Accelerating auto electronics reliability using physics of failure modeling

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Reliability is the measure of a product's ability to perform specified functions in the customer environment over the desired lifetime. Reliability must be designed in. Traditional approaches to design for reliability in the automotive world, such as empirical predictions like MIL-HDBK-217F, industry specifications, and "test-in" reliability, all have significant limitations. Part of a better approach to designing for reliability uses reliability assurance software based upon Physics of Failure (PoF) algorithms.

The Physics of Failure approach uses science (physics, chemistry, etc.) to capture an understanding of failure mechanisms and evaluates useful life under actual operating conditions. The automotive electronics challenge is to survive more than 150,000 miles and 10 years of usage in harsh environments without an excessive rate of failure. The harsh environmental conditions include seasonal variations in thermal cycles over diverse regional climates, electromagnetic noise, vibration, shock, temperature, and humidity. Some of these extreme ranges are shown in Table 1.

Furthermore, electronics are now integrated in every aspect of the modern auto. Figure 1 illustrates many of the places they can be found.[1]

The traditional automotive product development process approach used a series of Design-Build-Test-Fix (DBTF) reliability growth events. This was a trial-and-error approach to finding and fixing problems. Today, this methodology is no longer sufficient.

Automotive design and computer-aided engineering

The automotive industry has reaped substantial benefits from virtual, computer-aided engineering (CAE) tools. This is a direct result of initiatives to migrate vehicle evaluations from the road to the lab to the computer at the vehicle, subsystem, and component levels. Increasing design complexity and vehicle electrification have prompted major changes in design processes. Intense competitive pressures continue to drive efforts to improve both efficiency and effectiveness.

Using a combination of physical and virtual testing accelerates the product development process by enabling early identification of deficiencies and evaluation of "what if" scenarios. Physics-based models make it much easier to try out new design ideas. Simulations can be created and run in far less time and with less cost than building and testing physical prototypes. As the use of modeling increases, physical testing can be refocused by optimizing when, where, and under what conditions actual tests should be performed.

Released in April 2011, DfR Solutions' Sherlock Automated Design Analysis (ADA) software is a reliability assurance tool suite that integrates design rules, best practices, and a physics-based understanding of product reliability. The four keys elements of a Sherlock PoF Analysis are:

Design Capture—Provide industry standard inputs to the modeling software and calculation tools;

Life-Cycle Characterization—Define the reliability objectives and expected environmental and usage conditions under which the device is required to operate;

Load Transformation—Automated calculations that translate and distribute the environmental and operational loads across a circuit board to the individual components;

PoF Durability Simulation/Reliability Analysis and Risk Assessment—Performs a design and application-specific durability simulation to calculate life expectations, reliability distributions, and prioritize risks by applying PoF algorithms to the printed circuit board assembly (PCBA) model.

PoF simulation reliability life curves are generated for each failure mechanism to produce a life curve for the entire module being analyzed. Detailed design and application-specific PoF life curves are far more useful than a simple single-point constant failure rate (MTBF) estimate.

The individual steps involved in actually running a modeling analysis are: Design Capture; Define Reliability Goals; Define Environments; Generate Inputs; Perform Analysis; and Interpret Results.

Design Capture involves importing standard PCB CAD/CAM design files such as Gerber or ODB++ to automatically create a circuit board model. The PCB laminate and layers are also defined. Using this information, Sherlock generates the PCB thickness, density, CTE x-y, CTE z, Modulus x-y, and Modulus z from the material properties of each layer using the built-in laminate data library. Sherlock also directly imports the bill of material (BOM) parts list. The software automatically recognizes supplier part numbers and standard industry JEDEC package types.

Defining reliability goals is critical. Two key metrics—*desired lifetime* and *product performance*—must be identified and documented. *Desired lifetime* is defined as time the customer is satisfied with and should be actively used in the development and qualification of the product. *Product performance* can be defined as returns during the warranty period, survivability over lifetime at a set confidence level, MTBF, or mean time to failure (MTTF).

Temperature	Vibration	Shock
Interior: -40 to +85C	Interior: 10–1000Hz 3–4 Grms	Road Events: up to 20 Gs
Under hood: -40 to +125C	On Engine: 10–2000Hz 18–20 Grms	Collisions: up to 100 Gs

Table 1—Automotive environmental conditions.

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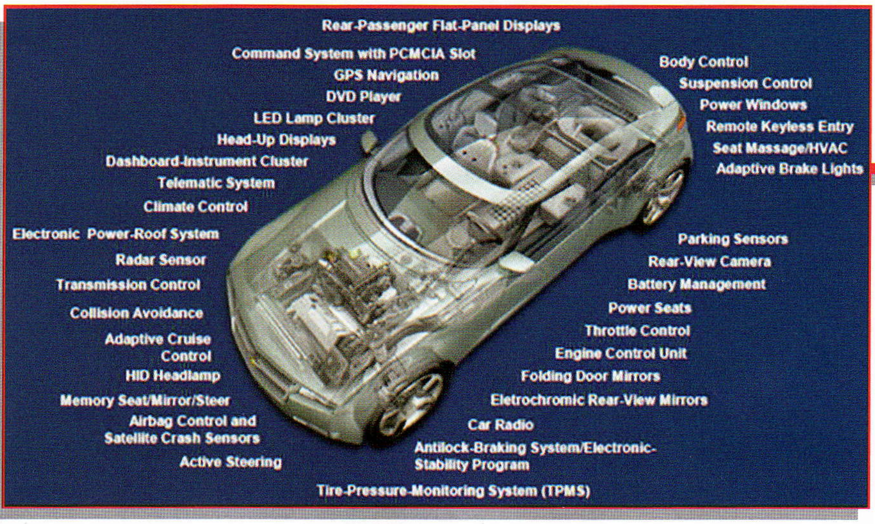

FIG. 1—Electronics in the modern auto.

The next step is to define the field environment. Several different approaches can be used. The first approach is to use industry specifications such as SAE J1211. The advantages of this approach are that there are no additional costs and there is agreement throughout the industry. The main disadvantage of standards is that they rarely truly match the actual user conditions in the field.

The second approach uses actual measurements of similar products in similar environments. The user determines average and realistic worst-cases. For this approach, the user must be careful to identify all failure-inducing loads from all relevant environments including manufacturing, transportation, storage, and use. Oftentimes, the transport and storage conditions are more severe than use conditions; and, they are frequently overlooked.

Within the software, the user has the ability to comprehensively define thermal, vibration, and shock stress profiles. An auto electronics field environment example might model the outside the engine compartment with minimal power dissipation, and diurnal (daily) temperature cycling providing the primary degradation-inducing load. The modeled conditions:

Absolute worst-case:
- Maximum temperature: 58°C,
- Minimum temperature: -70°C

Realistic worst-case:
- Phoenix, Arizona (USA)
- +10°C added due to direct exposure to the sun

After thermal cycling, the user defines the dynamic finite element analysis (FEA) load with random vibration, harmonic vibration, and/or shock.

Once the reliability requirements and environment have been defined, the analysis can begin. The software modeling currently has the following analysis capabilities:

- CAF—Conductive Anodic Filament Formation
- MTBF via MIL-HNDBK-217, SR-332, or IEC-62380
- Plated Through Hole Fatigue
- Solder Joint Fatigue
- In Circuit Test (ICT)
- Vibration
- Shock

Sherlock can also pre-populate a DMFEA (Design Failure Mode and Effects Analysis) spreadsheet using the netlist.

Conductive Anodic Filament (CAF)

Conductive Anodic Filament formation is the migration of copper filaments within a printed circuit board under an applied bias. Sherlock benchmarks the printed board design and quality processes to industry best practices, including wall-to-wall distance between the plated through holes (PTHs) along the orthogonal axes, degree of overlap, and the frequency and type of qualification performed to assess CAF performance. The CAF Analysis Module makes use of the size and location of all plated through-holes and vias the for the analysis calculations.

Failure rate

Empirical reliability prediction is the process of determining the reliability of current technology based on the failure rates of similar technology deployed in the field. This process has been standardized for the electronics industry through the establishment of government and commercial handbooks (MILHDBK- 217, Telcordia TR-332, etc.) that define a failure rate for a specific component technology. A Mean Time Between Failure (MTBF) value is calculated by taking the inverse of the sum of the various failure rates.

Plated through-hole fatigue analysis

Plated Through Holes (PTHs) are holes drilled through multi-layer printed circuit boards that are electrochemically plated with a conductive metal (typically copper). Because these plated holes are metallurgically bonded to annular rings on the top and bottom of the printed circuit board, they act like rivets and constrain the PCB. This constraint subjects the PTH to stresses when the PCB experiences changes in temperature.

Over time, the PTHs experience fatigue and eventually fail due to crack propagation. PTH fatigue is influenced by a number of drivers, including temperature range and PTH diameter. Sherlock calculates a time to failure using the industry-accepted model published in IPC-TR-579—Round Robin Reliability Evaluation of Small-Diameter Plated-Through Holes in Printed Wiring Boards.[2] Life calculation for PTHs subjected to thermal cycling is a three-step process, involving a stress calculation, strain range calculation, and an iterative lifetime determination.

Solder fatigue analysis

Solder joints provide electrical, thermal, and mechanical connections between electronic components and a printed circuit board. During changes in temperature, the component and printed board expand or contract by dissimilar amounts due to differences in the Coefficient of Thermal Expansion (CTE). This difference in expansion or contraction places the second-level solder joint under a shear load. Repeated exposure to temperature changes can introduce damage into the bulk solder. With each additional temperature cycle, this damage accumulates leading to crack propagation and eventual failure of the solder joint.

Thermo-mechanical solder joint fatigue is influenced by maximum temperature; minimum temperature; dwell time at maximum temperature; component design; component material properties; solder joint geometry; solder joint material; printed board thickness; and printed board in-plane material properties. Sherlock calculates a time to failure using strain energy, which requires determining the applied force, the strain range, and then extrapolating cycles to failure from the derived strain energy.

Mechanical shock analysis

Mechanical shock is the sudden application of single or multiple, but non-periodic, physical loads due to acceleration or deceleration that results in significant displacement or deformation. The performance of a solder joint when subjected to mechanical shock is primarily dictated by the ductility of the solder and the fragility of the interconnect. The strengths of these regions and the amount of stress transmitted to them during the shock event determine whether failure occurs. Due to questions about damage evolution during shock events, Sherlock follows the IPC approach in assessing the risk of interconnect failures. This assessment is based on calculating the board strain (or curvature) for the shock pulse based upon the natural frequency and board mode shape determined by finite element analysis and equations developed by Steinberg.[3] If this strain is found to exceed a maximum allowable strain, the component is identified as having an elevated risk.

Vibration analysis

When the printed board is subjected to vibration, it experiences global and local changes to the board shape and curvature. The degree of bending is different for specific components and the area of the printed board to which they are attached. This behavior introduces strain into the second-level solder joint. With repeated exposure, damage accumulates, leading to crack propagation and eventual failure of the solder joint.

Vibration-induced solder joint fatigue is →

Accelerating reliability using PofF modeling *(continued)*

influenced by the type of vibration; the shape of the vibration spectrum; the size and shape of the printed board; printed board in-plane material properties; support conditions; component design; component material properties; location of the component; solder joint geometry; and solder joint material. Sherlock calculates time to failure using a modified Steinberg model that takes into account board level strain.

PoF reliability auto case study: Thermal cycling solder fatigue

An automotive customer was evaluating a potential design. To help accelerate this process, an analysis of the module design using Sherlock was performed. Sherlock's initial evaluation predicted which parts would fail under the defined conditions. PoF modeling identified the risk of component failures before prototype and the customer modified the design accordingly. This information allowed critical, time-sensitive product development to continue as originally planned.

The N50 fatigue life was calculated for each of 705 components (68 unique part types) on the design, with risk color coding, prioritized risk listing, and life distribution plots based on known part type failure distributions. The analysis, shown in Table 2 and Figures 2 and 3, was performed in less than 30 seconds after the model was created where:

Red = Significant portion of failure distribution within service life or test duration.

Yellow = Lesser portion of failure distribution within service life or test duration.

Green = Failure distribution well beyond service life or test duration (not shown)

N50 life = # of thermal cycles where fatigue of 50 percent of the parts are expected to fail

RefDes	Package	Part Type	Model	Solder	Damage	TTF (yrs)	Fail Prob	Score
R1	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R2	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R3	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R4	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R5	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R6	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R7	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R8	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R9	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R10	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R11	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R12	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R13	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R14	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R15	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R16	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R17	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
R18	2512	RESISTOR	CC	63SN37PB	0.33	75.53	5.10	0.0
U13	TSOP-32	IC	Leaded	63SN37PB	0.27	93.21	2.75	2.6
U14	TSOP-32	IC	Leaded	63SN37PB	0.27	93.21	2.75	2.6
U15	TSOP-32	IC	Leaded	63SN37PB	0.27	93.21	2.75	2.6
U16	TSOP-32	IC	Leaded	63SN37PB	0.27	93.21	2.75	2.6
R19	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6
R20	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6
R21	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6
R22	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6
R23	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6
R24	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6
R25	1206	RESISTOR	CC	63SN37PB	0.21	117.71	1.37	5.6

Table 2—Automotive thermal cycling fatigue analysis.

A PoF reliability risk assessment enabled virtual reliability growth by identification of specific reliability/durability limits or deficiencies, of specific parts in, specific applications, and enabled the design to be revised with more suitable, robust parts that met reliability objectives.

The automotive manufacturer is now using Sherlock Automated Design Analysis to evaluate additional electronic module re-designs, providing them with rapid feedback on product design and

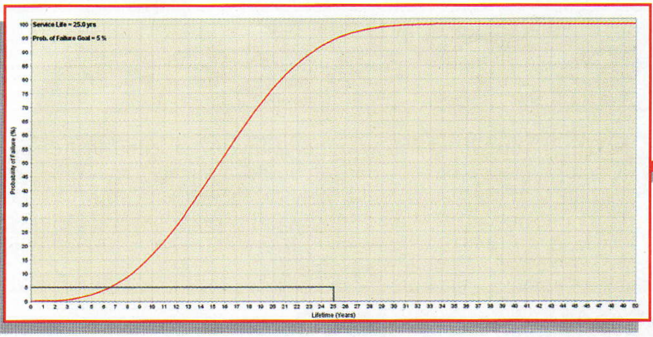

FIG. 2—Thermal cycle fatigue analysis—original design.

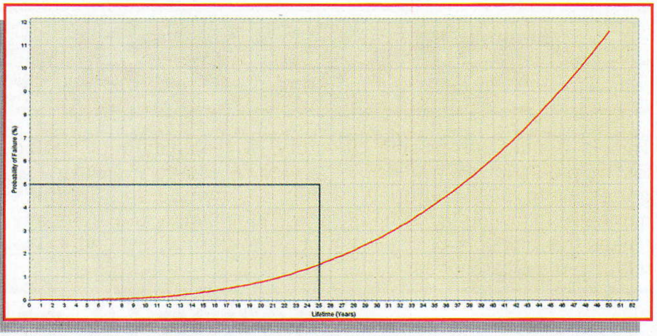

FIG. 3—Thermal cycle fatigue analysis after early failure parts replaced with more suitable, electrically equivalent components.

enabling them to deliver more reliable products to market in a shorter period time than previously.

Test plan development

Product test plans—also known as design verification, product qualification, and accelerated life testing—are critical to the successful launch of automotive products into the marketplace. These test plans require sufficient stresses to bring out real design deficiencies or defects, but not excessive levels that induce non-representative product failure. Tests must be rapid enough to meet tight schedules, but not so accelerated as to produce excessive stresses. Every test must provide value and must demonstrate correlation to the eventual use environment (which includes screening, storage, transportation/shipping, installation, and operation).

Selecting the appropriate environment conditions for design and test is critical. The recommended approach is the combined use of industry standards and physics of failure understanding. This results in an optimized test plan that is acceptable to both management and customers. Sherlock can also be used to assist in this process.

Typical industry standard testing falls short. It addresses a limited degree of mechanism-appropriate testing by using mechanism-specific coupons—not real devices. Test data may be hidden or scrubbed before reaching the end-users. Conflicts and gaps also exist between and within various industry standards. For example, JEDEC component test are often of limited duration (1000 hours), which hides wearout behavior. Use of simple activation energy, with the incorrect assumption that all mechanisms are thermally activated, can result in overestimation of failures in time (FIT) by 100X or more. Some critical components of test plans are identified in Table 3.

Test Objectives	Test Elements
Comparison	Reliability Goals
Qualification	Design
Validation	Materials
Research	Use Environment
Compliance	Budget
Regulatory	Schedule
Failure Analysis	Sample Availability
	Practicality
	Risk

Table 3—Critical components of test plans.

Summary

PoF modeling software reduces both the complexity and need for an expert when creating and running reliability models. It makes PoF analysis faster and cheaper than traditional Design-Build-Test-and-Fix reliability growth tests. Modeling can help determine if a design is capable of surviving the intended test and use environment conditions and is validated with real testing. Finally, software reliability modeling is completely compatible with the way modern automotive products are designed and engineered today.

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3. Steinberg, David S. 2000. Vibration Analysis for Electronic Equipment, John Wiley & Sons Inc.

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