University of Glasgow | School of Computing Science

Safety Critical Systems (Level H)

Risks Assessment Techniques for identifying the Safety Concerns from Environmental Change in the Rail Industry

March 4, 2020

Leonore Papaloizos
2264897V
2264897V@student.gla.ac.uk
University of Glasgow

Acknowledgements

This report is my own work except for the evaluation which was conducted in collaboration with Alexa Joyce (2241724J).

Contents

1 Introduction

In the context of the 26th Conference of the Parties for Climate Change (COP26) taking place in Glasgow this year, this report looks at applying a risk assessment technique to an industry that will be impacted by growing climate change concerns. The focus of this case study is on the railway industry, more specifically in the UK. If climate change follows scientific projections, weather conditions might impact railways and train rolling stock more frequently and more dramatically, causing further delays and accidents. Looking at current meteorological and railway data, we can assess the current risks that the environment causes in the rail industry, and develop a tool to offer stakeholders a way to visualise how these risks might be heightened by climate change so that they can mitigate them.

This report will start with a summary of statistics for climate change projections in the UK, as well as past rail incidents in the UK. These statistics will be used to identify an area where risks might be particularly increased in the rail industry under climate change. A risk assessment technique will then be applied to undertake impact analysis, following which the technique will be evaluated for usefulness.

2 Context

2.1 Climate Statistics

In the UK, the Met Office provides statistical projections for environmental change in their UK Climate Projections report. Their latest report was in 2018, which updated their 2009 projections. The report provides a large range of statistics for different years and scales. Some notable projections are reported here as follows.

- At the end of the century, all areas of the UK are foreseen to be warmer, and more so in the winter [37].
  - The current UK average temperature is 20.1C in the summer, and 7.2 degrees in the winter.
  - By 2070, in the high emission scenario, this might increase in a range of 0.9C to 5.4C in summer and 0.7 to 4.2C in winter.
- Rainfall patterns are not uniform and will vary within a range [37].

- The current UK average rainfall in summer is 191mm, and 229m in winter.
- By 2080, in the high emission scenario, this will increase in a range of -47% to +2% in summer, and -1% to +35% in winter by 2070. This corresponds to an average precipitation of 270mm across most of the country in winter.
- There will be changes in the type of rainfall, where rain events in winter will be more frontal and of higher intensity while summer rain events will come in short lived high intensity showers.

- Sea level might rise from 0.3m to 1.15m by 2100 in the high emission scenario [9].
  - The numbers for this vary from capital city but this corresponds to an average of 0.5m in the North and 0.6m in the South.

2.2 Railway Incident Statistics

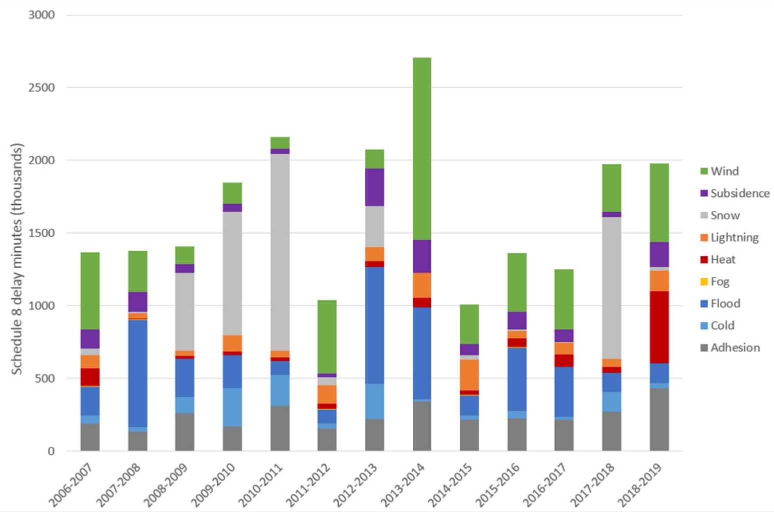


Figure 1: Bar-stacked graph showing weather-related delay minutes categorised by weather cause. *Source: Network Rail [31]*

A delay minute is a measure of performance in the rail industry. Over the 2018-2019 period, the Office of Rail and Road (ORR) reported a total of 16,743,884 delay minutes on the UK national rail network [23] and tallied up 3,239,671 weather-related delay minutes [26]. Hence, weather accounts for 19.3% of all delay minutes, which is in line with Thorne and Davis's 2002 research reporting that weather causes about 20% of all delay minutes [7].

Figure 1 highlights the weather sources of weather-related delay minutes [31]. As we can see the cause of delays varies a lot from year to year and seems relatively unpredictable. Nonetheless, we can note that floods have caused substantial delays in the past decade, and heat faults contributed to delays significantly more than it had before in the previous year.

The recent Storms Ciara and Dennis have also highlighted the significant cancellations and delays intense rainfall and subsequent flooding can cause [36].

Weather and Derailments

Between 2001 and 2019, there have been 334 derailments, 80 of which were on passenger trains. This number has been declining, with only 1 derailment on passenger trains recorded in 2018-2019 [10]. However, derailments can have significant impacts on both life and infrastructure, as evidenced by the recent Eastleigh derailment which has caused significant damage and cancellations to trains [4], or the 2002 Potters Bar Crash which killed 7 [3].

Derailments are an interesting incident to study, as they have varying causes, but are made more likely by extreme temperatures, which will become more likely under climate change. A study done by the University of Birmingham on the 2015 Summer heatwave found that 23,700 delay minutes at that time were attributed to emergency speed restrictions to reduce the risk of buckling, and 12,800 minutes were attributed to heat [5].

For the purpose of this study and the evaluation of a risk assessment technique, the incident of study will be of derailment due to extreme temperatures, both hot and cold.

3 Tool Development

3.1 Case Studies

It is accepted that doing risk assessment under growing concerns is necessary and has advantages for understanding potential impacts and leading to the adoption of mitigation strategies [21].

The UK government offers worksheets for companies to assess the impact of climate change on their own activities, however there does not seem to be a set standard that is used across or within industries [2]. In the rail industry, Network Rail reports on different techniques, such as BowTie risk assessments [30]. In the past few years, various rail companies have released reports on rail incidents that might be heightened by climate change and ways to mitigate them [32, 35].

Every report seems to use an in-house tool which might make comparisons harder. Hence, the immediate usability of such reports might not be evident to all stakeholders, as they may have different levels of experience or understanding.

External research has also been conducted, however the bulk of it involves modelling future risks via statistical methods, and not risk assessment tools [12, 11].

Fault Tree Analysis (FTA) is one risk assessment technique that has been applied successfully in the context of rail transport before [28, 16], however research on FTA combined with climate change is harder to come by. One case study applies FTA to the case of urban railway infrastructure as impacted by adverse weather [14]. Although the latter mentions climate change, it does not take into account climate statistical projections for the future in its calculations.

Hence, applying FTA to railway infrastructure in the context of changing environmental conditions under climate change does not seem to have been yet researched or published. However, the multiple case studies that use it in the context of the transport industry highlight that it might be a suitable tool for the scenario. Given the released statistics for climate change and railway incidents in the UK, this report will look at the applicability of the existing Fault Tree Analysis technique for qualitatively and quantitatively assessing the impact of climate change on the rail industry, and will later compare its usability to Failure Mode, Effects and Criticality Analysis (FMECA).

3.2 Fault Trees and Fault Tree Analysis

Fault Trees are a top-down deductive analysis technique to represent the relationships between an event and its root consequences. A fault tree consists of a top event, which represents the event to be studied. This top event is attached to basic events, which represent its causes, through logic gates. After being constructed, fault trees can be quantitatively and qualitatively analysed to identify which causes contribute the most to the top event, so that they can be mitigated [13].

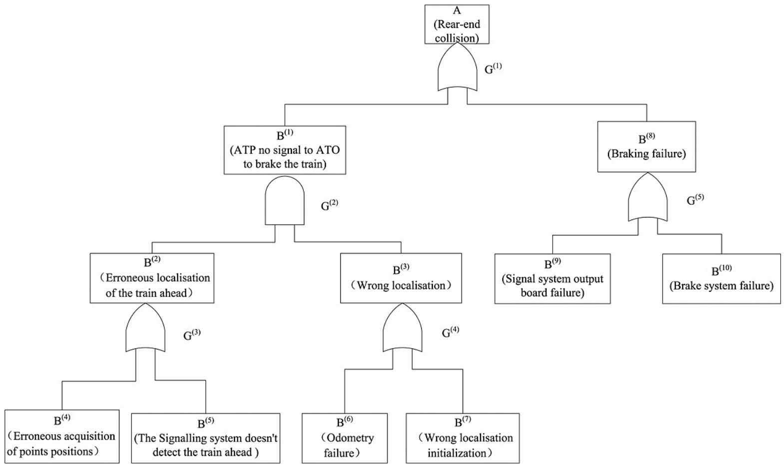


Figure 2: An example fault tree in a railway context [28].

3.3 Methodology

The following steps set out a general methodology for building a fault tree for assessing climate change impact.

1. Starting from the top event, research what can cause it until a basic event is reached.
2. For each basic event, assign a probability of it happening.
3. For each basic event whose probability might be heightened by climate change, combine climate change predictions with current probabilities to get an updated number.
4. Draw out the tree without considering the climate change impact.
5. Add the climate change probability change by attaching a special "climate change" event in a new diagram block (an octagon) and use arrows to draw out its impact on each higher-level event.
6. This new tree is the final tree and can be used for quantitative or qualitative analysis by considering either the base numbers or the climate change numbers, and the events shown as impacted by environmental causes.

3.4 Building the Tree

The tree built for this report covers a particular type of derailment caused by rail track failures that are related to the environment. A bigger tree

(a) A buckled track **(b)** A broken track

Figure 3: Illustrations of (a) a track buckle and (b) a track break.

could be constructed to incorporate the impact of faulty rolling stock or human error [16]. The choice for derailment due to track stressing is because of its vulnerability to both extreme cold temperatures and extreme high temperatures.

Root to causal events

Firstly, the top level event, **Train derailment due to track failure** has to be analysed for causes. A train can derail because of a **a rail track buckling**, which is a track geometry failure, or **a rail track breaking** [1, 38]. Figure 3 illustrates those failures.

A rail track will buckle under high temperatures combined with high pressure forces, which will usually come from high-speed trains [38, 12]. However, this might also depend on whether or not the rail track superstructure is solid enough to withstand the distribution of the pressure. A rail track will break under similar circumstances. A track becomes vulnerable if it has defects, and if the environment reaches near freezing temperatures, it makes the track at risk of breaking when a high speed train runs over it [20].

Both these events have a separate main factor, which is the extreme temperature. Combined with the high pressure factor, they cause the track failure.

High pressure being distributed onto the rail track has multiple sources, the main one being a high speed train. Most rolling trains are considered

Level	**Event**	**Source**
Top	Derailment due to track faults	To be calculated in the tree. 12 were recorded over 2018-2019 [27]
1	Track buckling	To be calculated in the tree. 25 were recorded over 2018-2019 [25]
1	Track breaking	To be calculated in the tree. 90 were recorded over 2018-2019 [25]
2	Track is vulnerable	To be calculated in the tree.
2	High pressure distributed onto rail tracks	To be calculated in the tree.
2	Temperature is too warm	This is the amount of days in Central England with maximum temperature over 27C in 2018-2019 [6].
3	Temperature is too cold	This is the amount of days in Central England with minimum temperature below 5C over 2018-2019 [6].s
3	Defective track	To be calculated in the tree. An underdeveloped event contributes to this probability.
3	Increased pressure forces from high speed train	This was calculated from the number of UK rail track kilometres which allow speeds of over 40 mph [24].
3	Weak track superstructure	To be calculated in the tree.
4	Manufacturing defects	No data was found for this event but its contributing factor comes from research on rail defects [33].
4	Usage defects	This corresponds to the ratio of detected continuous rail defects to the total length of the UK rail network [19, 22].
4	Weak sleepers	This corresponds to the percentage of sleepers Network Rail was consistently renewing every year at the start of the decade, assuming that there is a regular rate of defective sleepers [18].
4	Weak foundation	This corresponds to the length of ballast foundation Network Rail did not maintain over 2018-2019 [19].

Table 1: Sources of the different probabilities reported in the fault tree.

as high speed, which is highlighted by train companies cancelling services and putting speed restrictions in force in days of high temperatures [15]. The other main source is of a weak superstructure. A rail track is installed on a rail bed, which is usually made of ballast, and of sleepers. There are different types of sleepers and rail beds. They can get used or the different types might be less resistant, such as concrete sleepers being more expensive than ballast but sustaining pressure a lot better [38].

Assigning statistics to each event

After collecting all the possible events, the next step was to assign statistics to each. All the events are reported in Table 1 alongside the methodology for calculation.

Integrating the impact of climate change

For this scenario, we are interested in using temperature predictions as reported in Section 2.1. In the high emission scenario, the mean increase of temperature is of 3.1C in summer and 2.4C in winter. Using the same method as above to calculate the number of days above or below the "risk" threshold, that number was added to the Central England temperature data. The resulting probabilities for number of cold and hot days were respectively $p=0.227$ (a decrease) and $p=0.098$ (an increase). All this information was then attached to the right tree events.

Drawing the Fault Tree

Figure 4 shows the final drawn out fault tree. A climate change event is represented by an octagon, inspired by the "inhibit" hexagon event: these probabilities will be applicable if climate change projections are truthful. The climate change impact is then drawn out with arrows, which are coloured. The vibrancy of the colour represents if the risk will be lower or higher as it is carried out through the tree.

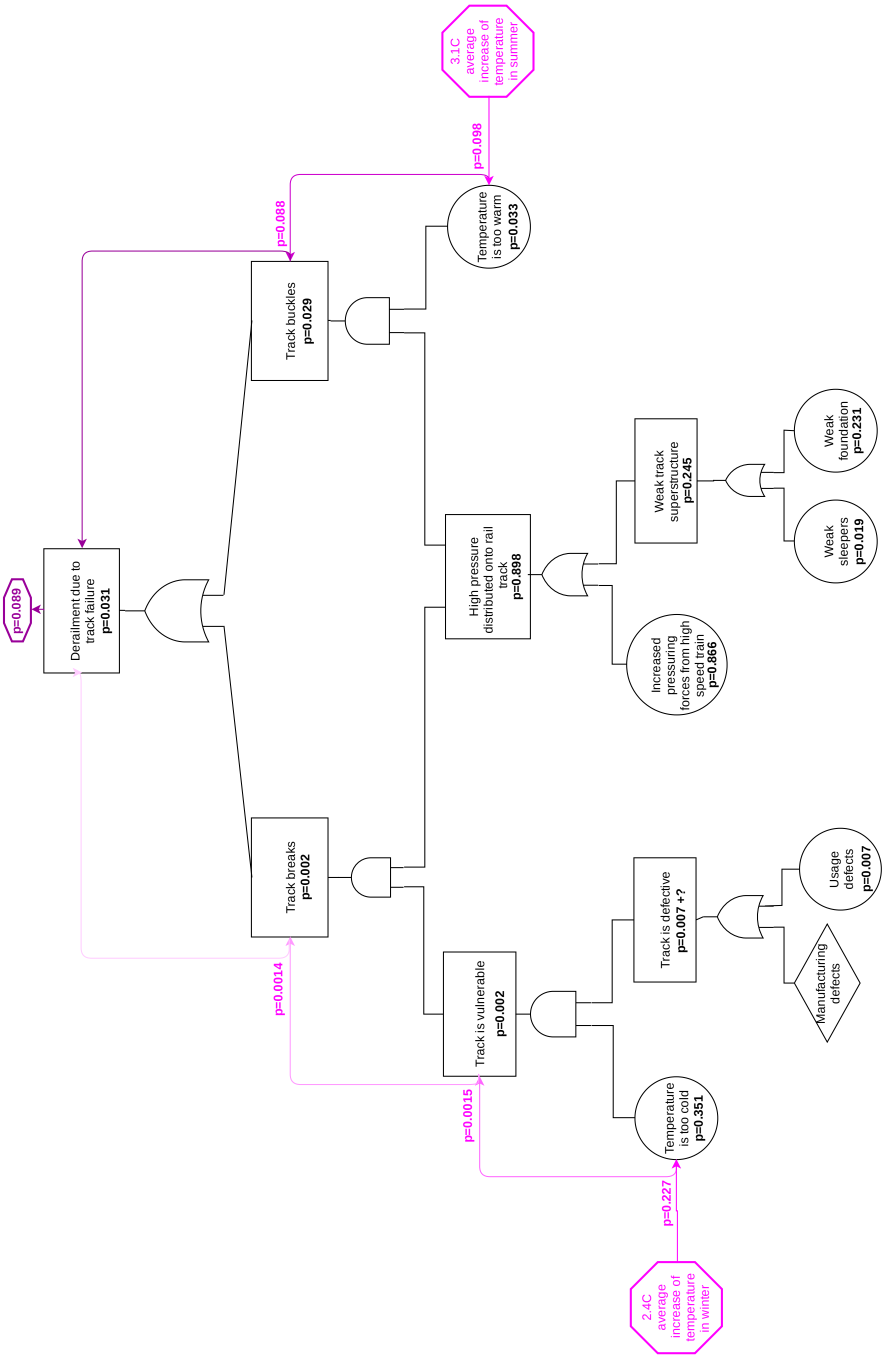


Figure 4: Climate Change Fault Tree for “Derailment due to track failure”

4 Evaluation

4.1 Failure Modes, Effects, and Criticality Analysis

In order to evaluate how effective Fault Tree Analysis is at assessing risk in the context of climate change, an evaluation was ran in collaboration with another student, who developed a Failure Modes, Effects, and Criticality Analysis (FMECA) assessment in the context of train rolling stock in the rail industry in the UK.

FMECA is a popular methodology used to analyse the different components that might fail in a system, as well as how they might fail. Each failure mode has a risk number which is calculated by the severity of the failure, its probability of occurrence, and its detection factor. There are case studies which apply FMECA to both railway rolling stock [8] and a safety-related industry in the context of varying climates [34].

The FMECA tool that was developed can be found in Appendix B. It was adapted from the railway rolling stock FMECA research. The industry of study is the same for consistency, but the scenario is different in order to prevent learning effects in participants.

4.2 Structure of the Evaluation

Each participant was presented with the following two scenarios:

Scenario 1: Your are presented with a fault tree. The fault tree represents the event "Derailment due to track failure" and its causes. Each element of the tree, which might lead to the top event, is a potential fault with a probability associated with it. Derailment probability could be increased by a changing climate, which is highlighted in the tree.

Scenario 2: You are presented with a spreadsheet. The first sheet shows a filled out FMECA table, which shows how train components can fail and what risk score is associated with each failure. Please experiment with changing fields related to ***climate change****. The components are related to the door mechanisms on a train. The second sheet has data on climate change, and the third sheet shows what the numerical failure ratings indicate. You may explore the second and third sheets but they are not essential for the evaluation.*

Each participant had to complete tasks related to each of these scenarios and answer psychometric questions related to their attitude towards climate change, as well as answer some questions obtained from NASA's Task Load Index to evaluate the tool's usability and user-friendliness [17]. The signed Ethics form for this evaluation is available in Appendix C.

Running through the experiment was as follows:

1. The participant's attitude towards climate change was assessed using questions taken from the Climate Change Attitude Survey [29] with a true/false answer or a Likert scale of 1-5.
    (a) I am concerned about climate change.
    (b) I think most of the concerns about environmental problems have been exaggerated.
    (c) It is a waste of time to work to solve environmental problems.
2. For each of the scenarios, the participant's responses and time-to-completion were recorded for the following tasks:
    (a) Task 1: can you count the number of events that can cause failure?
    (b) Task 2: can you identify the failure that has the biggest risk associated with it?
    (c) Task 3: can you count the number of events that can cause failure that are impacted by climate change?
    (d) Task 4: can you identify which failure is most at risk from climate change?
3. For each scenario, participants were then asked questions about the usability of the tool, which included taken from NASA's Task Load Index, all to be answered on a 1-5 Likert scale.
    (a) How confident are you in understanding the presented risk scenario?
    (b) How well did the visual elements of the tool convey the associated risks?
    (c) How mentally demanding was the task?
    (d) How rushed was the pace of the task?
    (e) How successful were you in accomplishing what you were asked to do?
    (f) How hard did you have to work to accomplish your level of performance?

(g) How insecure, discouraged, irritated, stressed, and annoyed were you?

4. The same climate change psychometric questions from before the tasks were asked to observe any changes.

4.3 Results

Audience

A total of 7 people participated in the evaluation. All participants were taking the Safety Critical Systems course. All participants described themselves as being concerned by climate change, and believed that it is not a waste of time to work to solve environmental problems. Only one participant was neutral about believing that most concerns about environmental problems have been exaggerated. These opinions did not change after completing the scenario tasks.

Task performance

Time to completion for the tasks is summarised in Table 2. Full times are available in Appendix 4. Table 3 shows the accuracy of people's answers.

Participant		**Time to completion (mm:ss)**	
ID	**Task**	**FTA**	**FMECA**
Mean	1	0:43 $\pm 22s$	0:37 $\pm 15s$
	2	0:44 $\pm 16s$	0:47 $\pm 18s$
	3	0:39 $\pm 19s$	0:38 $\pm 26s$
	4	0:39 $\pm 18s$	0:33 $\pm 16s$

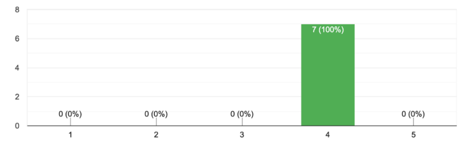
Table 2: Average time and standard deviation for completion of the tasks for each scenario.

Task-load

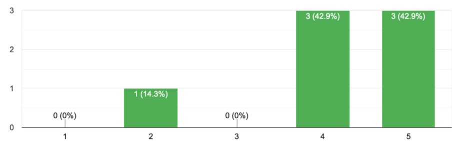
Each participant was asked about their confidence level, the visual elements of the tools, mental demand, feeling rushed, how hard they worked at the task, and if they felt any negative feelings related to stress or frustration while completing the tasks. Figure 5 reports the participants' confidence in the two scenarios. All participants felt the same level of confidence for scenario 1 with FTA, but there was an outlier for scenario 2 with FMECA,

Task	Accuracy (%)	
	FTA	FMECA
1	43	14
2	87	57
3	43	57
4	75	85

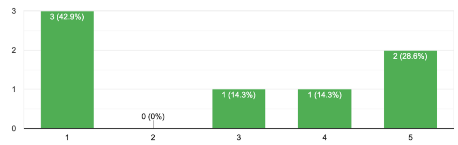
Table 3: Table reporting average accuracy of people's answers to different tasks with each tool.



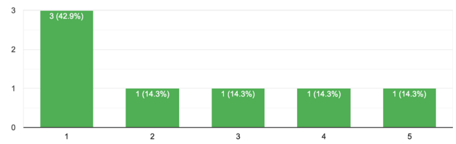
(a) Confidence levels for **Fault Tree Analysis**



(b) Confidence levels for **FMECA**



(c) Frustration/stress/annoyance levels for **Fault Tree Analysis**



(d) Frustration/stress/annoyance levels for **FMECA**

Figure 5: Frustration and confidence levels for each scenario under different tools.

although understanding seemed to be in general higher. Figure 5 also shows that frustration levels were distributed for both tools.

6 out of 7 participants thought that FTA visually conveyed the associated risks with the scenario well or very well. 6 participants thought that FMECA visually conveyed the risks very well.

For mental demand, participants were distributed for FTA. 60% of participants gave it a low mental demand score. For FMECA, 70% of participants gave the tool a low score.

When it came to participants rating how hard they had to work for their level of performance, the results were distributed all across the scale, with results reported for each point. The result were almost identical for both tools, with FTA having a slightly lower score than FMECA. Most participants also did not feel rushed at the task, and again those results were the same for both tools.

Final task load indices for FTA was 3/5 on the scale, and 2.8/5 for

FMECA. Overall, both tools seem to have gathered similar statistics for task load indices. However, when asked for a final choice between Fault Trees and FMECA, 5 out of 7 ranked FMECA first.

5 Conclusions

The goal of this report was to investigate using risk assessment techniques for analysing the impact of climate change. For the purpose of this, the popular risk assessment techniques Fault Trees and Failure Modes, Effects, and Criticality Analysis were tweaked to show climate events and associated numbers quantifying their impacts.

The results obtained from evaluating FTA and FMECA show that neither tool seemed to be difficult to use to participants. Times to complete tasks were low. Task Load for both techniques was very similar, and quite average. However, there did seem to be some frustration for both tools in some participants. It is also worth noting participants were evaluated as users and not creators, so we cannot at this point quantify the the task load index for actually building the scenario.

Participants' answers to tasks for the Fault Tree were also on average more accurate than for FMECA, although this accuracy decreased for climate change-related tasks, which should have been made easier for the purpose of this tool. This might have been exacerbated by the wordings of some questions, where participants had trouble distinguished whether they should report on basic events, or just any fault in the tree. The confusing wording came from trying to standardise the questions across both scenarios. Future evaluation might need to use wordings specific to each tool. Other limitations of the evaluation setup include the repetitive questions, which might have encouraged participants to work through questions faster without thinking about their experience too much.

Time to complete tasks was very short and very similar across participants. Knowing that they were timed, participants might have rushed into the tasks to finish faster rather than perform well. However, not all participants reported feeling rushed. In the case of FTA, there is a decrease for time to completion between the general tasks and the climate-related tasks, which could show that the addition of climate-related events with a distinct visualisation and event box could work well for stakeholders. However, there was also a slight drop in accuracy. On the other hand, FMECA times also dropped, but accuracy increased.

This report has shown that risk assessment techniques could be easily adapted to highlight climate change impact. A Fault Tree can easily be tweaked to add external "multiplicator" events which might worsen or lighten the probability of events. The same goes with FMECA, where "climate-adjusted" risk numbers can be put in place in the worksheet. These additions to the additional tools did not seem to catch out participants and their confidence in answering the tasks, as recorded confidence levels were high.

To conclude on the information gathered throughout this report, I believe that a mix of FMECA and FTA would be a viable option to perform a thorough risk assessment. In terms of applicability to climate change scenarios, they can be easily extended to take into account statistical projections. For content and usage, I cannot recommend FTA over FMECA as people do seem to prefer the latter and it includes a higher level of detail. For stakeholders that require more granular understanding of a scenario in order to perform subsequent quantitative and qualitative analyses, FMECA might be more adapted. It could allow for more detailed analysis of different concepts involved in a failure i.e. probability, severity of consequence, detection factor. FTA might be more applicable for external stakeholders such as the general public as it could give a more visual, broken-down view of faults involved in a potential accident.

Appendices

A Task completion times

Participant		**Time to completion (mm:ss)**	
ID	**Task**	**FTA**	**FMECA**
SCS1	1	0:33	0:45
	2	0:46	0:15
	3	0:31	0:18
	4	0:22	0:50
SCS2	1	1:32	0:19
	2	0:30	0:52
	3	0:10	0:26
	4	0:59	0:49
SCS3	1	0:52	0:19
	2	0:36	1:00
	3	0:33	0:15
	4	1:00	0:57
SCS4	1	0:42	0:32
	2	0:52	1:00
	3	0:20	0:13
	4	0:11	0:20
SCS5	1	0:26	0:30
	2	1:14	1:09
	3	1:04	0:47
	4	0:29	0:10
SCS6	1	0:40	0:52
	2	0:22	0:23
	3	0:58	0:58
	4	0:36	0:26
SCS7	1	0:16	1:01
	2	0:54	0:52
	3	1:00	1:29
	4	0:59	0:23

Table 4: Time taken to complete the tasks for each scenario.

B FMECA Climate Change Tool

FMECA

Process:	Train Door failure
Product:	Train
Operation / Part:	Door mechanisms

Failure Mode:	How the component fails
Failure Causes:	What causes the failure
Failure Effects:	What happens due to a failure

See Ratings Description sheet for more information

Likelihood of Occurrence (O):	1–10 [10 = very likely to occur]
Likelihood of Detection (D):	1–10 [10 = very unlikely to detect]
Severity (S):	1–10 [10 = most severe effect]

$$RPN = \text{severity} * \text{occurence} * \text{detection}$$

Component	Failure Mode	S	Failure Cause	O	Failure Effect	Network rail standard	Detection	D	RPN	Climate change factor	Deg. of Uncertainty	Climate Adjusted RPN
Portable mast mounting	Screw has cracks	7	Too much stress	2	Door may not operate	NR/GN/OPS/005	Routine checks	1	14	Increased warm spells	0.04	350
Portable mast mounting	Mounting bolts loose	1	No ajustment inplace; vehicle vibrations	2	The door can't be closed tightly	NR/GN/OPS/006	Routine checks	1	2	None	0	2
Nut component	Poor lubrication	1	lacking of maintenance; lubricant quality bad	2	door operates slowly, abnormal sound	NR/L3/SIG/1130 3	Routine checks	3	6	None	0	6
Nut component	Angle offset	1	no adjustment in place	2	start the pinch, the door can't operate	NR/L3/SIG/1130 3	Routine checks	1	2	None	0	2
Nut component	Loose	5	locking washers no into the slot	2	start the pinch, the door can't operate	NR/L3/SIG/1130 3	Routine checks	1	10	Increased windstorms	0.03	333.33333
Nut component	Bushing for cracks	3	material defects; improper heat treatment	2	the door can't be closed tightly	NR/L3/SIG/1130 3	Routine checks	1	6	Increased warm spells	0.04	150
Door closing limit switch	Abnormal clearance	3	no adjustment in place	3	start the pinch function; the train won't start	NR/SP/ELP/21018	Routine checks	1	9	None	0	9
Door closing limit switch	function failure	6	quality defects; end of life	3	indicator light anomalies; the train won't start	NR/L2/SIG/3001 0	Routine checks	1	18	None	0	18
Door closing limit switch	breakage	7	screw bolts missing; shifter level fracture	3	door can't operate; unable to lock and unlock the door	NR/L2/SIG/3001 0	Routine checks	1	21	Increased warm spells	0.04	525
EDCU (door control unit)	Plug loose	5	Not inserted in place; vehicle vibrations	5	Door can't operate normally	NR/L2/SIG/3001 0	Routine checks	1	25	Increased heavy rain	0.12	208.33333
EDCU (door control unit)	Function failure	9	safety relays/communication interfaces are damaged	5	Door can't operate normally	NR/L2/SIG/3001 0	Routine checks	1	45	Increased heavy rain	0.12	375
EDCU (door control unit)	Breakage	8	retainer lose; thrust pressure ring lose; arm spring failure	5	The train won't start	NR/L2/SIG/3001 0	Routine checks	2	80	Increased windstorms	0.03	2666.6667
							Current Conditions RPN:		238		Future Adjusted RPN:	4645.3333

C Evaluation Ethics form

School of Computing Science
University of Glasgow

Ethics checklist form for assessed exercises (at all levels)

This form is only applicable for assessed exercises that use other people ('participants') for the collection of information, typically in getting comments about a system or a system design, or getting information about how a system could be used, or evaluating a working system.

If no other people have been involved in the collection of information, then you do not need to complete this form.

If your evaluation does not comply with any one or more of the points below, please contact the Department Ethics Committee for advice.

If your evaluation does comply with all the points below, please sign this form and submit it with your assessed work.

---

1. Participants were not exposed to any risks greater than those encountered in their normal working life.
   Investigators have a responsibility to protect participants from physical and mental harm during the investigation. The risk of harm must be no greater than in ordinary life. Areas of potential risk that require ethical approval include, but are not limited to, investigations that occur outside usual laboratory areas, or that require participant mobility (e.g. walking, running, use of public transport), unusual or repetitive activity or movement, that use sensory deprivation (e.g. ear plugs or blindfolds), bright or flashing lights, loud or disorienting noises, smell, taste, vibration, or force feedback

2. The experimental materials were paper-based, or comprised software running on standard hardware.
   Participants should not be exposed to any risks associated with the use of non-standard equipment: anything other than pen-and-paper, standard PCs, mobile phones, and PDAs is considered non-standard.

3. All participants explicitly stated that they agreed to take part, and that their data could be used in the project.
   If the results of the evaluation are likely to be used beyond the term of the project (for example, the software is to be deployed, or the data is to be published), then signed consent is necessary. A separate consent form should be signed by each participant.

   Otherwise, verbal consent is sufficient, and should be explicitly requested in the introductory script.

4. No incentives were offered to the participants.
   The payment of participants must not be used to induce them to risk harm beyond that which they risk without payment in their normal lifestyle.

5. No information about the evaluation or materials was intentionally withheld from the participants.
   Withholding information or misleading participants is unacceptable if participants are likely to object or show unease when debriefed.

6. No participant was under the age of 16.
   Parental consent is required for participants under the age of 16.

7. No participant has an impairment that may limit their understanding or communication.
   Additional consent is required for participants with impairments.

8. Neither I nor my supervisor is in a position of authority or influence over any of the participants.
   A position of authority or influence over any participant must not be allowed to pressurise participants to take part in, or remain in, any experiment.

9. All participants were informed that they could withdraw at any time.
   All participants have the right to withdraw at any time during the investigation. They should be told this in the introductory script.

10. All participants have been informed of my contact details.
    All participants must be able to contact the investigator after the investigation. They should be given the details of both student and module co-ordinator or supervisor as part of the debriefing.

11. The evaluation was discussed with all the participants at the end of the session, and all participants had the opportunity to ask questions.
    The student must provide the participants with sufficient information in the debriefing to enable them to understand the nature of the investigation.

12. *All the data collected from the participants is stored in an anonymous form.*
    All participant data (hard-copy and soft-copy) should be stored securely, and in anonymous form.

Module and Assessment Name Safety Critical Systems (H) Assessed Coursework

Student's Name Leonore Papaloizos

Student's Registration Number 2264897v

Student's Signature ____________

Date 04/03/2020

References

[1] Tracy A. and Reznik T. Broken Rails Are Leading Cause of Train Derailments. https://www.scientificamerican.com/article/broken-rails-are-leading-cause-of-train-derailments/, May 2015. Retrieved on 2020-02-29.

[2] UK Environment Agency. Adapting to climate change: risk assessment worksheets. https://www.gov.uk/government/publications/adapting-to-climate-change-risk-assessment-worksheets, October 2019. Retrieved on 2020-02-29.

[3] BBC. Potters Bar crash: Network Rail fined £3m. https://www.bbc.co.uk/news/uk-13389147, May 2011. Retrieved on 2020-02-29.

[4] Rail Accident Investigation Branch. Freight train derailment at eastleigh. https://www.gov.uk/government/news/freight-train-derailment-at-eastleigh, February 2020. Retrieved on 2020-02-29.

[5] Ferranti E., Chapman L., Lee S., Jaroszweski D., Lowe C., McCulloch S., and Quinn A. The hottest July day on the railway network: insights and thoughts for the future. *Meteorological Applications*, 25(2):195–208, 2018.

[6] Parker D. E., Legg T. P., and Folland C. K. Met Office Hadley Centre Central England Temperature Data. https://www.metoffice.gov.uk/hadobs/hadcet/data/download.html. Retrieved on 2020-02-29.

[7] Thornes J. E. and Davis B. W. Mitigating the impact of weather and climate on railway operations in the UK. In *ASME/IEEE Joint Railroad Conference*, pages 29–38, April 2002.

[8] Dinmohammadi F., Babakalli A., Mahmood S., Christophe B., and Ashraf L. Risk Evaluation of Railway Rolling Stock Failures Using

FMECA Technique: A Case Study of Passenger Door System. *Urban Rail Transit*, 2(3-4):128–45, October 2016.

[9] Fung F., Palmer M., Howard T., Lowe J., Maisey P., and Mitchell J. F. B. *UKCP18 Factsheet: Sea Level Rise and Storm Surge*. Met Office Hadley Centre, Exeter, 2018.

[10] Department for Transport. Rail accidents and safety (rai05) statistical datasets. `https://www.gov.uk/government/statistical-data-sets/rai05-rail-accidents-and-safety`, December 2019. Retrieved on 2020-02-23.

[11] Hall J. and Jenkins K. Modelling the impacts of climate change on cities: economic costs of rail buckle events. `https://arcc.ouce.ox.ac.uk/wp-content/pdfs/ARCADIA-09-buckling.pdf`. Retrieved on 2020-02-29.

[12] Dobney K., Baker C.J., Chapman L., and Quinn A. D. The future cost to the United Kingdom's railway network of heat-related delays and buckles caused by the predicted increase in high summer temperatures owing to climate change. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(1):25–34, 2010.

[13] Rausand M. Lundteigen M. A. Chapter 5: Fault Tree Analysis (FTA). `https://www.ntnu.edu/documents/624876/1277046207/SIS+book+-+chapter+05+-+Introduction+to+fault+trees/`. Retrieved on 2020-02-29.

[14] Jiaqi Ma, Yan Bai, Jianfeng Shen, and Fang Zhou. Examining the impact of adverse weather on urban rail transit facilities on the basis of fault tree analysis and fuzzy synthetic evaluation. *Journal of Transportation Engineering*, 140(3):04013011, 2014.

[15] Murray D. Buckled rail risk could see a third of trains cancelled in UK heatwave. `https://www.standard.co.uk/news/transport/buckled-rail-risk-could-see-a-third-of-trains-cancelled-in-uk-heatwave-a4197281.html`. Retrieved on 2020-02-29.

[16] Pavlović N., Kostadinović M., Marković M., Ivić M., and Kosijer M. Analysis of the train derailment causes using Fault Tree Analysis. *Faculty of Transport and Traffic Engineering, University of Belgrade.*

[17] NASA. Task Load Index. `https://humansystems.arc.nasa.gov/groups/TLX/downloads/TLXScale.pdf`. Retrieved on 2020-02-29.

[18] National Rail. Annual Return 2014: Sleepers renewed (Table 4.4). https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/annual-return-2014.pdf. Retrieved on 2020-02-29.

[19] National Rail. Annual Return 2019. https://cdn.networkrail.co.uk/wp-content/uploads/2019/07/Network-Rail-Infrastructure-Limited-annual-return-2019-data-tables.xls. Retrieved on 2020-02-23.

[20] National Rail. Breaks. https://www.nationalrail.co.uk/service_disruptions/80826.aspx. Retrieved on 2020-02-29.

[21] Adger W. Neil, Brown Iain, and Surminski Swenja. Advances in risk assessment for climate change adaptation policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2121):20180106, 2018.

[22] Office of Rail and Road. Infrastructure on the railways 2018-2019. https://dataportal.orr.gov.uk/statistics/infrastructure-and-emissions/rail-infrastructure-and-assets/. Retrieved on 2020-02-23.

[23] Office of Rail and Road. Passenger rail performance: Delay minutes. https://dataportal.orr.gov.uk/statistics/performance/passenger-rail-performance/. Retrieved on 2020-02-29.

[24] Office of Rail and Road. Rail Infrastructure and Assets: Network capability changes. https://dataportal.orr.gov.uk/statistics/infrastructure-and-emissions/rail-infrastructure-and-assets/. Retrieved on 2020-02-23.

[25] Office of Rail and Road. Rail Safety: Broken rails and Buckled Rails 2018-2019. https://dataportal.orr.gov.uk/statistics/health-and-safety/rail-safety/. Retrieved on 2020-02-23.

[26] Office of Rail and Road. Delay attribution review: Scoping stage report. https://orr.gov.uk/__data/assets/pdf_file/0016/41353/delay-attribution-review-scoping-stage-report.pdf, July 2019. Retrieved on 2020-02-29.

[27] Department of Transport. Railway accidents: train accidents: Gb annual from 2001/02. https://www.gov.uk/government/collections/rail-statistics. Retrieved on 2020-02-29.

[28] Zhaoguang Peng, Yu Lu, Alice Miller, Chris Johnson, and Tingdi Zhao. Risk Assessment of Railway Transportation Systems using Timed Fault Trees. *Quality and Reliability Engineering International*, 32(1):181–194, 2016.

[29] Christensen R. and Knezek G. The Climate Change Attitude Survey: Measuring Middle School Student Beliefs and Intentions to Enact Positive Environmental Change. http://stelar.edc.org/sites/stelar.edc.org/files/ijese_2015_276a.pdf, August 2015. Retrieved on 2020-02-29.

[30] Network Rail. Risk management. https://www.networkrail.co.uk/who-we-are/our-approach-to-safety/safety-assurance/risk-management. Retrieved on 2020-02-29.

[31] Network Rail. Weather impacts on performance. https://www.networkrail.co.uk/communities/environment/climate-change-and-weather-resilience/weather-impacts-on-performance. Retrieved on 2020-02-29.

[32] Network Rail. Weather Resilience and Climate Change Adaptation Strategy 2017-2019. https://safety.networkrail.co.uk/wp-content/uploads/2017/02/NR-WRCCA-Strategy-2017-2019.pdf, January 2017. Retrieved on 2020-02-29.

[33] Kumar S. Study of Rail Breaks: Associated Risks and Maintenance Strategies. https://www.diva-portal.org/smash/get/diva2:995250/FULLTEXT01.pdf, 2006. Retrieved on 2020-02-29.

[34] Ozturk S., Fthenakis V., and Faulstich S. Failure modes, effects and criticality analysis for wind turbines considering climatic regions and comparing geared and direct drive wind turbines. *Energies*, 11, September 2018.

[35] Rail Safety and Standards Board. Tomorrow's Railway and Climate Change Adaptation: Work Package 1 - Summary Report. https://catalogues.rssb.co.uk/research-development-and-innovation/research-project-catalogue/t1009, June 2015. Retrieved on 2020-02-29.

[36] County Times. Trains cancelled and 'significant' delays after storm dennis. https://www.countytimes.co.uk/news/18240374.trains-cancelled-significant-delays-storm-dennis/, February 2020. Retrieved on 2020-02-29.

[37] UKCP Team, 2019. UK Climate Projections: Headline findings. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp-headline-findings-v2.pdf. Retrieved on 2020-02-29.

[38] Volpe Center, U.S. Department for Transportation. Track Buckling Research. https://www.volpe.dot.gov/infrastructure-systems-and-technology/structures-and-dynamics/track-buckling-research, January 2018. Retrieved on 2020-02-29.