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Do a Timeline Distribution Before doing a Weibull Failure Analysis

Weibull Analysis has become popular as a means of identifying equipment parts' failure patterns. The shape of the failure curve allows us to identify whether the failure mode was an 'early life' failure, a randomly induced failure or due to wear-out and aging. The Weibull shape parameters provides the owners, users and maintainers of equipment with a tool to use the failure history of their operating plant and predict the behaviour of components and items of equipment replaced complete. The analysis directs selection of effective equipment maintenance strategies and design-out efforts to reduce parts failure.

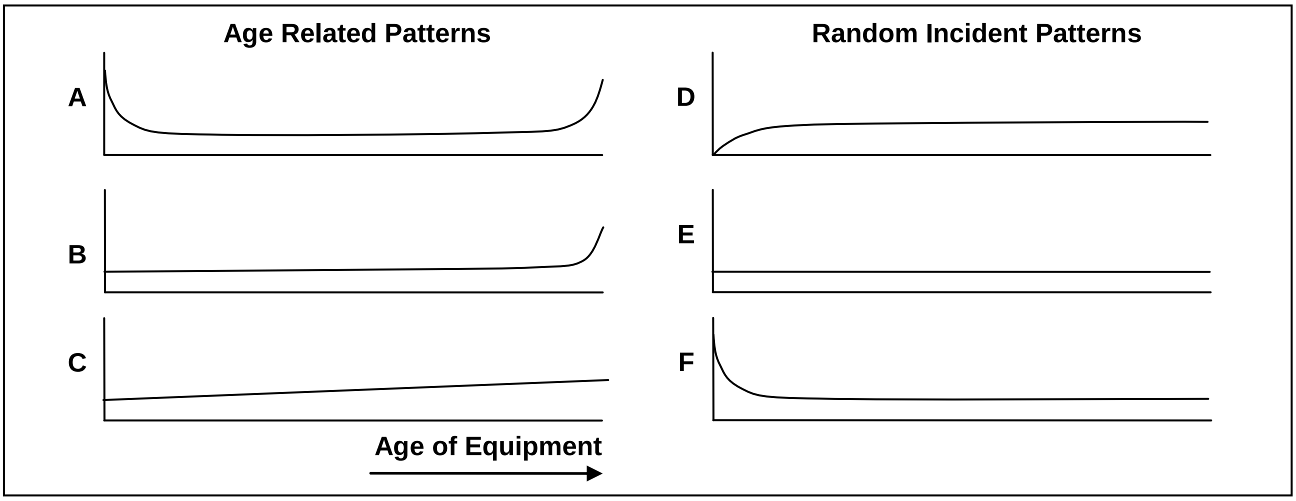

Figure 1 – Six Failure Patterns for Parts (only applies to 'parts', not overhauled assemblies)

Waloddi Weibull identified the Weibull distribution in 1937 while seeking a formula for the failure rate of welds. It is now one of the most commonly used methods for fitting equipment life data and used extensively in the aviation industry to optimise maintenance intervention and select maintenance strategy. The essence of Weibull's work was to discover he could represent the Bathtub Curve of Figure 2 using mathematical formula. His equation could mimic the behaviour of a combination of other statistical distributions, which were each of limited use, by changing its shape. It could represent all the zones of the bathtub curve by using the three Weibull parameters - beta β (shape parameter), eta η (life) and gamma γ (start location).

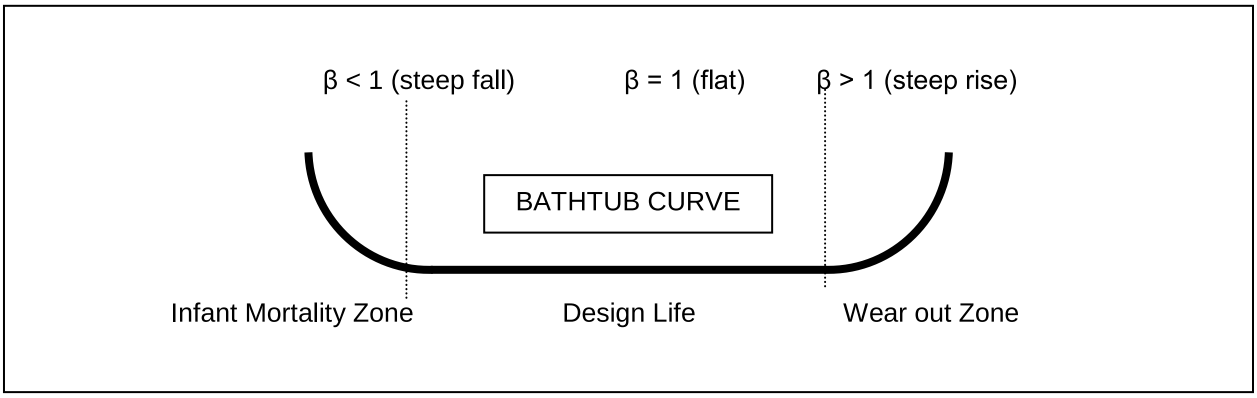

Figure 2 - Weibull Wear-out Life Curve

$\beta < 1$ implies infant mortality. Electronic and mechanical components often have high failure rates initially. Some components are purposely 'burnt in' prior to use, while others require careful commissioning after installation. The presence of infant mortality indicates poor training, lack of procedures and poor quality control.

β = 1 implies random failures. These failures are independent of time where an old part is as good as a new part. Maintenance overhauls are not appropriate for random failures. Condition monitoring and inspection are strategies used to detect the onset of failure, and reduce the consequences of failure. This zone is affected by random incidents and accidents. It reflects poor operating procedures, poor risk management and poor materials selection at design.

1< β <4 implies early wear out. You would not expect this type of failure within the design life. Failure mechanisms such as corrosion, erosion, low cycle fatigue and bearing failures fall in this range. Maintenance often involves a periodic rework or life extension task. The shape can be altered by better materials selection, by degradation management and by good control of operating practices.

β > 4 are wear-out or end of life failures. They should not appear in the design life. Age related failures include stress corrosion cracking, creep, high cycle fatigue, and erosion. Appropriate maintenance is often renewal of the item with new.

An ideal profile for equipment is to have a negligible failure probability throughout its operating life followed by a steep beta that predicts the replacement age. Figure 3 shows such a profile.

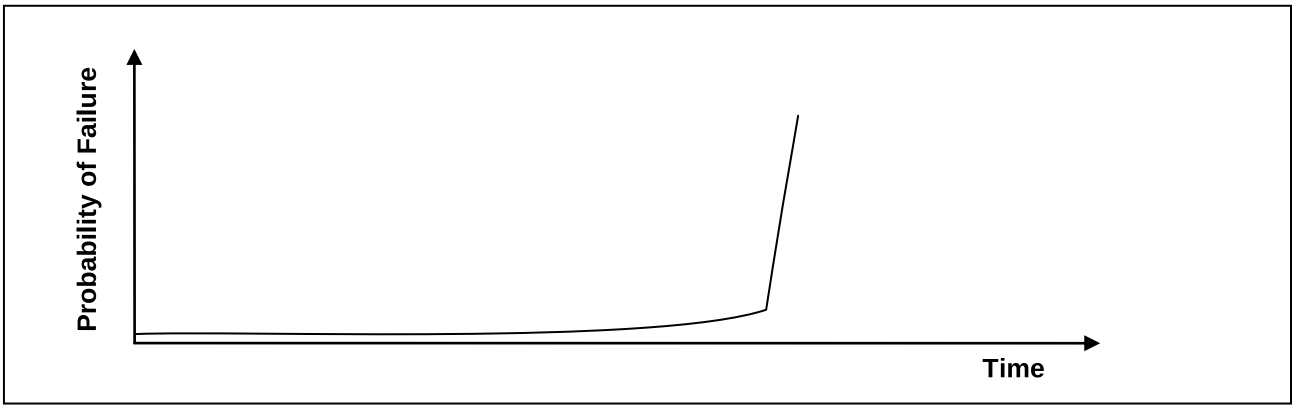

Figure 3 - Ideal Failure Profile for Parts

A drawback of Weibull analysis is the implied assumption that the future is the same as the past. As soon as design, maintenance or operating policies and practices change, the prior failure history becomes unrepresentative of the future. An analysis using the old data would produce poor decisions in that case. Weibull Analysis requires complete and accurate failure data over a period of stable practices, along with an analyst who has thorough understanding of the effects of past and current maintenance and operating policies and practices.

Weibull Analysis is used on failures of the same mode. This is most important, a Weibull plot only applies to one failure mode of an item. It is a false analysis to predict the life of a part that fails for several reasons (e.g. a bearing can have several failure modes - overload, distortion, run short of lubricant, run with water in the lubricant, etc), or for a complex machine made of many parts. You must plot each part's failure modes separately[1]. Note that in Weibull Analysis a 'part' is defined as

[1] Sherwin, David., Retired Maintenance and Reliability Professor, 'Introduction to the Uses and Methods of Reliability Engineering with particular reference to Enterprise Asset Management and Maintenance' Presentation, 2007.

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a replaceable item. Provided the complete assembly or equipment is replaced at every failure, Weibull Analysis can be used for complex systems. For example, if a mechanical seal, or a drive coupling, or gearbox fails and each is always replaced with a complete assembly, then the mechanical seal, coupling and gearbox are seen as a 'part'. If however the assembly is stripped, the failed parts replaced, and the repaired assembly reinstalled, then it is not suitable for Weibull Analysis. A part replaced in the assembly would qualify for analysis, but not the entire rebuilt assembly.

Beware that repeated overhauls of complex equipment result in ever decreasing times between failures after each overhaul. When old parts are reused from one overhaul to the next, the equipment has increasing chance that it will fail sooner than last time. The reused parts are already fatigued and distorted. When used again they fail sooner because prior service stresses reduce their remaining usable life. Having already had a life, they are perhaps close to the end. It is good strategy to identify when equipment parts have accumulated too many service hours of use, or too many overstress cycles, and replace the entire equipment with new[2].

Weibull Analysis predicts probabilistic safe intervals for operation. It helps in selecting the optimum maintenance type and interval so the cost of spares and downtime are minimised for maximum reliability. With sufficient failure data points Weibull Analysis can advise if Preventive and Predictive Maintenance, or re-design, be investigated to improve a component's reliability. With Weibull Analysis, you can compare the cost and estimated effectiveness of your options. You can determine if re-design, or extra quality precautions in manufacture, or whether to initiate measures to reduce operational loads and stresses, are the best choice for the business. It applies to deciding warranty periods, shutdown intervals and setting maintenance and inspection intervals. Accurate Weibull Analysis needs trustworthy parts failure data with clear failure modes. With a sophisticated CMMS in use, the collection of failure mode data is more reliable and data analysis can be done electronically.

Many organisations have kept records of failures manually or in computer systems, but not used the data in any useful way. Failure data is the best source of reliability information available. It is relevant and site people can relate their own experience to it. By transforming maintenance and parts history into useful data used to make failure forecasts, it models the benefits of alternative strategies, or analyses the reliability of current systems and their capacity to meet operating needs.

Life Cycle Simulation

Once the Weibull parameters that best fit failure mode behaviours are available, they can be used to simulate performance over extended periods. If you have a mathematical model of a part's past, you can use the same model to predict its future. Provided the part is treated the same in future as it was in the past, the model is believable. Modern simulation packages involve a Monte Carlo simulation engine that generates random effects in accordance with the historic Weibull parameters over a specified system lifetime. It attempts to mimic what will happen to the part in service if its future were to remain the same as its past. Used in conjunction with FMECA principles, the process of selecting maintenance and inspection intervals becomes a process of playing 'what if' with the Weibull software by comparing the probabilistic effects of different reliability strategies. You then know how to adjust your maintenance to bring the most benefits to the business.

[2] Gurgenci, Hal., Zhihqiang, Guan, 'Mobile Plant Maintenance and the Duty Meter Concept', Journal of Quality in Maintenance Engineering, Vol 7, No4, 2001

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Example Weibull Analysis

It is first necessary to separate each failure into its specific failure mode. Ideally about 10 data points are required for each failure mode to ensure a robust analysis. Too few points for a failure mode causes uncertainty that the Weibull equations are the best fit for the data and so any interpretation from the curves cannot be trusted.

In Figure 4 the mining truck fleet tyre failures collected during service are colour coded by failure mode. The assessment of each failure is by experienced and knowledgeable technicians proficient in tyre failure analysis. Each mining truck tyre costs about $150,000 and the sum of the failures and replacements is about $28 million.

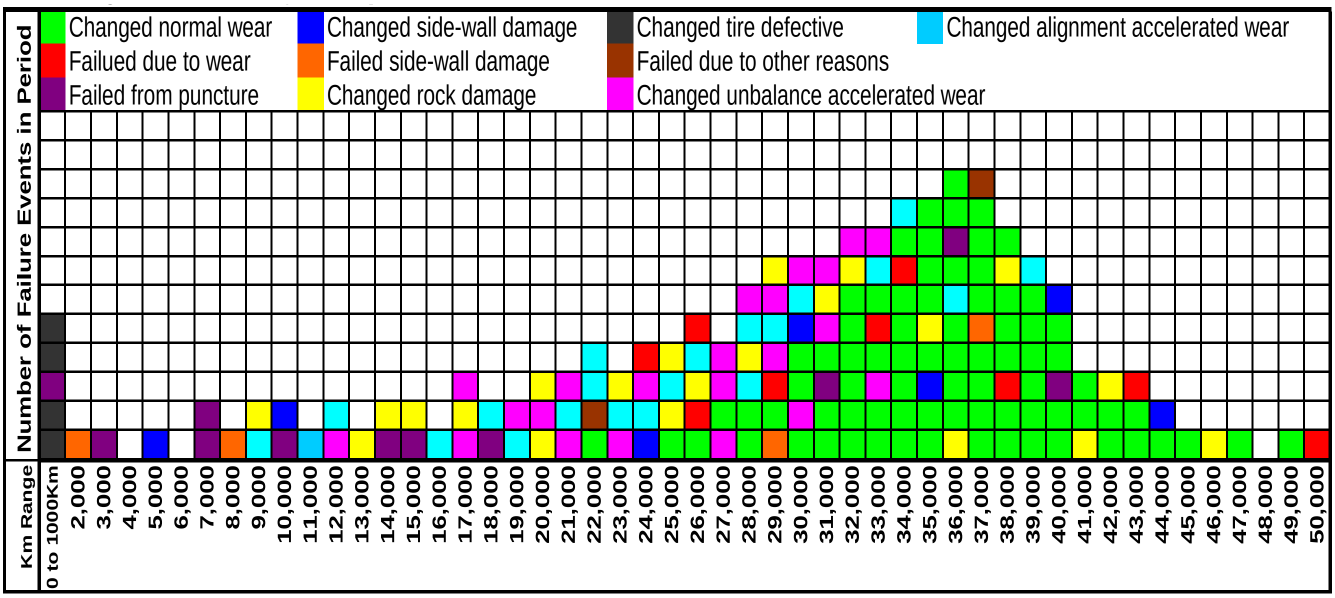

Figure 4 Truck Tyre Failure Events by Failure Mode

The first activity in a Weibull Analysis is not to do a Weibull Analysis, just yet. First plot the failure mode events in a timeline to make sure the data makes sense. Age related failures should have a timeline clearly related to age or usage. Random failure events should have a timeline evidencing ad-hoc occurrences. Early life failures should show-up soon after parts started into operation.

Figure 5 shows distribution charts of the various tyre failure modes. The failure data was manually put into a spreadsheet from the colour coded table which was then used to create the distribution plots. Even without drawing Weibull failure curves the timeline distributions tell a clear story. Tyre wear is mostly grouped between 30,000 to 40,000 kilometres. It is clear that increased stocking of tyres will be necessary as trucks in the fleet near 30,000 km. Punctures, side wall damage and rock damage are operational procedure problems. It would be a smart, proactive decision to more regularly grade the roads on which these mining trucks operate. The 43 tyres lost to un-kept roads cost $6.5 million, an amount which would more than adequately cover the cost of the extra road grading to protect the tyres against damage.

Much can be learnt from failure mode time distributions even without using Weibull curve plotting software.

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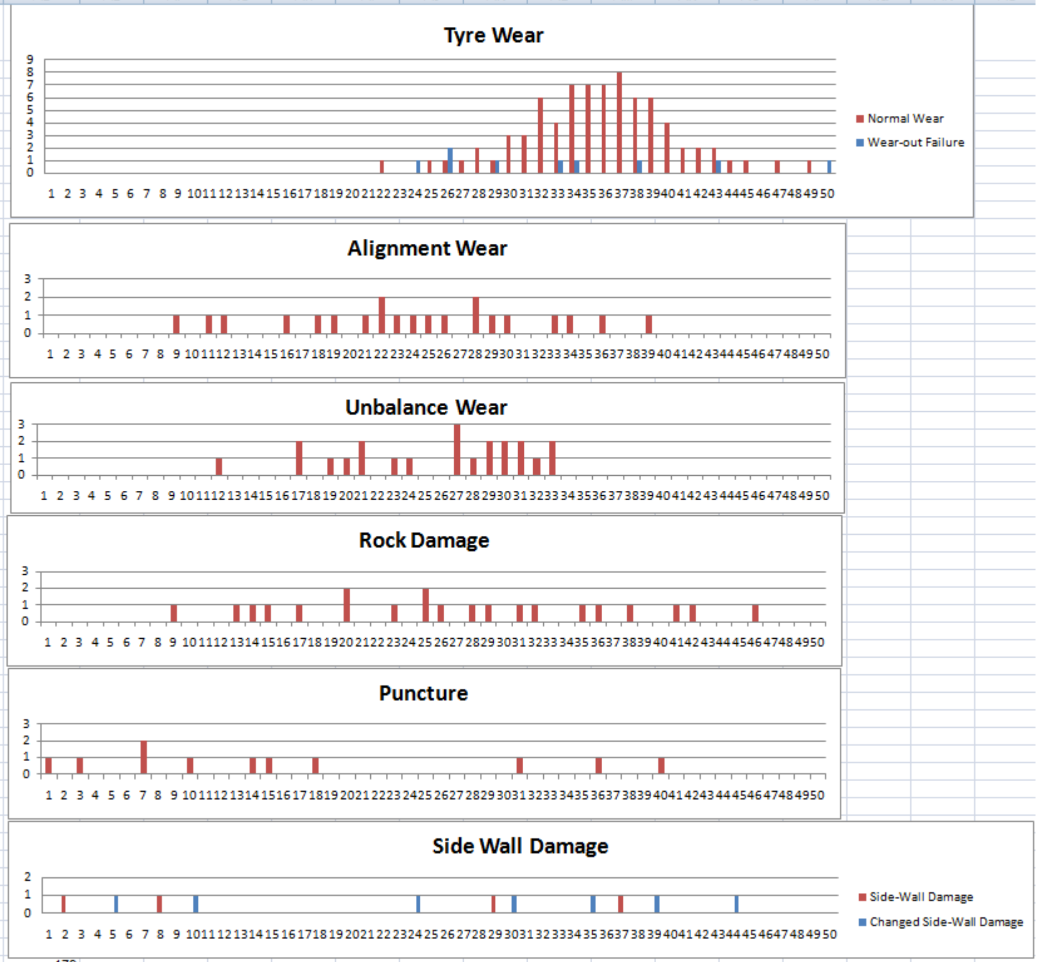
	Kilometers	Replaced Normal Wear	Wear-out Failure	Alignment Wear	Unbalance Wear	Rock Damage	Puncture	Failed Side-Wall Damage	Changed Side-Wall Damage	Unknown Failure	Defective Tyre	
	1,000						1				4	
	2,000							1				
	3,000						1					
	4,000											
	5,000								1			
	6,000											
	7,000						2					
	8,000							1				
	9,000			1		1						
	10,000						1		1			
	11,000			1								
	12,000			1	1							
	13,000					1						
	14,000					1	1					
	15,000					1	1					
	16,000			1								
	17,000				2	1						
	18,000			1			1					
	19,000			1	1							
	20,000				1	2						
	21,000			1	2							
	22,000	1		2						1		
	23,000			1	1	1						
	24,000		1	1	1				1			
	25,000	1		1		2						
	26,000	1	2	1		1						
	27,000	1			3							
	28,000	2		2	1	1						
	29,000	1	1	1	2	1		1				
	30,000	3		1	2				1			
	31,000	3			2	1	1					
	32,000	6			1	1						
	33,000	4	1	1	2							
	34,000	7	1	1								
	35,000	7				1			1			
	36,000	7		1		1	1					
	37,000	8						1		1		
	38,000	6	1			1						
	39,000	6		1					1			
	40,000	4					1					
	41,000	2				1						
	42,000	2				1						
	43,000	2	1									
	44,000	1							1			
	45,000	1										
	46,000					1						
	47,000	1										
	48,000											
	49,000	1										
	50,000		1									
Total												
Count		78	9	21	22	21	11	4	7	2	4	179
MTTF (km)		35667	33667	24048	25500	26905	16545	19000	26714	29500		
Mean Life	28832											
Failure Rate per 10,000 km							0.60	0.53	0.37			

NOTES A tyre is a non-repairable item, hence MTTF is used. MTBF is for repairable items.



Data | Distributions | Wear-out Failure | All Rock Damages | Just Rock Damage

Figure 5 Failure Mode Event Timeline Distributions

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A close look at the distances of unbalance and poor alignment failures show them starting at about 10,000km with each mode causing frequent loss of tyres thereafter. An immediate maintenance strategy that becomes evident is to schedule all trucks for tyre balance and alignment every 10,000km. The more than 40 tyres lost from these two preventable failure modes is worth over $6 million. With all trucks coming in for a service every 10,000km anyway the additional balance and alignment would add an extra day off the road and cost a technician's time. A full costing model needs to be developed to be sure savings will be gained, but on face value it seems that the inclusion of alignment and balance preventive maintenance will make money for the operation.

Example Weibull Plots on Weibull Graph Paper

The computer screen dumps below show the Weibull failure curves for various tyre failure modes, along with the calculation tables developed for the Weibull curve equations. The data points are plotted on Weibull graph paper, which was developed for Weibull failure analysis before computer software was commercially available. When you learn Weibull Analysis you are first required to plot failure data using Weibull graph paper and you only use computer programs later once you are accomplished with manual graphing.

The closeness with which the individual data points match the straight line through them all is an indication of the suitability of using a Weibull curve to fit the data. The nearer to being on a straight line where the data points plot on the graph paper the more sure you are that Weibull math is the appropriate distribution to use.

From each failure mode graph the three Weibull parameters - beta β (shape parameter), eta η (characteristic life) and gamma γ (start location) can be identified.

Figure 6 is for tyres' normal wear failure mode. It has a beta of 7, which means a strongly age related failure. The gamma indicates no wear-out failures are likely until 22,000km. The tyres' characteristic life (by which 62.7% of tyres have failed) due to wear-out is 42,000km.

Figure 7 shows the Weibull plot for all tyres lost to rock damage of various modes. The expectation is that all such damage would be random since no one can know when a rock will damage or puncture a tyre. Up until about 30,000km the beta is 1, which identifies random failure. But after 30,000km the curve has a strong age related bias. One possible reason for the hip is that once tyres have built-up stresses from 30,000km of service they are more prone to rock damage due to their accumulated inner fatigue.

The Weibull plot of Figure 8 is only for tyres changed due to rock damage. The beta of 2.4 confirms wear and tear is a factor affecting when tyres start suffering damage from rocks. Here again one is suspicious that tyre fatigue weakens tyres and makes them more susceptible to damage from rocks.

By using a timeline and doing Weibull Analysis of each failure mode your maintenance history can provide you with a very sound understanding of that is happening to your plant and equipment and what you can do to improve reliability and reduce operational and maintenance costs.

My best regards to you,

Mike Sondalini
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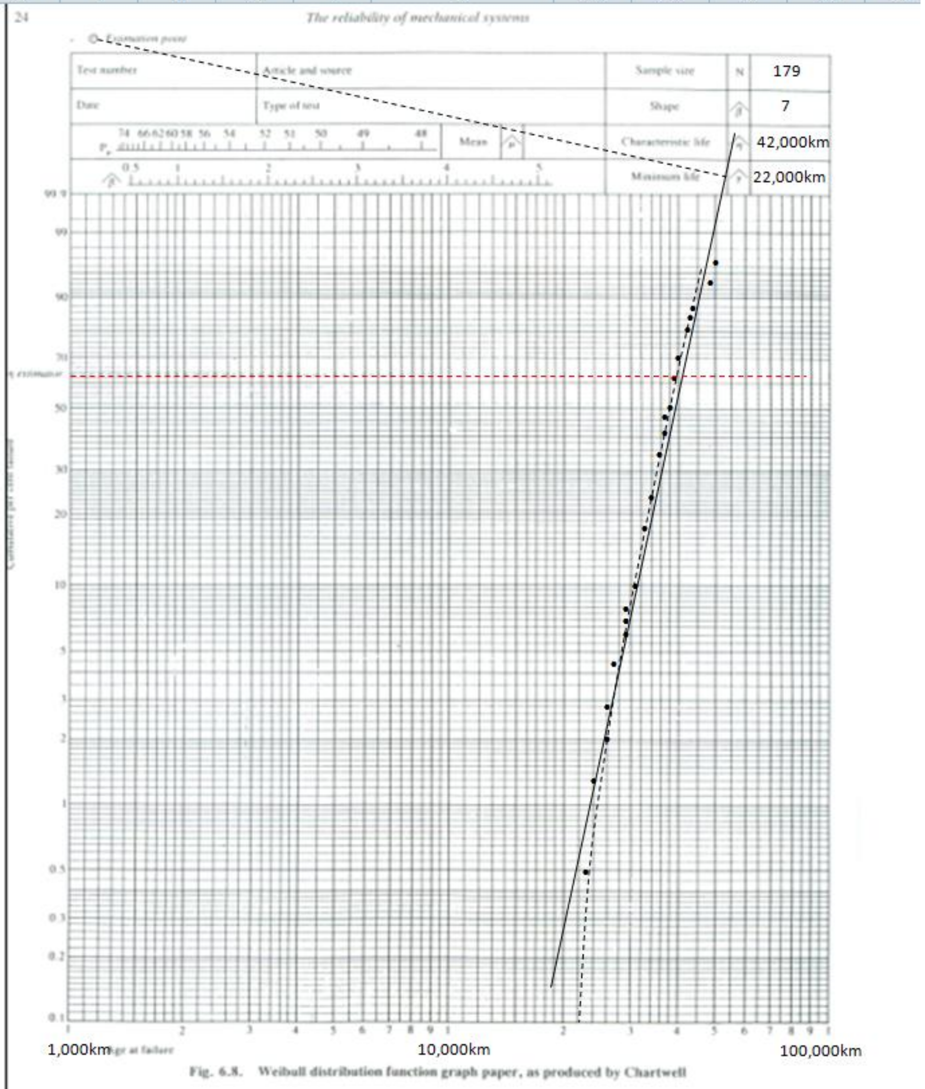
	Wear-Out Failure Number	Age at Failure or Censoring Km	Failure or Censored F or S	Survivors Just Before	Mean Order Number Mi	Failure Function Median Rank by Benards Approximation
2		1,000		179		
3		1,000		178		
4		1,000		177		
5		1,000		176		
6		1,000		175		
7		2,000		174		
8		3,000		173		
9		5,000		172		
10		7,000		171		
11		7,000		170		
12		8,000		169		
13		9,000		168		
14		9,000		167		
15		10,000		166		
16		10,000		165		
17		11,000		164		
18		12,000		163		
19		12,000		162		
20		13,000		161		
21		14,000		160		
22		14,000		159		
23		15,000		158		
24		15,000		157		
25		16,000		156		
26		17,000		155		
27		17,000		154		
28		17,000		153		
29		18,000		152		
30		18,000		151		
31		19,000		150		
32		19,000		149		
33		20,000		148		
34		20,000		147		
35		20,000		146		
36		21,000		145		
37		21,000		144		
38		21,000		143		
39		22,000		142		
40		22,000		141		
41		22,000		140		
42	1	23,000	F	139	1.29	0.5%
43		23,000		138		
44		23,000		137		
45		23,000		136		
46	2	24,000	F	135	2.60	1.3%
47		24,000		134		
48		24,000		133		
49		24,000		132		
50		25,000		131		
51		25,000		130		
52		25,000		129		



Data | Distributions | Wear-out Failure | All Rock Damages | Just Rock Damage

Figure 6 Tyre Wear-Out Failure Mode

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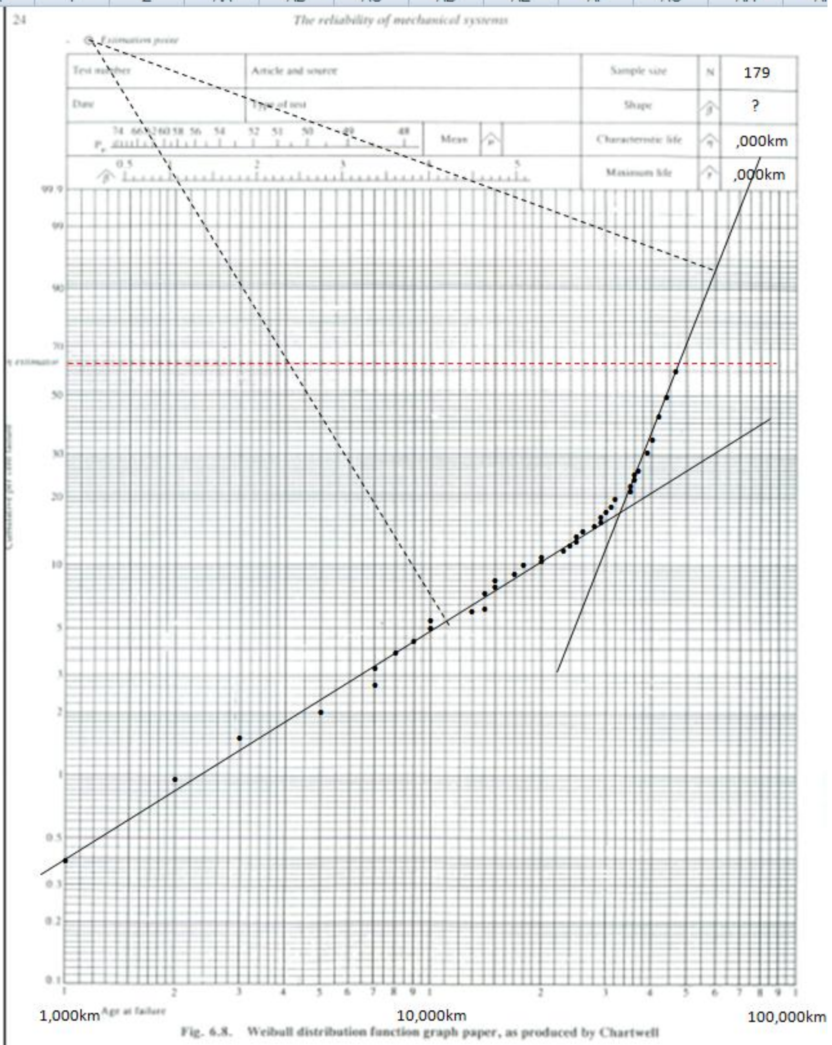
	M	N	O	P	Q	R	S	T	U	V	W
1	Kilometers	Rock Damage	Puncture	Failed Side-Wall Damage	Changed Side-Wall Damage	Failure Number	Age at Failure or Censoring Km	Failure or Censored F or S	Survivors Just Before	Mean Order Number Mi	Failure Function Median Rank by Benards Approximation
2	1,000		1			1	1,000	F	179	1.00	0.39%
3	2,000			1			1,000		178		
4	3,000		1				1,000		177		
5	4,000						1,000		176		
6	5,000				1		1,000		175		
7	6,000					2	2,000	F	174	2.02	0.96%
8	7,000		2			3	3,000	F	173	3.05	1.53%
9	8,000			1		4	5,000	F	172	4.07	2.10%
10	9,000	1				5	7,000	F	171	5.09	2.67%
11	10,000		1		1	6	7,000	F	170	6.11	3.24%
12	11,000					7	8,000	F	169	7.14	3.81%
13	12,000						9,000		168		
14	13,000	1				8	9,000	F	167	8.17	4.38%
15	14,000	1	1			9	10,000	F	166	9.20	4.96%
16	15,000	1	1			10	10,000	F	165	10.22	5.53%
17	16,000						11,000		164		
18	17,000	1					12,000		163		
19	18,000		1				12,000		162		
20	19,000					11	13,000	F	161	11.27	6.12%
21	20,000	2				12	14,000	F	160	12.32	6.70%
22	21,000					13	14,000	F	159	13.37	7.28%
23	22,000					14	15,000	F	158	14.42	7.87%
24	23,000	1				15	15,000	F	157	15.46	8.45%
25	24,000				1		16,000		156		
26	25,000	2				16	17,000	F	155	16.52	9.04%
27	26,000	1					17,000		154		
28	27,000						17,000		153		
29	28,000	1				17	18,000	F	152	17.59	9.64%
30	29,000	1		1			18,000		151		
31	30,000				1		19,000		150		
32	31,000	1	1				19,000		149		
33	32,000	1				18	20,000	F	148	18.68	10.24%
34	33,000					19	20,000	F	147	19.77	10.85%
35	34,000						20,000		146		
36	35,000	1			1		21,000		145		
37	36,000	1	1				21,000		144		
38	37,000			1			21,000		143		
39	38,000	1					22,000		142		
40	39,000				1		22,000		141		
41	40,000		1				22,000		140		
42	41,000	1					22,000		139		
43	42,000	1				20	23,000	F	138	20.92	11.49%
44	43,000						23,000		137		
45	44,000				1		23,000		136		
46	45,000					21	24,000	F	135	22.09	12.15%
47	46,000	1					24,000		134		
48	47,000						24,000		133		
49	48,000						24,000		132		
50	49,000					22	25,000	F	131	23.29	12.81%
51	50,000					23	25,000	F	130	24.48	13.48%
52		21	11	4	7		25,000		129		



Data | Distributions | Wear-out Failure | All Rock Damages | Just Rock Damage

Figure 7 All Rocks Damage Failure Mode

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	M	N	O	P	Q	R	S	T	U	V	W
1	Kilometers	Rock Damage	Puncture	Failed Side-Wall Damage	Changed Side-Wall Damage	Failure Number	Age at Failure or Censoring Km	Failure or Censored F or S	Survivors Just Before	Mean Order Number Mi	Failure Function Median Rank by Benards Approximation
2	1,000		1				1,000		179		
3	2,000			1			1,000		178		
4	3,000		1				1,000		177		
5	4,000						1,000		176		
6	5,000				1		1,000		175		
7	6,000						2,000		174		
8	7,000		2				3,000		173		
9	8,000			1			5,000		172		
10	9,000	1					7,000		171		
11	10,000		1		1		7,000		170		
12	11,000						8,000		169		
13	12,000						9,000		168		
14	13,000	1				1	9,000	F	167	1.07	0.43%
15	14,000	1	1				10,000		166		
16	15,000	1	1				10,000		165		
17	16,000						11,000		164		
18	17,000	1					12,000		163		
19	18,000		1				12,000		162		
20	19,000					2	13,000	F	161	2.18	1.05%
21	20,000	2				3	14,000	F	160	3.28	1.66%
22	21,000						14,000		159		
23	22,000					4	15,000	F	158	4.39	2.28%
24	23,000	1					15,000		157		
25	24,000				1		16,000		156		
26	25,000	2				5	17,000	F	155	5.52	2.91%
27	26,000	1					17,000		154		
28	27,000						17,000		153		
29	28,000	1					18,000		152		
30	29,000	1		1			18,000		151		
31	30,000				1		19,000		150		
32	31,000	1	1				19,000		149		
33	32,000	1				6	20,000	F	148	6.69	3.56%
34	33,000					7	20,000	F	147	7.86	4.21%
35	34,000						20,000		146		
36	35,000	1			1		21,000		145		
37	36,000	1	1				21,000		144		
38	37,000			1			21,000		143		
39	38,000	1					22,000		142		
40	39,000				1		22,000		141		
41	40,000		1				22,000		140		
42	41,000	1					22,000		139		
43	42,000	1				8	23,000	F	138	9.10	4.90%
44	43,000						23,000		137		
45	44,000				1		23,000		136		
46	45,000						24,000		135		
47	46,000	1					24,000		134		
48	47,000						24,000		133		
49	48,000						24,000		132		
50	49,000					9	25,000	F	131	10.39	5.63%
51	50,000					10	25,000	F	130	11.69	6.35%
52		21					25,000		129		

Data / Distributions / Wear-out Failure / All Rock Damages / **Just Rock Damage**

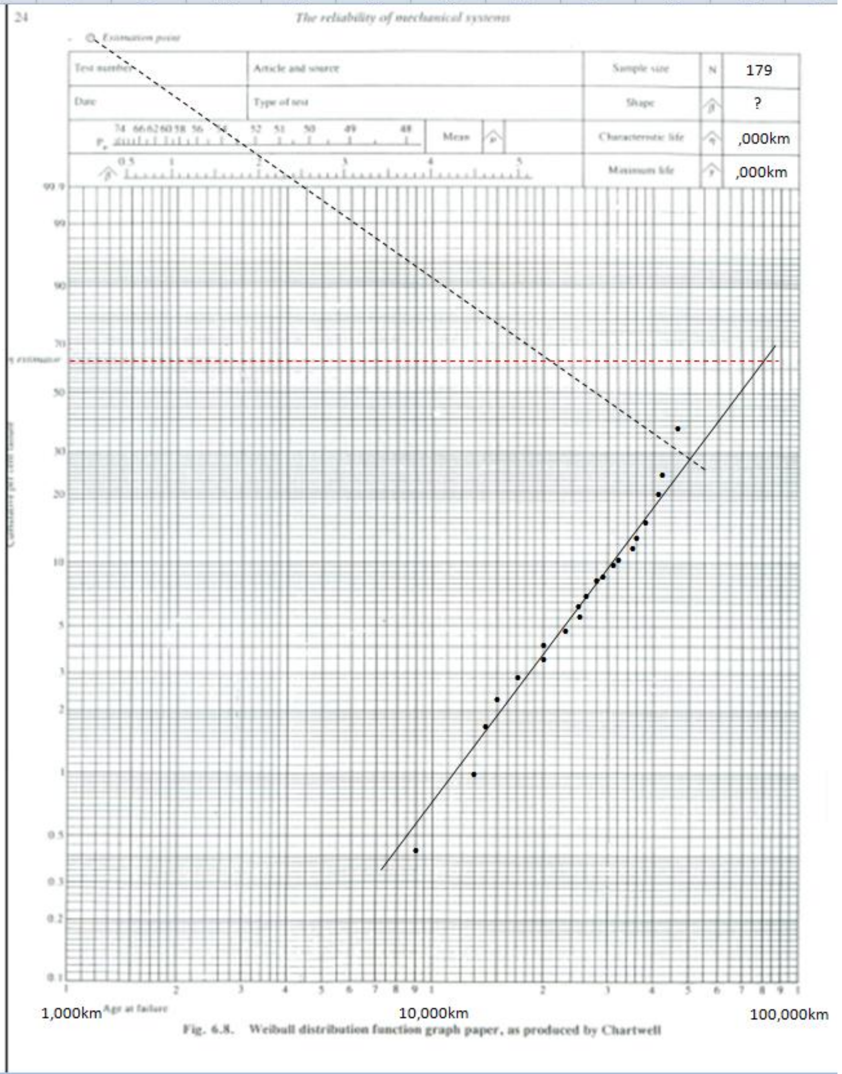

Figure 8 Just Tyres Changed from Rocks Damage Failure Mode