UNIVERSITY OF TORONTO | Engineering

Subway Rail Re-Inspection Schedule Optimization

Centre for Maintenance, Optimization & Reliability Engineering (C-MORE)

Background

- Client’s rail maintenance strategies includes detection and resolution of track defects
- Each defect is assigned a priority level, with a time limit to resolve/repair the defects
- In case, maintenance resources are not available to repair defects within time limit, the non-destructive testing (NDT) team will re-inspect the defect (resetting the time limit clock)
- Re-Inspections are done with the same time limit interval until defects are resolved

- A significant portion of NDT team’s resources are spent on these re-inspections
- Client would like to review the time limits with each priority level based on evidence

Objectives

- To determine the optimal re-inspection interval for each defect priority level based on evidence while at least maintaining the current reliability of tracks
- Further, the objective will be also to include defect failure modes to determine optimal re-inspection intervals

Defects Priority Levels & Re-Inspections

Priority	Time Limit (days)	Average Time between Re-Inspections (actual)
Gray	365	231.64
Brown	365	139.42
Blue	45	36.42
Purple	21	17.38
Yellow	10	5.67
Red	1	1.29

- Red, Yellow & Purple considered “high priority”
- Red & Yellow are resolved relatively quickly, hence can be excluded from this study
- Gray defects are not required to be updated, they are for information only, in case they get upgraded to higher priority. Gray is considered least priority for this study.
- Analysis show that ***re-inspections are done much earlier*** than the standard time limit

Approach

- NDT re-inspection data from years 2015-18 was analyzed

- The statistical data of defect transitions was collected such as:
  - Transitions: From (Origin) – To (End)
  - Count, average & standard deviation of time for:
    - Transitions
    - Completions with & without transitions
    - Open defects with & without transitions
  - Count of transitions per unique defect
  - No. of re-inspections for:
    - Defects before transition
    - Defects before completion
    - Defects still open

Approach (contd.,)

- Pre-liminary analysis was conducted to identify data deficiencies
- Data was cleaned to eliminate all known data gaps
- Transition analysis was performed to quantify defects' stay in same priority level i.e. before transition
- Weibull & other distribution fitting was performed
- Reliability Analysis was done to identify risk with each re-inspection interval
- Findings & Recommendations were summarized

Data Set

- Data for years 2015-18 from MOWIS system
- Each defect has a unique identifier "DEFECT_NUMBER"
- 1,384 unique defect records
- Status:
  - New: Defect entry when first detected
  - Updated: Follow-up / Re-inspection done
  - Completed: Defects repaired by Maintenance

Description	Count
No. of unique defects	1384
Completions	527
Open defects	857
Transitions	71

Status “Not Found”

- ***154*** entries had “Not Found” status

- This was due to limitations in data system
- It was found that most of these records were closed, and a new record was opened for the same defect

- It was deemed important to link these old and new defect records

- Intensive data cleaning done to eliminate these “Not Found” statuses, most of them requiring manual checking

Other Data Gaps

- Some records were duplicated, and some were entered by mistake but still remained in the record. These records had to be removed.
- In some cases, defects transitioned very quickly (mostly downgrades), when examined, it was evident that these were due to manual changes ex. NDT team would change the priority level on 2nd or 3rd inspection. These had to be manually checked and changed.
- Most of the downgrades were eliminated by the manual clean up, but some still remained due to longer time between change. These had to be ignored for study purposes.

Defect Transition Analysis

Transitions	Count
Blue to Gray	5
Blue to Purple	4
Brown to Gray	4
Gray to Blue	3
Gray to Purple	32
Gray to Yellow	1
Purple to Blue	8
Purple to Yellow	13

Stay in same color without Transition	Count	Average of Stay in Same Color (days)	Std. DevP of Stay in Same Color (days)
Blue	76	306.01	264.41
Brown	24	292.33	264.09
Gray	825	495.70	319.35
Purple	364	153.49	138.67
Red	4	2.25	1.09
Yellow	54	7.56	10.11

- Downgrades (ex. ***Purple to Blue***) were not considered for defect analysis
- The transition analysis results showed that average and standard deviation are close to each other, indicating a possible exponential distribution behaviour

Defect Transition Analysis (contd.,)

Color	Count	Average of Stay (days)	St. DevP of Stay (days)	Sum of Stay (days)
⊟ Blue	**76**	**306.01**	**264.41**	**23257**
f	4	172.25	126.14	689
s	72	313.44	268.07	22568
⊟ Brown	**24**	**292.33**	**264.09**	**7016**
s	24	292.33	264.09	7016
⊟ Gray	**825**	**495.70**	**319.35**	**408950**
f	36	382.28	212.86	13762
s	789	500.87	322.42	395188
⊟ Purple	**364**	**153.49**	**138.67**	**55872**
f	13	114.77	92.78	1492
s	351	154.93	139.88	54380
⊟ Red	**4**	**2.25**	**1.09**	**9**
s	4	2.25	1.09	9
⊟ Yellow	**54**	**7.56**	**10.11**	**408**
s	54	7.56	10.11	408
Grand Total	**1347**	**367.86**	**318.11**	**495512**

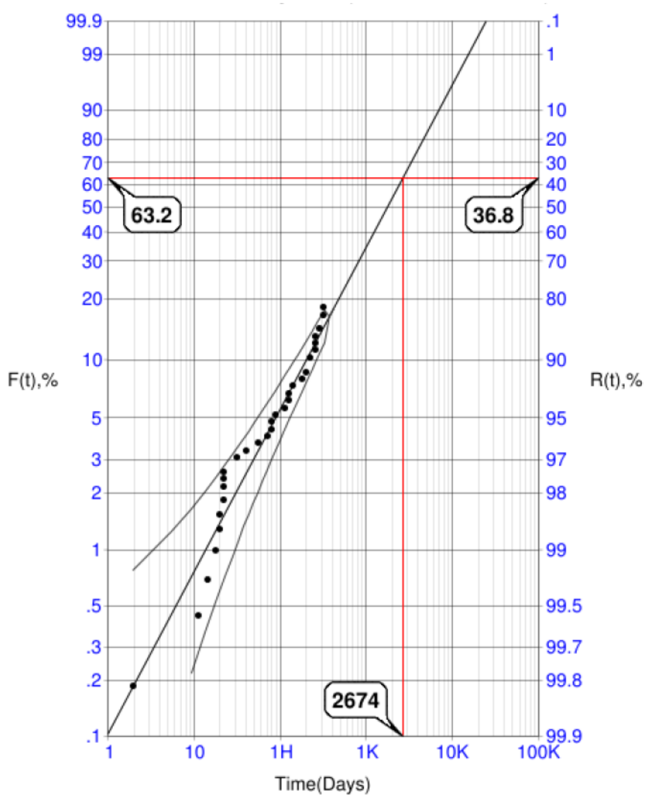
- The “stay in same color without transition” data is incomplete if to be considered for failure data
- Many defects were resolved before transitioning and some still remain open
- These are incomplete data and are to be considered as censored data
- The time data until transitions are considered as failures
- The table here shows failures as “f”, and censored/suspension data as “s”.

Weibull Analysis

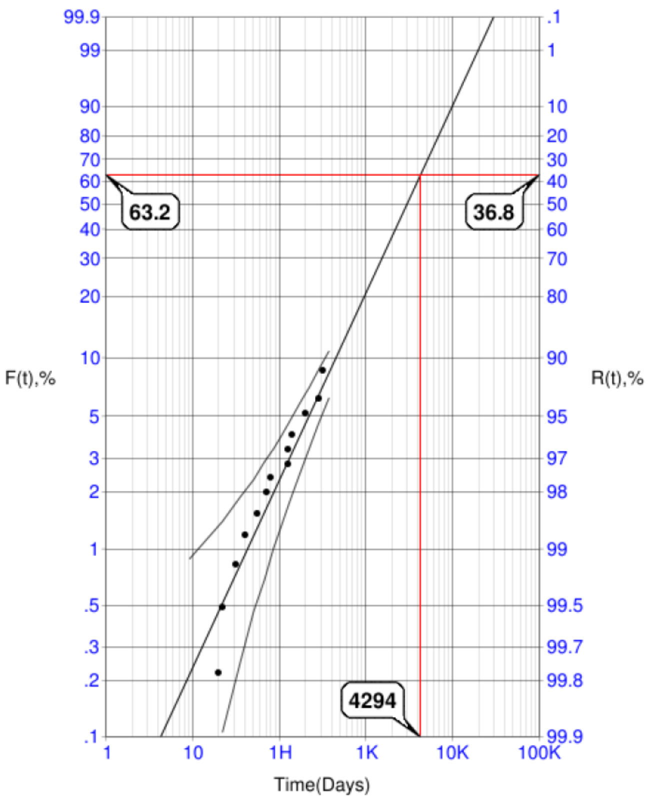
Priority Level	Stay in same color (days)	Transition (f) / Pending & Completed (s)
Blue	31	s
	33	s
	38	s
	42	f
	45	s
	45	s
	52	f
	54	s
	270	s
	277	f
	293	s
	318	f

- “Stay in same color (days)” for each color was individually analyzed
- Sample data from Blue shown here
- Completion, Pending as Suspensions “s”
- Transition as Failures “f”
- Initially, Weibull analysis was done with data considering downgrades, and the Weibull plot was not a good fit
- When further examined, the frequent downgrades was found to affect the Weibull fit
- The downgrades were cleaned up and Weibull analysis was done again

Weibull Analysis (contd.,)



Weibull plot for Purple defects considering downgrades



Weibull plot for Purple defects without considering downgrades

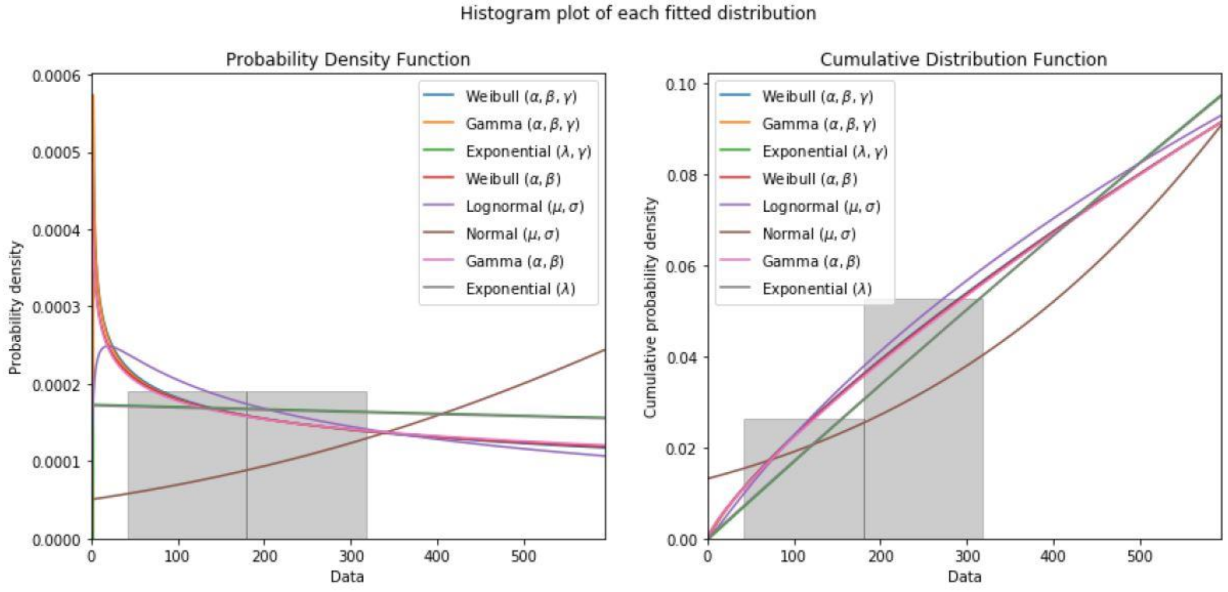
Priority Level	Parameter	Lower 95% CI	Point Estimate	Upper 95% CI
Purple	**Shape Parameter (β)**	0.65	**1.00**	1.54
	Characteristic Life (η)	1,062.66	4,293.60	17,347.95
	Mean Life (μ)		4,292.99	
	Variance (σ^2)		18,417,503.57	
Blue	**Shape Parameter (β)**	0.35	**0.81**	1.85
	Characteristic Life (η)	550.67	10,776.11	210,877.65
	Mean Life (μ)		12,116.25	
	Variance (σ^2)		227,872,329.79	
Gray	**Shape Parameter (β)**	1.01	**1.33**	1.75
	Characteristic Life (η)	2,979.37	5,565.82	10,397.63
	Mean Life (μ)		5,116.06	
	Variance (σ^2)		15,039,633.40	

Parameters based on Weibull Analysis

- The shape parameter (β) for purple and gray priority was near or equal to 1
- This suggested a possible Exponential behavior

Distribution Fitting

Distribution	Alpha	Beta	Gamma	Mu	Sigma	Lambda	AICc	BIC
Exponential_2P			2			0.000173134	79.3464	81.6231
Exponential_1P						0.000172008	79.3986	81.6753
Lognormal_2P				9.85864	2.6244		80.7487	85.2458
Weibull_3P	11237.3	0.796492	1.991				81.1391	85.6361
Gamma_3P	12980.3	0.792068	1.991				81.1653	85.6624
Weibull_2P	10776.1	0.808708					81.2321	85.7292
Gamma_2P	12295.3	0.805132					81.2575	85.7546
Normal_2P				1488.88	669.798		87.1493	91.6464



Distribution fitting results for Blue defects (using *reliability* python library)

Priority Level	2P – Exponential Dist.		2P – Lognormal Dist.	
	Gamma (γ)	Lambda (λ)	Mu (μ)	Sigma (σ)
Purple	1	2.34208×10^{-4}	-	-
Blue	2	1.73134×10^{-4}	-	-
Gray	-	-	9.08364	1.65952

Distribution Fitting Results

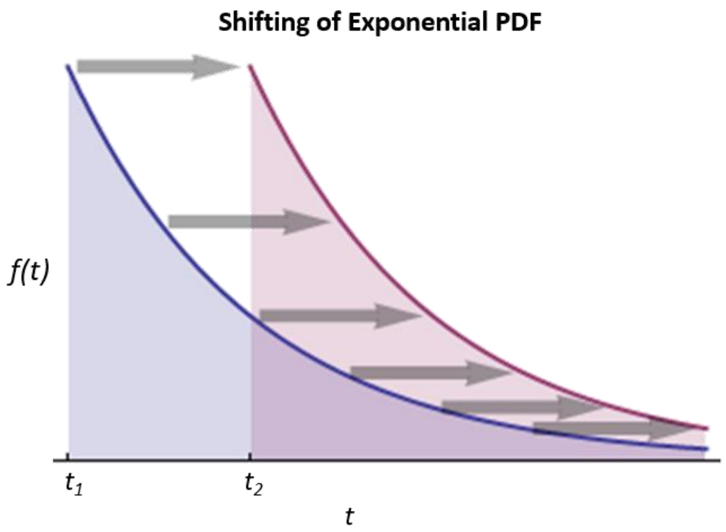
- Purple and Blue defects followed a 2-parameter Exponential distribution
- The results of Gray defects are in-line with the Weibull shape parameter, following a 2-parameter Lognormal distribution
- TTC did not want to consider Gray defects for further analysis as they will be re-inspected only once a year regardless

Reliability Analysis

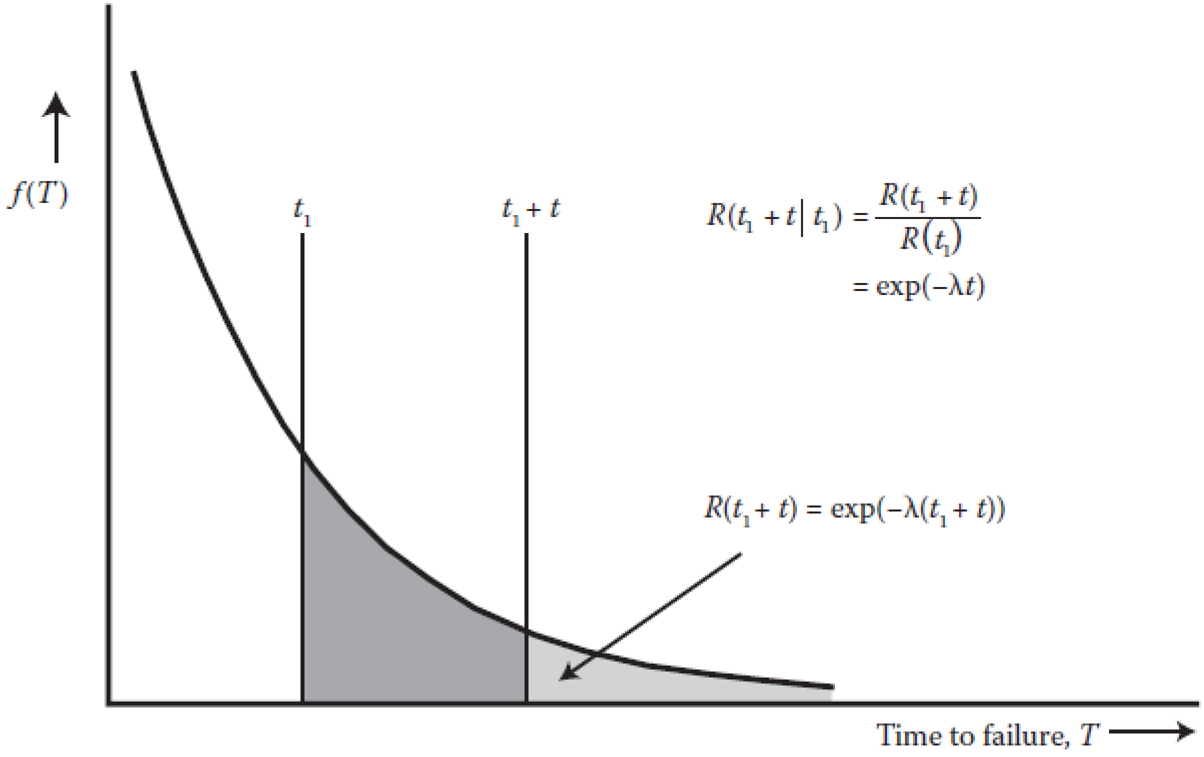
- The objective of the study was to optimize re-inspection intervals with at least maintaining current reliability levels
- The next step was to plot the reliability of a rail defect transitioning from either purple or blue priority to a higher priority
- This was done by using the reliability function of a 2-parameter exponential distribution given by

$$R(t) = e^{-\lambda(t-\gamma)}$$

- It is a valid assumption that time between re-inspection, *t*, resets after every re-inspection owing to the memoryless property of exponential distribution
- But, the overall reliability of the defect is a decreasing function with time



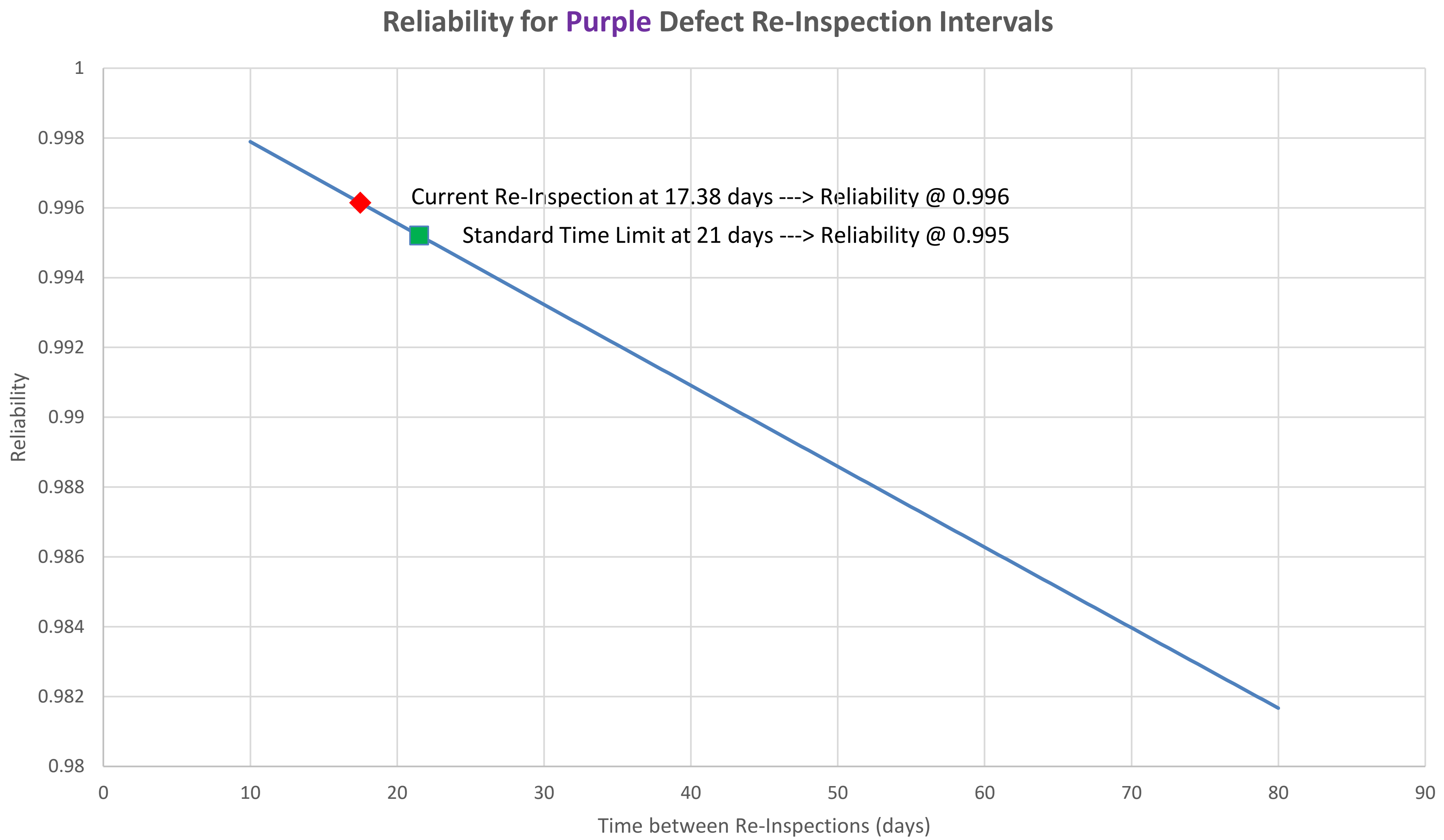
Memoryless Property of Exponential Distribution



Source: "Maintenance, Replacement and Reliability: Theory and Applications", 2nd edition, Andrew K.S. Jardine & Albert H.C. Tsang

- For example, when re-inspection interval is set at 20 days
- The reliability of a defect transitioning to any higher priority will be the same at 20, 40, 60 days and so on
- But, provided only if the defect had not transitioned to higher priority during every re-inspection
- To apply and compare with the graph shown here, t = 20 days, t_1 = 20, 40, 60…
  - R (20) = R (40 | 20) = R (60 | 40)
  - But, R (20) ≠ R (40) ≠ R (60)

Reliability Analysis (contd.,)



- At current re-inspection interval of ***17.38 days***, track reliability is at ***99.6%***
- Expected track reliability at set re-inspection interval of ***21 days*** is at ***99.5%***
- Even at re-inspection interval of ***80 days***, expected reliability is at ***98.2%***

Reliability Analysis - Results

Priority Level	Time between Re-Insp.,	Interval Description	Reliability		Un-Reliability	
			R(t)	% decrease from current level	F(t)	% increase from current level
Purple	17.38	Current	0.996	0.00	0.003829	0.00
	21	Standard	0.995	0.08	0.004673	22.05
	40	1 / 40 days	0.991	0.53	0.009093	137.47
	60	1 / 60 days	0.986	0.99	0.013723	258.40
	80	1 / 80 days	0.982	1.46	0.018332	378.78
	100	1 / 100 days	0.977	1.92	0.022920	498.59
	120	1 / 120 days	0.973	2.37	0.027486	617.84
Blue	36.42	Current	0.994	0.00	0.005942	0.00
	45	Standard	0.993	0.15	0.007417	24.83
	60	1 / 60 days	0.990	0.41	0.009992	68.16
	80	1 / 80 days	0.987	0.75	0.013414	125.76
	100	1 / 100 days	0.983	1.09	0.016824	183.16
	120	1 / 120 days	0.980	1.44	0.020223	240.36
	140	1 / 140 days	0.976	1.78	0.023609	297.36

- This result can be useful for the TTC to optimize its re-inspection intervals
- It shows the effects of reliability and unreliability in terms of % increase / decrease from current levels
- For example, when purple defect is re-inspected every 40 days (instead of current 17.38 days):
  - Reliability decreases by 0.53%
  - Unreliability increases by 137.47%

Reliability Analysis by Failure Mode

- TTC wanted to further analyse the data using failure mode classification
- There were ***51 failure modes*** in the original data, which were classified into 5 major categories such as:
  - Bond Web Crack (BW)
  - Bolt Hole Crack (BH)
  - Corrosion (Cor)
  - Weld and
  - Miscellaneous (Misc)
- After pre-liminary analysis, based on TTC's input only purple defects were considered for further analysis owing to nature of data quality and priority level significance
- The distribution fitting results are shown in the table here
- Again, all failure modes follow a 2-parameter exponential distribution, but unlike before, the gamma (γ) parameter is comparatively larger.

Purple Defects - Failure Mode	2P – Exponential Dist. Parameters	
	Gamma (γ)	Lambda (λ)
BW	8	5.36854×10^{-4}
Cor	2	1.37384×10^{-4}
Weld	5	2.38023×10^{-4}

Future Work

- The number of transitions is small in comparison with the total number of defects. This can be further examined to validate the results of this study

- The comparatively small number of failures also pose a challenge while trying to drill down to defect modes. Focus in this area can strengthen the project objectives

- Scope for further study can be developed in the area of track defect transition using Markovian principles. Transition rate matrix has already been developed.

- To develop a mathematical model for re-inspection interval optimization, more data such as cost of inspection, cost of failure is required, which needs to be further discussed with the TTC. The limited nature of transition data will again be a challenge to develop a mathematical model.

Questions?

Thank you