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DOI:

[10.1061/AJRUA6.0001012](https://doi.org/10.1061/AJRUA6.0001012)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Kaewunruen, S, Bin Osman, MH & Wong, HCE 2019, 'Risk-based maintenance planning for rail fastening systems', *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, vol. 5, no. 3, 04019007. <https://doi.org/10.1061/AJRUA6.0001012>

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Risk-based maintenance planning for rail fastening systems

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Abstract

Failures in rail fasteners can lead to misalignments of the rails and even cause a train derailment. Current inspection and maintenance regimes for rail fasteners, however, do not adequately address the credible failure modes found in the field. In response to these improvement opportunities, a risk-based maintenance philosophy, driven by a risk management framework, is proposed for rail fasteners. The framework is primarily developed from ISO 31000 with underlying principles inferred from other applicable international standards. Reliability tools were then incorporated, allowing practitioners to arrive at an appropriate combination of reliability tools based on the circumstances under which the assessment is to be conducted. Monte Carlo simulations were undertaken on the imbedded anchors of rail fasteners to demonstrate how the resultant framework can be innovatively adopted in practice. The general findings highlight that accurate risk depiction is vital for track components (e.g. imbedded anchors, the failure modes of which are dependent on time), thereby, the timeframes at which risk for the component transits to different risk categories should be obtained. Note that the finding is unique to the example; thus, the proposed risk framework should be treated carefully before it is applied for other failure modes.

Keywords: rail fastener; rail failure; risk management; reliability analysis; inspection.

32

32 **Introduction**

33 Located at the interface between the rail and the sleeper (as depicted in Fig.1), the rail fastener
34 maintains the vertical, lateral and longitudinal position of the rails relative to the sleepers. It
35 also provides resilience to the rail-sleeper configuration so as to reduce the dynamic forces trans-
36 ferred from rails to the sleepers. For electrified railways, the rail fastener performs the additional
37 function of providing electrical isolation between the rail and the sleepers.

38 Most fasteners today are elastic fasteners which typically embody an imbedded anchor, a clip
39 or spring, an insulator, and a pad. Degradation in these components can ultimately lead to the
40 inability of the fastener to execute the functions cited above. Proactively, a visual inspection is
41 regularly performed which takes various types of patrols; routine walking patrols, detailed walk-
42 ing examination and detailed sleeper examinations (RailCorp Network 2013). However, the de-
43 fects that the patrollers look out for in rail fasteners do not adequately address the generic failure
44 modes. For instance, failure modes such as abrasion and high hydraulic pressures, which can
45 lead to rail seat deterioration, are unable to be detected through visual inspection. The detection
46 of rail seat deterioration would require the lifting of rail and removal of rail pad (Kernes et al.
47 2014).

48 As rail fasteners are intrinsically linked to the rest of the track system, having an inspection
49 regime which does not identify defects at the failure modes brings the organization closer to se-
50 rious incidents. In the case of rail seat deterioration, this means that the problem may only sur-
51 face when there is a loss of rail cant or when there is gauge-widening. For records, rail fasteners
52 have failed prematurely or deteriorated drastically within a short timeframe. A diode-grounded

53 transit system which was designed to last for 35 years had to be replaced within seven years due
54 to stray current corrosion (Barlo and Zdunek 1995) . Also, a rail corrosion defect in Sydney had
55 deteriorated to five consecutive rail fasteners failures within a short span of three and a half years
56 (The Office of Transport Safety Investigations 2014). Note that, elastic rail pads generally have a
57 design life of 10 years. Without appropriate renewal of pads, those fastenings can be damaged
58 faster. Nonetheless, unless a detailed investigation is triggered, the underlying failure modes may
59 remain hidden until a serious incident presents itself. By then, the cost and resources required to
60 address the failure mode may have become significantly higher.

61 In terms of resource allocation, inspection frequencies and mitigation priorities are currently
62 determined by the expected and actual conditions of the rail fasteners. One would be to allow the
63 frequency of inspection to depend on how aggressively the service has damaged the track. While
64 reduction of inspection frequency is allowed, this is done ad hoc and is only permitted to a max-
65 imum of half (Network Rail 2009). Another would be to allow frequency of inspection and ur-
66 gency of repair to depend, not only on how likely a serious incident can occur, but also on how
67 serious that incident would be. For instance, though both may fall into the same track category, a
68 line which runs high volumes of passenger service should be inspected and maintained more rig-
69 orously than a line which predominantly runs freight service because of the former's higher safe-
70 ty implications. Such optimization directs resources in accordance to risk criticality and not
71 merely by the likelihood of risk.

72 In addressing abovementioned opportunities, a risk based maintenance approach is proposed
73 for rail fasteners. Intuitively, each inspection or maintenance activity is treated as a risk control
74 process intended to address a failure mode. This study concerns itself with the establishment of a
75 risk management framework to ensure that risks remain relevant and accurate throughout the

76 system lifecycle. In this regard, relevant international standards and reliability tools are embod-
77 ied in a risk management framework. Overall, the proposed framework has features such as im-
78 proves proactiveness of the inspection and maintenance regime for rail fasteners, further opti-
79 mise resources allocation within the regime and improve the comprehensiveness of this regime.

82 **Background study**

83 **Inspection on rail fastening system**

84 In the UK, defects associated to rail fasteners are identified via foot patrols. The patrollers look
85 out for the following defects in rail fasteners (Network Rail 2009):

- 86 i. Loose, missing, falling out and broken rail fasteners,
- 87 ii. Missing/displaced, expired and incorrectly fitted pads , and
- 88 iii. Broken/cracked and galled baseplates.

89 Frequency of foot patrols are determined by predefined track category, which is in turn deter-
90 mined by the speed of rail traffic and the equivalent tonnage of the line. Track categories range
91 from Cat 1A, where speeds are high and equivalent tonnage are high, to Cat 6, where the con-
92 verse is true. Frequency of basic visual inspection on plain line continuous welded rail, for in-
93 stance, is weekly for Cat 1A track and once every four weeks for Cat 6 track, see Table 1 for in-
94 spection frequencies for other track categories (Network Rail 2009, 2017).

95 Track inspection frequency is typically fixed but a review can be triggered by the engineer
96 when there is a clear history of reliability issues such as poor track geometry, rolling contact fa-
97 tigue or evidence of track bed failure. The extent to which frequency is increased predominantly
98 lies on the engineer's judgement. On the other hand, when track condition has been found to be
99 satisfactory, the engineer is able to reduce inspection frequency, but to a maximum of half. This

100 review is normally driven by the need to optimize the patrolling regime or by difficulties in com-
101 plying with the existing frequency. When a defect is found, response to rectify is not necessarily
102 immediate. The urgency of response depends on how likely the defect can translate to an unde-
103 sired event. For example, four missing or ineffective fastenings in a 60ft length of a Cat 1A track
104 has a priority of M3 while the same phenomenon in a 60ft length of a Cat 6 track has a priority
105 of M24 (Network Rail 2009, 2017). The former needs to be addressed within thirteen weeks
106 while the latter has two years for resolution. This disparity is because the likelihood of an unde-
107 sired consequence occurring is higher for the former than the latter.

108 In Australia, patrollers look out for similar rail fastening defects as that in the UK (RailCorp
109 Network 2013);

- 110 i. Missing/corroded/over sprung/ineffective fastenings,
- 111 ii. Worn, incorrectly inserted or squeezed out insulators, and
- 112 iii. Severely worn pads which can be checked visually or with reference to gauge read-
113 ings.

114 Inspection of rail fasteners is covered by various types of patrols. These are namely standard
115 track patrols, detailed walking examination and detailed sleeper examinations. There is however
116 very little variance in the frequencies. Standard track patrols and detailed walking examinations
117 are fixed at twice a week and once in three months respectively for practically all track catego-
118 ries in the suburban mixed-traffic networks. Detailed sleeper examinations, on the other hand,
119 are either annual or biennial depending on the sleeper type (RailCorp Network 2016).

92 **Reliability tools**

93 Failure mode, effects and criticality analysis

94 Failure mode, effects and criticality analysis (FMECA) is a systematic process to identify credi-
95 ble failure modes. According to (Quality—One International 2017), there are seven steps in de-
96 veloping an FMECA;

97 Step 1: FMECA pre-work and assemble the FMECA team

98 Step 2: Path 1 development (requirements through severity ranking)

99 Step 3: Path 2 development (potential causes and prevention controls through occurrence rank-
100 ing)

101 Step 4: Path 3 development (testing and detection controls through detection ranking)

102 Step 5: Action priority & assignment

103 Step 6: Actions taken / design review

104 Step 7: Re-ranking risk criticality & closure

105 In Step 1, key documents, such as design, inspection and maintenance documents, are con-
106 solidated and an experienced multi-disciplinary team is formed to facilitate the analysis. In Path
107 1 development, the failure modes by which functions can fail and the associated effects of fail-
108 ures are identified. Each effect is assigned a severity ranking. After which, in Path 2 develop-
109 ment, the causes associated with each failure mode are identified and the mitigation actions for
110 each failure mode are formulated. Each cause is assigned an occurrence ranking. Path 3 devel-
111 opment then adds detection controls such as real-time condition monitoring. Step 5 identifies the
112 risk criticality for each failure mode based on its assigned occurrence and severity ranking and
113 accordingly determines the priority of action for risk treatment. FMECA should be an evergreen
114 process where risks and actions are regularly reviewed. Step 6 and 7 depicts this requirement.

115 Fault tree analysis

116 A fault tree analysis (FTA) is a top down failure analysis which analyses the failure of a system
117 in terms of its contributory causes. In a fault tree diagram, the relationships between the causes
118 and system failure are represented in terms of Boolean logic. The two main Boolean operators
119 used are the OR and the AND gates. The OR gate is used under the situation that the output is
120 TRUE when any one of the inputs is TRUE. The AND gate, on the other hand, is used under the
121 situation that the output is only TRUE when all inputs are TRUE. If the probability values for all
122 inputs are known, it would also be possible to calculate the probability of overall system failure
123 using the Fault Tree Diagram.

124 Fuzzy probability analysis

125 When quantitative historical or comparative failure data are not available, risk analysis can be
126 qualitatively conducted based on expert opinions. However, experts can diverge in opinions. In
127 this regard, fuzzy probability analysis can be used to reduce the amount of subjectivity and un-
128 certainty introduced from consolidating these opinions (Arunraj et al. 2013). As there are no
129 standard rules that define how these can be selected, this makes fuzzy probability analysis inher-
130 ently subjective. Nevertheless, if this tool is universally applied across all expert-based risk anal-
131 yses in an organization, this consistent application reduces the overall subjectivity in such anal-
132 yses.

133 The steps for conducting a fuzzy probability include expert weightages, membership func-
134 tions, aggregation techniques and defuzzification. Initially, weighting factor, w is determined for
135 each expert that will be involved in the risk analysis. This can be derived using criteria such as
136 their years of experience and their job designations. The weighting factors for all experts in-
137 volved should add up to 1. Following this, probability of a primary event at question is judged
138 and expressed by the experts in linguistic terms which correspond to probability categories in the

139 risk matrix. An example of how probability categories can be defined linguistically is as follows:
140 0.1 to 1 for 'A', 0.01 to 0.1 for 'B', 0.001 to 0.01 for 'C', 0.0001 to 0.001 for 'D' and <0.0001 for
141 'E'.

142 Step 3 presents numerous fuzzy membership functions can be used to represent the linguistic
143 expressions, and the uncertainties and inaccuracies associated to these judgements. Out of which,
144 trapezoidal fuzzy membership functions have been found to be one of the most practical (Duan
145 et al. 2016). For the probability categories defined in Step 2, the corresponding trapezoidal
146 membership functions can be as illustrated in Fig. 2 (Ahn and Chang 2016). Lastly, the aggregat-
147 ed fuzzy set Z is defuzzified into a fuzzy probability score, FPS. Techniques that can be used for
148 defuzzification include centre of gravity, bisector of area, mean of maxima, leftmost maximum
149 and rightmost maximum (Shi et al. 2014). The centre of gravity technique, for instance, uses the
150 expression below to obtain the probability score.

184 **Development of the framework**

185 The following criteria have been defined for the development of the risk management frame-
186 work. Firstly, the framework should be in compliant to relevant international standards. This is
187 important as failure to do so may lead to incongruence with other frameworks that have been de-
188 veloped or will be developed. Secondly, the framework should provide guidance on what relia-
189 bility tools can be adopted at each stage. In this section, standards and reliability tools have been
190 analysed and incorporated to form the framework.

191 **Standards**

192 PAS 55:2008 – Asset management

193 The Publicly Available Specification for Asset Management 55-1:2008 and 55-2:2008 was first
194 released in 2004. Under this specification, asset management has been defined as the systematic
195 and coordinated activities and practices through which an organization optimally and sustainably
196 manages its assets and asset systems, their associated performance, risks and expenditures over
197 their life cycles for the purpose of achieving its organizational strategic plan (The Institute of
198 Asset Management 2008). This definition contains concepts that depart distinctly from the tradi-
199 tional approach towards inspection and maintenance.

200 Firstly, asset management should not concern itself with just the management of assets but
201 also the management of asset systems. In light of complex interactions between assets today, the
202 macro perspective of assets is as important as the traditional minuscule approach. Failure of an
203 asset may have far-reaching effects on the reliability of other assets. Conversely, these effects
204 can be insignificant if the asset is redundant within the asset system.

205 Secondly, the standard advises that interventions should be planned based on their costs and
206 the asset system's performance and risks. In this regard, preventive and even predictive mainte-
207 nance, which advises the next course of action based on asset's condition and not risk, fall short
208 on this requirement.

209 Lastly, the standard states that performance, risks and costs ought to be evaluated over the
210 asset's or the asset system's life cycle, i.e. from acquisition/creation, utilization, maintenance to
211 ultimate renewal/disposal. As these aspects vary at various stages of the life cycle, elements of
212 performance evaluation and improvement are necessary in the asset management structure and,

213 similarly, in the risk management framework to affirm the relevance and accuracies of their por-
214 trayals.

215 The overview of an asset management system, as depicted by PAS 55:2008, can be found in
216 Fig. 3. Within which, the use of terminologies such as asset systems and criticalities reverberate
217 the key concepts that have been highlighted above.

218 ISO 31000-Risk management

219 ISO 31000 (International Organization for Standardization 2009) offers its interpretation of a risk
220 management framework. It dictates that there should be four main stages, namely, establishing
221 the context, risk assessment, risk treatment, and monitoring and review. Before assessing any
222 risks, the context under which the assessment is to be executed should be defined. One important
223 aspect is the risk criteria, which are essential as they are used for evaluation of risk significance.
224 Depending on factors such as the views of stakeholders and the nature of the industry, risk crite-
225 ria can vary from organization to organization. One way by which risk criteria can be defined is
226 via risk matrices, which will be touched on later in a subsequent subsection.

227 The risk assessment stage consists of three sub stages, namely risk identification, risk analy-
228 sis and risk evaluation. The risk identification sub stage generates a comprehensive list of failure
229 modes that are capable of jeopardising the functionality or performance of the asset or asset sys-
230 tem. All credible failure modes should be identified here, otherwise it will be left out from the
231 assessment totally. The risk analysis sub stage develops an understanding of the risk associated
232 with each failure mode by determining its likelihood and consequences. Lastly, the risk evalua-
233 tion sub stage identifies risks which need treatment and the priority by which treatment should be
234 implemented.

235 Information sources such as historical data, experience, stakeholder feedback, observations,
236 forecasts and expert judgement can be used for risk analysis. However, ISO 31000 explains that,
237 in order for risk management to be effective, it should be based on the best available information
238 which can be facilitated via a feedback loop of monitoring and review. This stage enables the
239 organization to correct risks which have been inaccurately assessed and, in so doing, reduce dis-
240 crepancies as soon as more accurate data presents itself. This stage coincides well with PAS
241 55:2008 which mandates the element of performance and condition monitoring in asset man-
242 agement systems.

243 ISO 15288:2008-System life cycle process

244 ISO 15288:2008 identifies seven phases in a system life cycle. These are namely the exploratory
245 phase, concept phase, development phase, production phase, utilization phase, support phase and
246 retirement phase. During the exploratory phase, research studies are undertaken to generate new
247 concepts or capabilities which can ultimately lead to the initiation of new projects. In the concept
248 phase, these concepts or capabilities are further specified with guidance from the risk manage-
249 ment process which commences from this phase. Stakeholders' needs are identified, clarified and
250 documented as system requirements (International Organization for Standardization 2008). From
251 the system requirements, evaluation on risks and opportunities are then executed to arrive at the
252 appropriate design specifications (International Organization for Standardization 2008).

253 Subsequently, the system is developed in the development phase while the system compo-
254 nents are produced and integrated in the production phase. Verification and validation activities
255 are executed throughout these phases to ensure continued compliance to system requirements
256 (International Council on Systems Engineering 2015). Once the system is commissioned, the uti-
257 lization and support phases run in parallel. The former ensures operational effectiveness while

258 the latter supports system operation with logistics, maintenance and support services
259 (International Council on Systems Engineering 2015). Finally, the system and its associated ser-
260 vices are removed in the retirement phase. In any of these phases, risks can be introduced or al-
261 tered. During the utilization phase, for instance, the operating environment of the system can
262 change unexpectedly and lead to significant alteration in risk behaviour. Thus, in line with ISO
263 31000, the iterative process of risk assessment, risk treatment, and monitoring and review should
264 perpetuate throughout the system's life cycle and can only end at the retirement phase.

265 In Fig. 4, the risk management process as defined by ISO 31000 has been incorporated into
266 the system life cycle as defined by ISO 15288 to illustrate where each stage of the risk manage-
267 ment process is applicable in a system life cycle. This systems representation of the risk man-
268 agement framework underlines the message that risk management ought to be a continuous feed-
269 back loop which stretches throughout the system life cycle.

270 EN 50126-Railway applications: Specification and demonstration of RAMS

271 In Europe, EN 50126 provides railway industry guidance on how reliability, availability, main-
272 tainability and safety ("RAMS") can be managed. It elaborates that, in order for safety and avail-
273 ability targets to be achieved, reliability and maintainability requirements need to be met, and
274 maintenance and operational activities need to be controlled. The correlations between the ele-
275 ments of RAMS are portrayed in Fig. 5. In the jurisdiction of risk management, it corroborates
276 with PAS 55:2008 that risk analysis shall be performed at various phases of the system life cycle.
277 The system lifecycle, applicable to the rail context, has been suggested by EN 50126 to be as de-
278 picted in Fig. 6. This model follows quite closely with the generic lifecycle model proposed by
279 ISO 15288: Phases 1 to 5 correspond with the exploratory and concept phases, 6 to 10 to the de-
280 velopment and production phases, 11 to the utilization and support phases and, lastly, 14 to the

281 retirement phase of the generic lifecycle model. However, this system lifecycle seems to suggest
282 at face value that risk analysis is just a one-time activity when, in fact, EN 50126 acknowledges
283 that risk management ought to be an on-going process that perpetuates throughout the system
284 lifecycle.

285 EN 50126 also recommends that risk analysis at each stage be performed by the authority re-
286 sponsible for that phase. This may not be judicious as such clear segregation of responsibilities
287 can lead to future risks being overlooked and the loss of opportunities to nip risks in the bud be-
288 fore they manifest. In Europe, heavy fragmentation of rail industry could aggravate the risks.
289 This problem is averted with the guidance from PAS 55:2008 that risk should be evaluated for
290 the entire system life cycle at any point in time.

291 EN 50126 agrees that three main stages, namely, specification, risk analysis and risk evalua-
292 tion, should form part of the risk management process. Specifically, the usage of a risk matrix is
293 recommended for risk evaluation. The risk matrix is a risk management tool rationalised across
294 an organization which prescribes the significance of risks. The tool first requires the likelihood
295 and severity of the risk to be categorized based on defined categories. Based on the likelihood
296 category and the severity category which the risk falls into, the risk category, also known as risk
297 criticality, can then be read off from the risk matrix. However, pertaining to the categorization
298 and risk matrix that EN 50126 has proposed, there are two main concerns. Firstly, risks are eval-
299 uated based on their frequencies of occurrence. Risk is in fact a function of likelihood and not a
300 function of frequency. The use of frequency categories can lead to risks of failure patterns which
301 are time dependent to be erroneously misrepresented. This can be a significant problem as Fig. 7
302 shows that, according to the concept of six RCM failure patterns, only one has a fixed rate of
303 failure throughout the asset's life.

304 Besides this, critical, marginal and insignificant severity has been defined as the loss of major
305 system, severe system damage and minor system damage respectively. This is another area for
306 concern because it is ambiguous on what defines a major system and what warrants severe sys-
307 tem damage. To reduce subjectivity in the risk evaluation, this ambiguity can be removed by
308 simply quantifying as far as possible the definition of severity and likelihood categories.

309 The specification of categories and risk matrix depends on the organization's values, objec-
310 tives and resources, and should take into consideration any relevant legal and regulatory re-
311 quirements (International Organization for Standardization 2009). Thus, these will not be speci-
312 fied in the paper. Nevertheless, for the example later, a hypothetical risk matrix will be adapted
313 from EN50126 with the two areas of concern highlighted above addressed.

314 **Integration of reliability tools**

315 Reliability tools presented in Section 2 are incorporated into the model in Fig. 4 to form a pre-
316 liminary risk assessment framework as shown in Fig. 8. FMEA triggers the practitioner to identi-
317 fy credible failure modes (risk identification), assess the risks for these failure modes (risk analy-
318 sis), rank the risks in terms of criticality and identify the most appropriate action for each risk
319 (risk evaluation). Accordingly, step 1 in FMECA establishes the context prior to risk analysis.
320 Path 1 to Path 3 development stages are equivalent to the risk identification and risk analysis
321 stages. Step 5 corresponds with the risk evaluation stage. Last of all, Steps 6 and 7 represent the
322 monitoring and review stage.

323 Note that, if FMECA were to be used independently for risk identification, not all credible
324 failure modes may be captured. This is undesirable as any failure modes left out in the risk iden-
325 tification sub stage will be left out from the analysis altogether. However, when FMECA is com-
326 plemented with FTA, the modelling approach of the latter is able to ensure that identification of

327 credible failure modes is comprehensive and holistic. In particular, FTA can be deployed on the
328 identification of failure modes and the causes behind each failure mode in Path 1 and Path 2 de-
329 velopment steps of FMECA. This is a combination of FMECA and FTA.

330 In theory, the proposed framework integrates the element of monitoring and assessment for
331 enforcing a proactive inspection and maintenance regime for rail fasteners. This aim would be
332 achieved through the use of risk matrix for risk evaluation which addresses the need for optimiz-
333 ing resource allocation. Apart from that, the embedment of FTA with FMECA within the inte-
334 grated framework assures that the regime is comprehensive.

347 **Application**

348 An example has been constructed to demonstrate how the risk management framework can be
349 applied in practice. This example shall focus on the imbedded anchor, indicated as the plate
350 screw in Fig. 1.

351 **Stage 1: Establishing the context**

352 Amendments have been made to the risk matrix in EN 50126. Firstly, the correct portrayal of
353 failure behaviours has been promoted by classifying occurrence in terms of probability instead of
354 frequency. Secondly, ambiguity is reduced by providing, wherever possible, numerical values for
355 likelihood and severity categorization. The resultant risk matrix is similar to that suggested in
356 academia (Duan et al. 2016; Dumbrava and Iacob 2013) and implemented in industries (Sutton
357 2010). The adopted risk criteria will be that risks must be resolved before they migrate into the
358 intolerable risk category.

359 **Stage 2: Risk assessment**

360 Fault Tree Analysis for risk identification

361 A fault tree analysis was executed to identify the failure modes which are applicable for imbed-
362 ded anchors. The fault tree diagram, as shown in Fig. 9 will form the basis for the ensuing
363 FMECA.

364 Risk analysis

365 i. FMECA

366 By identifying credible failure modes, the FTA conducted in the previous section sets the stage
367 for FMECA. FMECA then analyses each failure mode individually for the likelihood of its oc-
368 currence and the severity of its associated consequence. In the subsequent demonstration, only
369 one of the time-dependent failure modes will be put through FMECA. This failure mode has
370 been chosen to be the reduction in component strength due to corrosion.

371 Considerations will now be made on whether Monte Carlo simulation is applicable. A Feder-
372 al Railroad Administration research from 2011 had concluded that a minimum of three consecu-
373 tive rail fasteners failures is required for gauge widening to be a credible concern (Federal
374 Railroad Administration 2011). In addition, the Asset Standards Authority under Transport for
375 North South Wales recommends that, for curves less than 1000m in radius, failure of three con-
376 secutive rail fasteners require a Priority 2 response. Beyond which, an emergency response
377 would be warranted (RailCorp Network 2013). As multiple rail fasteners are required to fail in
378 order for an undesired event to occur, risk should be evaluated from an asset system level, i.e.
379 from a rail fastening system perspective. According to the risk management framework, Monte
380 Carlo simulation should be considered for the example.

381 In Table 2, the failure effect has thus been identified as a potential derailment scenario (The
382 Office of Transport Safety Investigations 2014) which arises when more than three consecutive
383 rail fasteners fail. If this is a track with frequent passenger service, derailment can potentially
384 lead to fatality with severe disruption of train service. As such, this failure effect has been ac-
385 corded in Table 2 a severity category 1 for both effect on people and financial damage.

386 ii. Weibull analysis

387 The relationship between the shape parameter of Weibull distribution and RCM failure be-
388 haviour is shown in Fig. 10. Corrosion increases in severity with time, thus Weibull distribution
389 for imbedded anchor corrosion is expected to assume a slope parameter of more than 1. It has
390 been specifically suggested by the Weibull handbook that, for corrosion and erosion related fail-
391 ure modes, the shape parameter can be predicted to be between 2 and 3.5 (Robert B Abernethy
392 1996). The scale parameter, on the other hand, is defined as the timeframe at which there is a
393 63.2% chance that the component will fail. This parameter is thus analogous to the average
394 lifespan of the component. The average lifespan of rail fasteners can thus vary substantially and
395 this variability needs to be reflected in the analysis of the framework.

396 iii. Monte Carlo simulation

397 The assumptions and corresponding bases made for the Monte Carlo simulations are as follow.
398 These assumptions have also been illustrated in Fig 11.

- 399 • System definition: A rail fastening system will be defined by the smallest unit possible,
400 i.e. a rail section which is anchored by five consecutive rail fasteners,
- 401 • Assumption: According to Network Rail standards for Inspection and Maintenance of
402 Permanent Way, three consecutive missing or ineffective rail fastenings will warrant the

403 maximum priority level of M1*, i.e. rectify as soon as practicable (Network Rail, 2009).

404 Thus, the system is said to be failed when more than 3 consecutive rail fasteners fail.

- 405 • Assumption: When a sleeper is unable to support a train-induced load, the adjacent sleep-
406 ers will be required to carry loads which are higher than normal, reducing their remaining
407 lives. The extent to which lives are reduced are as suggested above (Zhao et al. 2007). As
408 rail fasteners are subjected by the same loads which are subjected to the sleepers, paral-
409 lels will be drawn between the remaining lives of sleepers and that of rail fasteners. Thus,
410 when one rail fastener fails, the residual life of the adjacent fastener reduces by 50%. If a
411 rail fastener is bounded by two failed fasteners, its residual life is reduced by 75%.

412 **Stage 3: Risk evaluation**

413 In Fig. 12, the availability of a single rail fastener has been plotted against that of a rail fastening
414 system for the Weibull distribution of scale parameter 8000 and shape parameter 3. There are
415 two main observations that can be made from Fig. 12. Between 0 to approximately 5670 days,
416 the availability of the rail fastening system is higher than that of a singular rail fastener. Howev-
417 er, beyond this timeframe, the availability of the rail fastening system deteriorates faster than that
418 of a singular rail fastener.

419 The availability of the rail fastening system is linked to the availability of multiple rail fas-
420 teners. Thus, even if a rail fastener fails prematurely, the rail fastening system will remain sup-
421 ported by fasteners with longer useful lives and does not fail until three consecutive rail fasteners
422 fail. This explains the first phenomenon.

423 This dependency, however, often causes the availability of the rail fastening system to be de-
424 termined by the three shortest useful lives of its constituent fasteners. Besides, the failure of one

425 rail fastener reduces the residual lives of the subsequent fasteners. Thus, the second phenomenon
426 results.

427 The time required for probability to transit from E to D, to C, to B and then to A can be read
428 from Fig. 13 using the definition of probability categories from Table 3. For the rail fastening
429 system, probability transits to D after 1937 days, to C after 2438 days, to B after 3202 days, and
430 finally to A after 4388 days. In fact, there is no difference in severity categories for effect on
431 people and financial damage; the failure of a rail fastening system amounts to a severity level of
432 I for both. Therefore, for both effect on people and financial damage, risk is tolerable for the first
433 1937 days, then undesirable for the subsequent 501 days and, beyond which, intolerable. This
434 analysis result has been updated in the Failure Mode, Effect and Criticality Analysis in Table 4.
435 It can also be noted from Fig. 13 that the probability of failure for a singular rail fastener transits
436 to C after 796 days. This means that, if risk is erroneously depicted at the component level in-
437 stead of the system level, the organisation could have been misguided in taking action at one-
438 third of the actual allowable timeframe, i.e. within 796 days instead of within 2438 days, leading
439 to a less-than-optimal allocation of maintenance resources within the organisation. In the next
440 sub-section, it shall be further demonstrated on how the evaluated risks can be used for the opti-
441 mization of maintenance resources in risk treatment.

442 **Stage 4: Risk treatment**

443 In the corrective approach, only rail fasteners which have failed are replaced. Currently, rail fas-
444 teners are inspected on a fixed frequency and the timeframe for action is determined by the con-
445 dition of the defect. In this sub-section, risk assessment is used to optimize this approach further
446 by extending the intervention interval until risk migrates into intolerable category. The orange
447 arrows in Fig. 14 shows how the availability of the rail fastening system would evolve under this

448 optimized corrective approach. Each black dot indicates the point in time where intervention is
449 required prior to migration to intolerable risk. Table 6 shows that maximum intervention inter-
450 vals should be gradually reduced with time to prevent intolerable risk. As the current inspection
451 and maintenance regime looks at the extent of deterioration and not the rate of deterioration,
452 there may come a point in time when risk becomes intolerable if the priority of action is unable
453 to catch up with the risk transition timeframe.

454 In the proactive approach, all fasteners are inspected and those which have failed or are ex-
455 pected to fail within the next few years are proactively replaced. The replacement includes those
456 that are expected to fail within a specified number of years from the point of intervention. Apart
457 from that, only one point of intervention is considered and the blue lines correspond to various
458 extents of proactiveness at that intervention. The extent of proactiveness is adjusted by varying
459 the projected number of years from that point of intervention. The results can be seen from Table
460 6 and Fig. 15. In general, proactively changing rail fasteners increases the availability of the rail
461 fastening system more than if done by the optimized corrective approach. As shown in Table 7,
462 if 21% of the worst rail fasteners are changed out proactively, fastening systems reach intolerable
463 risk after 2651 days. Reactively changing 21% of the rail fasteners, on the other hand, averts in-
464 tolerable risk for 2481 days.

465 However, from an execution perspective, proactive maintenance would require all imbedded
466 anchors to be removed for inspection and subsequently reinstated post inspection. This is not
467 only time-consuming but also exposes the rail fastening system to additional infant mortality
468 risks. In addition, making a judgement on whether a rail fastener will fail within the next few
469 years can also be very subjective. Thus, while proactive maintenance is ideally a more effective

470 risk mitigation approach, the amount of resources and complexities associated to its execution
471 does not make it a viable strategy.

472 Another approach would be to renew the imbedded anchors of the rail fastening system, re-
473 gardless of their condition, and by doing so, eliminate the subjectivity that characterises the pro-
474 active approach. To optimize maintenance resources, renewal can be synchronised with the time
475 at which risk migrates into intolerable risk category, i.e. after 2417 days in service. Upon com-
476 plete renewal, the risk at question resets fully and will only migrate into intolerable after another
477 2417 days. This approach appears to be more effective than the optimized corrective approach as
478 the timeframe at which risk migrates to intolerable risk is more than three times longer than that
479 for the latter. This proposition, however, needs to be carefully evaluated against other factors.
480 One such factor is the consideration that, like the proactive approach, this strategy involves all
481 rail fasteners as any segments that remain un-renewed will continue to see risk propagate into the
482 intolerable category. Thus, it may not be as effective as it seems as it requires more resources
483 and introduces more infant mortality risks.

484 There are a few factors that can define what is the most appropriate approach to adopt. These
485 factors include the amount of additional risks introduced and the cost effectiveness associated
486 with each approach. This sub-section will delve specifically into how cost effectiveness can be
487 evaluated and compared between the optimized corrective approach and the renewal approach.
488 Table 5 states that five corrective cycles are required to prevent migration of risk into the intoler-
489 able category for a duration of 4898 days. For the case of the renewal approach, only one cycle is
490 required to achieve the same effect. With effectiveness of risk mitigation approximately equiva-
491 lent between five corrective cycles and one renewal cycle, the associated costs can be evaluated
492 using Net Present Value analyses to compare the cost effectiveness for these approaches. In the

493 following NPV analysis for the optimized corrective approach, Year 0 is defined as the year in
494 which the first corrective intervention is to be executed. Let the cost of renewing all fasteners at
495 Year 0 be X , the discount factor be 5%, and the effect of inflation to be negated.

496 In Year 0, 2.73% of the fasteners require replacement, thus the cost for the first corrective
497 cycle is indicated as $0.0273X$. Subsequently, 3.37%, 3.48%, 3.59% and 3.73% require replace-
498 ment in Years 2, 3, 4 and 5 respectively. The total cost for five corrective cycles in terms of net
499 present value becomes approximately $0.15X$. It can be concluded that, while one renewal cycle
500 has a greater impact in terms of risk mitigation, the renewal approach is at least six times less
501 cost effective when compared with the optimized corrective approach.

502 Nevertheless, as the intervention intervals for the optimized correction approach becomes in-
503 creasingly shortened, there will come a stage where maintenance resources become strained or
504 where the long-term cost of the optimized corrective approach outweighs that of the renewal ap-
505 proach, such that the latter becomes a more viable option. This conclusion has been updated into
506 the Failure Mode, Effect and Criticality Analysis in Table 7.

507 The example has demonstrated the effective use of FTA in conjunction with FMECA for risk
508 identification. When executed methodically, this combination allows the comprehensive identifi-
509 cation of credible failure modes and the systematic risk analysis of each failure mode. This ex-
510 ample has also shed light on how risk can be assessed quantitatively and how it can subsequently
511 be used for selecting the optimal risk treatment option. When diverse options are available for
512 risk treatment, a life cycle cost analysis can be done for cost effectiveness comparison.

513 **Discussion**

514 Monte Carlo assumptions could have significant effects on the probability analysis and ultimate-
515 ly the appropriate risk treatment to adopt. These rules, if defined too conservatively, can lead to

516 lost opportunities in maintenance optimization. Conversely, if the failure mode is not well under-
517 stood or if over-optimistic rules have been set, undesired consequences may materialise before
518 expected. In this regard, the second assumption has thus been modified such that, when a rail fas-
519 tener fails, the residual life of the fastener which is one position away reduces by 30% while that
520 which is two positions away reduces by 20%. The simulation is then repeated to understand how
521 this ultimately affects the risk analysis. The new set of assumptions is listed below and illustrated
522 in Fig. 16.

- 523 • No change in system definition: A rail fastening system will be defined by the smallest
524 unit possible, i.e. a rail section which is anchored by five consecutive rail fasteners
- 525 • No change in first assumption: Rail fastening system fails when three consecutive rail
526 fasteners fail
- 527 • Amendment in second assumption: When one rail fastener fails, the residual life of the
528 adjacent fastener reduces by 30%. That of the subsequent fastener reduces by 20%.

529 Table 8 and Fig. 17 illustrate the results from the amended simulation. The blue line indicates
530 the availability curve of a singular rail fastener. The red solid line, on the other hand, indicates
531 the availability curve from the case study simulation and the red dotted line indicates that of the
532 amended simulation. It is observed that the change is mainly characterised by a parallel shift in
533 the availability curve to the right. The change in the risk transitions has been found to be rather
534 pronounced. Specifically, transition to intolerable risk has been shifted back by 8.5%, from Day
535 2432 to Day 2641. The second aspect is the number of consecutive rail fasteners which consti-
536 tutes a rail fastening system failure. Based on Network Rail's track inspection standards, the case
537 study has assumed this number to be three. The track inspection standard from Australia, howev-
538 er, advises that immediate corrective action is required if four consecutive rail fasteners have

539 been found to have failed (Asset Standards Authority, 2013). The higher tolerance in the latter
540 means that there is a lower amount of safety margin. The Monte Carlo simulation has been modi-
541 fied in accordance to the latter guidance and repeated to understand how this affects the risk
542 analysis. The new set of assumptions is listed below and illustrated in Fig. 18.

- 543 • Change in system definition: A rail fastening system will be defined by the smallest unit
544 possible, i.e. a rail section which is anchored by seven consecutive rail fasteners
- 545 • Change in first assumption: Rail fastening system fails when four consecutive rail fasten-
546 ers fail
- 547 • No change in second assumption: When one rail fastener fails, the residual life of the ad-
548 jacent fastener reduces by 50%. If a rail fastener is bounded by two failed fasteners, its
549 residual life is reduced by 75%.

550 Using similar line representations as Fig. 17, Fig. 19 illustrates the results from the amended
551 Monte Carlo simulation. The availability curve has similarly shifted to the right. However, its
552 gradient has steepened and the curve intercepts the original availability curve. It is also observed
553 from Table 9 that transition into intolerable risk has been shifted back by a significant 19%, from
554 Day 2437 to Day 2899.

555 The above analysis underscores the importance of understanding how the failure mode re-
556 lates to the undesired consequence. Inadequate understanding or having too low a safety margin
557 can spread the butter too thin, causing undesired consequences to transpire. On the other hand,
558 having conservative safety margins can translate to suboptimal resource allocation.

545 **Conclusion**

546 The current inspection and maintenance regime for rail fasteners has been assessed and opportu-
547 nities have been found in terms of preventing undesired consequences and allocating resources.
548 These opportunities are namely in increasing its comprehensive, proactiveness and resource op-
549 timization. As a result, this study proposes capitalizing these by shifting towards risk-based
550 maintenance and puts forth a risk management framework to facilitate and reinforce this. A nov-
551 el framework for integrated risk-based maintenance planning has been developed in this study.
552 The structure of the risk management framework is mainly extracted from ISO 31000 which ad-
553 vises that the main stages should include establishing the context, risk identification, risk analy-
554 sis, risk evaluation, risk treatment and, lastly, monitoring and review. PAS 55:2008 recommends
555 that asset management activities ought to be executed across the asset life cycle. To inculcate this
556 philosophy, a system lifecycle has been integrated into the framework to provide a systems per-
557 spective. For risk evaluation, EN 50126 advises that the appropriate reliability tool to use is the
558 risk matrix. For other risk assessment stages, appropriate reliability tools have been studied and
559 the circumstances under which each are applicable have been understood.

560 An example is then prepared on the imbedded anchors on rail fasteners. Its intention is to
561 highlight how the risk management framework can be innovatively adopted in practice and how
562 it delivers on the improvement opportunities. In the example, the timeframes at which risk for
563 corroded imbedded anchors transits to different risk categories were obtained. The overall out-
564 come of this exercise can be found in Table 7. The example has been demonstrated on how FTA
565 can be used for the systematic identification of credible failure modes and how FMECA ensures
566 that risk is evaluated for each failure mode identified. Life cycle analysis is then conducted to

567 demonstrate how the optimal risk treatment strategy can be sought for resource optimization. The
568 Weibull analysis used is inherently a monitoring and review reliability tool. It should be noted
569 that findings are unique to the example and should be treated carefully. Thus, before the novel
570 framework can be applied onto other failure modes, it is imperative that the framework is simu-
571 lated and analysed for the identification of any unique considerations that may affect the frame-
572 work's effectiveness.

573 **Acknowledgement**

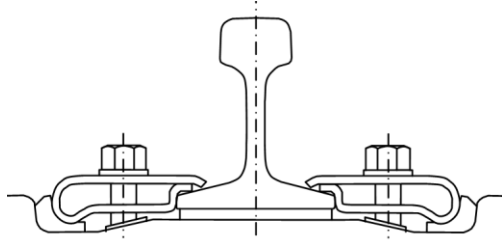
574 All authors are sincerely grateful to European Commission for the financial sponsorship of the
575 H2020-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network,”
576 which enables a global research network that tackles the grand challenge in railway infrastruc-
577 ture resilience and advanced sensing.

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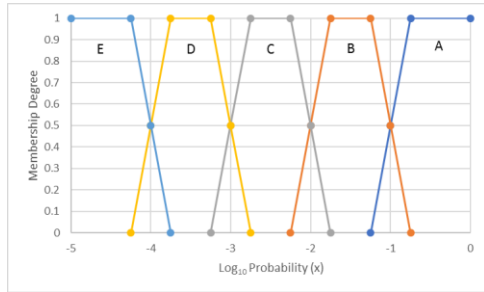
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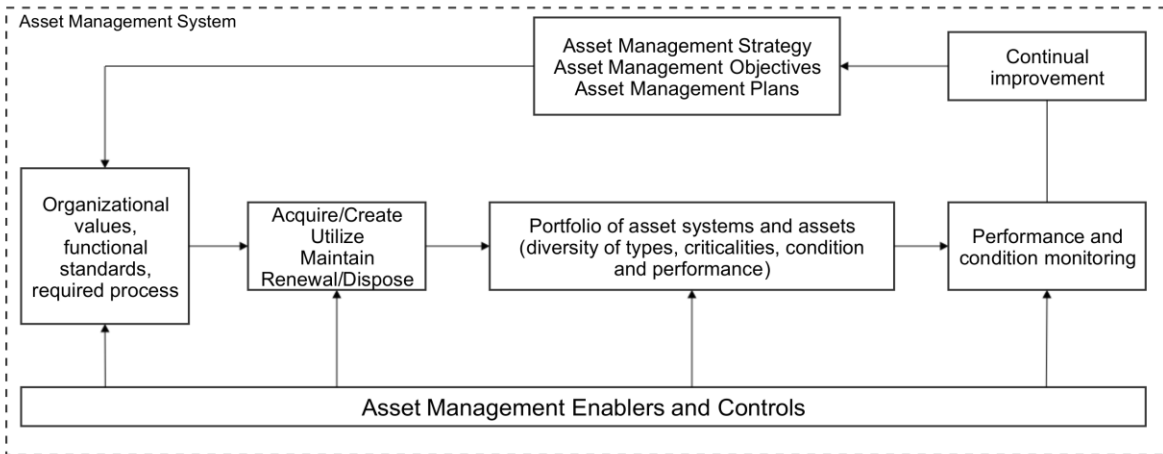
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638 Fig.1. Schematic of anchor bolts on concrete sleeper



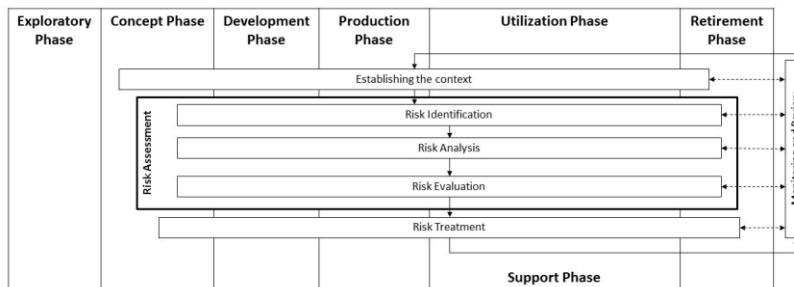
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640 Fig. 2. Trapezoidal membership functions



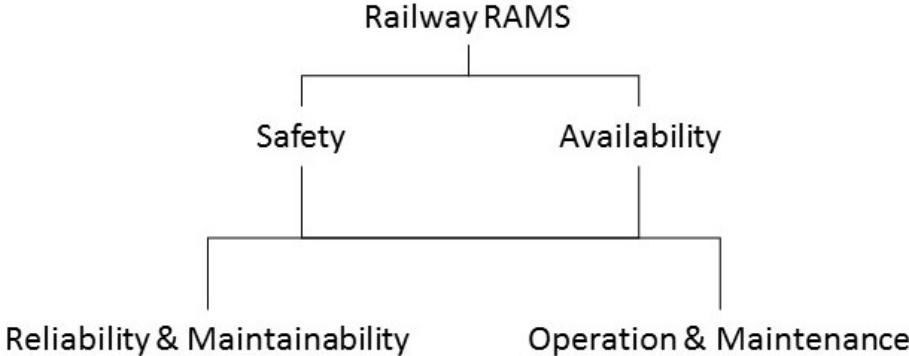
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642 Fig. 3. Overview of asset management system



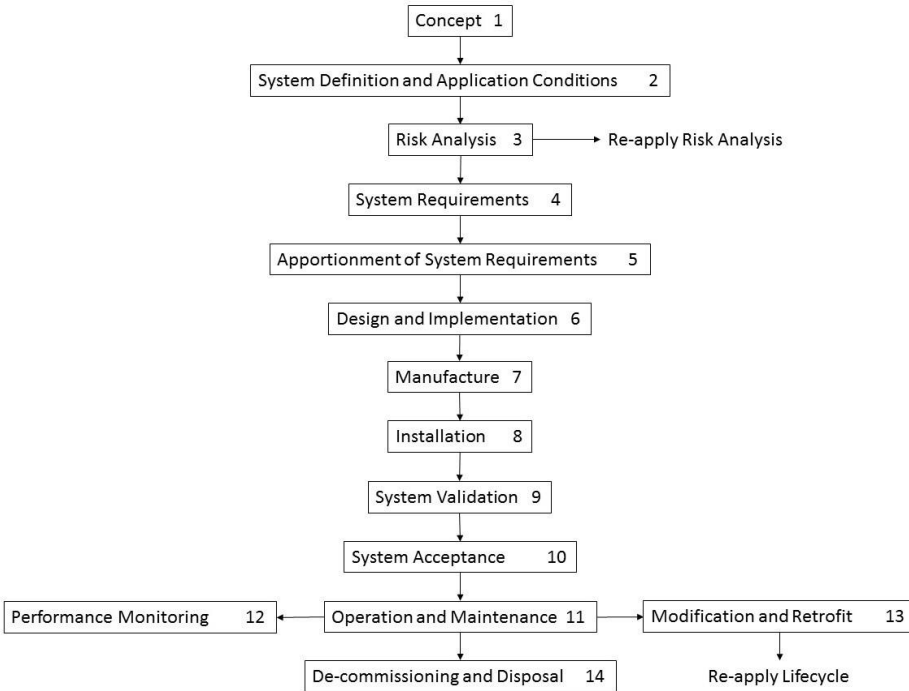
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644 Fig. 4. Systems perspective of risk management framework



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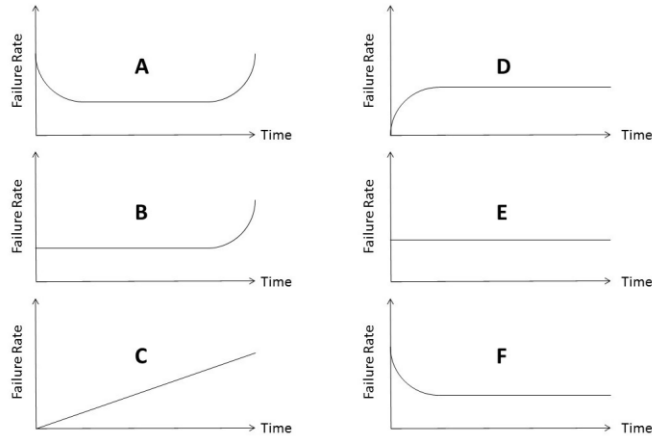
646 Fig. 5. Relationships between RAMS elements



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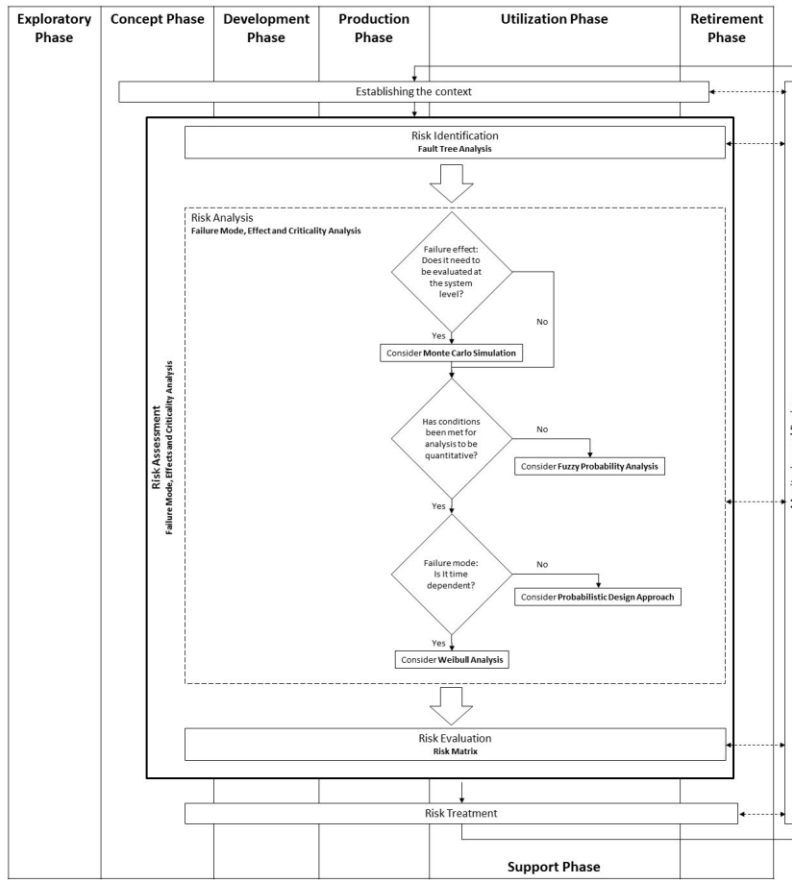
648 Fig. 6. System lifecycle model

Integrated analysis for failure of rail fastener



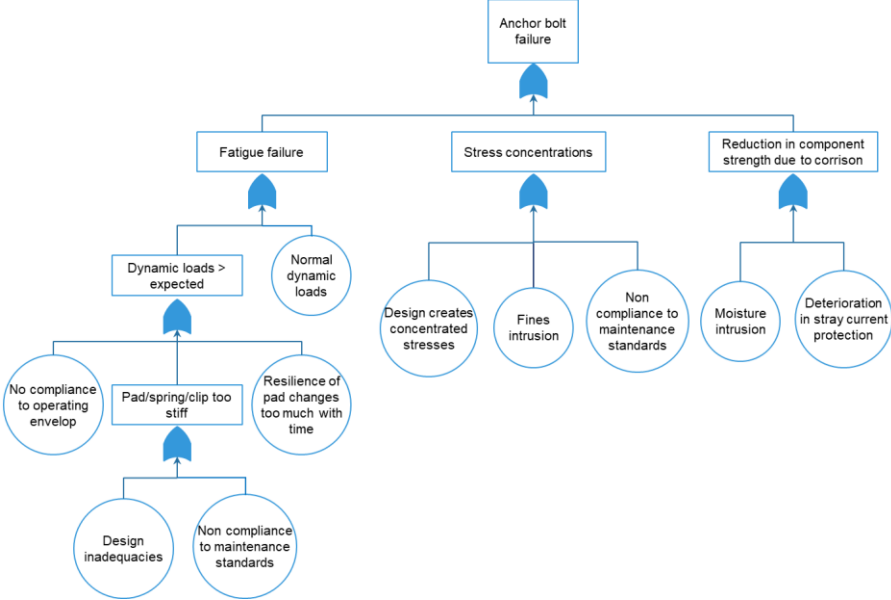
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650 Fig. 7. Six RCM failure pattern curves



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652 Fig. 8. Preliminary risk management framework



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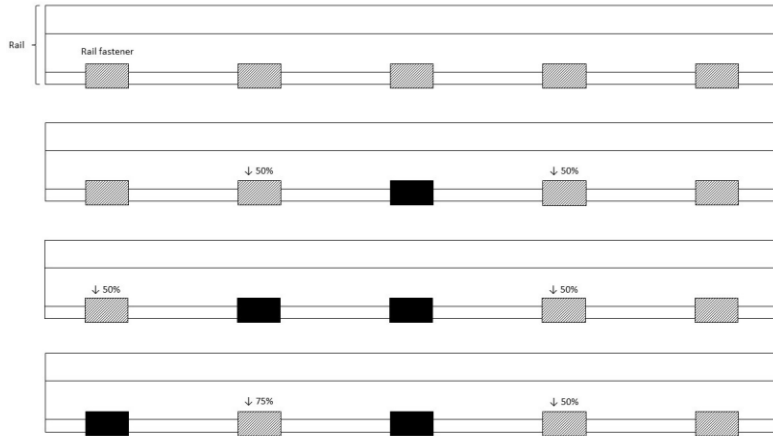
654 Fig. 9. Fault Tree Analysis for anchor bolt failure

β	RCM failure behaviour curves
< 1	Curve F, part Curve A
= 1	Curve E, part Curve A, part Curve B and part Curve D
= 1.5	
= 2	Curve C
> 2	Part Curve A and part Curve B
= 3.44	

655

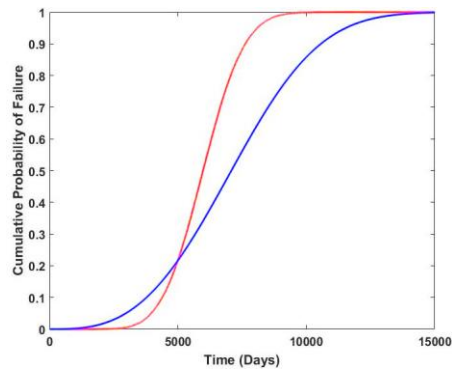
656 Fig. 10. Relationship between shape parameter and failure behaviour curves

Integrated analysis for failure of rail fastener



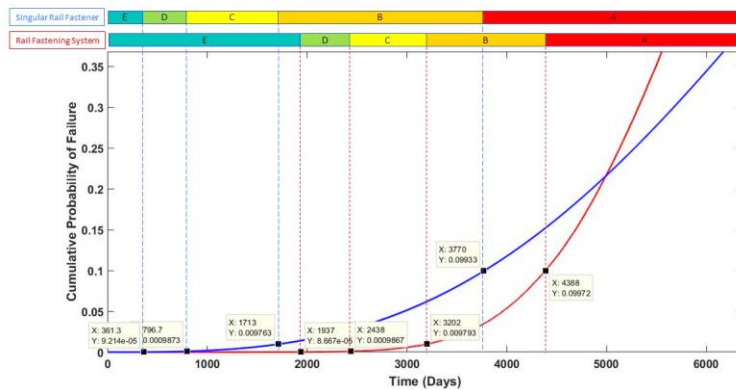
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658 Fig 11. Illustration of the Monte Carlo simulation assumptions



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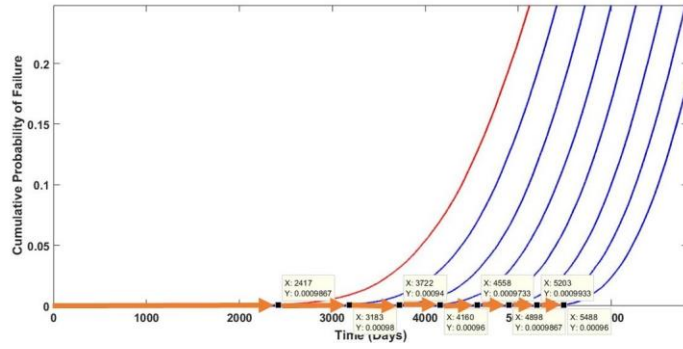
660 Fig. 12. Cumulative distribution function plot of a single rail fastener (blue) and rail fastening
661 system (red)



662

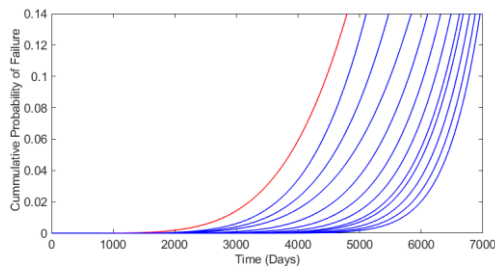
663 Fig. 13. Timeframe at which probability transits from E to D, to C, to B, to A indicated on the
664 respective cumulative distribution function plots

Integrated analysis for failure of rail fastener



665

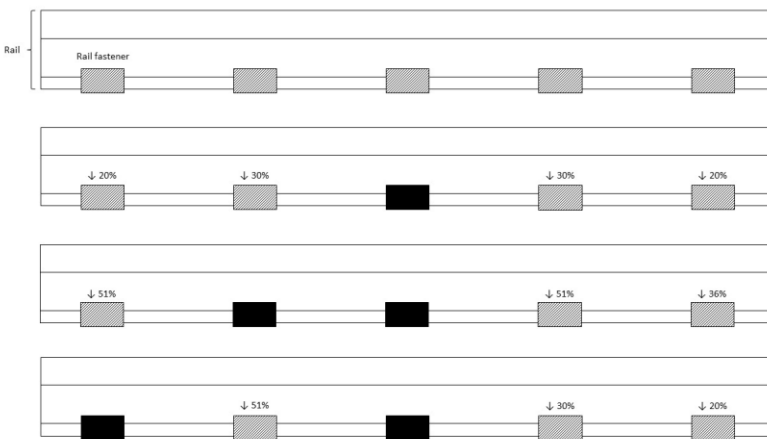
666 Fig. 14. Availability of rail fastening system after consecutive corrective cycles



667

668 Fig. 15. Availability of rail fastening system with corrective maintenance (red line) and increas-

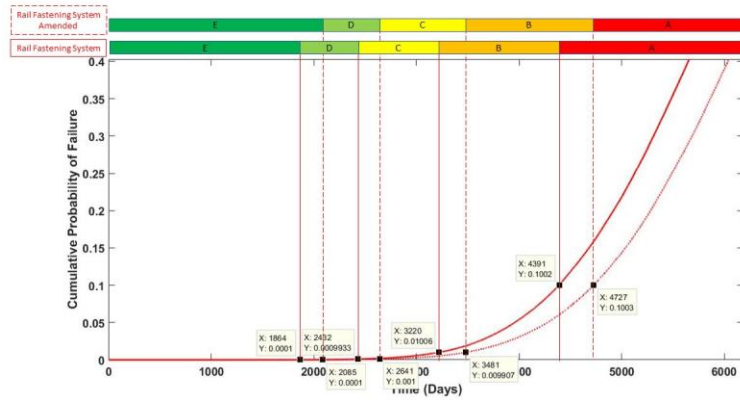
669 ing extent of proactive maintenance (blue lines)



670

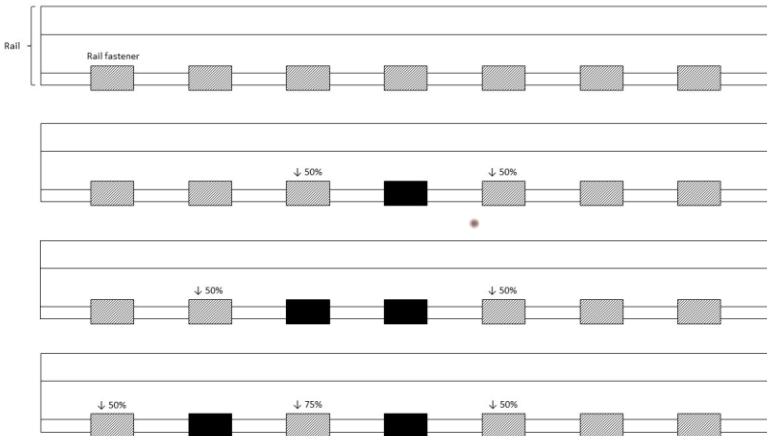
671 Fig. 16. Illustration of new assumptions, with the impact on adjacent fasteners changed

Integrated analysis for failure of rail fastener



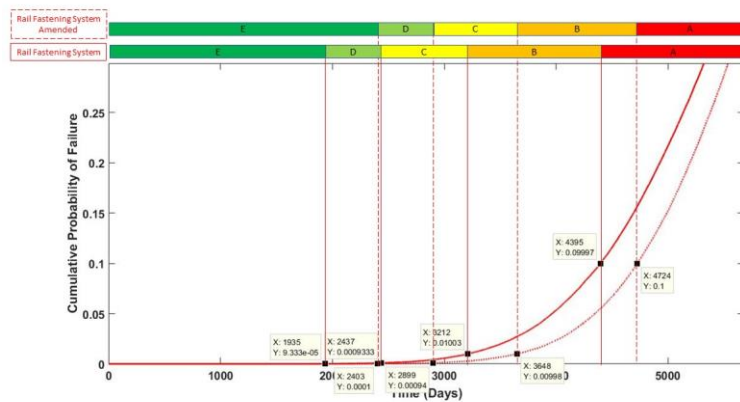
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673 Fig. 17. Shift in availability curve after changes to impact on residual life



674

675 Fig. 18. Illustration of new assumptions, with definition of system failure changed



676

677 Fig. 19. Change in shape of availability curve after changes on system failure definition

678

679

Table 1 Minimum inspection frequency recommended in NR/L2/TRK/001/A01

Inspection frequency	Once per week	Once per two weeks	Once per four weeks
Track category	Cat 1A, Cat 1 & Cat 2	Cat 3 & Cat 4	Cat 5 & Cat 6

680

681 **Table 2 Failure Mode, Effect and Criticality Analysis after severity assignment**

Function	Failure and Cause of Failure	Failure effect	Severity
Imbedded anchor - To maintain vertical, lateral and longitudinal position of rail relative to sleepers	Strength reduction due to corrosion	Derailment due to failure of more than three consecutive rail fasteners	Effect on People: Severity I Financial Damage: Severity I

682

683

684 Table 3 Risk matrix to be adopted for the example

Likelihood	0.1-1	0.01-0.1	0.001-0.01	0.0001-0.001	0.00001-0.0001
Severity					
I	Intolerable	Intolerable	Intolerable	Undesirable	Tolerable
II	Intolerable	Intolerable	Undesirable	Tolerable	Negligible
III	Undesirable	Undesirable	Tolerable	Negligible	Negligible
IV	Tolerable	Negligible	Negligible	Negligible	Negligible

685

686

687 Table 4 Failure Mode, Effect and Criticality Analysis after risk assignment

Function	Failure and Cause of Failure	Failure effect	Severity	Probability	Risk criticality
Imbedded anchor - To maintain vertical, lateral and longitudinal position of rail relative to sleepers	Strength reduction due to corrosion	Derailment due to failure of more than three consecutive rail fasteners	Effect on People: Severity I Financial Damage: Severity I	0 to 1937 th day: Probability E 1937 th to 2438 th day: Probability D 2438 th to 3202 nd day: Probability C 3202 nd to 4388 th day: Probability B 4388 th day and beyond: Probability A	0 to 1937 th day: Tolerable (E-I) 1937 th to 2438 th day: Undesirable (D-I) 2438 th day and beyond: Intolerable (C-I and beyond) Financial Damage 0 to 1937 th day: Tolerable (E-I) 1937 th to 2438 th day: Undesirable (D-I) 2438 th day and beyond: Intolerable (C-I and beyond)

688

689

690 **Table 5 Change in optimized intervention interval with time**

Corrective Cycle	Time of intervention (days)	Elapsed time from previous corrective action (days)	Cumulative percentage of fasteners replaced
1	2417	2417	3%
2	3183	766	6%
3	3722	539	10%
4	4160	438	13%
5	4558	398	17%
6	4898	340	21%
7	5203	305	24%
8	5488	285	n/a

691

692

693 **Table 6 Impact of risk mitigation with changing extent of proactive maintenance**

Fastener replacement criteria (number of years before failure)	Estimated percentage of fasteners to be changed (%)	Time at which risk next transits into intolerable risk category (Days)
0	3	3180
1	4	3410
2	6	3693
3	8	3978
4	11	4272
5	14	4564
6	17	4818
7	21	5068
8	26	5196
9	30	5231
10	35	5330
11	40	5343
12	46	5352

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695

696 Table 7 Failure Mode, Effect and Criticality Analysis after risk evaluation

Function	Failure and Cause of Failure	Failure effect	Severity	Probability	Risk criticality	Recommended action
Imbedded anchor - To maintain vertical, lateral and longitudinal position of rail relative to sleepers	Strength reduction due to corrosion	Derailment due to failure of more than three consecutive rail fasteners	Effect on People: Severity I Financial Damage: Severity I	0 to 1937 th day: Probability E 1937 th to 2438 th day: Probability D 2438 th to 3202 nd day: Probability C 3202 nd to 4388 th day: Probability B 4388 th day and beyond: Probability A	0 to 1937 th day: Tolerable (E-I) 1937 th to 2438 th day: Undesirable (D-I) 2438 th day and beyond: Intolerable (C-I and beyond) Financial Damage 0 to 1937 th day: Tolerable (E-I) 1937 th to 2438 th day: Undesirable (D-I) 2438 th day and beyond: Intolerable (C-I and beyond)	Optimized Corrective approach Renewal approach can be expected in future – to be reviewed.

698 **Table 8 Change in probability timeframe after changes to impact on residual life**

	Time (days) taken to migrate to			
	Probability D	Probability C	Probability B	Probability A
Case Study	1864	2432	3220	4391
Amended Assumptions	2085 (+221)	2641 (+209)	3481 (+261)	4727 (+336)

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700 **Table 9 Change in probability timeframe after changes to impact on residual life**

	Time (days) taken to migrate to			
	Probability D	Probability C	Probability B	Probability A
Case Study	1864	2432	3220	4391
Amended Assumptions	2085 (+221)	2641 (+209)	3481 (+261)	4727 (+336)

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