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PERFORMANCE ANALYSIS OF NHPP-BASED SOFTWARE RELIABILITY MODEL WITH INVERSE-TYPE LIFE DISTRIBUTION PROPERTY

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ABSTRACT

In this work, the performance of the NHPP-based software reliability model applying the Inverse-type distribution, which is widely utilized to various types of reliability life distributions, was newly identified. Accordingly, software failure time data was used to analyze reliability performance by predicting failures that may occur in the software operation, and the solution of parameters were estimated using maximum likelihood estimation. As a result, first, as a result of evaluating the criteria value (MSE and R^2) for efficient model selection, the efficiency of the Inverse-Exponential model was evaluated as the best. Second, as a result of analyzing the attributes data (m(t), λ(t), $\hat{R}(\tau)$) that determine reliability performance, the Inverse-Exponential model was the most efficient. In conclusion, through various comparative analyses, the Inverse-Exponential model was found to have the best performance. Through the results of this study, the reliability performance of the Inverse-type life distribution for which there is no existing research data was newly analyzed, and basic design and test data necessary for an efficient software development process could also be presented. In the future, after exploring applicable statistical distributions for each software convergence industry, follow-up studies to find an optimal model will be needed.
Keywords: *Goel-Okumoto, Inverse-Exponential, Inverse-Rayleigh, Inverse-type, NHPP Model, Reliability Performance*

1. INTRODUCTION

In the current era of digital convergence, software technology is widely spreading and being utilized to various related industrial fields. Accordingly, the need for reliable software is rapidly increasing. Therefore, developers are currently concentrating on reliability studies to improve software quality. That is, the problem of improving the reliability of software becomes the most important issue for software developers. For this purpose, reliability models applying Non-homogeneous Poisson Process (NHPP) have been studied in various forms. Among these studies, the NHPP-based model applying the reliability performance attribute is attracting attention [1]. Also, regarding the Inverse-distribution proposed in this study, Pavlov and Lliev, Rahnev, Kyurkchiev [2] presented a method for calculating the error of the optimal approximation based on a modified Inverse-Exponential software reliability model. Fatima and Ahmad [3] proposed an improved Inverse-Rayleigh distribution by applying a new reliability analysis method to determine the goodness of fit after parameter estimation, Malik and Ahmad [4] proposed an improved model of the Inverse-Rayleigh distribution using Alpha Power Transformation. Therefore, Voda [5] explained with an example that the Inverse-Rayleigh distribution is applicable to various lifetime distributions. Also, with respect to the software reliability model, Prasad and Rao [6] analyzed the performance of the NHPP model applying the Inverse-Rayleigh distribution, and Huang [7] evaluated the NHPP software reliability properties by applying the performance attribute function. Kim [8] compared the efficiency in terms of statistical process control for the reliability attributes of the NHPP model using Inverse-Rayleigh and Rayleigh distributions, Yang [9] also defined the performance of NHPP software reliability models using Exponential-type distributions. Additionally, many researchers are working on exploring the best distribution by applying various types of lifetime distributions to studies related to software reliability.

Accordingly, this study presented a new NHPP-based software reliability model using the Inverse-type life distribution, which has been proven to be efficient in reliability testing of various life distributions. Along with this, the reliability attributes of the proposed model were explored and its performance was newly identified. Also, we will propose an optimal model through the analyzed data.

2. RELATED RESEARCH

2.1.1 NHPP model

The NHPP is known as a probability-based distribution model that predicts future failures based on the number of failures that occur at a given area. Thus, this study aims to evaluate the performance of the reliability model using this probability-based NHPP model. That is, the NHPP model has been widely used to model the number of failures N(t) found between observation times (0, t) in reliability measurement. In a software system where failure times occur at different intervals and failures occur continuously, if the number of failures occurring per unit time is N(t), then N(t) follows the Poisson distribution and also satisfies inhomogeneity.

Accordingly, the NHPP model can be said to be a probability-based model that can predict software reliability based on the number of failure occurrence. Thus, using these properties of the NHPP model, it can be defined as follows.

$$P\{N(t)=n\}=\frac{[m(t)]^n\cdot e^{-m(t)}}{n!} \tag{1}$$

Note that $n=0,1,2,\cdots\infty$.

where m(t) refers to a mean value function that has the property of estimating the true value and can be defined as Equation (2). Thus, the intensity function λ(t), which has properties representing the instantaneous failure occurrence rate, can be developed as follows.

$$m(t)=\int_0^t \lambda(s)ds \tag{2}$$

$$\frac{dm(t)}{d(t)}=\lambda(t) \tag{3}$$

2.1.2 NHPP software reliability model

In this work, we seek to solve the cost attribute problem of the proposed NHPP software development model based on failure time collected during normal operation. This study reflects the failure phenomenon of generally developed software and aims to study it based on finite failure, in which no further failures occur after the failure is repaired.

Therefore, this study is intended to be developed based on the finite failure NHPP model by reflecting realistic failure situations. Accordingly, applying Equations (2) and (3), the attribute functions representing the performance of the cost model are as follows [10].

$$\mathrm{m}(\mathrm{t}|\theta,\mathrm{b})=\theta F(\mathrm{t}) \tag{4}$$

$$\lambda(\mathrm{t}|\theta,\mathrm{b})=\theta F(\mathrm{t})'=\theta f(t) \tag{5}$$

Note that θ is the residual failure rate, and F(t) is the cumulative distribution function.

From the result derived above, m(t) represents the performance that can predict the true value, and λ(t) represents an attribute that represents the intensity at which a failure may occur.

Accordingly, the likelihood function of the NHPP model applying the attribute functions m(t) and λ(t) can be developed as follows.

$$L_{NHPP}(\Theta|\underline{x})=\left(\prod_{i=1}^{n}\lambda(x_i)\right)exp[-m(x_n)] \tag{6}$$

Note that $\underline{x}=(x_1,x_2,x_3\cdots x_n)$

2.2 NHPP Goel-Okumoto Basic Model

The Goel-Okumoto model is widely known as the most basic NHPP model because it is based on the basic concept that the number of faults discovered per unit time is proportional to the number of faults remaining at that time. Also, because the time distribution for failure occurrence per defect in the Goel-Okumoto basic model has exponential distribution characteristics, it is also called an exponential-type basic distribution model.

Therefore, if the expected value of the defect causing the failure in the finite failure situation of this model is expressed as θ and the defect search rate is b, it can be developed by considering b as a fixed constant.

Since the failure rate can be considered a constant with a certain form, the performance function is as follows [11].

$$m(t|\theta,b)=\theta F(t)=\theta(1-e^{-bt}) \tag{7}$$

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$$\lambda(t|\theta,b) = \theta f(t) = \theta b e^{-b} \quad (8)$$

Accordingly, the log-likelihood function of this distribution model calculated by applying Equation (6) is as follows.

$$lnL_{NHPP}(\Theta|\underline{x}) = nln\theta + nlnb - b\sum_{k=1}^{n} x_k - \theta(1-e^{-bx_n}) \quad (9)$$

Finally, the parameter estimator ($\hat{\theta}_{MLE}$, $\hat{b}_{MLE}$) of the Exponential-basic model to be obtained in this work can be calculated using maximum likelihood estimation (MLE) to Equation (9) and then using the bisection method. Therefore, Equations (10) and (11) show the final calculation equations for calculating the parameters.

$$\frac{\partial lnL_{NHPP}(\Theta|\underline{x})}{\partial\theta} = \frac{n}{\hat{\theta}} - 1 + e^{-\hat{b}x_n} = 0 \quad (10)$$

$$\frac{\partial lnL_{NHPP}(\Theta|\underline{x})}{\partial b} = \frac{n}{\hat{b}} - \sum_{i=1}^{n} x_n - \hat{\theta}x_n e^{-\hat{b}x_n} = 0 \quad (11)$$

2.3 NHPP Inverse-Exponential Model

The Inverse-exponential distribution has a bathtub-shaped risk rate function, so it is a useful distribution for the analysis of reliability life data with the characteristic that the risk rate varies with time. In particular, the Inverse-exponential distribution is known as a distribution suitable for load-intensity reliability, which represents the probability that the system will operate normally when stress is applied to the system stochastically. Accordingly, the Inverse-exponential distribution plays a very important role in measuring the reliability of a system in the field of reliability.

Therefore, the function F(t) can be defined as follows.

$$\mathrm{F(t)} = e^{-(bt)^{-1}} \quad (12)$$

If the functions obtained above are substituted into Equations (4) and (5), the performance attribute functions of this model are as follows [12].

$$\mathrm{m(t}|\theta,\mathrm{b)} = \theta e^{-(bt)^{-1}} \quad (13)$$

$$\lambda(\mathrm{t}|\theta,\mathrm{b}) = \theta b^{-1}t^{-2}e^{-(bt)^{-1}} \quad (14)$$

Thus, the log-likelihood function of this NHPP model calculated by applying Equation (6) is as follows.

$$\ln L_{NHPP}(\Theta|\underline{x}) = nln\theta - nlnb + 2\sum_{i=1}^{n} x_i - \sum_{i=1}^{n}(bx_i)^{-1} - \hat{\theta}e^{-(bx_n)^{-1}} = 0 \quad (15)$$

Therefore, the parameter estimator ($\hat{\theta}_{MLE}$, $\hat{b}_{MLE}$) of the Inverse-exponential model can be calculated by applying MLE to Equation (15) and then using the bisection method. Accordingly, Equations (16) and (17) show the final calculation equations for calculating the parameters.

$$\frac{\partial \ln L_{NHPP}(\Theta|\underline{x})}{\partial\theta} = \frac{n}{\hat{\theta}} - e^{-(\hat{b}x_n)^{-1}} = 0 \quad (16)$$

$$\frac{\partial \ln L_{NHPP}(\Theta|\underline{x})}{\partial b} = -\frac{n}{\hat{b}} + \frac{1}{\widehat{b^2}}\sum_{i=1}^{n}\frac{1}{x_i} - \theta\frac{1}{b^2 x_n}e^{-(\hat{b}x_n)^{-1}} = 0 \quad (17)$$

2.4 NHPP Inverse-Rayleigh Model

Like the Rayleigh distribution, which is known to be a suitable model in the field of system lifetime testing, the Inverse-Rayleigh distribution is also a life distribution that has many applications in the field of software reliability. In particular, the Inverse-Rayleigh distribution is a model that has been proven to be efficient in reliability analysis of various life distributions and has been confirmed to be suitable for software reliability testing.

Accordingly, after applying these characteristics to reliability research, many researchers confirmed that this model can be used as a life distribution in reliability test and property analysis as follows.

$$F(\mathrm{t}) = exp\left(-\frac{b}{t^2}\right) \quad (18)$$

$$f(\mathrm{t}) = \frac{2b}{t^3}exp\left(-\frac{b}{t^2}\right) \quad (19)$$

Therefore, if the functions obtained above are substituted into Equations (4) and (5), the performance attribute functions of this model are as follows [13].

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$$\mathrm{m}(\mathrm{t}|\theta,\mathrm{b}) = \theta F(\mathrm{t}) = \theta exp\left(-\frac{b}{t^2}\right) \quad (20)$$

$$\lambda(\mathrm{t}|\theta,\mathrm{b}) = \theta \mathrm{f}(\mathrm{t}) = \theta\left[\frac{2b}{t^3} exp\left(-\frac{b}{t^2}\right)\right] \quad (21)$$

Therefore, if arranged in the same way as Equation (15), the log-likelihood function of this model can be written as follows.

$$\ln L_{NHPP}(\Theta|\underline{x}) = n\ln 2 + n\ln\theta + n\ln b$$

$$+b\sum_{i=1}^{n}\ln\left(\frac{1}{x_i^3}\right) - b\sum_{i=1}^{n}\frac{1}{x_i^2} - \theta exp\left(-\frac{b}{x_n^2}\right) \quad (22)$$

That is, the parameter estimator ($\hat{\theta}_{MLE}$, $\hat{b}_{MLE}$) of the Rayleigh model to be obtained in this work can be calculated by applying MLE to Equation (22) and then using the bisection method. Thus, Equations (23) and (24) show the final calculation equations for calculating the parameters.

$$\frac{\partial \ln L_{NHPP}(\Theta|\underline{x})}{\partial\theta} = \frac{n}{\hat{\theta}} - exp\left(-\frac{\hat{b}}{x_n^2}\right) = 0 \quad (23)$$

$$\frac{\partial \ln L_{NHPP}(\Theta|\underline{x})}{\partial b} = \frac{n}{\hat{b}} + \sum_{i=1}^{n}\ln\left(\frac{1}{x_i^3}\right) - \sum_{i=1}^{n}\frac{1}{x_i^2} + \frac{\hat{\theta}}{x_n^2} exp\left(-\frac{\hat{b}}{x_n^2}\right) = 0 \quad (24)$$

3. RELIABILITY PERFORMANCE ANALYSIS

In this work, the performance properties applying Exponential-type life distribution model were analyzed by the step-by-step sequence of the presented solution as follows. Also, the optimal model was presented based on the analyzing data.

Table 1 [14] shows the software failure time data cited in this paper. This data refers to the collection of failure times that occurred while operating the software system.

Also, this data is a collection of 30 failures for a total of 187.35 hours, which occurred due to design and analysis errors in the software development process.

In this study, Laplace trend analysis was used to judge whether the software failure time cited were applicable to this work.

Table 1: Software Failure Time Data.

Failure number	Failure time (hours)	Failure time (hours)$\times 10^{-1}$
1	4.79	0.479
2	7.45	0.745
3	10.22	1.022
4	15.76	1.576
5	26.10	2.610
6	35.59	3.559
7	42.52	4.252
8	48.49	4.849
9	49.66	4.966
10	51.36	5.136
11	52.53	5.253
12	65.27	6.527
13	69.96	6.996
14	81.70	8.170
15	88.63	8.863
16	107.71	10.771
17	109.06	10.906
18	111.83	11.183
19	117.79	11.779
20	125.36	12.536
21	129.73	12.973
22	152.03	15.203
23	156.40	15.640
24	159.80	15.980
25	163.85	16.385
26	169.60	16.960
27	172.37	17.237
28	176.00	17.600
29	181.22	18.122
30	187.35	18.735

In general, if the Laplace trend analysis result of the cited data is distributed between '-2 and 2', this data is said to be reliable.

Figure 1 shows the results of the Laplace trend test analyzed by applying the data presented in Table 1. That is, it can be seen that all result data exists between '0 and 2'. Accordingly, it can be said that the cited software downtime data is applicable to this study.

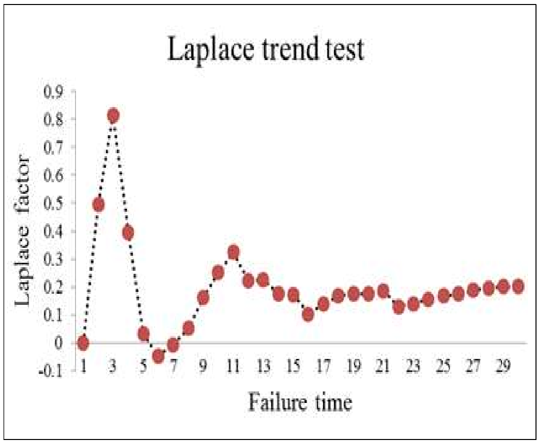

Figure 1: Results of Laplace Trend Test.

The parameters ($\hat{\theta}$, $\hat{b}$) of the NHPP model were calculated using the MLE as shown in Table 2 [15]. Therefore, among the parameters of the applied model, $\hat{\theta}$ is a software residual failure, and $\hat{b}$ is a shape parameter that makes the shape of the applied life distribution.

In this study, we will also analyze the R^2 and MSE, which are criteria for determining an efficient model.

Table 2: Parameter Solution Using MLE.

Type	NHPP model	MLE	
		$\hat{\theta}$	$\hat{b}$
Basic model	Goel-Okumoto	32.9261	0.1297
Inverse-type life distribution	Inverse-Exponential	41.2881	0.1692
	Inverse-Rayleigh	30.0100	1.6520

R^2, which is used as a standard for explaining the difference between actual values and observed values, is expressed as follows.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(m(x_i) - \hat{m}(x_i)\right)^2}{\sum_{i=1}^{n}\left(m(x_i) - \sum_{j=1}^{n} m(x_j)/n\right)^2} \quad (25)$$

Note that $\hat{m}(x_i)$ is the cumulative number of failures estimated from m(t).

In comparison, if the coefficient of determination is large, the error is small and it is considered a relatively useful model. In other words, eventually the error becomes smaller, so it is considered a relatively efficient model.

MSE is a standard for comparing the difference between the real value (actually observed value) and estimated value (predicted value) and is as follows.

$$MSE = \frac{\sum_{i=1}^{n}\left(m(x_i) - \hat{m}(x_i)\right)^2}{n-k} \quad (26)$$

Note that n used in this equation is the number of observed failures.

Figure 2 is the result of analyzing the model properties using MSE, and this study intends to use this value as reference data to determine the suitability together with the efficiency.

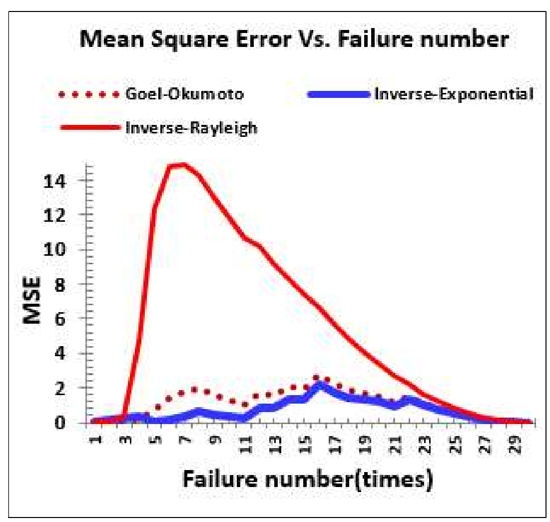

Figure 2: Analysis of MSE.

When selecting an efficient model, the smaller the value of MSE, the smaller the error predicting the true value, so it is determined as a relatively efficient.

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Table 3 shows detailed data analyzing the change in MSE value with failure time to verify the efficiency of the model [16].

In general, if the coefficient of determination is greater than 0.8 (80%), this model is said to be efficient. As shown in Table 4, among the models proposed in this work, the Inverse-exponential and Goel-Okumoto models are judged to be efficient. In other words, the Inverse-Exponential model is judged to be more efficient and useful than the Inverse-Rayleigh model.

Table 3: Analysis Data Using MSE.

Failure number (times)	MSE		
	Goel-Okumoto	Inverse-Exponential	Inverse-Rayleigh
1	0.0345	0.0357	0.0341
2	0.0380	0.1407	0.0078
3	0.0422	0.2947	0.3591
4	0.1555	0.3276	4.6671
5	0.7089	0.0180	12.2861
6	1.3612	0.1216	14.7762
7	1.7288	0.3851	14.8474
8	1.9403	0.6310	14.2484
9	1.5723	0.4524	12.9819
10	1.2910	0.3352	11.8146
11	0.9907	0.2062	10.6470
12	1.6535	0.7870	10.1624
13	1.5735	0.8021	9.1588
14	2.0167	1.2981	8.3345
15	2.0065	1.3703	7.3907
16	2.7545	2.2018	6.5918
17	2.2422	1.7572	5.6664
18	1.8545	1.4350	4.8191
19	1.6418	1.2851	4.0544
20	1.4851	1.1880	3.3577
21	1.2036	0.9583	2.7137
22	1.4367	1.2811	2.1707
23	1.1181	1.0013	1.6553
24	0.8167	0.7307	1.2082
25	0.5697	0.5117	0.8317
26	0.3834	0.3520	0.5261
27	0.2066	0.1894	0.2887
28	0.0877	0.0815	0.1222
29	0.0221	0.0227	0.0263
30	0.0000	0.0004	0.0006

The m(t), which refers to the reliability performance properties of the proposed model, is an important function to measure reliability performance. In particular, the m(t) function represents the expected value of software failure occurrence and is also an important indicator of the predictive power of estimating the true value.

Table 4: Model Efficiency.

Type	NHPP model	R^2	MSE
Basic model	Goel-Okumoto	0.8956	32.9379
Inverse-type lifetime distribution	Inverse-Exponential	0.9359	20.2035
	Inverse-Rayleigh	0.4747	165.750

Table 5 is a simplified summary of the equations for calculating the m(t) [17].

Figure 3 shows the trend of prediction ability to estimate the true value over the passage of failure time.

Table 5: Mean Value Function ($m(t)$).

Type	NHPP model	m(t)
Basic model	Goel-Okumoto	$\theta(1-e^{-bt})$
Inverse-type lifetime distribution	Inverse-Exponential	$\theta e^{-(bt)^{-1}}$
	Inverse-Rayleigh	$\theta exp\left(-\frac{b}{t^2}\right)$

When analyzing the trend curve, all models show results that do not accurately predict the true value but estimate the error value. However, in analyzing the performance of predicting the true value, the

Inverse-Exponential model with the smallest error can be said to be the most efficient.

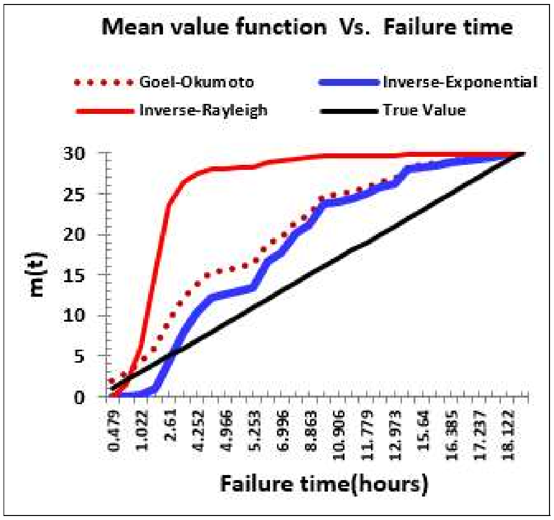

Figure 3: Performance Analysis of $m(t)$.

The λ(t), along with the m(t), is an important function to measure the reliability performance properties. In particular, the λ(t) is a failure rate function, which means a failure rate per fault and is also an important index indicating the intensity of software failures.

Therefore, Table 6 briefly summarizes the equations for calculating the intensity function [18].

Table 6: Intensity Function ($\lambda(t)$).

Type	NHPP model	λ(t)
Basic model	Goel-Okumoto	$\theta b e^{-bt}$
Inverse-type lifetime distribution	Inverse-Exponential	$\theta b^{-1} t^{-2} e^{-(bt)^{-1}}$
	Inverse-Rayleigh	$\theta \left[\frac{2b}{t^3} exp\left(-\frac{b}{t^2}\right) \right.$

Figure 4 shows the trend of failure rate occurrence intensity over the entire failure time range. Therefore, as a result of analyzing the failure rate trend of the proposed NHPP models, similar to general failure phenomena, the intensity function initially increased, but as time elapsed, the failure rate was removed and the intensity function showed an efficient trend with a gradually decreasing pattern.

That is, the Inverse-Exponential model showed the lowest failure rate and was very efficient, but Goel-Okumoto model showed inefficiency that only decreased continuously.

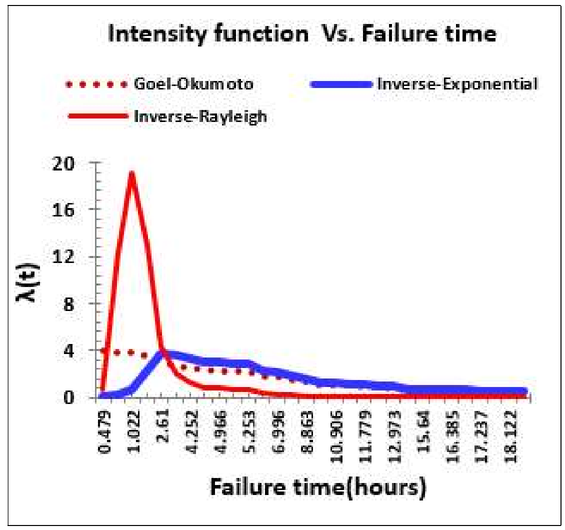

Figure 4: Performance Analysis of $\lambda(t)$.

Table 7 shows data values analyzed in detail according to the number of failures that occurred 30 times using attribute functions (m(t), λ(t)) that represent reliability performance, which is the core topic of this study.

Table 7: Trend Analysis Values of Reliability Performance Attributes.

Failure Time (hours) $\times 10^{-1}$	Reliability Performance Attributes					
	m(t)			λ(t)		
	Goel-Okumoto	Inverse-Exponential	Inverse-Rayleigh	Goel-Okumoto	Inverse-Exponential	Inverse-Rayleigh
0.479	1.9833304	0.000180826	0.022402619	4.013277217	0.004657891	0.673491752
0.745	3.03265707	0.0148088	1.529725269	3.877179548	0.157691016	12.22319278
1.022	4.08757242	0.127152711	6.171169908	3.740357027	0.719487867	19.10094504
1.576	6.087035513	0.97090109	15.43155317	3.481026664	2.310267154	13.02509917
2.61	9.45549807	4.28938387	23.54753178	3.04413707	3.721461591	4.375864933
3.559	12.17366983	7.845569763	26.34050043	2.691590193	3.660733839	1.930545743
4.252	13.95757064	10.28412305	27.38941079	2.460218258	3.361865963	1.177180233
4.849	15.3708973	12.20361469	27.97387557	2.276909791	3.067494269	0.810655111
4.966	15.63528464	12.55913601	28.0655465	2.242618752	3.009857776	0.757169997
5.136	16.01235751	13.06374933	28.18821237	2.1937124	2.926964464	0.687436406
5.253	16.26708425	13.40290443	28.26608262	2.160674343	2.870673238	0.64429307
6.527	18.80438397	16.69450096	28.86855356	1.831586569	2.316038941	0.343023777
6.996	19.63779326	17.7392949	29.01398079	1.723493385	2.142083486	0.27996127
8.17	21.51465663	20.02889247	29.27638411	1.480064205	1.773423517	0.17737455
8.863	22.49559635	21.19443287	29.38546636	1.352836323	1.594630045	0.139453808
10.771	24.78221812	23.85188828	29.58569753	1.05626148	1.215095342	0.078226477
10.906	24.92357228	24.01444705	29.59606464	1.037927845	1.193276934	0.075383713
11.183	25.20597499	24.33897063	29.61618333	1.001300213	1.150231344	0.069967145
11.779	25.78026724	24.99860162	29.65479731	0.926814509	1.064874711	0.059952836
12.536	26.44852342	25.76762543	29.69618234	0.840141683	0.969072062	0.049803941
12.973	26.80545455	26.18011141	29.7168665	0.793847715	0.919369931	0.044969887
15.203	28.34272074	27.98935819	29.79626959	0.59446429	0.715704899	0.028016511
15.64	28.59527673	28.29503943	29.80800676	0.561707779	0.683654139	0.025743212
15.98	28.78210766	28.52345327	29.8164833	0.537475806	0.660158462	0.024141605
16.385	28.99416702	28.78540434	29.82590261	0.509971707	0.633693254	0.022402387
16.96	29.27673326	29.13958574	29.83813881	0.473322866	0.598730413	0.020208507
17.237	29.40551645	29.30322664	29.84360286	0.456619686	0.582896868	0.019253347
17.6	29.567428	29.51118859	29.85037786	0.435619758	0.563068208	0.018090554
18.122	29.78729468	29.79802889	29.8594184	0.40710305	0.53625941	0.016576888
18.735	30.02718608	30.11770269	29.86908831	0.375989135	0.507123911	0.015007243

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The reliability function ($\widehat{R}(\tau)$) is an important function that can predict future reliability performance along with the attribute function (m(t), λ(t)) analyzed above. In particular, the purpose of the reliability function is to analyze the trend of future reliability by assigning a random duty time again after the final failure time ($x_n = 18.735$).

Therefore, in this study, after putting mission time into the proposed model, we try to predict and evaluate the future reliability performance. Here, reliability means the probability that a failure occurs at the test point and no failure occurs between the confidence intervals. Therefore, future reliability ($\widehat{R}(\tau)$) can be defined as follows [19].

$$\widehat{R}(\tau|x_n) = exp[-\{m(x_n+\tau) - m(x_n)\}]$$
$$= exp[-\{m(18.735+\tau) - m(18.735)\}] \quad (27)$$

Note that τ is the mission time.

As shown in Figure 5, as a result of analyzing the reliability trend after putting in the mission time, the Goel-Okumoto model can be said to be inefficient because the reliability decreases as time goes by. But, the Inverse-Exponential and Inverse-Rayleigh model, which show a consistently high and stable trend compared to the Goel-Okumoto model, can be defined to be very efficient.

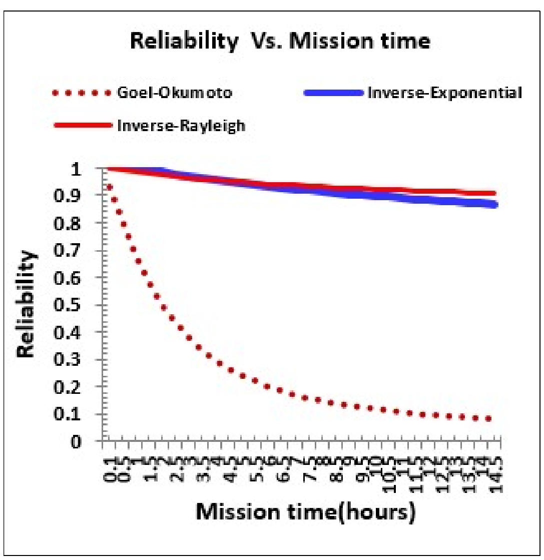

Figure 5: Performance Analysis of $\hat{R}(\tau)$.

Table 8 shows the result of analyzing the reliability performance trend in detail after putting future mission time into the NHPP models proposed in this study. For reference, the mission time ($145H \times 10^{-1}$) presented in Table.5 was numerically converted to facilitate calculation.

Table 8: Analysis Data of $\hat{R}(\tau)$.

Mission Time (hours)	Reliability Function $\widehat{R}(\tau)$		
	Goel-Okumoto	Inverse-Exponential	Inverse-Rayleigh
0.1	0.927164451	1.018796859	0.998512277
0.5	0.802280729	1.011038047	0.992811511
1	0.676450995	1.001857211	0.986206928
1.5	0.576499026	0.993205514	0.980123792
2	0.496273344	0.985038791	0.974507874
2.5	0.43125056	0.977317633	0.969311894
3	0.378066466	0.970006765	0.964494471
3.5	0.334191906	0.96307452	0.960019252
4	0.29770601	0.956492393	0.955854192
4.5	0.267135716	0.950234657	0.951970948
5	0.241340956	0.944278033	0.948344372
5.5	0.219431657	0.938601408	0.944952091
6	0.200707148	0.93318559	0.941774137
6.5	0.184611493	0.928013092	0.938792645
7	0.17070028	0.923067953	0.935991589
7.5	0.15861571	0.91833557	0.93335656
8	0.14806775	0.913802561	0.930874571
8.5	0.138819776	0.909456638	0.928533889
9	0.13067754	0.905286501	0.926323895
9.5	0.12348064	0.901281737	0.924234956
10	0.117095878	0.897432737	0.922258316
10.5	0.111412048	0.89373062	0.920386006
11	0.106335825	0.890167165	0.918610752
11.5	0.101788508	0.886734753	0.91692591
12	0.097703414	0.883426309	0.915325399
12.5	0.094023786	0.880235259	0.913803644
13	0.09070111	0.877155483	0.912355524
13.5	0.087693741	0.874181279	0.910976334
14	0.084965794	0.871307326	0.909661737
14.5	0.082486226	0.868528654	0.908407738

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The topic of this study was the analysis results of model efficiency (MSE, R^2) and attribute data (m(t), λ(t), R(t)) that have a significant impact on model performance. Also, Table 9 shows the final evaluation results after comprehensively comparing the performance attribute data of the proposed model based on the research data developed in this work.

Accordingly, if this research data can be utilized efficiently in the early stages of software development, it is believed that this data can be helpful not only as basic design data needed by developers but also as attribute data required to improve reliability [20].

Table 9: Reliability Performance Evaluation.

NHPP model	Model Efficiency		Performance Attributes		
	MSE	R^2	m(t)	λ(t)	$\hat{R}(\tau)$
Goel-Okumoto	Best	Good	Good	Good	Worst
Inverse-Exponential	Best	Best	Best	Best	Best
Inverse-Rayleigh	Worst	Worst	Worst	Worst	Best

4. CONCLUSION

If a software developer can design a reliability prediction model with failure time data collected in the early stage of analyzing and testing a program, developers will be able to predict software failure time in advance to increase reliability and ultimately improve software quality. Thus, the performance of the NHPP reliability model applying Inverse-type life distribution property, which has been widely known to be suitable for reliability analysis, was analyzed and its attributes were identified.

The results of this work are as follows.
First, as a result of analyzing the reference data (MSE and R^2) for efficient model selection, the efficiency of the Inverse-Exponential model was evaluated as the best.

Second, as a result of analyzing the performance attribute data (m(t), λ(t)), the Inverse-Exponential model with excellent predictive ability of true value and low failure rate was the most efficient.

Third, as a result of the reliability test, the Inverse-Exponential and the Inverse-Rayleigh model, which showed consistently high and stable reliability, were efficient. However, the Goel-Okumoto model, which showed the attribute of continuously decreasing reliability with mission time, was inefficient.

In conclusion, this study can present solution techniques and basic design data that can analyze and predict performance attribute data needed by developers during the early software development process. Additionally, follow-up research will be needed to use the results of this study to find an optimized reliability model suitable for related software industry fields and to explore attribute data related to reliability performance.

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