# THERMAL SIMULATION AND CHARACTERIZATION OPTIMIZES LEDs FOR AUTOMOTIVE APPLICATIONS

W H I T E P A P E R

M E C H A N I C A L   A N A L Y S I S

## INTRODUCTION

This paper addresses methods that can help to achieve the best-in-class thermal management for the lighting industry. We discuss selecting and measuring the thermal characteristics of LEDs, choosing the most suitable LED, and conducting accelerated aging tests. We also cover thermal simulation of complex-shaped lighting systems such as headlights and tail lights, and using concurrent computational fluid dynamics (CFD) technology to design higher quality products and to develop automotive lighting systems more quickly, efficiently, and cost-effectively.

## INDUSTRY TRENDS

According to McKinsey & Company's perspective on the global lighting market [1], the automotive lighting market currently is estimated at $18 billion (€13 billion), representing about 20% of the total lighting market and expected to climb to $25 billion (€18 billion) by 2020. With advancements in light-emitting diodes (LED) development, LEDs in automotive applications is expected to increase drastically in the next 10 years. With LED prices from 2010–2020 lowered to a tenth of the current price, LEDs will be even more competitive compared to conventional light sources. High-brightness LEDs used in headlamps are still very expensive compared to halogen and high-density discharge lamps (HID).

Unlike traditional automotive light sources, LEDs are much more temperature-sensitive and using them in a design requires knowledge of their structure and behavior over time, as well as a suitable thermal management system from heatsink to the cooling fluid flow. Armed with this repertoire, lighting designers can optimize their design to ensure a long lifetime of the LEDs, lowest shift in the emission wavelength, or a minimal reduction in light output, which leads to a shorter useful life. They can more effectively use LEDs as a light source thus enabling better growth of overall LED use in the automotive industry.

## THE CHALLENGES OF USING LEDS IN AUTOMOTIVE LIGHTING

With the change of luminaire designs from incandescent bulbs to LED, the old concept of thermal management is now redundant and new ways of thinking need to be established. While incandescent bulbs mostly radiate (~83%) and dissipate (~12%) heat loss and do not face thermal challenges related to the light source, LEDs mostly transfer their heat loss (~60–85%) by conduction and are sensitive to thermal management. The efficiency of a 100-W incandescent bulb is ~5% while the efficiency of LEDs is ~15–40% and constantly improving.

The main thermal challenges with LEDs are to maintain a high color stability and life expectancy. LEDs in the automotive industry need to have lifelong durability. With LEDs being not only more efficient, but also valuable in terms of higher visibility and therefore higher safety, the Economic Commission for Europe (ECE) set the daytime running lamp (DRL) as mandatory from 2011 for all new models of cars.

Because exterior lights such as headlights and tail lights are almost completely sealed systems, except for the very small airflow inlet, outlet, and the small opening for regular incandescent bulbs, it is not realistic to change an LED in case of a defect. Therefore, high reliability and quality not only of the LED but also of the overall lamp design is compulsory because the change of a whole headlight is expensive; and if it falls under warranty, it can be very expensive for the OEM and supplier of the system.

## CHARACTERIZING THERMAL AND RADIOMETRIC BEHAVIOR ENSURES RELIABILITY

Original data sheets do not always provide the data necessary for accurate and reliable results from fluid or structural simulation nor does the manufacturer usually provide a guarantee or an indication of the measurement error. So to ensure reliability of the components and materials before using them in your product, you will need to test and measure their characteristics for your application.

## THERMAL CHARACTERIZATION

The thermal resistance ($R_{th}$) of LEDs affects the products' life-time, efficiency, and operation in multiple domains, as well as their electrical, thermal, and optical performance (Figure 1). An LED package, just like any other semiconductor device package, can be well-characterized for steady-state operation by its thermal resistance. This thermal resistance, $R_{th}$, is a number that tells us how many degrees of temperature elevation is caused if a unit of power is applied to the device.

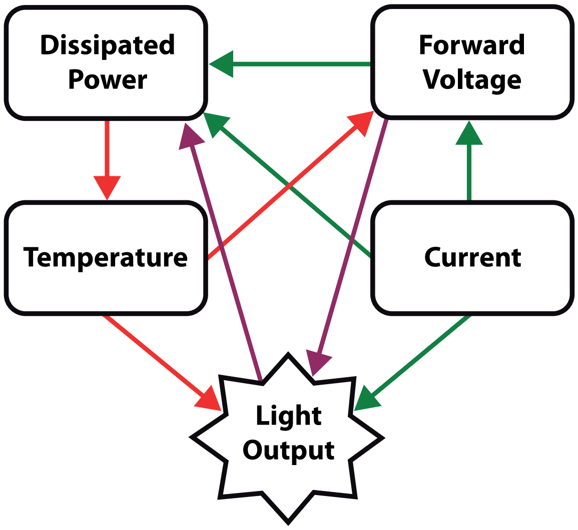



*Figure 1: Thermal issues affect everything in an LED package.*

The basic technique is to measure the temperature-dependent voltage of the component. The LED is switched on (or off) from one steady state, and, after some time, it reaches the other steady state condition (hot/cool or vice versa). During this process, transient measurements are taken continuously, providing a thermal transient response curve at a small measurement current. With help of the measured temperature difference and the power difference (Figure 2), used for switching the component, a structure function can be derived (Figure 3).

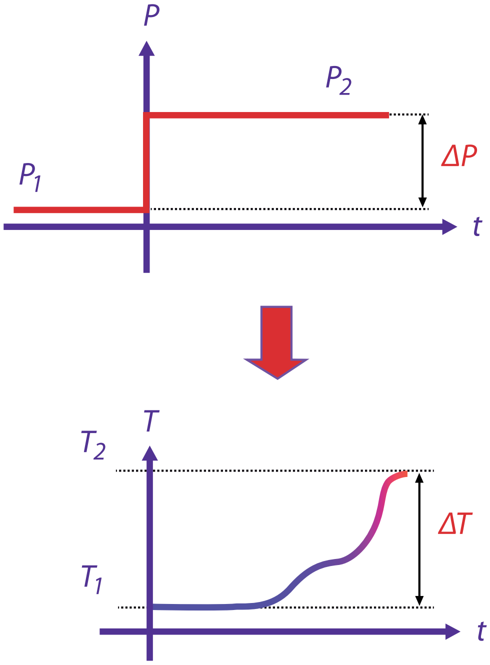



*Figure 2: Thermal transient response curve.*

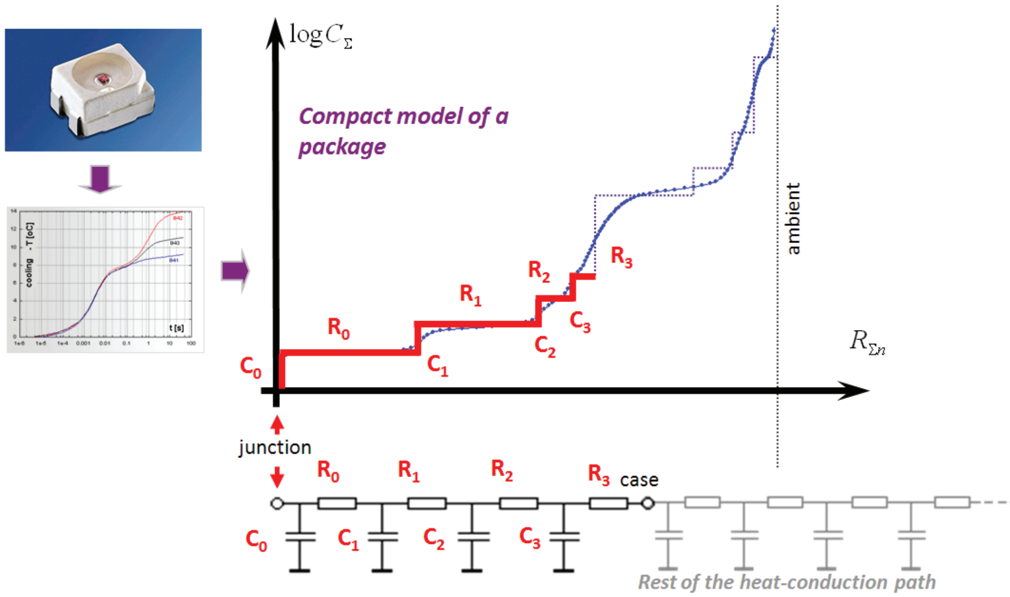



*Figure 3: Cumulative structure function of an LED package example.*

In November 2010, the JESD51-14 standard for junction-to-case ($R_{thJC}$) measurement with the *Dual Thermal Interface Method* was published by the Joint Electron Devices Engineering Council (JEDEC) [2]. The standard specifies measuring twice: without and with an extra layer, where the location of deviation indicates the thermal resistance for a package. This method is applicable to power semiconductor device packages with an exposed cooling surface and a 1-dimensional heat-flow path. This condition also is valid for power LEDs.

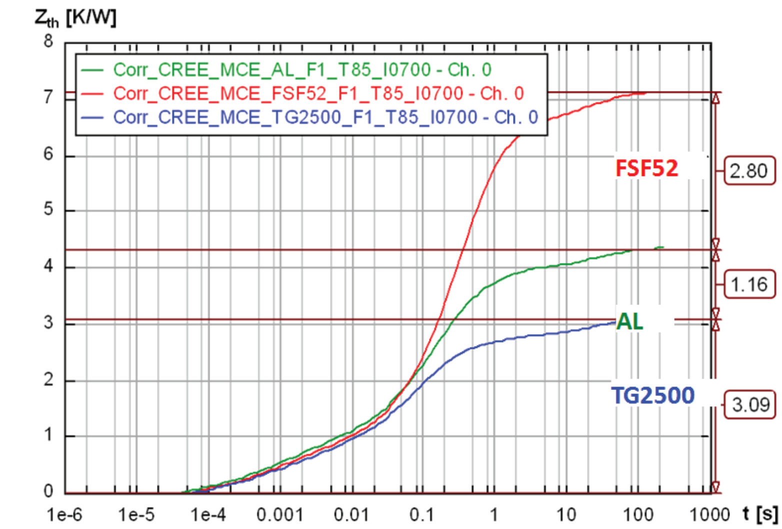
According to the JESD51-14 standard, the junction-to-case thermal resistance measurement is based on the latest transient measurement techniques. The metric for junction-to-case thermal resistance measurement has been used for decades, but measurement procedures according to older standards were not accurate enough and did not allow a sufficiently high level of repeatability of the measurement results so new standards needed to be developed.

For LED testing, JESD51-50, 51, 52, and 53 series LED thermal testing guidelines have been recently approved and published. They provide specifications for combining the optical results (measured light) and temperature behavior. These new standards combined with a JESD51-14–compliant $R_{thJC}$ measurement allow test-based compact thermal modeling of power LED packages.

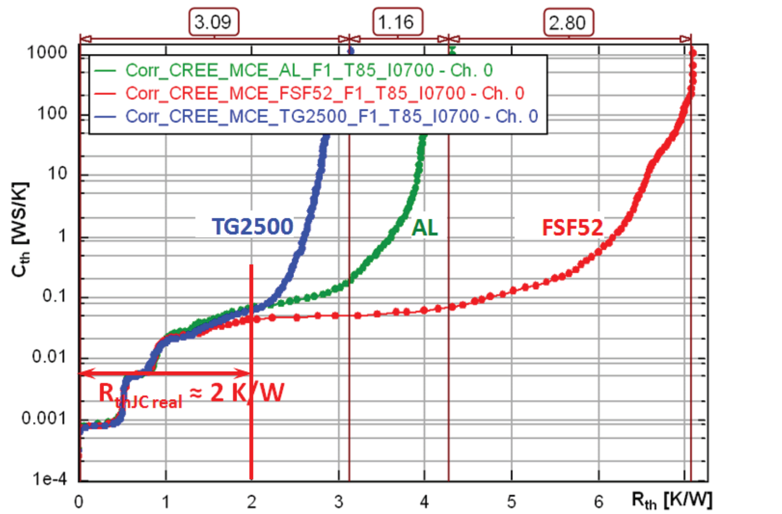
The structure function shown in Figure 3 allows us to determine the thermal resistance junction-to-case ($R_{thJC}$), which is important for an accurate thermal simulation. Not only can such a structure function help to determine the thermal resistance, it also can be used to compare different LEDs, solder/glue quality, defects and location of the defects, and the performance of different PCB/MCPCB types on the cooling efficiency and their temperature dependency. Everything between die and ambient can be seen on the structure function and changes caused by defects or aging can be seen compared to a normal or ideal assembly.

As shown in the paper on emerging standards for thermal testing of power LEDs and its possible implementation [3], the LED package characteristic stayed the same for different temperatures, controlled by a cold plate, but the characteristic of the PCBs and the thermal interface material (TIM) is varying over the temperatures and therefore influencing the thermal management because of higher thermal resistance (Figure 4).

4a)


Zth [K/W]
Corr_CREE_MCE_AL_F1_T85_I0700 - Ch. 0
Corr_CREE_MCE_FSF52_F1_T85_I0700 - Ch. 0
Corr_CREE_MCE_TG2500_F1_T85_I0700 - Ch. 0
FSF52
2.80
1.16
AL
TG2500
3.09
t [s]

4b)


3.09
1.16
2.80
Corr_CREE_MCE_AL_F1_T85_I0700 - Ch. 0
Corr_CREE_MCE_FSF52_F1_T85_I0700 - Ch. 0
Corr_CREE_MCE_TG2500_F1_T85_I0700 - Ch. 0
TG2500
AL
FSF52
Cth [WS/K]
RthJC real ≈ 2 K/W
Rth [K/W]

4c)

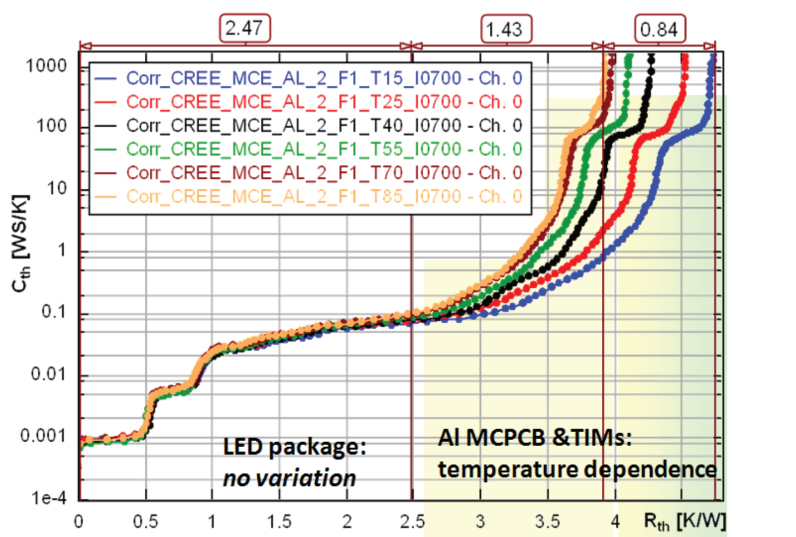

2.47
1.43
0.84
Corr_CREE_MCE_AL_2_F1_T15_I0700 - Ch. 0
Corr_CREE_MCE_AL_2_F1_T25_I0700 - Ch. 0
Corr_CREE_MCE_AL_2_F1_T40_I0700 - Ch. 0
Corr_CREE_MCE_AL_2_F1_T55_I0700 - Ch. 0
Corr_CREE_MCE_AL_2_F1_T70_I0700 - Ch. 0
Corr_CREE_MCE_AL_2_F1_T85_I0700 - Ch. 0
Cth [WS/K]
LED package:
no variation
Al MCPCB &TIMs:
temperature dependence
Rth [K/W]

Figure 4: Results of thermal impedance measurements: a) real $Z_{th}$ curve of three different LED samples measured at $I_F$ = 700 mA and 85 °C cold-plate temperature, b) the real thermal impedance of (a) in structure function, c) the structure function representation of the thermal impedance of a sample measured at different cold-plate temperatures (courtesy of Budapest University of Technology, Department of Electron Devices).

The LEDs' structure function does not change whereas the TIM and PCB structure functions do, depending on material and temperature. In case of a bad die attach, the LED thermal resistance is of course higher, which is shown in the structure function in Figure 5. In these measurements, the method explained in the next section was used to obtain the real internal thermal resistance, which allows us to include temperature change and the change in the luminous flux.

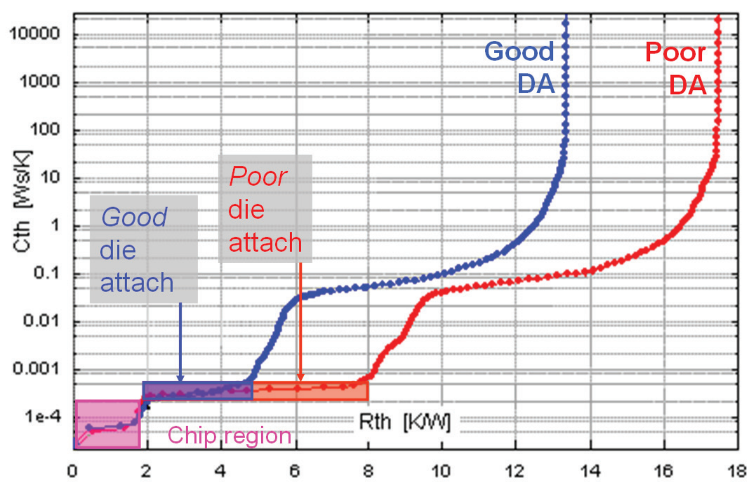



*Figure 5: Structure function with good and bad die-attach.*

## RADIOMETRIC CHARACTERIZATION

Thermal characterization is important for insight into the defects of LEDs, to obtain the thermal resistance, and to test the proper glue or TIM to ensure best thermal management capabilities of the assembly. But the overall electricity that is used to power an LED is converted into both heat and light. So for a correct thermal characterization, the optical power emitted by the LED should be subtracted from the supplied electrical power corresponding to equation (1) to give the real internal thermal resistance $R_{th\text{-}real}$ that is purely based on the heating power of the LED. For regular integrated circuits (ICs), processors, etc., equation (2) is sufficient because no optical power is emitted from these components.

$$R_{th-real} = \Delta T/P_{heat} = \Delta T/(P_{el} - P_{opt}) \quad \textbf{(1)}$$

$$R_{th} = \Delta T/\Delta P \quad \textbf{(2)}$$

Where $R_{th}$ and $R_{th\text{-}real}$ are the thermal resistances in Kelvin per Watt for general semiconductor and solid-state lighting (SSL) components, respectively; $\Delta T$ is the temperature difference between the two steady states (hot and cold) in Kelvin [K]; $P_{heat}$ and $\Delta P$ are the actual power used to heat the component and power difference between the power to drive the component and the small power to measure it in Watt [W], respectively; $P_{el}$ is the electrical power to drive the component; and $P_{opt}$ is the optical power the SSL component emits.

Without consideration of the optical power, the structure function of the LED would change for different junction temperatures and driving currents, because the luminous flux is dependent on these parameters, as already shown in Figure 1.

Figure 6 of the paper on thermal characterization of LEDs [4], shows how the temperature and current influences the intensity and spectrum of a selected LED. To compensate for this, the experimental setup would have to include a CIE 127-20076–compliant photometric and radiometric measurement sphere as shown in the schematic of Figure 7.

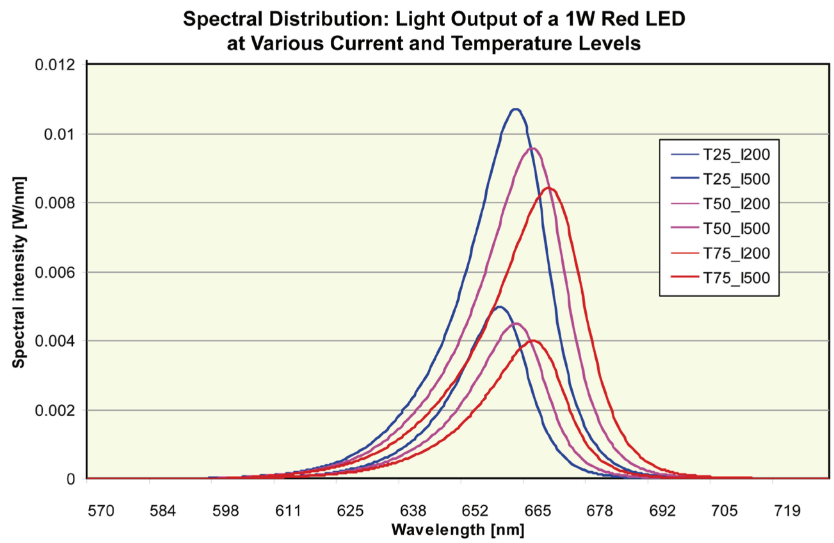



*Figure 6: Current and temperature dependence in the spectral distribution of an LED's light output (courtesy of Budapest University of Technology, Department of Electron Devices.)*

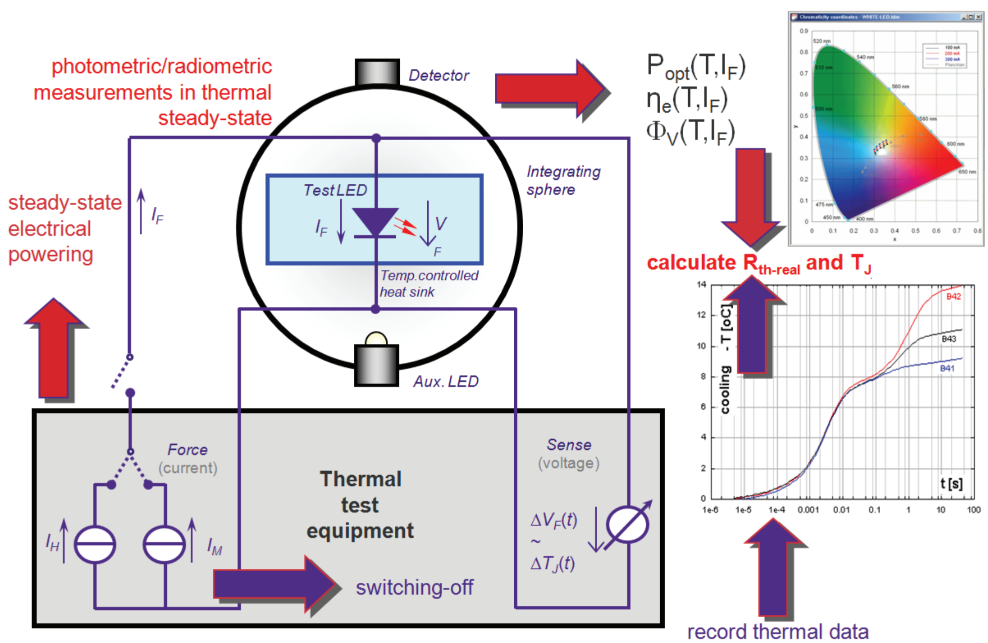



*Figure 7: Thermal transient testing schematic for consideration of optical power for LED measurements.*

With such a setup, measurements can also derive parameters such as total luminous flux, total radiometric flux, x, y, and z tristimulus values, and a spectral analysis can be done. The current and temperature dependence of the diode characteristics, optical power, radiant efficiency, luminous flux, efficacy, scotopic flux, and color coordinates are possible to achieve in a single combined measurement and displayed as a function of the LED's driving current, junction temperature ($T_j$) or cold-plate temperature as seen in the example of Figure 8.

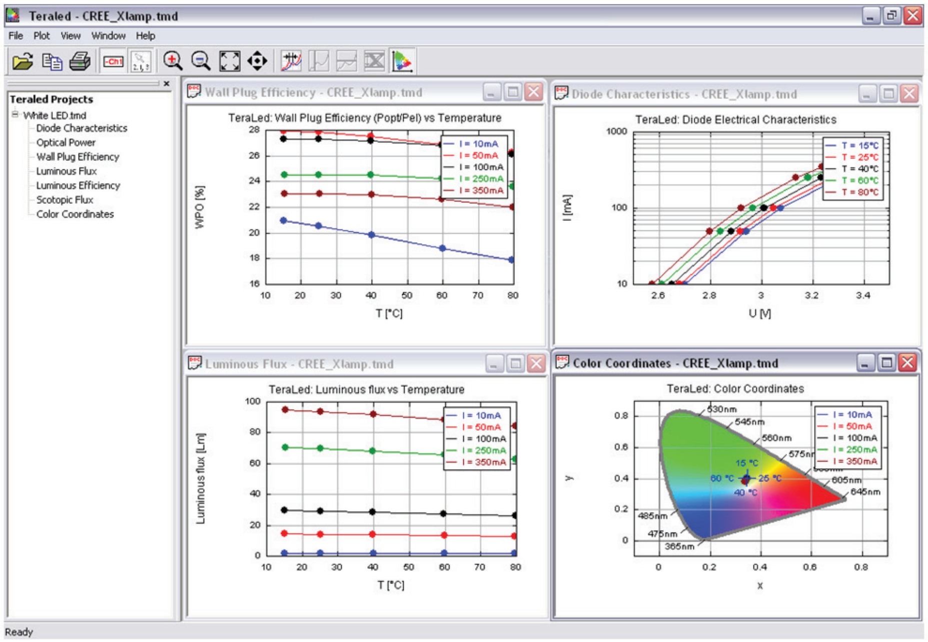



*Figure 8: Example of a photometric and radiometric measurement.*

## TESTING ENSURES QUALITY AND CONSISTENCY

LEDs lose their luminous flux when they age, and the rate depends on the junction temperature ($T_j$). The worst case would be if they failed completely early in their life. Thus they are usually put through a highly accelerated life testing process involving conditions such as temperature shocks, long-time high-temperature activity, high humidity and pressure exposures, etc. to validate or certify new LEDs for a product. This is necessary to ensure their reliability and performance during their expected lifetime.

In automotive exterior lights, the wavelength of LEDs should not change over a certain range and also should not lose their luminous flux below a certain value that is either defined by regulations or required to ensure high visibility and illumination of the surroundings. Warranty costs are high for failed LEDs in headlights and tail lights because the LEDs themselves cannot be changed like conventional light sources, so often the whole defective unit has to be replaced.

Using the JEDEC standard static test method for transient thermal measurements in accordance with JESD51-51, -52 and CIE 127-2007 has increased the level of accuracy in LED thermal characterization. These higher standards have resulted in increased customer confidence and market share. In compliance with these standards, the Mentor Graphics T3Ster system can complete more than 100 LED thermal measurements in a single day, and it is the most accurate. The T3Ster post-processing software fully supports the latest thermal testing standard for junction-to-case thermal resistance measurement.

T3Ster uses a "smart" implementation of the JEDEC static test method (JESD51-1) that allows for almost continuous measurement during a heating or cooling transient, which also forms the basis of the JESD51-14 test method. The result is far richer data that is measured from much earlier in the transient than possible with other techniques.


*Figure 9: Mentor Graphics T3Ster Thermal Transient Tester captures the transient response of an LED after just 1 µs (1 x $10^{-6}$ seconds), with a temperature resolution of 0.01 °C.*

The T3Ster system can complete more than 100 JESD51-51/JESD51-52–compliant LED thermal and radiometric measurements in a single day, which is the fastest possible thermal testing available on the market today (Figure 9). It is also the most accurate, capturing the transient response of an LED after just 1 µs (1 x $10^{-6}$ seconds), with a temperature resolution of 0.01 °C. This means that the earliest possible part of the LED's thermal response is captured; thus, you can see the influence of key constructional features close to the heat source within the LED package, such as the thermal resistance of the die attach after a short time.

The T3Ster post-processing software fully supports the JESD51-14 standard for junction-to-case thermal resistance measurement, allowing the temperature versus time curve obtained directly from the measurement to be re-cast as "structure functions" (described in JESD51-14 Annex A), and then automatically find the value of the junction-to-case thermal resistance.

The results of a study done at the University of Pannonia, which compared the color stability of several LEDs, demonstrated that even high-quality brands vary in the color quality and changes in their behavior during aging [5]. The strength of the degradation of the relative luminous flux also can be seen in the T3Ster TeraLED measurements.

## ANALYZE LED HEAT AND LUMINOSITY BASED ON A SPECIFIC CURRENT

The Mentor Graphics FloEFD™ version 12 thermal simulation tool with its unique LED Compact Model offers post-processing capability that allows you to not only see how hot the LEDs become but also how much actual heat is generated by the LED according to the current you use. From that information, you also can see how "bright" the LEDs are. Without this capability, engineers would define a thermal resistance model for the LED and apply a heat generation rate, but not actually know how big it is exactly because the voltage and optical power has a range that depends on the temperature of the LED for that specific current (as shown in Figure 1).

Figure 10 shows that with the LED Compact Model you can define the current and then use the T3Ster data or manually entered data (which is usually not as accurate as T3Ster data) from the calculation, you can obtain the temperature that is a result of the thermal characteristic of the LED from T3Ster or datasheet; and then you can get the luminous flux or "hot lumens" and the heat generation rate the LED has at this junction temperature and current. The temperature of the LEDs varies based on the different currents on which they are running, these different currents and the temperature variation results in different luminous fluxes.

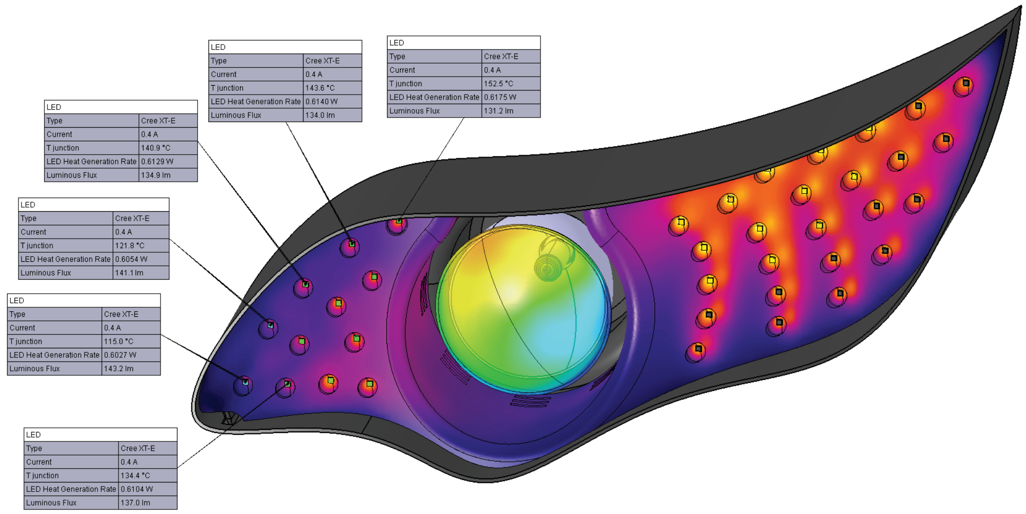



*Figure 10: With the FloEFD LED Compact Model, you can obtain the luminous flux or "hot lumens" an LED has at a particular junction temperature and current.*

## EARLY SIMULATION ACCELERATES PRODUCT DEVELOPMENT

With LEDs, a revolutionary change is needed not only to the thermal design but also the lighting system. LEDs enable the designers to be more creative and differentiate the brand or vehicle model through individualistic and impressive designs. But with more influence on performance, the geometry becomes more complex with reflectors and heatsinks almost for each single LED. Increasing complexity and changes in thermal management strategies means that old experience in thermal design of lighting systems does not apply anymore and simulation has become even more important in the design process.

As design and performance are becoming more interdependent, designers are confronted with simulation results and CFD specialists overloaded with the rapid design cycles and the effort required meshing complex cluttered geometry. Truly automated meshing, producing high-quality meshes without manual intervention, have correspondingly gained in importance. Indeed, this is a prerequisite for a design-concurrent CFD solution that enables designers to do early simulations within the design process and without in-depth numerical and CFD knowledge, accelerating the product development process.

## CONCURRENT CFD ENSURES SUCCESSFUL THERMAL MANAGEMENT FOR AUTOMOTIVE LED SYSTEMS

A concurrent CFD approach enabled by FloEFD allows you to shorten the design cycle by including accurate thermal simulation for every design iteration. Unlike upfront CFD, which relies on the export of the CAD model for import into the CFD system, concurrent CFD is fully embedded within the mechanical computer-aided design (MCAD) environment, thereby eliminating the need to transfer the model with a neutral file format such as STEP or IGES which loses any parametric definition present in the original CAD model. Parametrically defined geometry aids simulations involving design variants analysis.

Meshing and other technologies enable use of CFD technology with just the understanding you need to have of the product and its behavior. Simulation times, and particularly mesh generation, which is traditionally the longest step in the process, is reduced to a minimum. Applications of this technology extend into many regions in the automotive industry as well as other industries. Figures 11 and 12 are some examples of how OEM engineers are using this technology with success to simulate different automotive applications from within their MCAD system.

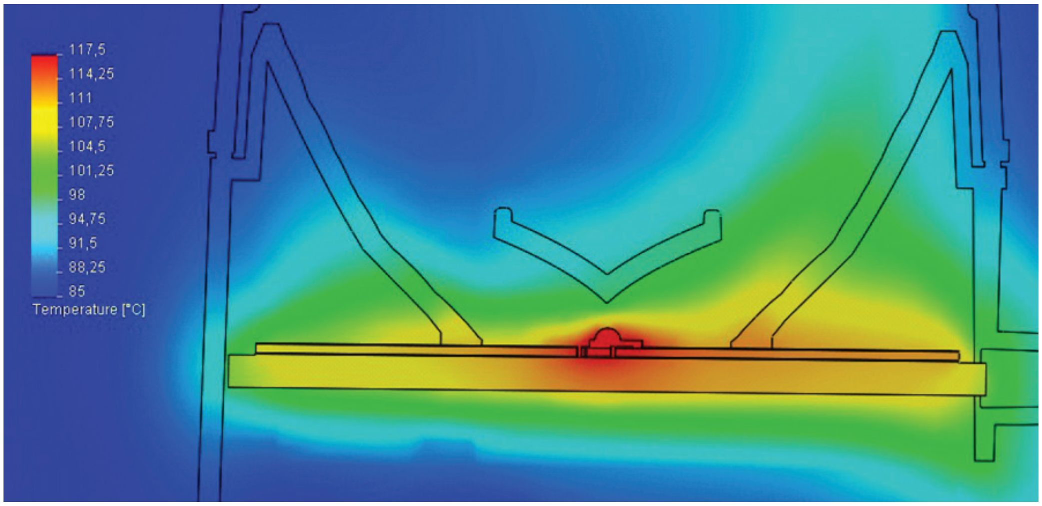



*Figure 11: CATIA-embedded simulation model of the day-time running lamp of the Mercedes SLK version 2011. Image courtesy of Merceds-Benz. All rights reserved.*

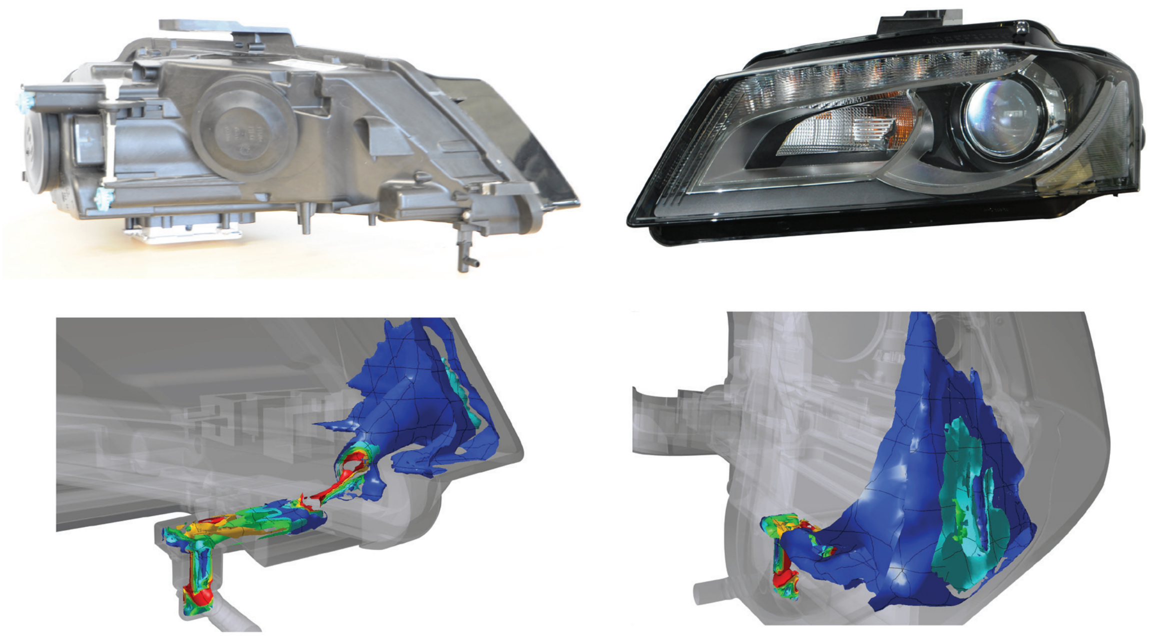


*Figure 12: FloEFD Simulation images of an Audi A3 headlight showing the velocity isosurfaces providing fresh air to the headlight system for cooling and evaporation. (Image courtesy of Audi AG. All rights reserved.)*

## CONCLUSION

When using T3Ster for thorough thermal transient testing of LEDs that includes photometric and radiometric measurements, you can produce highly accurate and repeatable real thermal resistance measurements and convert these into thermal resistor-capacitor models for use in CFD simulations during product design.

Conducting highly accelerated life testing also helps you to select the best suitable LED with high reliability over the designed product's life. And thermal simulation guarantees that the thermal management system will provide the proper climate for the LEDs over a lifetime with minimum loss in quality and performance. The FloEFD concurrent CFD method also speeds up your product design cycle by enabling simulation earlier in the design process, reducing time-to-market and lowering your development and prototyping costs.

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