Repair Interval of Locomotive Wheel Axle Based on Reliability

Vo Trong CANG, Nguyen Anh TUAN , *Member, IAENG*

***Abstract*–The paper introduces the conclusions of lifetime research of D19E locomotive at Saigon Locomotive Enterprise (SGLE) in HCMC, Vietnam. This research bases on reliability theory to define the gamma-percent lifetime of locomotive. The authors build the CT2010 spreadsheet for empirical statistical data process of D19E locomotive. CT2010 can rapidly calculate the gamma-percent lifetime and define the suitability of seven probability distributions including exponential, normal, gamma, lognormal, Weibull, Rayleigh, and Maxwell distribution.**

***Index Terms*– CT2010, gamma-percentage lifetime, probability distribution, reliability theory, Locomotive wheel axles**

I. INTRODUCTION

Locomotive is an essential part of train and strongly impacts both economics and engineering in train performance management. The fuel cost has to be minimized to optimize operative cost. Correspondingly, engineering condition of locomotive should annually be maintained to keep low fuel cost. Pulling power, climbing ability, and acceleration decrease that it means the engine work ineffectively. Rollers of locomotive are one of basic essential parts that effects train operative performance. The failure of rollers is usually including surface abrasion. Therefore, the research of rollers' abrasion is an urgent demand of train operative managers. It is also important role for adjusting the maintenance cycle appropriate to operative condition in Vietnam [3, 4, 5].

The research applies CT2010 spreadsheet to carry out the empirical statistical data process and calculate the gamma-percent lifetime of D19E locomotive at SGLE [13]. Based on these results, the research help SGLE optimizes the maintenance cycle to save the operative cost and increase the train performance management.

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II. CT2010 SPREADSHEET

CT2010 spreadsheet was completed in 2010 for processing and analyzing the empirical statistical data. CT2010 is a product of the student research project "Application of Excel-VBA in Reliability Analysis of Transport Vehicles" funding by the Ho Chi Minh city University of Technology, Vietnam National University Ho Chi Minh City [6].

CT2010 can automatically calculate gamma-percentage lifetime, exactly analyze the suitability and rapidly export the graphs of 7 probability distributions based on Excel functions [7, 8].

A. The method of the empirical statistical data process in CT2010

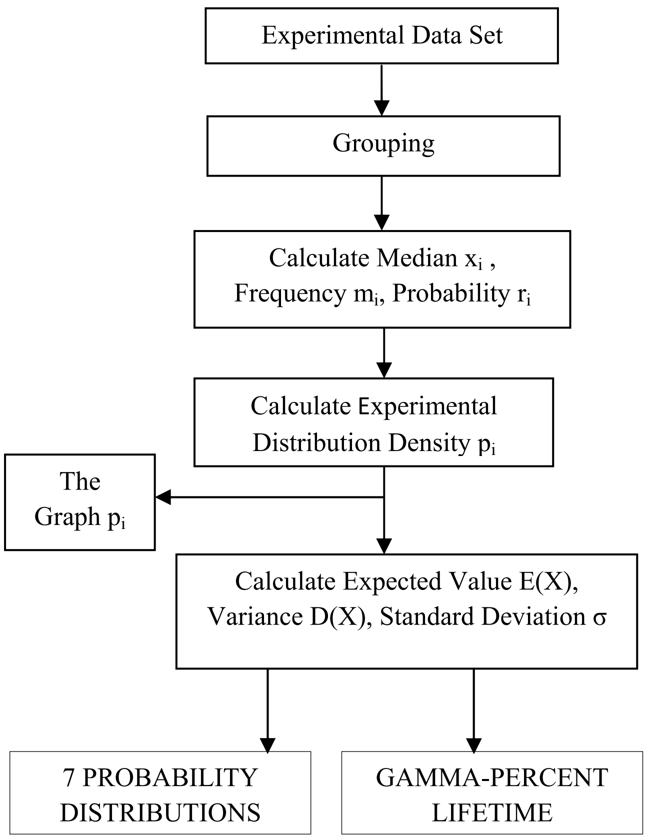

Fig. 1. Flow chart of empirical statistical data process in CT2010 spreadsheet

Data set will be divided into small groups. According to formula (1.81) in [2], the group width h:

$$h = \frac{x_{max} - x_{min}}{1 + 3.32 \lg n}$$

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Where:

n - The total of statistic data;

x_{max} ,x_{min} - The maximum and minimum of random value in statistic data;

Group 1 from x_{min} to x_{min} + h

Group 2 from x_{min} + h to x_{min} + 2h

Group 3 from x_{min} + 2h to x_{min} + 3h

The maximum value of the experimental statistic data will be in the final group.

The median of group 1: $x_1 = x_{min} + \frac{h}{2}$;

The median of group 2: $x_2 = x_{min} + \frac{3h}{2}$;

The median of group 3: $x_3 = x_{min} + \frac{5h}{2}$;

The probability in each group r_i:

$$r_i = \frac{m_i}{n}$$

Where:

m_i - The frequency in each group;

n - The total of values in the experimental statistic data

Note: $\sum_{i=1}^{k} r_i = 1$ with k is number of group.

The experimental distribution density p_i

$$p_i = \frac{r_i}{h}$$

The expected value of the experimental distribution

$$E(X) = a = \sum_{i=1}^{k} x_i . r_i$$

The variance of the experimental distribution

$$D(X) = \sigma^2 = \sum_{i=1}^{k} (a - x_i)^2 . r_i$$

The square root of the variance is the standard deviation in the experimental.

$$\sigma = \sqrt{D(X)} = \sqrt{\sigma^2}$$

In previous researches such as Prof. B.T. Long [1], Prof. D.D. Tuan [2], Dr. T.T.Dich [10], the suitability of distribution will be defined by many methods, for instance, Kolmogov, geometry, omega-squared, least square, and Chi square method. CT2010 applies Chi square method for this research because it is high reliability for processing huge data set [1]. Otherwise, the method has the disadvantage that a part of information will be lost when data set is divided into small groups [2].

Chi square deviation

$$\chi^2 = n.h \sum_{i=1}^{k} \frac{[p_i - f(x_i)]^2}{f(x_i)}$$

Where:

Pi - The experimental distribution density;

f(xi)- Theory density function value of group i;

k - The number of group;

n - The total of statistic value (size of sample).

Freedom coefficient L = k – s – 1.

s is number of character parameter in each distribution rule.

The suitable probability *P_{ph} (X^2, L)> 0.05.*

Exponential Distribution

Theory distribution density function

$$f(x) = \lambda e^{-\lambda x}$$

With $\lambda = \frac{1}{a}$ is a character parameter of exponential distribution (s=1).

Theory probability distribution function

$$F(x) = 1 - e^{-\lambda . x}.$$

Normal Distribution (Gauss)

Theory distribution density function

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-a)^2}{2\sigma^2}}.$$

a and σ are Gaussian distribution parameters (s = 2).

Converting variable $z = \frac{x-a}{\sigma}$, theory probability distribution function will be

$$F(x) = \frac{1}{\sqrt{2\pi}} e^{-\left(\frac{x^2}{2}\right)}.$$

Gamma Distribution

Theory distribution density function

$$f(x,\eta,\lambda) = \frac{\lambda^\eta}{\Gamma(\eta)} x^{\eta-1} e^{-\lambda x}$$

η and λ are 2 parameters of Gamma distribution (s=2). The relation of parameters is as

$$a = \frac{\eta}{\lambda} ; D = \frac{\eta}{\lambda^2} \Longrightarrow \lambda = \frac{a}{\sigma^2} ; \eta = \lambda a$$

Gamma function $\Gamma(\eta)$is defined by integral Erlang $\Gamma(\eta) = \int_0^\infty x^{\eta-1} e^{-x} dx$.

Theory probability distribution function

$$F(x) = \int_0^x \frac{\lambda^\eta}{\Gamma(\eta)} x^{\eta-1} e^{-\lambda x} dx$$

Lognormal Distribution

Theory distribution density function

$$f(x) = \frac{1}{x\sqrt{2\pi}\sigma_{lnx}} e^{-\frac{(lnx - lnx_0)^2}{2\sigma_{lnx}^2}}$$

Where:

x - Consecutive random value;

lnx_0 - moral expectation of random amount lnx;

σ_{lnx}^2 - Variance of random amount lnx;

σ_{lnx} - mean square variation of random amount lnx.

Two parameters of lognormal distribution (s = 2) are:

$lnx_0 = 2lna – 0.5 \ln[D + a^2]$

$$\sigma_{lnx} = \sqrt{\ln(D + a^2) - 2lna}$$

Converting variable= $\frac{lnx - lnx_0}{\sigma_{lnx_0}}$, theory probability distribution function will be:

$$F(x) = \Phi(z) = \frac{lnx - lnx_0}{\sigma_{lnx_0}}$$

Weibull Distribution

Theory distribution density function:

$$f(x) = \frac{\alpha}{\beta} (x - x_{min})^{\alpha-1} e^{\frac{-(x-x_{min})^\alpha}{\beta}}$$

α and β are two distribution parameters (s = 2).

α is calculated by linear interpolation of variance coefficient $\nu = \frac{\sigma}{a}$ of Weibull distribution (See Tab.1).

$$\beta = \sum_{i=1}^{k} r_i x_i^\alpha$$

Theory probability distribution function

$$F(x) = 1 - e^{-\frac{(x-x_{min})^\alpha}{\beta}}$$

Reyleigh Distribution

Theory distribution density function

$$f(x) = \frac{x}{\sigma_r^2} e^{-\frac{x^2}{2\sigma_r^2}}$$

$\sigma_r = \frac{a}{1.253}$ is distribution parameter (s = 1).

Theory probability distribution function:

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$$F(x) = 1 - e^{-\frac{x^2}{2\sigma_r^2}}$$

Maxwell Distribution

Theory distribution density function (x >0):

$$f(x) = \sqrt{\frac{2}{\pi}} \frac{x^2}{\sigma_c^3} e^{-\frac{x^2}{2\sigma_c^2}}$$

$\sigma_c = \frac{a}{1.596}$ is distribution parameter (s = 1).

Theory probability distribution function:

$$F(x) = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_c^3} \int_0^x x^2 e^{-\frac{x^2}{2\sigma_c^2}} dx$$

B. The method of gamma-percent lifetime calculation in CT2010

According to Prof. D.D.Tuan [2], the gamma percentage lifetime

$$P(L) = \Phi\left\{\frac{I_{gh} - E(c).L}{[D(c).L^2]^{\frac{1}{2}}}\right\} = \Phi\left\{\frac{I_{gh} - E(c).L}{\sigma(c).L}\right\} = \Phi(z)$$

$$\Rightarrow L = \frac{I_{gh}}{[E(c) + \sigma(c).z]}$$

Where:

P(L): reliability function (Operative probability without failure);

L: lifetime of locomotive roller [10^5km];

I_{gh}: abrasion critical [mm];

E(c) = a: expected value of abrasion [$mm^2/10^5km^2$];

D (c) = σ^2: variance of abrasion [$mm^2/10^{10}km^2$];

σ (c) =σ: standard deviation of abrasion [$mm/10^5km$];

Φ(z) is calculated through Laplats function;

Z is percentile of normal distribution with corresponding γ% (P(L)).

I_{gh} is $\leq$ 7 mm, obeying the maintenance process of Vietnam Railway Corporation [13].

Fig. 2. D19E – "936" and "939" locomotive rollers at the SGLE workshop [11]

III. THE ANALYSIS OF D19E LOCOMOTIVE ROLLER'S ABRASION IN CT2010

In the below illustrated case, we use the data on the wear of D19E locomotive's wheel roller surface in the period 2007-2009 (shown in fig. 2).

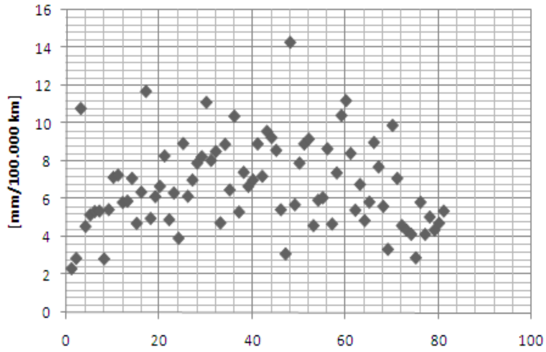

Fig. 3. The empirical data set of D19E locomotive rollers' abrasion in CT2010

After inputting data, CT2010 will analysis the suitability of 7 probability distributions based on Chi square method (see fig. 4).

No TT	Group Nhóm		Median x_i Trung vị x_i	Freq. m_i Tần số m_i	r_i Tần suất r_i
1	2.308 ÷	3.940	3.12406	7	0.08642
2	3.940 ÷	5.573	4.75679	23	0.28395
3	5.573 ÷	7.206	6.38953	22	0.27160
4	7.206 ÷	8.839	8.02226	13	0.16049
5	8.839 ÷	10.471	9.65500	11	0.13580
6	10.471 ÷	12.104	11.28773	4	0.04938
7	12.104 ÷	13.737	12.92047	0	0.00000
8	13.737 ÷	15.370	14.55320	1	0.01235
				n = 81	Tổng = 1

Fig. 4. Frequency of each group ri

In seven distributions, CT2010 indicates 3 suitable distributions including gamma, lognormal and Maxwell distribution and it also shows that 4 remaining distributions are unsuitable (see fig. 5).

The result of 7 probability distributions

		Analysis of Suitability
1	Exponential Distribution	Unsuitable Distribution
2	Normal Distribution	Unsuitable Distribution
3	Gamma Distribution	Suitable Distribution
4	Lognormal Distribution	Suitable Distribution
5	Weibull Distribution	Unsuitable Distribution
6	RayLeigh Distribution	Unsuitable Distribution
7	Maxwell Distribution	Suitable Distribution

Fig. 5. Analysis of the suitability of 7 distribution rules in CT2010 (screen shot)

The below images show the results of Maxwell distribution and its graphs in CT2010 (fig. 6, 7, 8).

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Result of MAXWELL Distribution			
Total of Statistic Values n			81
Expected Value E(X) = a			6.692
Variance	$D(X) = \sigma^2$		5.471
Standard Deviation	σ		2.339
Square Error χ2			6.866
P(6.8655,6) =	0.33	>	0.050
Conclusion: Suitable Distribution			

Fig. 6. The results of Maxwell distribution in CT2010 (screen shoot)

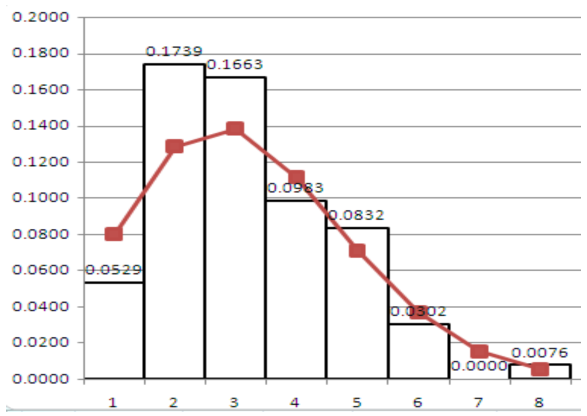

Fig. 7. The Maxwell experimental distribution density pi and the distribution density f(xi)

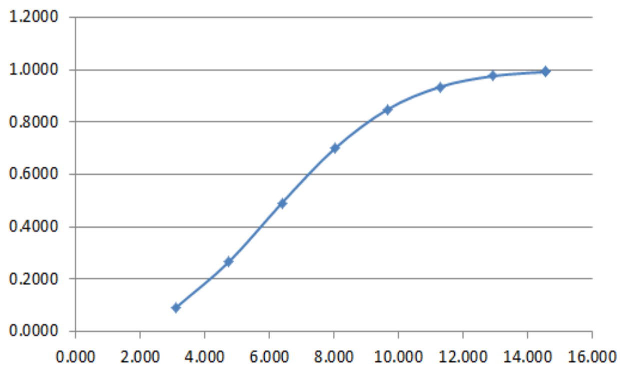

Fig. 8. The Maxwell theory distribution F(xi)

After defining the suitable distribution, CT2010 concurrently calculates the Gamma-percentage lifetime with reliability from 50% to 99% (see fig. 9). For the locomotive rollers' abrasion [13], the research obeys the maintenance process of Vietnam Railway Corporation with abrasion critical $I_{gh} = 7$.

The criteria of reliability will be from 50% to 70% corresponding to inessential details, from 70% to 90% with replacement parts and from 90% to 99% with essential parts. For the locomotive rollers, the reliability should be 90% to 99% because it is import role that directly impact pulling power, brake power, and acceleration of train [12]. Hence, the maintenance cycle of rollers should be carried out at 72,244 km. Similarly, remaining details of locomotive can be set up the suitable repairing cycle.

IV. CONCLUSION

With CT2010 spreadsheet, the train operative manager of SGLE will save time and cost through giving the satisfactory solution in maintenance of D19E locomotive. The factory vehicle operator, maintenance professionals can estimate the period of maintenance and repair properly. CT2010 is applied to not only locomotives and wagons, but also other transportation equipment such as marine engine.

On the other hand, this study also helps engineers and students understand the statistical process of experimental data [2, 9]. Teachers can use CT2010 to train students on data analysis techniques [8]. CT2010 is developing into version CT2011 to optimize the repair procedure.

P(L)%	Igh	E(c)=a	σ(c) = σ	z	Lifetime $L_{\gamma\%}$, 10^5 [Km]
50	**7**	**6.69189**	**2.33893**	**0.00**	**1.04604**
55	7	6.69189	2.33893	0.13	1.00203
60	7	6.69189	2.33893	0.25	0.96095
65	7	6.69189	2.33893	0.39	0.92189
70	7	6.69189	2.33893	0.52	0.88401
75	7	6.69189	2.33893	0.67	0.84649
80	7	6.69189	2.33893	0.84	0.80828
85	7	6.69189	2.33893	1.04	0.76788
90	**7**	**6.69189**	**2.33893**	**1.28**	**0.72244**
95	7	6.69189	2.33893	1.64	0.66419
99	7	6.69189	2.33893	2.33	0.57694

Figure 9. The Gamma-percentage lifetime calculation in CT2010 (screen shot)

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APPENDIX

TABLE I
WEIBULL COEFFICIENT OF VARIANCE

ν	**α**	**N**	**A**	**ν**	**α**
0.1201	10	0.2866	3.9	0.5001	2.1
0.1241	9.5	0.2937	3.8	0.5227	2
0.1289	9	0.3008	3.7	0.5471	1.9
0.136	8.5	0.3087	3.6	0.5752	1.8
0.1461	8	0.3167	3.5	0.6052	1.7
0.1572	7.5	0.3247	3.4	0.6401	1.6
0.1632	7	0.3336	3.3	0.6794	1.5
0.1801	6.5	0.3425	3.2	0.7235	1.4
0.1941	6	0.3553	3.1	0.7755	1.3
0.211	5.5	0.3631	3.0	0.8366	1.2
0.227	5.05	0.3748	2.9	0.9101	1.1
0.229	5	0.3865	2.8	1	1
0.2332	4.9	0.4009	2.7	1.1	0.91
0.2426	4.7	0.4135	2.6	1.21	0.83
0.2519	4.5	0.4279	2.5	1.32	0.77
0.2632	4.3	0.4441	2.4	1.43	0.71
0.2744	4.1	0.4643	2.3	1.53	0.67
0.2806	4	0.4803			

TABLE 2

THE EMPIRICAL DATA OF LOCOMOTIVES IN SAIGON LOCOMOTIVE ENTERPRISE (JAN. 2007 - MAY 2009)

No. of D19E Locomotive	Km (x1000)	Abrasion (max) [mm]	
		2-Faces	1-Face
911	130	3,0	1,5
	105	3,0	1,5
	102	11,0	5,5
	110	5,0	2,5
912	97	5,0	2,5
	75	4,0	2,0
913	112	6,0	3,0
	106	3,0	1,5
	92	5,0	2,5

No. of D19E Locomotive	Km (x1000)	Abrasion (max) [mm]	
		2-Faces	1-Face
914	98	7,0	3,5
	124	9,0	4,5
	172	10,0	5,0
915	102	6,0	3,0
	127	9,0	4,5
	170	8,0	4,0
916	110	7,0	3,5
	77	9,0	4,5
	161	8,0	4,0
917	98	6,0	3,0
	135	9,0	4,5
	145	12,0	6,0
	102	5,0	2,5
918	95	6,0	3,0
	102	4,0	2,0
	112	10,0	5,0
	114	7,0	3,5
919	100	7,0	3,5
	114	9,0	4,5
	170	14,0	7,0
920	108	12,0	6,0
	112	9,0	4,5
	94	8,0	4,0
	169	8,0	4,0
931	90	8,0	4,0
	139	9,0	4,5
	106	11,0	5,5
	113	6,0	3,0
932	108	8,0	4,0
	135	9,0	4,5
	100	7,0	3,5
	101	9,0	4,5
933	125	9,0	4,5
	94	9,0	4,5
	119	11,0	5,5
	105	9,0	4,5
934	129	7,0	3,5
	97	3,0	1,5
	84	12,0	6,0
	123	7,0	3,5
935	114	9,0	4,5
	101	9,0	4,5
	120	11,0	5,5
	109	5,0	2,5
936	118	7,0	3,5
	132	8,0	4,0
	104	9,0	4,5
	107	5,0	2,5
937	122	9,0	4,5
	96	10,0	5,0
	125	14,0	7,0
	107	9,0	4,5
938	111	6,0	3,0
	133	9,0	4,5
	103	5,0	2,5
939	120	7,0	3,5
	89	8,0	4,0
	104	8,0	4,0
	107	6,0	3,0
940	120	4,0	2,0
	91	9,0	4,5
	127	9,0	4,5
951	109	5,0	2,5
952	115	5,0	2,5
953	121	5,0	2,5
954	104	3,0	1,5
955	103	6,0	3,0
956	97	4,0	2,0
957	119	6,0	3,0
958	115	5,0	2,5
959	106	5,0	2,5
960	112	6,0	3,0

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