Bivariate Lifetime Model for Organic Light-Emitting Diodes

Dae Whan Kim, Hyunseok Oh, Byeng Dong Youn, and Dongil Kwon

***Abstract*—Despite advantages of organic light-emitting diode (OLED) displays over liquid crystal displays, reliability concerns persist. These concerns must be addressed before OLED displays are widely adopted. In particular, existing methods are unable to reliably estimate the lifetime of large OLED displays (i.e., displays of 55 in or larger). This study proposes a novel model that incorporates physical and statistical uncertainty to estimate the lifetime of large OLED panels under normal usage conditions. A likelihood-ratio-based validation method is presented to determine the validity of the calculated model parameters. A bivariate acceleration model with two critical factors—temperature and luminance—is presented. The lifespan predicted by the proposed lifetime model shows a good agreement with the experimental results.**

***Index Terms*—Acceleration factor (AF), lifetime model, organic light-emitting diodes (OLEDs).**

I. INTRODUCTION

ORGANIC light-emitting diode (OLED) displays are known to be more visually compelling and energy efficient than liquid-crystal displays (LCDs). In recent years, OLED displays have received significant attention from the electronics industry. OLEDs are expected to have significant impacts as next-generation lighting devices and are likely to reshape the future display market. For example, some of the major manufacturers have already introduced large-size OLED TVs in the market. However, reliability issues still remain to be resolved before OLED displays are widely adopted by manufacturers and end users. The primary issue is that OLED luminance degrades over time. The degradation not only reduces the display luminance, but also shifts its emission color. The reliability of the thin-film transistor (TFT) and light-emitting layers is known to be the most significant barrier preventing widespread adoption of OLED displays [1], [2].

Numerous experimental studies have been conducted to date to assess the reliability of solid-state lighting, mostly through accelerated testing (ALT) [3]–[5]. The goal of ALT is to estimate the nominal lifetime of OLEDs when subjected to normal usage conditions that would be expected in service [6]. The steps for ALT include: 1) testing samples under accelerated loading conditions; 2) estimating life distribution and determining an acceleration factor (AF); and 3) calculating lifetime distributions under normal usage conditions. The second step is regarded as the most critical to the prediction of an accurate lifetime distribution [7], [8].

Previously, both parametric and nonparametric approaches have been used to estimate lifetime distributions. The parametric approach involves a selection process for choosing a set of distribution parameters that gives the largest correlation for the given experimental data. For example, Zhang *et al.* [9] showed that the lifespan of a white OLED under current loading conditions meets lognormal and Weibull distributions. Wang and Lu [10] presented a general procedure for the parametric approach on lifespan prediction. The nonparametric approach involves estimating the lifetime without relying on a closed-form expression for statistical distributions. The nonparametric approach can be implemented for any type of experimental data. However, one of the challenges of this approach is to calculate second-order derivatives of the performance degradation equation. For example, Park and Bae [11] compared the performance of conventional lifetime distribution-based approaches (such as Weibull and lognormal distributions) with that of the nonparametric method. Park's work showed that the nonparametric method to determine the OLED degradation gives a comparable result to parametric methods when the proper lifetime distribution is unknown. In contrast, the parametric approach provides more accurate estimates in terms of the percentile lifetime.

Extensive prior studies have also been conducted to find a relevant acceleration model that represents the effect of operational loading conditions on the degradation of OLEDs. First, it has been shown that the acceleration of degradation due to luminance intensity is governed by the inverse power relationship [12]. Second, the acceleration of degradation due to temperature is dictated by the Arrhenius equation. It was shown that the localized Joule heating significantly reduces the operational lifetime of OLEDs [13]. Several studies in the literature [4], [10]–[12] employed a single AF to build an acceleration model. However,

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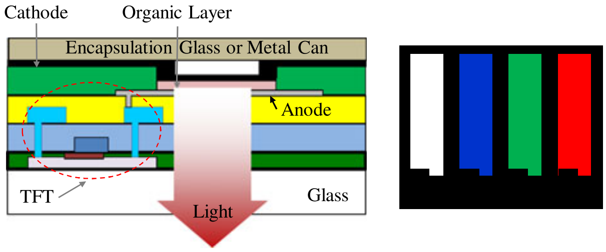


Fig. 1. Subpixel in an OLED TV: cross-sectional view (left) and top view (right).

OLED panels in real-world applications (e.g., TV sets) are subjected to a combination of AF. It is commonly observed that a different amount of heat is dissipated by conduction and natural convection from individual electric components. Moreover, luminance intensity produced by the driving current nonlinearly increases with respect to the operating temperature [14]. To the best of our knowledge, no study to date has incorporated multiple AF.

In real-world applications, individual OLED pixels in a panel are subjected to various physical and operating uncertainties [15]. For example, in the process of plasma-enhanced chemical vapor deposition, the TFT in an OLED panel does not crystallize in a perfectly uniform manner. Thus, the current consumed by each individual pixel of the TFT varies [16]. Numerous studies have suggested advanced TFT fabrication processes and developed new compensation methods for minimizing this uncertainty; however, it still remains as an issue [17], [18]. Another example of uncertainty is the large spatial deviation in temperature that occurs due to local heat sources and natural convection in the slim design of a large display. Although numerous mature technologies that were developed for LCDs are being incorporated into OLED displays [5], [19], [20], it is still challenging to address these uncertainties in large OLED panels. Thus, to date, no statistical analysis procedures have been developed that incorporate physical and statistical uncertainties to accurately estimate the lifetime distribution of large OLED panels.

To this end, this study aims to develop a lifetime model that incorporates uncertainty, and accurately predicts the lifetime of large OLED panels under various usage conditions. This paper is organized as follows. Section II provides a review of the structure of OLEDs and the degradation model. The experimental method for the accelerated life test is explained in Section III. Next, in Section IV, we show that the life distribution of OLEDs follows the Weibull distribution statistically and we estimate the common shape parameter. This section also outlines the construction of the bivariate acceleration model and estimation of usage life. Section V provides conclusions and suggestions for future work.

II. REVIEW: OLED DEGRADATION

A. Degradation Mechanism

A cross-sectional view of an OLED device is illustrated in Fig. 1. Typically, an OLED panel in a large TV is composed of two structures: 1) a light-emitting layer between two sandwiched electrodes and 2) a TFT backplane [21], [22]. Degradation of the light-emitting layer can be attributed to both intrinsic and extrinsic causes. The extrinsic degradation is caused by contamination and humidification during the fabrication process. The intrinsic degradation occurs due to the materials electrochemical degradation during the application of electric excitation, which leads to the formation of charge trapping and excited-state quenching defects [23]. While the extrinsic degradation can be effectively controlled through proper device encapsulation and adequate fabrication process control, the intrinsic degradation is more challenging. Thus, intrinsic degradation continues to be a problematic issue that prevents widespread OLED commercialization.

The TFT controls the amount of current flow by adjusting the voltage potential in the gate of the TFT. If a critical amount of current flows through the electrode of the organic layer, it generates light while it dissipates heat. The threshold voltage of the TFT is the minimum gate-to-source voltage gap required to create a conducting path. The conducting path is then used to deliver the driving current to the light-emitting layer. As OLEDs degrade, the threshold voltage shifts over time under the elevated temperature conditions [24]. As a result, the luminance of OLEDs is also gradually reduced over time. It should be noted that the degradation of the two components—the light-emitting layer and the TFT backplane—is correlated. Thus, both failure mechanisms should be considered together to model the accurate OLED degradation modeling.

B. Performance Degradation Models

Several functional forms are used to describe the performance degradation of OLEDs. The double-exponential model was derived by incorporating energy transfer rates between the lowest unoccupied molecular orbit and the highest occupied molecular orbit [25]

$$l(t) = ae^{-\alpha_1 t} + be^{-\alpha_2 t} \tag{1}$$

where a and b are the constants determined by the initial conditions; α_1 is the parameter that presents the initial decay; and α_2 is the parameter that indicates the long-term degradation according to time (t).

The stretched exponential decay (SED) model [26] is defined as

$$l(t) = \exp\left[-\left(\frac{t}{\tau_0}\right)^{\gamma}\right] \tag{2}$$

where τ_0 is the characteristic time by which the performance degrades to 63.2% of the initial performance; and γ is the parameter that characterizes the degradation rate.

The SED model is useful to fit the lifetime of the OLED to the failure of the light-emitting layer of the OLEDs [27]. For example, Zhang *et al.* [4] tested OLEDs under different stress conditions and fitted the degradation data to an exponential function.

C. Acceleration Models

As discussed earlier, the AF for degradation of OLEDs are the operating temperature and driving current (or initial luminance intensity) [28], [29]. First, the AF for initial luminance intensity

Fig. 2. Pattern of the ADT: the display size is 55 in; the number of pixels is 1920 × 1080; and the number of pixels in an individual pattern is 160 × 96.

has an inverse power relationship [3], [4], [10]. The acceleration factor (AF_{lum}) for initial luminance intensity between the usage condition and the stress level is expressed by

$$AF_{\mathrm{lum}} = \frac{L_{\mathrm{d}}}{L_{\mathrm{a}}} = \left(\frac{I_{\mathrm{lum_d}}}{I_{\mathrm{lum_a}}}\right)^{-B} \tag{3}$$

where L_{d} and I_{lumd} are the lifespan and the initial luminance intensity under the normal usage conditions, respectively; L_{a} and I_{luma} are the lifetime and initial luminance intensity under the accelerated loading conditions, respectively.

Another acceleration factor for temperature (AF_{temp}) is expressed by [3]:

$$AF_{\mathrm{temp}} = \exp\left[\frac{E}{k}\left(\frac{1}{T_{\mathrm{d}}} - \frac{1}{T_{\mathrm{a}}}\right)\right] \tag{4}$$

where E is the activation energy; k is the Boltzmann constant ($= 8.62 \times 10^{-5}$); T_{d} is the temperature under the nominal loading condition; and T_{a} is the temperature under the accelerated loading condition. It is worth noting that the acceleration models for OLEDs in previous studies employed only with a single AF.

III. ACCELERATED DEGRADATION TESTING (ADT) FOR OLEDS

A. Experimental Setup

Three sets of OLED panels with the size of 1920 × 1080 pixels (see Fig. 2) were used for the degradation test at a room temperature while another three sets were degraded in a convection oven with a temperature of 40 °C. Four levels of luminance intensity were set for the individual OLED panels: an initial luminance intensity, and then twice, four times, and six times the initial luminance intensity (see Table I). The current intensity was internally maintained during the testing. White OLED panels have a WRGB subpixel structure. In order to emit a gray color, the initial luminance intensity of three components (i.e., red, green, and blue) in a single pixel must be identical [21], [30].

The luminance was measured in each pattern at variable intervals between 24 and 180 h. A Yokogawa multimedia display tester (Model 3298F) was used for luminance measurement. Measurements were conducted until the operating time reached 1500 h or the OLEDs failed.

TABLE I
DESCRIPTION OF THE DISPLAY PATTERN IN EACH TV SET

Panel	Temperature condition	Initial luminance intensity (The number of pattern)				Total number of patterns
		×1	×2	×4	×6	168
#1	25 °C	7	7	6	8	28
#2	25 °C	7	7	7	7	28
#3	25 °C	7	7	7	7	28
#4	40 °C	7	7	7	7	28
#5	40 °C	7	7	7	7	28
#6	40 °C	7	7	7	7	28

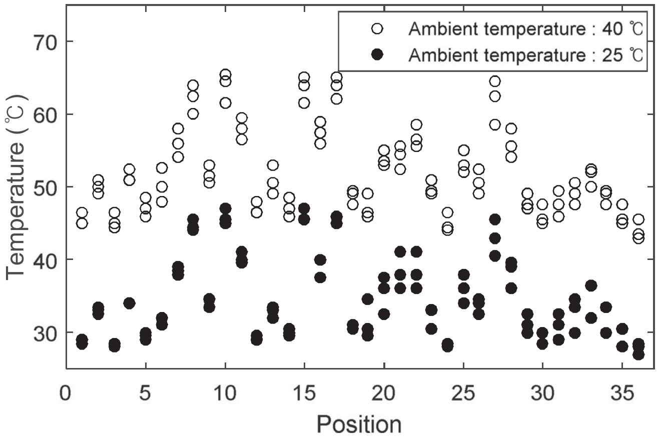


Fig. 3. Temperature deviation in the OLED panel at each ambient temperature. Position 1 corresponds to the spot in the top-left corner of the panel, while Position 36 is the spot in the bottom-right of the panel.

In this study, 50% or less than the initial luminance intensity was defined as failure of the OLEDs [1], [9], [31]. This type of failure is regarded as "soft failure," since the units are still working; however, they are unacceptable for users.

Simultaneously, the temperature was measured at identical intervals. As shown in Fig. 3, the difference between maximum and minimum temperatures at the same temperature condition was 10 °C or higher. In some cases, the difference was as high as 15 °C.

B. Lifespan Test Results and Discussion

Fig. 4 with a normalized luminance for the ordinate shows the test result with the curve fitting obtained by the SED model in (2). We found that R-square values were between 0.962 and 0.991. This indicates good agreements between the experimental data and the curve-fitting results. Using the individual SED curve, the time to failure (TTF, t_f; time to 50% performance degradation) was calculated. The mean, along with the 1st, 25th (Q1), 75th (Q3), and 99th percentile TTFs are presented in the box plot, as shown in Fig. 5. The bottom and top of the box are the first and third quartiles (Q1, Q3); whiskers represent 1.5 times the interquartile range; and "+" symbol indicates outlier data.

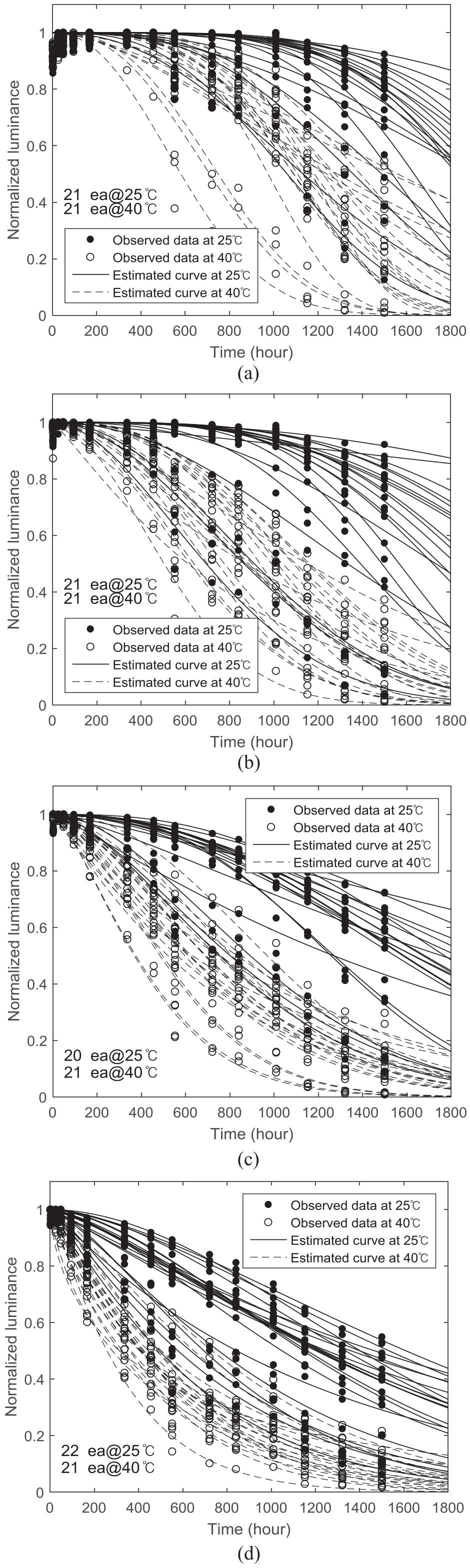


Fig. 4. Test and curve-fitting results. The solid circle is the test result at room temperature (25 °C) and the unfilled circle is that at 40 °C. The solid line is the SED curve estimated with the data at room temperature, while the dashed line is that estimated with the data at 40 °C. (a) Initial luminance intensity (×1); (b) Twice the initial luminance intensity (×2); (c) Four times the initial luminance intensity (×4); and (d) Six times the initial luminance intensity (×6).

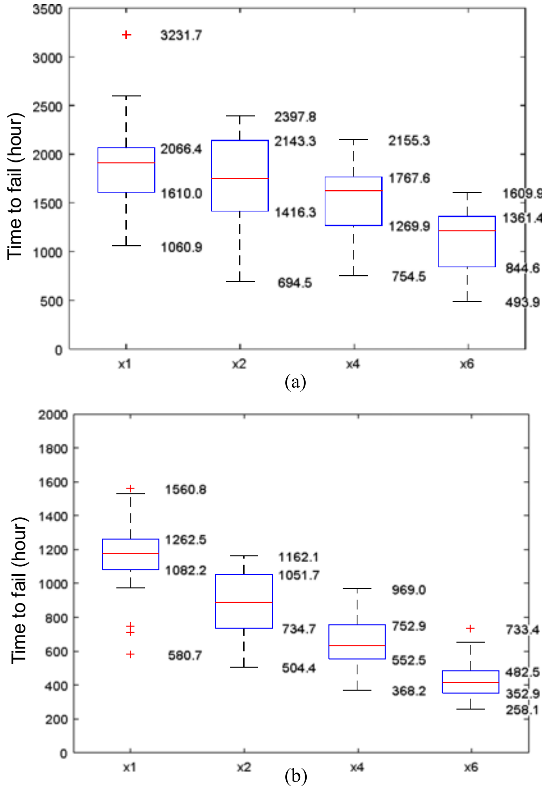


Fig. 5. TTF estimated from the SED curve: (a) at 25 °C and (b) at 40 °C.

IV. BIVARIATE LIFETIME MODEL FOR OLEDS

A. Fitting TTF Data to the Statistical Distribution

1) Estimation of Lifetime Distribution Parameters:

In order to determine the proper distribution type, three candidates were considered: normal, log-normal, and Weibull distributions. It was found that the Weibull distribution was most appropriate to represent the TTF data for OLEDs, based on chi-square (χ^2) and Kolmogorov–Smirnov (K–S) goodness-of-fit (GoF) tests shown in Table II.

The functional form of the Weibull distribution is expressed as

$$f(t) = (\beta/\eta)(t/\eta)^{(\beta-1)} e^{-\left({t}/{\eta}\right)^{\beta}} \tag{5}$$

where β is the shape parameter that directly affects the shape of the failure density distribution curve of the Weibull distribution and η is the scale parameter. The parameters were estimated using the maximum likelihood estimator.

The likelihood function is the joint density function of n random variables given unknown parameters (θ):

$$L = \prod_{i=1}^{n} f(x_i, \theta) \tag{6}$$

TABLE II
GoF TEST RESULTS

Temperature	Initial luminance scale	Type	*p*-value	
			Chi-square GoF test	K–S GoF test
25 °C	×2	Normal	0.204	0.746
		Lognormal	0.250	0.360
		Weibull	**0.267**	**0.823**
	×4	Normal	0.390	0.354
		Lognormal	0.136	0.145
		Weibull	**0.500**	**0.506**
	×6	Normal	0.204	0.281
		Lognormal	0.147	0.088
		Weibull	**0.273**	**0.397**
40 °C	×1	Normal	0.535	0.508
		Lognormal	0.073	0.207
		Weibull	**0.710**	**0.701**
	×2	**Normal**	**0.999**	0.806
		Lognormal	0.343	0.459
		Weibull	0.785	**0.962**
	×4	**Normal**	0.839	**0.999**
		Lognormal	0.338	0.890
		Weibull	**0.989**	0.989
	×6	Normal	0.224	0.565
		Lognormal	**0.261**	**0.750**
		Weibull	0.189	0.512

*Bold text indicates the maximum value among three distributions.

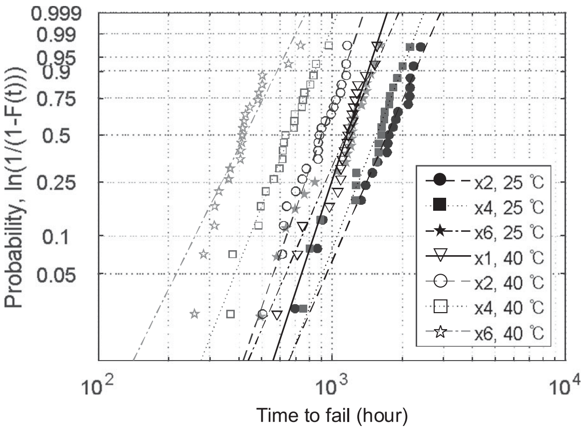


Fig. 6. Lifetime distribution plot drawn on Weibull probability paper.

TABLE III
PARAMETER ESTIMATION RESULT WITH MAXIMUM-LIKELIHOOD ESTIMATION

Temperature	Initial luminance scale	Different shape parameter			Common shape parameter		
		Scale (η)	Shape (β)	Negative -log likelihood	Scale (η)	Shape (β)	Negative -log likelihood
25 °C	×2	1871.86	4.37	143.50	1881.98	4.67	143.56
	×4	1669.20	4.91	139.24	1662.87		139.28
	×6	1243.52	4.41	156.99	1249.39		157.04
40 °C	×1	1234.63	5.81	143.87	1216.90		144.59
	×2	964.21	5.48	139.77	953.06		140.16
	×4	710.43	4.85	135.09	708.03		135.12
	×6	467.63	3.84	129.43	481.31		130.35

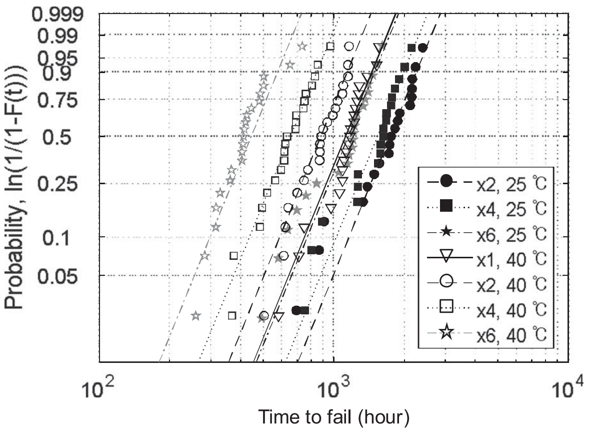


Fig. 7. Lifetime distribution plot drawn on Weibull probability paper.

Considering the Weibull parameters, namely the shape and scale parameters, the likelihood function is

$$L(t_1, t_2, \cdots, t_n|\eta, \beta) = \prod_{i=1}^{n} \frac{\beta}{\eta}\left(\frac{t_i}{\eta}\right)^{\beta-1} e^{-\left({t_i}/{\eta}\right)^{\beta}} \tag{7}$$

As shown in Fig. 6, the shape parameter corresponds to the slope of the Weibull probability paper with $\{\ln t\ \&\ \ln[-\ln(1-p)]\}$. The scale parameter is the characteristic lifespan that represents the time for 63.2% failure to occur.

2) Estimation of the Common Shape Parameter: The slopes (i.e., shape parameter) in Fig. 6 show variation. If OLEDs degrade with an identical failure mechanism, the shape parameters should theoretically be identical regardless of the loading conditions. In this study, we assumed that the failure mechanism did not shift, and, thus, a common shape parameter in the Weibull distribution can be calculated using the maximum-likelihood estimator. The logarithm of (7) was taken. Then, it was differentiated with respect to η and β and equated to be zero

$$\frac{\sum_{j=1}^{J}\sum_{i=1}^{n_j} t_{ji}^{\tilde{\beta}} \ln t_{ji}}{\sum_{j=1}^{J}\sum_{i=1}^{n_j} t_{ji}^{\tilde{\beta}}} - \sum_{j=1}^{J}\frac{1}{\tilde{\beta}} - \sum_{j=1}^{J}\frac{1}{r_j}\sum_{i\in D_j}\ln t_{ji} = 0 \tag{8}$$

$$\tilde{\eta}_J = \left(\frac{1}{r_j}\sum_{j=1}^{n_j} t_{ji}^{\tilde{\beta}}\right)^{1/\tilde{\beta}} \tag{9}$$

where n_j is the number of samples in each stress level (j = 1, 2, …, J); n is the total number of samples ($n = n_1 + n_2 + \ldots + n_J$); and t_{ij} is the TTF in the ith sample of the jth stress level. By solving (8) using the numerical analysis (e.g., the Newton–Raphson method), a common shape parameter ($\tilde{\beta}$) can be calculated. As shown in Table III, the common shape parameter was estimated to be 4.67. The corresponding scale parameter was calculated using (9). The visual inspection of the slopes shown in Fig. 7 allowed qualitative confirmation on the validity of our assumption by which a common shape parameter is applied.

3) Likelihood-Ratio Analysis: To quantitatively verify the assumption that lifetime distributions under different loading

TABLE IV
RESULTS OF GOF TEST AND ESTIMATED MTTF USING A COMMON SHAPE PARAMETER

Temperature	Initial luminance scale	*p*-value		MTTF
		Chi-square GoF test	K–S GoF test	
25 °C	×2	0.34	0.80	1721.07
	×4	0.44	0.42	1520.70
	×6	0.34	0.50	1142.57
40 °C	×1	0.42	0.24	1112.85
	×2	0.93	0.69	871.57
	×4	0.92	0.99	647.50
	×6	0.06	0.16	440.16

conditions have a common shape parameter for the ADT of OLEDs, the likelihood ratio test [32] was employed. The null hypothesis is that Weibull distributions at different stress levels have a common shape parameter ($\tilde{\beta}$)

$$H_0 : \beta_1 = \beta_2 = \cdots = \beta_J = \tilde{\beta} \tag{10}$$

The alternative hypothesis (H_1) is that shape parameters at different stress levels are not the same. The function of test statistics (Λ) is defined as

$$\begin{aligned}\Lambda &= 2\left(\hat{\Lambda}_1 + \cdots + \hat{\Lambda}_J - \hat{\Lambda}_0\right)\\ &= 2\log L\left(\hat{\eta}_1, \hat{\eta}_2, \cdots, \hat{\eta}_J, \hat{\beta}_1, \hat{\beta}_2, \cdots, \hat{\beta}_J\right)\\ &\quad - 2\log L\left(\hat{\eta}_1, \hat{\eta}_2, \cdots, \hat{\eta}_J, \hat{\beta}\right)\end{aligned} \tag{11}$$

where $\hat{\Lambda}_1$, ..., and $\hat{\Lambda}_J$ are the likelihood values obtained by fitting a distribution to the data from each test stress level; and $\hat{\Lambda}_0$ is obtained by fitting a model with the common shape parameter and a scale parameter for each stress level. The distribution of Λ follows a chi-square distribution with *J*-1 degrees of freedom (*J*: DOF of the alternative hypothesis, 1: DOF of the null hypothesis), where *J* is the number of stress levels. If Λ is equal to or less than $\chi^2(1-\alpha; J-1)$, H_0 is accepted, where $\chi^2(1-\alpha; J-1)$ is the $100(1-\alpha)$ percentile of the chi-square distribution with $J-1$ degrees of freedom. Otherwise, H_0 is rejected. Using the results in Table III, Λ is calculated to be 4.43, which is less than 12.59 ($=\chi^2(0.95; 6)$). Since the calculated value is smaller than the criterion of the chi-squared statistics, it was concluded (with a significance level of 5%) that the shape parameter estimates are not significantly different. Therefore, through visual inspection of Fig. 7 and the likelihood-ratio test, the assumption that the lifetime distributions have a common shape parameter is valid.

Consequently, the mean time to failure (MTTF) and the *p* percentile life (t_{p}) are obtained by

$$\mathrm{MTTF} = \eta\Gamma\left(1 + \frac{1}{\beta}\right) \tag{12}$$

$$t_p = \eta[-\ln(1-p)]^{1/\beta} \tag{13}$$

The results are summarized in Table IV.

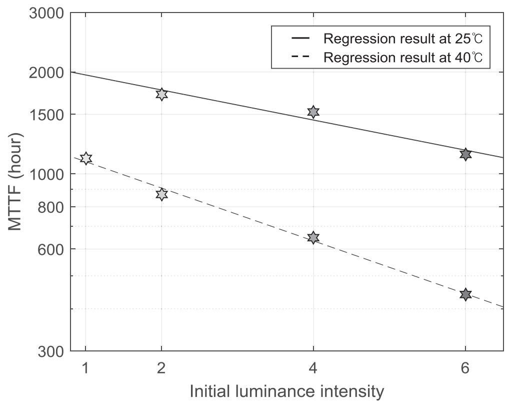


Fig. 8. MTTFs calculated with the proposed bivariate lifetime model.

B. Bivariate Lifetime Model

As presented in Section II, the dominant AF for OLEDs is temperature and luminance. Relevant lifetime models for the accelerated factors are the Arrhenius equation and the inverse power law, respectively. In this section, we propose a novel bivariate lifetime model for OLEDs by integrating the two lifetime models. The proposed model is

$$\mathrm{MTTF}\left(T, I_{\mathrm{lum}}\right) = \frac{A}{T} \cdot e^{\frac{B}{kT}} \cdot e^{I_{\mathrm{lum}}\left(C + \frac{D}{kT}\right)} \tag{14}$$

where k is the Boltzmann constant (8.62×10^{-5}); T is the ambient temperature (*K*); I_{lum} is the initial luminance intensity; and *A*, *B*, *C*, and *D* are the model parameters.

By definition, the AF is

$$\mathrm{AF} = \frac{\mathrm{MTTF}_d}{\mathrm{MTTF}_a} \tag{15}$$

where MTTF_d is the mean time to failure under the normal usage condition; MTTF_a is the mean time to failure under the accelerated condition. Substituting (14) into (15), the AF for the proposed model becomes

$$\mathrm{AF} = \frac{T_a}{T_d} \cdot \exp\left[\frac{B}{k}\left(\frac{1}{T_d} - \frac{1}{T_a}\right)\right] \cdot \frac{\exp\left[I_{\mathrm{lum}_d}\left(C + \frac{D}{kT_d}\right)\right]}{\exp\left[I_{\mathrm{lum}_a}\left(C + \frac{D}{kT_a}\right)\right]} \tag{16}$$

where T_d is the temperature under the normal usage condition; T_a is the temperature under the accelerated condition; I_{lumd} is the initial luminance intensity; and I_{luma} is the accelerated level of luminance intensity.

C. Validation of the Proposed Model

The least squares regression analysis was conducted to estimate the unknown model parameters of the proposed bivariate lifetime model. As shown in Fig. 8, by visual inspection, the proposed model showed a good agreement with the experimental data. The proposed model (i.e., straight line) could explain the data sufficiently. With a quantitative measure, the GoF was also evaluated. The *R*-squared value was as high as 0.9948 (see Table V). From the visual inspection and the quantitative evalu-

TABLE V
LEAST-SQUARES REGRESSION ANALYSIS

Model parameters				GoF			
A	B	C	D	SSE*	R^2	DOF*	MSE*
41.101	0.25	−1.72	0.04	0.0071	0.9948	3	0.0486

*SSE: sum of square error; DOF: degree of freedom; MSE: mean square error.

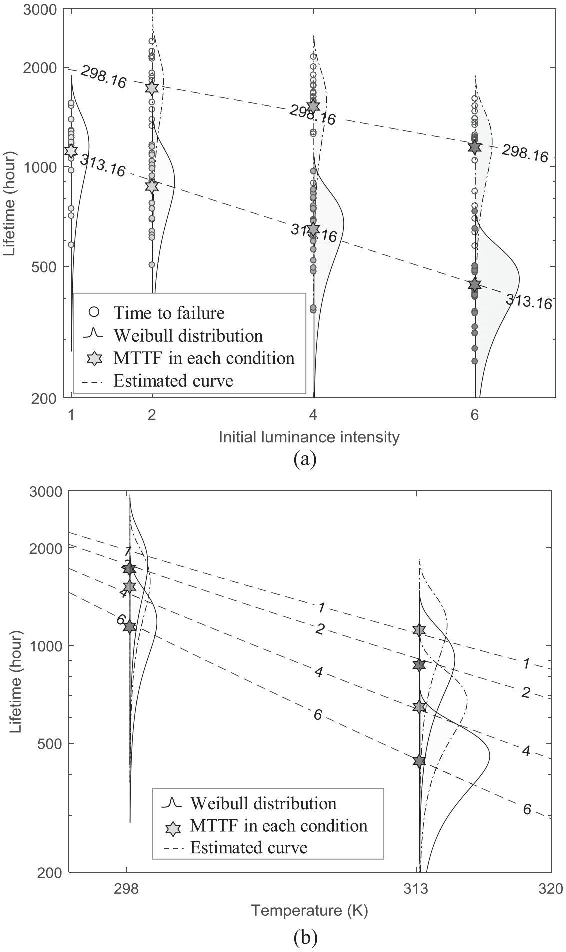


Fig. 9. Lifetime distribution calculated from the model and AF: (a) initial luminance intensity and (b) temperature.

TABLE VI
AF AT SIX TIMES THE INITIAL LUMINANCE INTENSITY AND 40 °C CONDITION
($I_{\mathrm{lumd}} = 1$, $I_{\mathrm{luma}} = 6$, $T_d = 298$, AND $T_a = 313$)

AF	Term 1	Term 2	Term 3*
5.91	1.05	1.59	3.53

*Interaction term with temperature and initial luminance intensity.

TABLE VII
ESTIMATED LIFETIME IN USE AND VALIDITY CHECK

Model	Estimated lifetime		Chi-square GoF test		K–S GoF test	
	$\mathrm{MTTF}_{\mathrm{obs}}$* = 1875	Error*	Hypothesis	*p*-value	Hypothesis	*p*-value
Proposed	1959	4%	Accept	1.66×10^{-1}	Accept	6.38×10^{-2}
Han and Narendran [33]	2607	39%	Reject	8.09×10^{-5}	Reject	5.61×10^{-5}
Intel's model [36]	2277	21%	Reject	8.77×10^{-4}	Reject	4.72×10^{-5}

*$\mathrm{MTTF}_{\mathrm{obs}}$: the observed MTTF, Error = $(\mathrm{MTTF}_{\mathrm{obs}} - \mathrm{MTTF}_{\mathrm{estimated}})/\ \mathrm{MTTF}_{\mathrm{obs}}$.

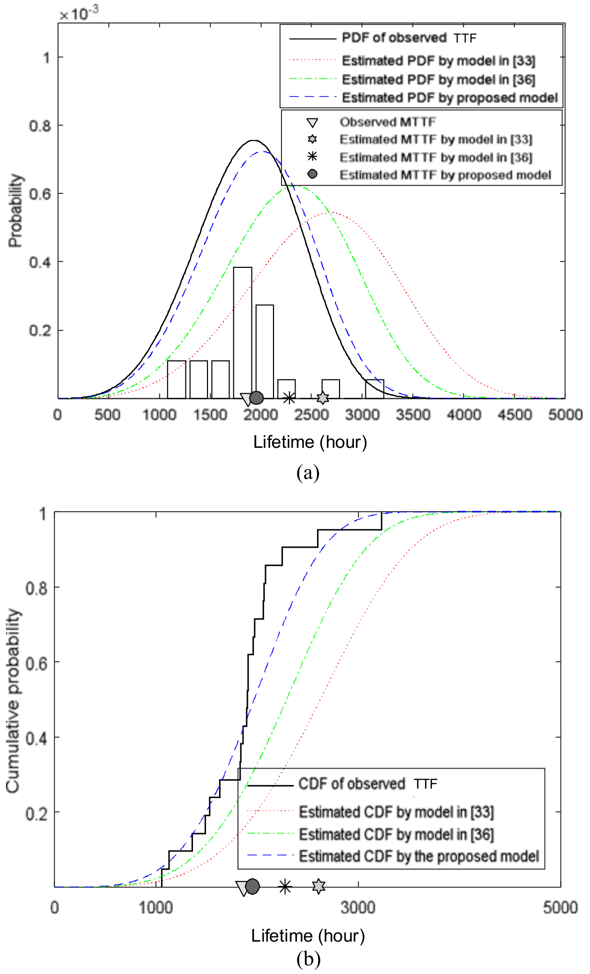
ation, it was concluded that the proposed model was appropriate to describe the relationship between the MTTFs of OLEDs and initial luminance intensity. Fig. 9 shows how well two acceleration factors follow the proposed model.

The AF between the normal usage (i.e., 25 °C and initial luminance intensity) and accelerated (i.e., 40 °C and six times of initial luminance intensity) conditions was calculated to be 5.91. The details are shown in Table VI. The magnitude of the interaction term was largest among others, which indicated that a univariate lifetime model with a single AF may provide a poor lifetime estimation due to the negligence of the interaction between temperature and luminance.

The accuracy of the proposed bivariate lifetime model was evaluated by comparing the experimental data with statistical distributions calculated by the model. The MTTF was used a metric for comparison. The MTTF of the 21 failure samples was 1876 h, whereas the MTTF estimated from the proposed model was 1959 h. The error was only 4% that was almost negligible. We also employed two GoF tests to evaluate the validity of the proposed model. The statistical distribution at the normal usage condition was calculated with the common shape parameter ($\tilde{\beta}$) of the Weibull distribution. The results from chi-square and K–S GoF tests showed that the statistical distribution predicted from the proposed model was not significantly different from the TTF data with a confidence level of 95%. Therefore, we concluded that the proposed model is valid.

The results from the proposed bivariate lifetime model were compared with those from other models available in the literature. It should be noted that, to the best of our knowledge, no bivariate lifetime model was developed for OLEDs. Therefore, a comparison was conducted with a model used for LEDs and another model used for general applications. First, Han *et al.* [33], [34] adopted Peck's relationship [35] to describe the lifetime for LEDs. Second, Intel's model [36] was used in various applications. The model parameters of Peck's and Intel's models were calculated by the nonlinear regression analysis. The MTTFs estimated using the two models were 2607 and 2277 h, respectively. The errors were 39% and 21%, respectively. The GoF test results showed that the results obtained from the two models were significantly different from the TTF data, which is not acceptable. Consequently, we concluded that the proposed model in this study outperformed the existing models. A summary of the comparison is shown in Table VII.

Fig. 10 compares statistical distributions (i.e., probability density and cumulative distribution functions) of OLED lifetime at the normal usage condition. They were obtained from the experimental data and the three models. The results showed that



(a)

(b)

Fig. 10. Comparison between testing and estimated results: (a) probability density plot and (b) cumulative distribution plot.

the statistical distribution by the proposed model best described the empirical distribution among other models. This is partially because the proposed model includes the interaction term and thus is more flexible.

V. CONCLUSION

Large OLED panels with a size of 55 inches or larger are subjected to physical uncertainty in real-world applications (e.g., spatial temperature variations in the OLED panel and inherent randomness in organic materials). Estimation of the nominal lifetime of OLED panels is important for quality and reliability assurance during the design stage. Nevertheless, previous studies for OLEDs have not fully addressed the physical uncertainty to enable accurate lifespan estimation for large OLED panels. To fill this research gap, in this paper, we proposed 1) a novel bivariate acceleration model, 2) a statistical approach considering physical and statistical uncertainties, and 3) a likelihood-ratio-based validation method.

First, a novel bivariate lifetime model was proposed to analyze the lifespan testing data for OLEDs. The nominal life estimated using the bivariate lifetime model showed only a 4% error compared to the experimental data. The proposed bivariate lifetime model with the interaction term between the ambient temperature and the luminance intensity outperformed existing models.

Second, a statistical approach was proposed to develop a lifetime model considering physical and statistical uncertainty sources in OLED panels. The proposed statistical analysis consists of: 1) design of ADT, 2) estimation of the TTF using accelerated degradation data and the SED model, 3) inference of a common shape parameter of lifetime distributions, 4) evaluation of validity through the likelihood-ratio analysis, 5) prediction of lifetime distributions of OLED panels with the proposed bivariate AF model. This statistical approach will help us to predict an accurate lifetime distribution of a large OLED panel subjected to various uncertainties.

Finally, a likelihood-ratio-based validation method was proposed to determine whether the common distribution parameter was significantly different from the individual distribution parameters estimated from lifespan testing data under the different acceleration levels. We demonstrated the applicability of the validation method using data from lifespan testing of OLEDs.

Quality and reliability engineers are encouraged to use the bivariate lifetime model for OLEDs proposed in this study. With the proposed model, the lifetime of large OLED panels subjected to normal usage conditions can be predicted by extrapolating accelerated life testing results from their own experiments. The future work is to examine the nonhomogeneity of temperature due to local heat sources (e.g., passive components on printed-circuit boards and natural convection). We will also focus on the development of an advanced method that estimates the degradation of OLED TVs with only temperature data, rather than using both temperature and luminance intensity. Spatial distribution of temperature must be estimated accurately. This warrants the development of a valid computational model of OLED TVs for thermal analysis considering the layout of heat-generating components and heat flow in the chassis of the OLED TVs. If necessary, techniques for model verification and validation can be employed to improve the predictive capability of the model. Ultimately, we anticipate to provide a design guidance that will enable designers and quality engineers optimize the design of large OLED TVs.

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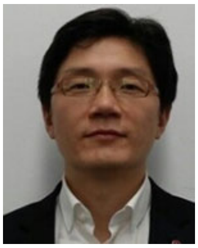

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