Statistical Analysis of Lumen Depreciation for LED Packages

Schuld, M.; van Driel, Willem Dirk ; Jacobs, B.

DOI
10.1007/978-3-319-58175-0_17

Publication date
2018

Document Version
Final published version

Published in
Solid State Lighting Reliability Part 2

Citation (APA)
Schuld, M., van Driel, W. D. (Ed.), & Jacobs, B. (2018). Statistical Analysis of Lumen Depreciation for LED Packages. In W. D. van Driel, X. Fan, & G. Q. Zhang (Eds.), *Solid State Lighting Reliability Part 2: Components to Systems* (1 ed., pp. 487-502). (Solid State Lighting Technology and Application Series; Vol. 3). Springer. https://doi.org/10.1007/978-3-319-58175-0_17

Chapter 17
Statistical Analysis of Lumen Depreciation for LED Packages

M. Schuld, Willem Dirk van Driel, and B. Jacobs

Abstract Commercial claims for LED-based products in terms of lumen maintenance are fully based on TM-21 extrapolations using LM-80 data. This chapter indicates that there may be a risk in doing this as TM-21 only relies on the behavior of the average LED degradation, instead of taking into account the degradation of all individual LEDs. Therefore, we propose a more profound statistical approach in order to make the appropriate step from TM-21 extrapolation to lumen maintenance on a product level. This is needed as some commercial claims are based on 10 years of warranty and some service bids provide periods of 20–25 years of operation. This chapter reviews the different approaches currently available to perform lumen maintenance extrapolations.

17.1 Introduction

Solid-state lighting (SSL) refers to a type of lighting that uses semiconductor light-emitting diodes (LEDs), organic or polymer light-emitting diodes (OLED/PLED) as sources of illumination rather than electrical filaments, plasma (used in arc lamps such as fluorescent lamps), or a gas. SSL applications are now at the doorstep of massive market entry into our offices and homes. This penetration is mainly due to the promise of an increased reliability with an energy saving opportunity: a low-cost reliable solution [1].

M. Schuld (✉)
CQM, Eindhoven, The Netherlands
e-mail: marc.schuld@cqm.nl

W.D. van Driel (✉)
Philips Lighting, High Tech Campus, Eindhoven, The Netherlands

Delft University of Technology, EEMCS Faculty, Delft, The Netherlands
e-mail: willem.van.driel@philips.com

B. Jacobs
Delft University of Technology, EEMCS Faculty, Delft, The Netherlands
e-mail: boudewijn.jacobs@philips.com

W.D. van Driel et al. (eds.), *Solid State Lighting Reliability Part 2*, Solid State Lighting Technology and Application Series 3, DOI 10.1007/978-3-319-58175-0_17

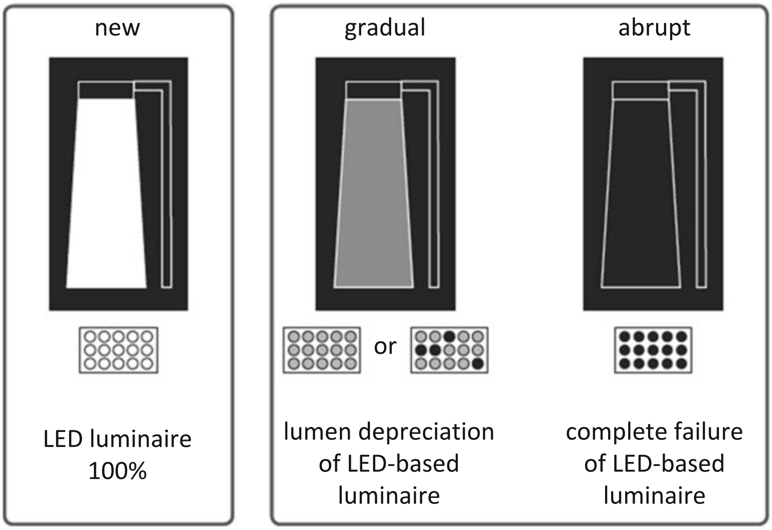

Fig. 17.1 Over time performance of an LED-based system

On system level, there are two relevant "over time" performance values to be considered: gradual and abrupt light output degradation; see Fig. 17.1. Gradual light output degradation relates to the lumen maintenance of a luminaire over time. It tells you how much of the initial lumen output of the luminaire is maintained after a certain period of time. The lumen depreciation can be a combination of degradation of optical elements used, individual LEDs giving less light and individual LEDs giving no light at all. Abrupt light output degradation describes the situation where the LED-based luminaire no longer gives any light at all because the system, or a critical component therein, has failed.

Per today, commercial claims for LED-based products in terms of lumen maintenance are fully based on LM-80 data[1] [2] and TM-21 extrapolations [3–5]. IES LM-80-08 is an approved method for measuring lumen maintenance of LED lighting sources. The IES standard TM-21-11 provides a guideline for lifetime prediction of LED devices. It uses an average normalized lumen maintenance data coming from LM-80 measurements and performs nonlinear regression for lifetime modeling. It cannot capture the dynamic and random variation of the degradation process of LED devices. The lumen maintenance life is defined as the time when the maintained percentages of the initial light output fall below a failure threshold. There may be a risk in doing this as TM-21 only relies on the behavior of the average LED degradation, instead of taking into account the degradation of all

[1]The LM-80 test is a Department of Energy (DOE)-approved method for measuring lumen depreciation of solid-state light packages, arrays, or modules. LM-80 requires testing to be conducted at least 6000 h at representative operating temperatures and currents, with luminous flux and colour properties collected at a minimum of every 1000 h.

individual LEDs. A more profound statistical analysis is required to make the step from TM-21 extrapolation to lumen maintenance on a product level. For that, we have analyzed several LM-80 data sets from a statistical point of view.

17.2 Problem Formulation

Lumen maintenance is the basis for commercial claims of LED-based products [6–8]. As such, it is extremely vital to perform projections that are statistically sound and correct. Being an industry agreement, TM-21 flaws in this respect, and alternative approaches are needed. Such an alternative approach should encompass the following nature:

- Use all the raw data, per setting, per LED, and per time point.
- Provide statistically sound results in terms of prediction stability.
- Provide a true value for the lumen life of the LED technology.

Paragraph 3 describes the current agreed methods and provides an alternative statistical approach.

17.3 Statistical Methods

17.3.1 Current Agreed Methods

Per today, all LED suppliers deliver LM-80 data sets typically at three currents and three temperatures. A typical data set is depicted in Fig. 17.2 [6]. This relative data is then used for the TM-21 extrapolation tool to create a prediction that is listed in Fig. 17.3. The result is truncated using the so-called $6\times$ rule, where one can only claim a value that is six times the LM-80 time (e.g., with 6 kh test time, one can only claim 36 kh lumen maintenance).

Within the TM-21 committee, an initial approach to the problem of projecting lumen maintenance life was the consideration of multiple mathematical models [4, 5]. These ranged from 1-parameter exponential decay until 3-parameter multi-exponential decay.

Note that there is a risk in accepting lifetimes that are predicted far beyond the LM-80 testing time because of the significant effect of measurement errors and lack of numerical convergence of estimators. Note that it may have an effect the other way round as well: impact of lack of numerical convergence and additional (not identified) degradation mechanisms that are expected to be more dominant.

Within TM-21, being an industry agreement, finally, the simplest possible form was chosen as

2.0 TEST CONDITION 1: 55 °C 0.200 A

TABLE 2.1 - LUMEN MAINTENANCE RESULTS
TEST CONDITION 1: 55 °C 0.200 A

Photometric test drive current: 0.200 A
Photometric test ambient temperature: 25 ± 2 °C
Failures observed: none

Load board ID	Device number	Zero hour measurements: Flux (lm)	Zero hour measurements: V_F (V)	Lumen Maintenance (%): 168	500	1000	2000	3000	4000	5000	6000	7000	8000	9000
A800000B9457031C	1	515.10	25.79	100.4	100.5	99.9	99.7	100.0	99.9	99.9	99.2	99.1	98.9	98.1
	2	518.67	26.40	99.9	99.9	99.4	99.1	99.3	99.2	98.9	98.5	98.4	98.3	97.6
	3	518.57	25.75	100.1	100.3	99.8	99.6	100.1	100.0	100.0	99.4	99.3	99.2	98.5
	4	511.77	26.23	100.7	100.9	100.3	100.3	100.7	100.8	100.7	100.3	100.1	100.0	99.1
	5	517.49	26.12	99.9	99.9	99.4	99.0	99.7	99.8	99.7	99.2	99.0	99.2	98.4
	6	516.60	27.17	100.2	100.2	99.6	99.6	99.9	99.8	99.8	99.2	99.1	99.0	97.7
	7	522.52	27.56	100.3	100.4	100.0	99.9	100.3	100.3	100.3	99.4	98.8	97.7	96.0
	8	512.03	26.30	100.4	100.4	99.8	99.7	100.1	100.0	99.9	99.3	99.1	99.1	98.5
	9	516.71	25.83	100.5	100.3	99.9	99.8	100.2	100.1	100.1	99.6	99.6	99.5	98.5
	10	516.33	25.70	100.3	100.3	99.8	99.9	100.4	100.4	100.5	99.9	99.7	99.5	98.6
	11	520.62	25.94	100.2	100.1	99.6	99.5	99.9	99.9	99.9	99.4	99.3	99.2	98.4
	12	515.88	26.51	100.1	100.1	99.6	99.6	100.2	100.2	100.3	99.7	99.6	99.3	98.5
F600000B9E7D031C	1	524.22	26.27	100.0	100.2	99.6	99.7	99.8	99.8	99.6	99.0	98.9	98.7	97.8
	2	516.25	27.44	99.9	100.0	99.4	99.5	99.6	99.4	99.4	98.6	98.2	97.4	95.8
	3	514.76	26.05	99.3	99.3	98.8	98.8	98.8	98.7	98.5	97.7	97.9	97.7	96.8
	4	515.71	25.99	99.5	99.7	99.1	99.1	99.3	99.2	99.2	98.8	99.0	99.0	98.3
	5	517.33	25.99	99.9	100.1	99.6	99.8	100.0	99.8	99.9	99.3	99.4	99.3	98.4
	6	512.51	25.96	99.9	100.0	99.8	100.1	100.4	100.3	100.3	99.8	99.8	99.4	98.0
	7	514.99	25.59	99.8	99.8	99.1	99.2	99.1	99.1	98.9	98.4	98.6	98.5	97.6
	8	514.99	26.45	99.9	100.1	99.7	99.9	100.0	100.1	100.0	99.6	99.6	99.3	98.2
	9	520.72	25.88	99.7	99.9	99.4	99.7	99.8	99.7	99.7	99.2	99.3	99.3	98.6
	10	517.69	25.52	99.8	100.1	99.6	99.8	99.9	99.9	99.9	99.5	99.6	99.6	98.9
	11	507.07	26.24	100.5	100.9	100.6	100.7	101.1	101.0	101.0	100.5	100.5	100.4	99.3
	12	522.09	25.92	99.8	100.0	99.4	99.5	99.8	99.7	99.6	99.1	99.1	99.1	98.2
			n	24	24	24	24	24	24	24	24	24	24	24
			mean	100.0	100.1	99.6	99.6	99.9	99.9	99.8	99.3	99.2	99.0	98.1
			median	100.0	100.1	99.6	99.7	100.0	99.9	99.9	99.3	99.2	99.2	98.4
			std. dev.	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.9
			min	99.3	99.3	98.8	98.8	98.8	98.7	98.5	97.7	97.9	97.4	95.8
			max	100.7	100.9	100.6	100.7	101.1	101.0	101.0	100.5	100.5	100.4	99.3

Fig. 17.2 Typical LM-80 data set showing lumen decay per LED as function of measurement time [6]

$$\Theta(t) = \exp\left(-\alpha t^{\beta}\right) \tag{17.1}$$

where:

- t is time in hour.
- $\Theta(t)$ is the averaged normalized luminous flux output at time t.
- α is the decay rate constant derived by a least squares curve fit.
- β is the shape parameter.

For each separate temperature and/or current L_{70}, that is $\Theta = 0.7$, can then be calculated using averaged normalized luminous flux output:

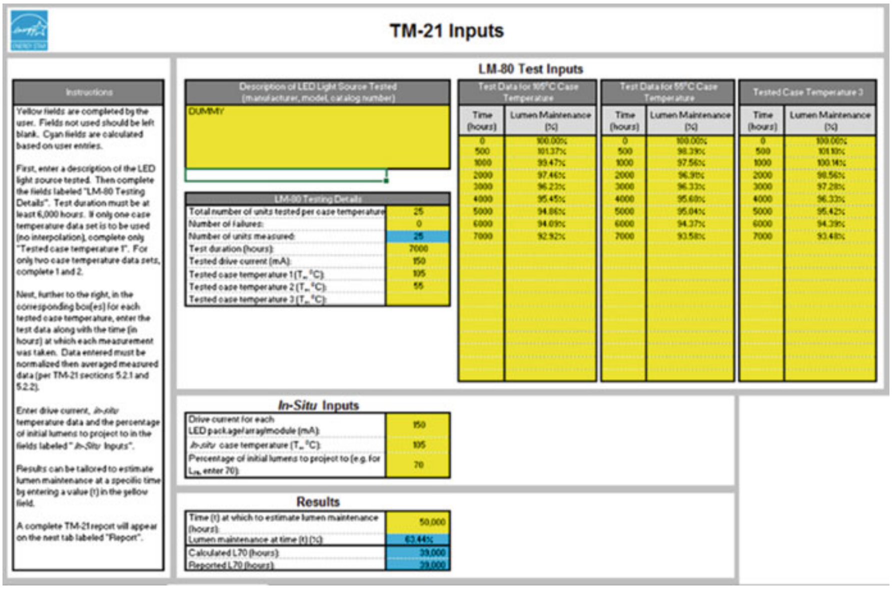

Fig. 17.3 TM-21 report example

$$L_{70} = (-\ln(0.7)/\alpha)^{1/\beta} \tag{17.2}$$

Estimates of (α, β) can be easily obtained by applying the least squares method. Temperature acceleration, within the measured temperatures, is allowed and supposed to follow the Arrhenius equation:

$$\alpha = C \exp\left(\frac{-E_a}{k_B T_s}\right) \tag{17.3}$$

where:

- C is a pre-exponential factor.
- E_a is the activation energy (in eV).
- T_s is the in situ absolute temperature (in K).
- k_B is the Boltzmann's constant ($8.617385 \times 10-5\,\mathrm{eV}/K$).

This model for α can be easily extended by using the inverse power law model that takes into account the effect of current:

$$\alpha = C \exp\left(\frac{-E_a}{k_B T_s}\right) I^n \tag{17.4}$$

where:

- I is the current.
- n is a life-stressor slope.

If applicable the interaction between temperature and current can be added easily.

The TM-21 method has become quite a standard way of working within the lighting industry. In the issue of LEDs Magazine from December 2014, Hansen and Davis [9] used the approach to assess LM-80 data across a variety of packaged LEDs in an effort to determine the effects of different LED platform designs and materials on performance, light quality metrics, and cost.

Alternative approaches are rare as only few other publications are built upon the TM-21 method. An exemption is the VDE standard VDE-AR-E2715-1 [10] currently published in Germany only. Here, the authors describe the so-called border function method (in German: Grenzfunction). This border function (BF) method is based on the assumption that an exponential model is a conservative estimation (worst-case scenario) of the actual long-term luminous flux maintenance as it is expected that most LED packages will show a long-term luminous flux maintenance which is better than the assumed exponential function. Fan et al. from the CALCE institute of technology [11] have used the degradation-data-driven method (DDDM) which is based on the general degradation path model. They use it to predict the reliability of high-power LEDs through analyzing the lumen maintenance data collected from the IES LM-80-08 lumen maintenance test standard. Their method is capable of getting much more reliability information out of the data (e.g., mean time to failure, confidence interval, reliability function). In an accompanying paper, Fan et al. [12] describe a particle filter-based (PF-based) prognostic approach based on both sequential Monte Carlo (SMC) and Bayesian techniques. These techniques are used to predict the lumen maintenance life of LED light sources. Also here the alternative approach achieves better prediction performance, with an error of less than 5% in predicting the long-term lumen maintenance life of LED light sources. Lall et al. [13] follow up on this approach by using Bayesian probabilistic models for the assessment of the onset of degradation in solid-state luminaires. The failure threshold decay rate has been calculated using an Arrhenius model, neglecting the effects of current density and humidity. The statistical approach is quite valid but also seen as complicated. Quan et al. [14] describe an in situ method to monitor the lumen degradation of LED packages. They conclude that the luminous flux of the LEDs shows a steady and slow depreciation, but no proper statistical analysis was performed on their measured data. Huang et al. [15–17] investigated the degradation mechanisms of mid-power white-light LEDs. In their studies, a modified Wiener process was employed for the modeling of the LED devices' degradation, following the earlier work of Tsai et al. [18]. Using this method, the dynamic, random variation, as well as the nonlinear degradation behaviors of the LED devices, was described. They applied the Hallberg-Peck's model to describe the effects of temperature and humidity on LED degradation thereby ignoring the crucial effects of the current density on this degradation. Other studies devote lumen decay to silicone degradation and/or crack formation [19, 20]. In these investigation, silicone degradation was quantitatively evaluated using finite element analysis and used to estimate the LED package lifetime depending on the operation conditions. Buffolo et al. [21] present the results of a reliability investigation performed on four different groups of commercially available mid-power white LEDs. Their data gathered all along the 4000 h of stress accumulated suggest the presence of multiple degradation mechanisms that may limit the useful lifespan of the LED packages. This study lacks a proper statistical analysis of the experimental data, nor proposes an alternative method.

17.3.2 Alternative for Model Fitting

An alternative approach is to study the "degradation" data of each LED individually. It means that for each individual LED, a model as stated in Eq. 17.1 is fitted. Then, we can predict L70 values for each LED and turn degradation values into failure times. The question is whether the differences between predicted lifetimes are due to production variation (and measurement spread) only, or due to operating variation, such as temperature and current as well. Such an experiment is called an accelerated degradation test (ADT). In order to conduct an ADT efficiently, there are several aspects that need to be considered. These aspects are termination time, the number of stress factors, the number of stresses, the choice of stress levels, and the sample size for each stress level. For instance, Nelson [22] and Meeker and Escobar [23] addressed those aspects.

Besides the mentioned aspects, one of the most important questions arising from a degradation experiment is how many hours (or cycles) an accelerated degradation experiment should last for gathering proper data to allow one to make inference about the product lifetime under the normal use condition. In this chapter we focus on the convergence of the quantile estimators (such as B10 or B50) to decide whether we are able to make this inference. Therefore, determination of the termination time cannot be decided upfront. Yu and Tseng [24] proposed to combine the outcomes of an ADT with a known accelerated life test (ALT) model. They showed that the termination time of a degradation experiment has a huge impact on the precision of estimating a product's lifetime. It appeared that the mean time to failure (MTTF) estimates oscillate severely at the beginning; however, as the termination time t_i (with $i = 1,2,\ldots n$) increases, more degradation data are collected, the MTTF estimate converges. It is obvious that B10 and B50 behave similarly. Our intuitive approach to determine the termination time for an LM-80 experiment is based on the work of Yu and Tseng [24]. In this paragraph we will explain the mentioned approach.

The approach for determining the termination time for an ADT has three steps:

1. Use the degradation paths to estimate the lifetimes of LEDs under specific temperatures and currents up to the testing time t_i. So for each LED the parameters (α, β) of Eq. 17.1 need to be estimated, such that L_{70} can be calculated.

2. Find a suitable life-stress model and use a maximum likelihood (ML) procedure to estimate B10 (50) under certain use conditions (T, I). Lognormal and Weibull distributions are both appropriate models to fit the (estimated) lifetime data. Check the distribution assumptions by making probability plots, and study the patterns of the parallel lines (for different values of T and I).
3. Investigate the behavior of B10 (50) for different times t_i ($i = 1,2,..n$), and propose an appropriate termination time. B10 (or B50) at time t_i often oscillates severely at the beginning but will converge in time. Yu and Tseng [24] mention three types of convergence patterns: monotonically increasing to a value, monotonically decreasing to a value, and slightly oscillating around a value. To derive an appropriate termination time, they also propose an algorithm that considers the relative rate of change of the asymptotic mean lifetime by using the 3-period moving average. In this study we focus mainly on the question whether we have sufficient testing data in time to show convergence at all using the mentioned LM-80 data.

In the next paragraph, we will demonstrate this alternative method for several LM-80 data sets coming from high-power (HP) and mid-power (MP) LEDs.

17.4 Analysis of the Selected Use Cases

17.4.1 Mid-power and High-Power LED Technology

In order to assess the applicability of our proposed statistical approach, we have gathered five use cases of long-term lumen maintenance data. These are:

- Case 1a: HP LED technology, 14 kh LM-80 data at four currents and four temperatures
- Case 1b: HP LED technology, 10 kh LM-80 data at three currents and four temperatures
- Case 2a: MP LED technology, 10 kh LM-80 data at three currents and three temperatures
- Case 2b: MP LED technology, 8 kh LM-80 data at three currents and three temperatures
- Case 2c: MP LED technology, 12 kh LM-80 data at three currents and three temperatures

For cases 1a and 1b, the target application settings are 85 °C and a forward current of 1A. For cases 2a, 2b, and 2c, the target application settings are also 85 °C but using a forward current of 150 mA.

All five data sets are subjected to the alternative method. For that, all data points with a sufficient level of degradation are used. Figure 17.4 shows the predicted B50L70 values as function of the LM-80 measurement time (or degradation time). The following is observed:

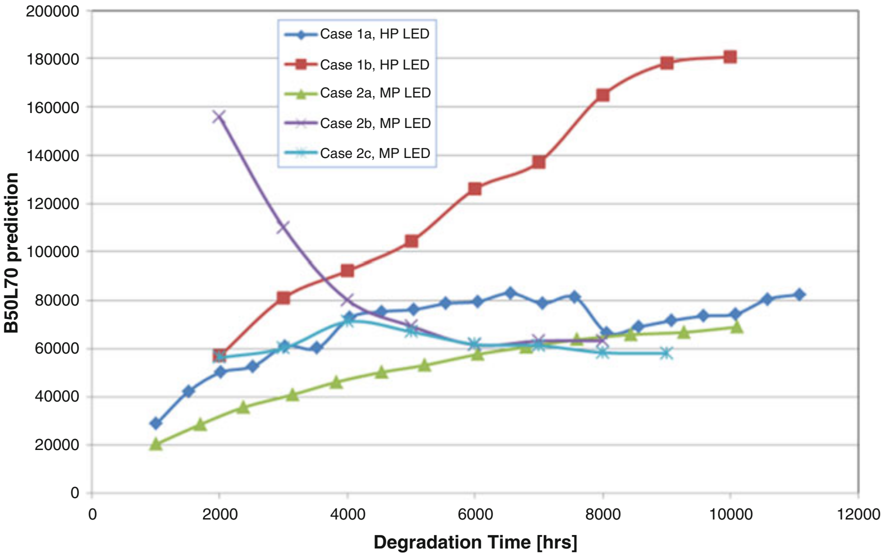

Fig. 17.4 Predicted B50L70 as function of the LM-80 measurement time for the five use cases

- Case 1a: The predicted B50L70 value gradually increases as function of time to reach almost stable values around 80 kh.
- Case 1b: The predicted B50L70 value keeps on increasing, and a stable value is not insight yet. A value of 180 kh seems to be reached, but the curve itself could start decreasing after that.
- Case 2a: The predicted B50L70 value keeps on increasing; stable value seems to hit 65 kh.
- Case 2b: The predicted B50L70 value gradually decreases as function of time to reach a stable value around 60 kh.
- Case 2c: The predicted B50L70 value first increases after which it gradually decreases as function of time to reach a stable value around 60 kh.

From a test termination point of view, cases 1a, 2b, and 2c have reached stable values for the model parameters (and thus B50), implying that the LM-80 tests can be stopped. For 1b and 2a however, stable values are not reached yet, meaning the test cannot be stopped.

Table 17.1 gives all the predicted acceleration model parameters following Eqs. 17.3 and 17.4. The activation energy is in the range 0.1–0.4 eV, which is believed to be the correct values for this failure mode. The standard deviation is quite reasonable. The effect of the current, parameter n, is quite different, and a large spread is found. A negative value indicates that with a higher current, the degradation is worse. A positive value is not reasonable (higher current improves the degradation level).

Table 17.1 Resulting fitted parameters following Eqs. 17.3 and 17.4. σ is the standard deviation assuming that ln(t) has a normal distribution. Note the positive value of n for case 2a

Case	C	n	Ea	σ
1a	7.82	−0.50	0.11	0.35
1b	9.98	−0.19	0.07	0.93
2a	0.55	0.15	0.34	0.27
2b	1.92	−2.89	0.11	0.25
2c	4.52	−0.72	0.16	0.68

Table 17.2 Comparison of the proposed statistical method with the existing TM-21 method for B50L70 values

Case	Reference	TM-21 prediction [h]	Proposed method [h]	Difference [%]
1a	1A, 85C	85,000	83,005	−2
1b	1A, 105C	142,000	161,669	14
2a	150 mA, 85C	65,000	68,981	6
2b	150 mA, 85C	63,000	63,227	0
2c	150 mA, 85C	45,000	51,355	14

The fitted parameters listed in Table 17.1 uniquely describe the lumen maintenance performance for the five LED packages under any application condition.

With the fitted parameters available, Table 17.2 depicts the comparison of the proposed statistical method with the TM-21 prediction. In general the deviation is found to be in the order of 0–14%. The main reason for this deviation is due to the fact that TM-21 only predicts the B50L70 values based on extrapolating the given test data. It does not take the other conditions into account, whereas the proposed method searches for congruency in the full data set using all tested conditions. We believe that the comparison is quite reasonable from an engineering point of view.

17.4.2 Deep Dive into High-Power LED Technology

Year to date the high-power LED technology is reaching a maturity level where all supplier uses the same kind of materials, i.e., very stable silicones (both for the optical system and the die attach), ceramic carriers, and gold wire bonding. As such, we expect that the lumen degradation would be quite identical between the different suppliers of this technology. At least if we can ignore the decay of the epitaxial, which is quite likely at moderate operation conditions. We have taken all the available LM80 data and analyzed that accordingly. The following data is available:

- LED 1
  - 9 kh LM-80 data at four currents and three temperatures (full matrix)
  - Measurement times: 0, 24, 168, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000 h
  - Total set of $300 \times 11 = 3300$ read points for analysis

- LED 2
  - 14 kh LM-80 data at four currents and four temperatures (partial matrix)
  - Measurement times: 0, 168, 1008, 1512, 2016, 2520, 3024, 3528, 4032, 4536, 5040, 5544, 6048, 6552, 7056, 7560, 8064, 8568, 9072, 9576, 10,080, 10,584, 11,088, 11,592, 12,096, 12,600, 13,104, 13,608, 14,112
  - Total set of 3,880 read points for analysis
- LED 3
  - 7 kh LM-80 data at three currents and two temperatures (partial matrix)
  - Measurement times: 0, 168, 1008, 1512, 2016, 2520, 3024, 3528, 4032, 4536, 5040 , 5544, 6048, 6552, 7056
  - Total set of 1300 read points for analysis
- LED 4
  - 10 kh LM-80 data at five currents and four temperatures (partial matrix)
  - Measurement times: 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 10,000
  - Total set of 2277 read points for analysis

In total these are over 10k data points, spread out over long testing times, and to be analyzed by our proposed statistical method. The target application settings are 85 °C and a forward current of 1A, the same as in the previous case. But we concentrate on L80 values instead of L70. Figure 17.5 shows the predicted B50L80

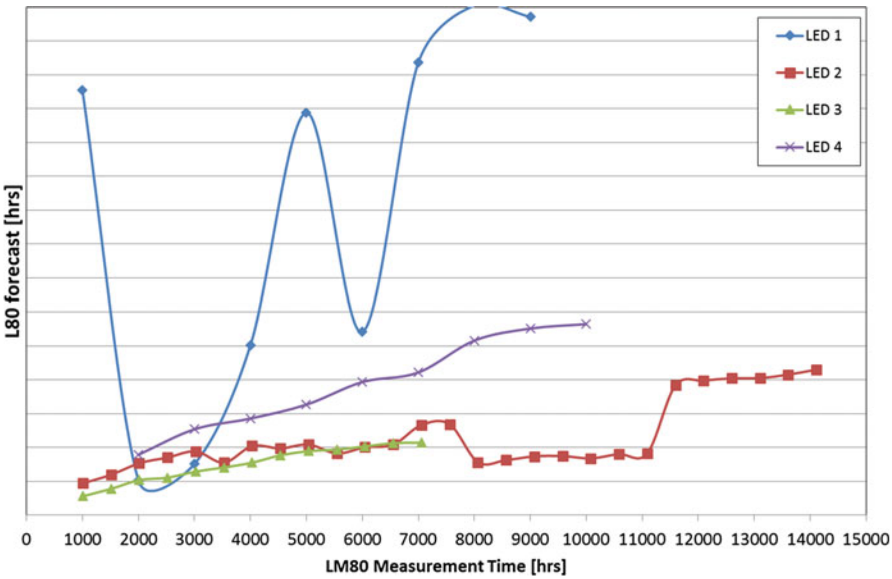

Fig. 17.5 Predicted B50L80 as function of the LM-80 measurement time for the four LEDs

values as function of the LM-80 measurement time (or degradation time). The following is observed:

- LED 1: The predicted B50L80 value fluctuates as function of time and reaches no stable values.
- LED 2: The predicted B50L80 value keeps on increasing, and a dip is seen in the period of 8,000–11,000 h, probably due to a measurement error (most likely a reference that is drifting).
- LED 3: The predicted B50L80 value keeps on increasing. Test time seems to be too short in order to judge the value until convergence.
- LED 4: The predicted B50L80 value keeps on increasing and apparently could level off. Also here, test time is too short to judge the converged value.

These results indicated that test time should be long enough and some level of degradation is to be detected in order to get a proper prediction of the long-term behavior.

As mentioned before, we believe that the high-power LED technology reached a certain level of maturity that allows us to put all the data into one set. Using the developed approach, we can then derive the B50L80 of this technology. Figure 17.6 shows the result of this exercise. Here we removed the prediction at 11,000 h as it showed a significant dip in the curve. The curve shows the increasing fingerprint of the other four LEDs in Fig. 17.5. For this generic curve, the fitted parameters are listed in Table 17.3. The activation energy Ea is in line with earlier findings [25, 26]. With these fitted parameters, the generic lumen maintenance behavior

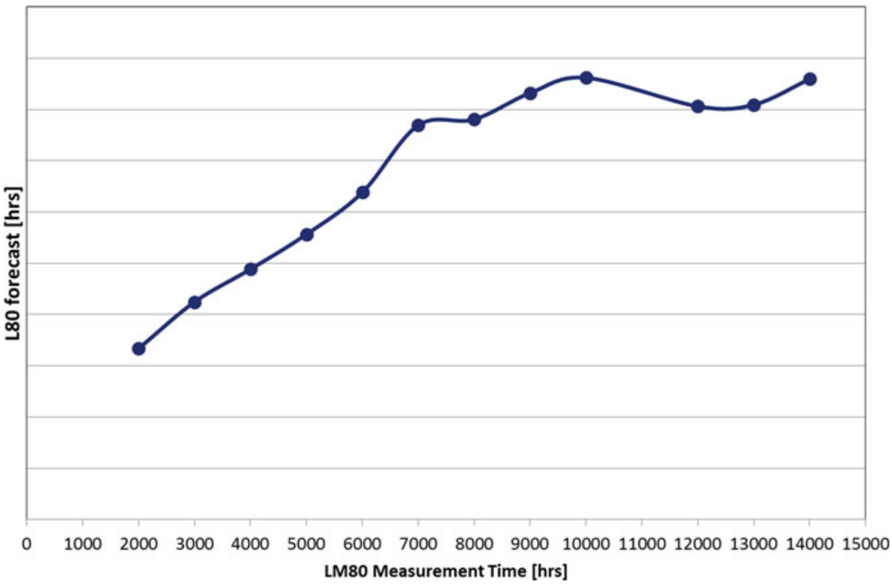

Fig. 17.6 Predicted B50L80 as function of the LM-80 measurement time when taken all the data is one set for high-power LED performance

Table 17.3 Resulting fitted parameters following Eqs. 17.3 and 17.4. σ is the standard deviation assuming that ln(t) has a normal distribution

Case	C	n	Ea	σ
HP LED	8.4	−0.8	0.1	0.3

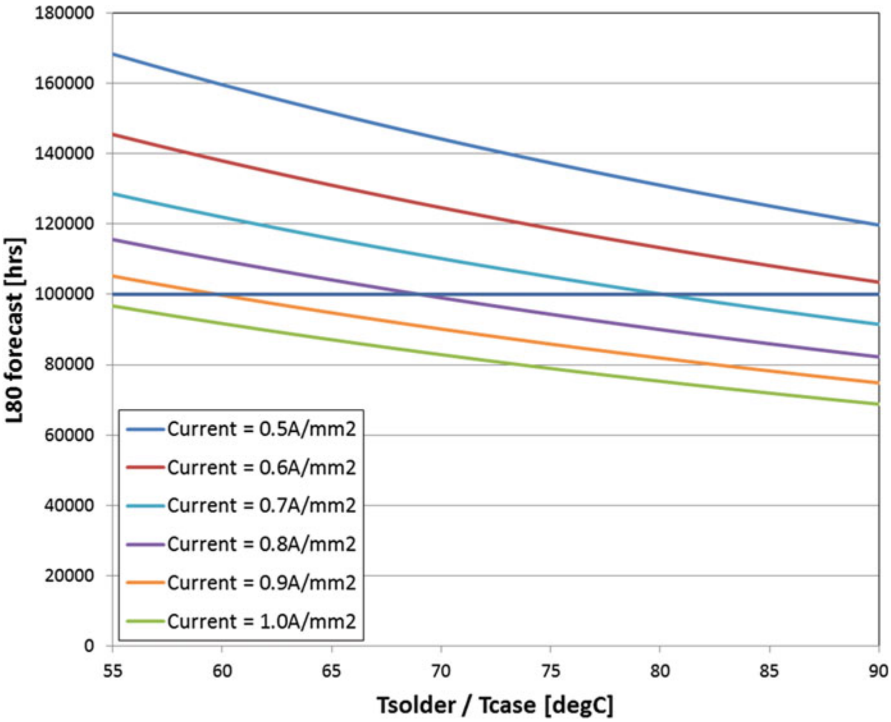

Fig. 17.7 Forward current density isolines for generic high-power LED lumen maintenance behavior using the fitted parameters $C = 8.4$, $n = -0.8$, $Ea = 0.10$ eV, and $\sigma = 0.3$

for high-power LEDs can be modeled following Eqs. 17.3 and 17.4. And accordingly, isolines can be given.

Figure 17.7 plots B50L80 isolines as function of the forward current density and the case/solder temperature using the fitted generic high-power LED model. A target line around 100 kh is given to indicate the current market demand in outdoor environments. Here we can also argue if values beyond 100 kh are possible or if truncation is required. However, this is not the topic of this chapter. The isolines indicate that the lumen maintenance performance decreases as function of temperature and current density. In the reference application of 85 °C and forward current of 1A, we find an L80 value of 72 kh. Actually, Fig. 17.7 can be seen as a look-up table for designs where one can target the requested L80 performance in terms of temperature and current.

17.5 Conclusions and Discussion

In this chapter we describe the different approaches currently available to perform lumen maintenance extrapolations for LEDs. We proposed an alternative statistical approach to estimate lumen depreciation of LEDs. In order to demonstrate this approach, we have analyzed five LM-80 data sets from a statistical point of view. A reasonable comparison with the existing TM-21 extrapolated values was found. We also analyzed several long-term LM80 high-power LED data to calculate a generic lumen maintenance model. Such a generic model allows the creation of isolines that may serve as a design guide. The analysis of these data sets shows the strength of the described method as the resulting unique fitted parameters describe the lumen maintenance of the LED over a long period. In principle there is also no need for a limitation based on the so-called $6\times$ rule from TM-21.

Other than the approach as described in Sect. 17.3.2, different – more complex – stochastic models are used to describe the degradation path. As stated, the big challenge is to get accurate estimates of a product's lifetime. The performance of an ADT, obviously, strongly depends on the appropriateness of the modeling of its degradation path. A typical degradation path consists of mean degradation curve and its error term (measurement error). There are two approaches available in the literature. First, the mixed effect model is one of the most popular approaches in degradation analysis. In order to describe the unit-to-unit variations of the test units, the unknown parameters of the mean degradation path are described in terms of the mixed (or random) effects. Often the mixed effect formulations do not take the time-dependent error structure into consideration. Therefore, the stochastic process formulation or Gauss-Markov method can be an alternative approach to model the product's degradation path. Dealing with those more complex models, to find the maximum likelihood estimates (MLEs) of the unknown parameters, the mixed effect model is computationally intensive. STATA (see: http://www.stata.com) or R (https://www.r-project.org) can be used. However, on-hand procedures do not always guarantee that the precise parameter estimations can be obtained. Besides the mixed and Gauss-Markov approaches, the application of Bayesian methods may be promising. Bayes allows a reliability engineer to incorporate one's prior knowledge about the unknown parameters of the model into data analysis to provide important improvements in precision. Based on previous experiments, an engineer may specify priors for the effects of temperature and/or current. As generally well known, such priors are key components in a Bayesian model specification and should be chosen carefully.

Acknowledgments The research leading to these results has received funding from the European Unions' Seventh Framework Program (FP7/2007-2013) for DEWI Dependable Embedded Wireless Infrastructure Joint Undertaking under grant agreement 621353 and from specific national programs and/or funding authorities.

References

1. W.D. van Driel, X.J. Fan, *Solid State Lighting Reliability: Components to Systems*, ISBN 978-1-4614-3066-7, (Springer, 2012), 617 pages
2. IES LM-80-08. Approved Method: Measuring Lumen Maintenance of LED Light Sources, Illuminating Engineering Society of North America, (2008)
3. IES TM-21-11, *IES Approved Method for Measuring Lumen Maintenance of LED Light Source* (Illuminating Engineering Society of North America, New York, 2008)
4. H.A. Qiao, T.C. Pulsipher, J.E. Hathaway, E.E. Richman, E. Radkov, A statistical method to analyze LED lumen depreciation and project useful LED product life, IES Annual Conference, Toronto, 9 Nov 2010
5. IES Conference, Development of a standard method for projecting lumen maintenance of LED products (TM- 21), Illuminating Engineering Society of North America, (2007)
6. R. Hechfellner, S. Landau, Understanding LED performance, Led light. (2009)
7. USA Department of Energy, Lifetime and reliability, fact sheet available at: ssl.energy.gov
8. Next Generation Lighting Industry Alliance and LED Systems Reliability Consortium (2014) *LED Luminaire Lifetime: Recommendations for Testing and Reporting. Pre-pared for the U.S. Department of Energy*. September 2014. Available at: http://energy. gov/sites/prod/files/2015/01/f19/led_luminaire_lifetime_guide_sept2014.pdf
9. M. Hansen, L. Davis, *Using LM-80 Measurement Methodology to Determine the True Value of Packaged Leds*, Leds Magazine, 9 Dec 2014
10. VDE-AR-E 2715-1, Measurement and prediction of reduction in luminous flux of LEDs, German Standard, November 2012
11. J. Fan, K.-C. Yung, M. Pecht, Lifetime estimation of high-power white LED using degradation-data-driven method. IEEE Trans. Device Mater. Reliab. **12**(2), 470–477 (2012)
12. J. Fan, K.-C. Yung, M. Pecht, Predicting long-term lumen maintenance life of LED light sources using a particle filter-based prognostic approach. Expert Syst. Appl. **42**(5), 2411–2420 (2015)
13. P. Lall, J. Wei, P. Sakalaukus, Bayesian models for life prediction and fault-mode classification in solid state lamps, in *16th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems*, (2015)
14. C. Quan, X. Luo, C. Qi, K. Wang, L. Sheng, L. Jingyana, Research on lumen depreciation related to LED packages by in-situ measurement method. Microelectron. Reliab. **55**, 2269–2275 (2015)
15. J.L. Huang, D.S. Golubović, S. Koh, D.G. Yang, X.P. Li, X.J. Fan, G.Q. Zhang, Degradation mechanisms of mid-power white-light LEDs under high temperature-humidity conditions. IEEE Trans. Device Mater. Reliab. **15**(2), 220–228 (2015)
16. J.L. Huang, D.S. Golubović, S. Koh, D.G. Yang, X.P. Li, X.J. Fan, G.Q. Zhang, Degradation modeling of mid-power white-light LEDs by using Wiener process, Opt Express. **23** (15) (2015). doi:10.1364/OE.23.00A966
17. J.L. Huang, D.S. Golubović, S. Koh, D.G. Yang, X.P. Li, X.J. Fan, G.Q. Zhang, Optical degradation mechanisms of mid-power white-light LEDs in LM-80-08 tests. Microelectron. Reliab. **55**(12, Part B), 2654–2662 (2015)
18. T.-R. Tsai, C.-W. Lin, Y.-L. Sung, P.-T. Chou, C.-L. Chen, Y. Lio, Inference from lumen degradation data under Wiener diffusion process. IEEE Trans. Reliab. **61**, 710–718 (2012)
19. S. Watzke, P. Altieri-Weimar, Degradation of silicone in white LEDs during device operation: a finite element approach to product reliability prediction, in *15th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems*, (EuroSimE, 2014). doi: 978-1-4799-4790-4/14
20. S.-U. Zhang, Quantification of silicone degradation for LED packages using finite element analysis. Microelectron. Reliab. **55**, 2678–2684 (2015)

21. M. Buffolo, C. De Santi, M. Meneghini, D. Rigon, G. Meneghesso, E. Zanoni, Long-term degradation mechanisms of mid-power LEDs for lighting applications. Microelectron. Reliab. **55**, 1754–1758 (2015)
22. W.B. Nelson, Accelerated testing: statistical models, test plans, and data analysis, 624, (2004). ISBN: 978-0-471-69736-7
23. Meeker, Escobar, A review of accelerated test models. Stat. Sci. **21**(4), 552–577 (2006)
24. H.-F. Yu, S.-T. Tseng, On-line procedure for terminating an accelerated degradation test. Stat. Sin. **8**, 207–220 (1998)
25. T. Yanagisawa, T. Kojima, Long-term accelerated current operation of white light emitting diodes. J. Lumin. **114**, 39 (2005)
26. S. Koh, C. Yuan, B. Sun, B. Li, X. Fan, G. Zhang, Product level accelerated lifetime test for indoor led luminaires, in *14th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems* (EuroSimE, 2013), pp. 1–6