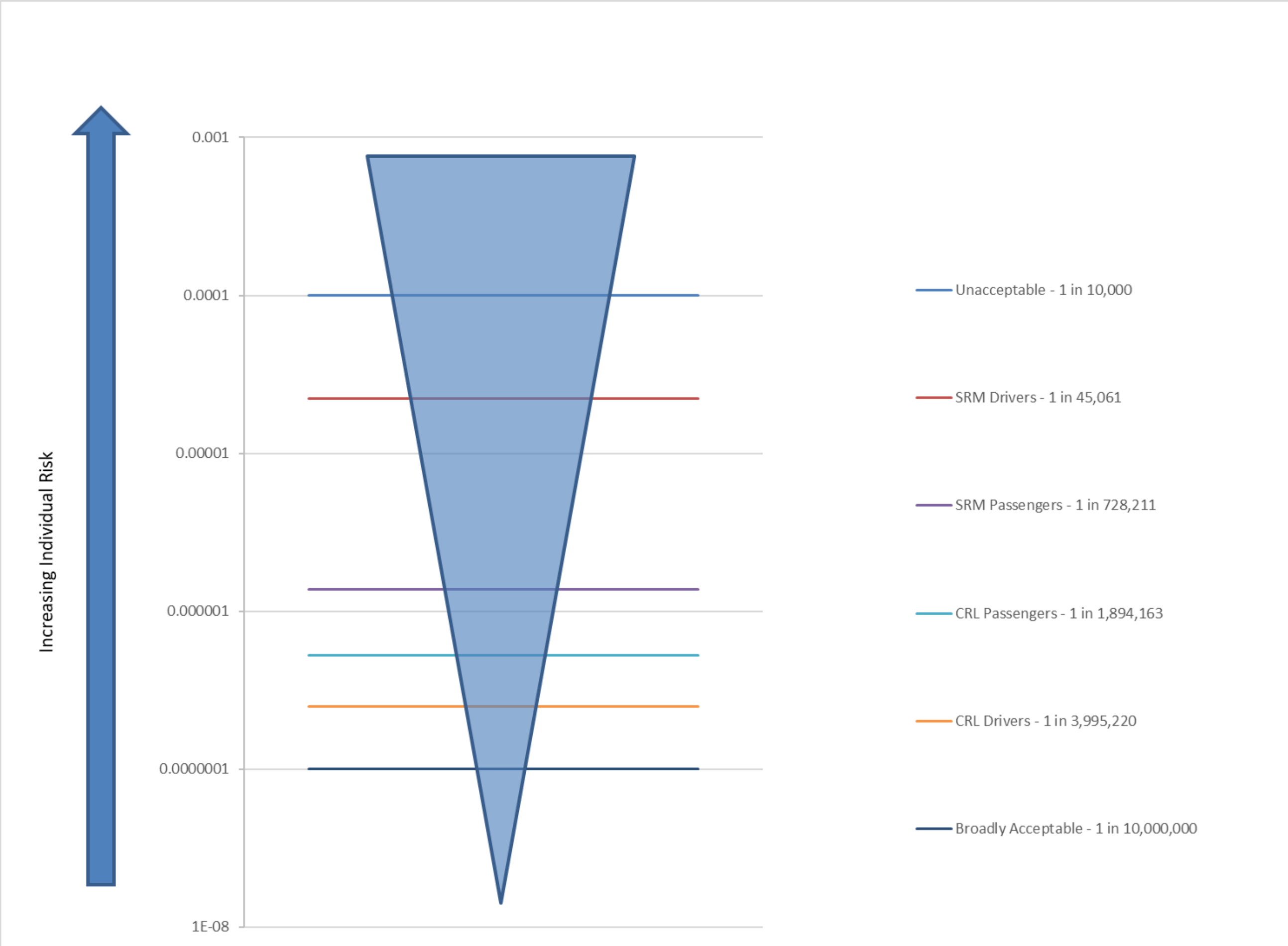
For the 5 hazards used in the comparison, the levels of passenger and driver individual risk are lower than the National average. This is partly because the average length of each passenger journey travelled on the Elizabeth Line is lower than that for the GB Mainline network. The remainder of the reduction in individual risk is due to the improvements within the rolling stock, infrastructure and signalling system in the central section.

5 CONCLUSIONS

The following can be concluded from the CSRM:

- The overall collective risk (from all seven hazards) was found to be 6.30E-01 FWI per year;
- In the COS the risk is dominated by the PTI risk (94%), which is in turn dominated by Member of Public trespass and suicide (accounting for 50%+ of PTI risk). Although PTI dominates, the risk is lower than LU due to the presence of platform screen doors at 8 of 10 of the stations. A direct comparison cannot be made to the GB Mainline but it is also expected to be lower for the same reasons.
- Excluding PTI risk, the following top events account for the most risk:
    - Derailment (42%) predominately due to a medium speed derailment in a single track caused by running into obstructions on the line or points failures; and
    - Train Held in Section (35%) due to total power failure from the grid, with a number of trains stalled in the section, and also due to localised failures e.g. signalling faults, train faults. Fainting due to overheating in open areas also dominates;
- The risk associated with the COS is generally lower than for the GB Mainline. This is due to the fact that the railway has been modelled as being designed according to the latest safety standards, supported by deviations where required; including all reasonable modern risk controls and mitigation measures. The major improvements in the system design are listed below:
    - Rolling Stock designed and procured to the latest safety standards (including for fire safety);
    - Use of an ATO/ATP signalling and train control system;
    - Improvements on the permanent way e.g. use of derailment containment etc.; and
    - Latest safety standards in stations (particularly for fire safety) and the use of tunnel ventilation;
- The individual risk in the COS for Elizabeth Line passengers and drivers is lower than the GB Mainline:
    - For Passengers this is a 1 in 1,894,163 chance of fatality when compared to 1 in 728,211 for the GB mainline
    - For drivers this is a 1 in 3,995,220 chance of fatality when compared to 1 in 45,061 for the GB mainline.

Figure 11 Individual risk (Fatality Probability per year per Person) with Comparison to National Figures



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