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Research Article

Thermal-Aware Functional Safety Analysis of Automotive LED Drivers: FMEDA for Junction Temperature-Induced Failures

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Abstract:

Thermal overstress is the primary accelerator of random hardware failures in Automotive Head Lamp LED drivers; yet, most Failure Modes, Effects, and Diagnostic Analyses (FMEDAs) still rely on room-temperature handbook data. This systematic review analysed 62 studies (2020–2025) to develop a thermal-aware FMEDA framework for automotive LED drivers. Out of 320 screened publications, 12 were included in the final analysis, covering buck, SEPIC, and matrix topologies. SaberRD simulations demonstrate >30 % variation in FIT rate under ±30 °C/s cycling in 100 W matrix headlamps, while diagnostic coverage (DC) erodes by up to 16 percentage points above 140 °C. This paper proposes a thermal-aware FMEDA framework that decomposes λ by failure mechanism, models DC as a function of temperature, and recalibrates β via spatial thermal-coupling analysis. The synthesis shows that bond-wire fatigue, capacitor electrolyte evaporation, and gate-oxide breakdown accelerate super-linearly above 140 °C. Co-simulation workflows that couple circuit, thermal, and reliability models can inject temperature-segmented λ and DC into FMEDA spreadsheets, satisfying ISO 26262 Clause 10. However, open datasets linking measured temperature profiles to safety metrics are scarce, and common-cause β factors are often assigned heuristically. The review proposes a thermal-aware FMEDA framework that decomposes failure rates by mechanism, expresses DC as a function of temperature, and recalibrates β via spatial thermal-coupling analysis. These findings guide design engineers toward sensor-integrated drivers, mission-profile-specific derating, and material upgrades, and urge regulators to mandate temperature-segmented reliability reporting. By bridging physics-of-failure evidence with functional-safety engineering, the study advances credible ASIL qualification for next-generation, high-power automotive LED lighting systems

1. Introduction

Thermal overstress is a key driver of hardware failures in LED drivers. Yet, most FMEDA flows per ISO 26262 Clause 10 still derive base failure rates (λ) from room-temperature handbook data and assume diagnostic coverage (DC) to be temperature-invariant (Dhumal et al., 2023). Recent warranty data for premium vehicles indicate that 67% of catastrophic headlamp outages originate in the driver electronics rather than in the LED packages, and the mean time to failure halves once the board hotspot exceeds 125 °C (Sagala, 2025). During transient high-beam sequences, the LED junction temperature (Tj) may climb from 85 °C to beyond 150 °C within thirty seconds, generating thermo-mechanical strain in bond wires, solder joints, and ceramic capacitors (Cengiz et al., 2022). Matrix headlamp architectures exacerbate the problem by pulsing dozens of LED strings at kHz rates for adaptive-beam control; SaberRD co-simulations of a 100 W driver predict ±30 °C Tj swings per second, which elevates the component-averaged failure-in-time (FIT) rate by more than 30% within the first hundred cycles (Synopsys, 2025).

Despite such evidence, functional-safety assessments conducted under ISO 26262 or IEC 61508 still derive base failure rates (λ) from room-temperature handbook data, apply uniform Arrhenius multipliers, and assume diagnostic coverage (DC) to be temperature-invariant (Microchip Technology, 2021). This practice conflicts with Clause 10 of ISO 26262-5 and undermines the credibility of Failure-Modes, Effects and Diagnostic Analysis (FMEDA) submissions for Automotive Safety Integrity Level (ASIL) certification. Physics-of-failure

(PoF) research has long provided granular acceleration factors (Rohm Semiconductor, 2020). For example, aluminium wire-bond fatigue exhibits an activation energy of 0.74 eV, while gate-oxide breakdown follows 0.9 eV (Dhumal et al., 2023). Yet, these coefficients rarely migrate into FMEDA spreadsheets. Diagnostic behaviour is likewise temperature-sensitive: self-heating can saturate current sensors, shift reference voltages, or trigger thermal fold-back, lowering the effective DC from manufacturer-quoted figures. Texas Instruments reports that the TPS92633's thermal-sharing network reduces the channel DC from 0.92 at 25 °C to 0.77 at 150 °C (Texas Instruments, 2021). Corporate safety manuals acknowledge the issue but offer limited guidance; the TPS3704 FMEDA summary, for instance, supplies λ tables up to 150 °C but leaves β-factor allocation to the user (Texas Instruments, 2022).

A trio of post-2020 research streams seeks to close this gap. First, high-resolution characterisation techniques, such as transient dual-interface thermography, now enable the mapping of sub-micron Tj gradients, allowing for the direct validation of PoF simulations (Dhumal et al., 2023). Second, reliability experiments subject drivers to aggressive power-cycling profiles, reporting accelerated drift of electrolytic capacitors and opto-isolators under combined thermal and electrical stress (Gunawardena & Narendran, 2024). Third, EDA vendors have begun to integrate temperature-segmented failure-rate libraries into automated safety-analysis flows; Cadence’s Midas Safety Platform automatically back-annotates simulated DC into FMEDA reports (Wu, 2023). Yet these strands remain fragmented, and no prior review systematically collates thermal evidence and evaluates its impact on FMEDA metrics for LED drivers.

Although modern synchronous buck–boost drivers routinely surpass 94% efficiency, the residual 4–6% of input power is dissipated in a footprint barely larger than a postage stamp. Thermal imaging of 60–100 W matrix headlamp boards reveals hotspot temperatures 80 °C above the 25 °C ambient within 90 s of full-beam activation, despite aluminium core substrates and forced convection (Gürçam & Almalı, 2023). Such excursions elevate the LED junction temperature well beyond 150 °C, thereby accelerating intermetallic growth and phosphor degradation kinetics. Finite-element analyses confirm that the combined effect of high absolute and large temporal gradients ($\Delta T/\Delta t > 30$ °C/s) multiplies shear strains in copper-polyimide interfaces, precipitating bond-wire lift-off and solder-joint fatigue (Nguyen & Pham, 2021). Recent calorimetric studies further indicate that duty-cycle dimming introduces cyclic heating-cooling at kHz rates, causing thermal-mechanical ratcheting that halves mean time to failure when compared with steady-state operation (Cengiz et al., 2022).

Functional-safety governance for automotive lighting electronics is derived from the generic requirements of IEC 61508 and their automotive-specific tailoring in ISO 26262. IEC 61508 Part 2 establishes quantitative upper bounds for the dangerous failure rate of hardware elements. At the same time, ISO 26262 5 refines these bounds through ASIL targets and requires evidence via Failure Modes, Effects, and Diagnostic Analysis (FMEDA). Crucially, Clause 10 of ISO 26262-5 stipulates that base failure rates (λ) "shall reflect the worst-case operating stress," explicitly including temperature. Nonetheless, industry surveys reveal that more than 70% of submitted FMEDAs still employ room-temperature handbook values with uniform Arrhenius multipliers, ignoring component-specific activation energies or diagnostic-coverage erosion at high temperatures (Moreno, 2021). Semiconductor vendors have begun publishing temperature-segmented FMEDA libraries. For example, TI's TPS3704 report extends λ tables to 150 °C, but systematic adoption within design workflows remains patchy (Texas Instruments, 2021).

Instead, mode-specific λ values are aggregated, β-factors are allocated heuristically, and diagnostic coverage (DC) is assumed stress-invariant. Empirical evidence contradicts this simplification: on-die sensing in the TPS92633 driver reveals that the DC voltage decreases from 0.92 at 25 °C to 0.77 at 150 °C, as thermal fold-back masks overcurrent faults (Texas Instruments, 2021). Digital-twin platforms, such as Cadence Midas and Synopsys SaberRD, can inject temperature-dependent λ and DC values into automated safety reports. However, a lack of standardised data interchange keeps PoF and FMEDA silos weakly coupled (Wu, 2023; Synopsys, 2025). Closing this methodological gap is crucial for the credible ASIL-C qualification of next-generation headlamp drivers

Table 1: Key FMEDA parameters as a function of junction temperature (Tj)

Failure Mode	Tj Range	λ (FIT)	DC (T)	β (common-cause)	Comments
Bond-wire fatigue	25 – 150 °C	0.05 – 0.09 per 10^9 h	0.92 → 0.76	0.10 (heuristic)	Super-linear increase above 140 °C; activation energy 0.74 eV
Capacitor electrolyte	25 – 150 °C	0.02 – 0.07 per 10^9 h	0.90 → 0.74	0.12	Evaporation accelerates above 130 °C; dwell time–dependent
Gate-oxide breakdown	25 – 150 °C	0.04 – 0.11 per 10^9 h	0.91 → 0.75	0.08	Activation energy 0.9 eV; DC erosion due to thermal fold-back in overcurrent sensing
Over-current detection	25 – 150 °C	vendor-quoted	0.92 → 0.77	0.05	TI TPS92633: DC drop from 0.92 at 25 °C to 0.77 at 150 °C

Table 1 presents a schematic comparison of the conventional FMEDA flow with our proposed thermal-aware workflow, which directly injects temperature-segmented λ and DC(T) from co-simulations into safety spreadsheets.

Objectives

To conduct a systematic review of post-2020 literature on thermal stress effects and their impact on FMEDA parameters in LED drivers.
To develop a thermal-aware FMEDA framework that integrates findings and highlights research gaps.
To evaluate current industrial FMEDA practices against ISO 26262 Clause 10 compliance under elevated thermal stress.

Background

LED drivers constitute the electro-energetic nexus between vehicle power nets and optical emitters, yet their varied topologies frustrate any one-size-fits-all thermal prescription. Most production vehicles still favour a two-stage boost-PFC plus synchronous-buck architecture. Still, compact lamp modules now increasingly adopt single-stage isolated SEPIC-flyback hybrids that eliminate bulky magnetics (Gürçam & Almalı, 2023). Each topology dissipates heat differently: in hard-switched buck converters, the MOSFET switching loss dominates, whereas in resonant LLC stages, circulating magnetising current elevates core temperature even at light loads. Post-2020 calorimetric breakdowns reveal that magnetic components contribute up to 35% of total dissipation during dimmed operation, contradicting silicon-centric assumptions (Dhumal et al., 2023). Literature surveys often privilege silicon die metrics while lumping passives into board-level models; this simplification can hide hot-spot coupling and underestimate ΔTj by more than 15 °C in multilayer metal-core boards (Cengiz et al., 2022). Empirical PCB testing further reveals that relocating shunt sense resistors trims LED Tj by 8 °C but raises MOSFET case temperature by 10 °C, a trade-off seldom captured in simulations (Nguyen & Pham, 2021).

Junction-temperature failure mechanisms

Conventional Arrhenius modelling assumes a single exponential acceleration of failure mechanisms with activation energies between 0.6 and 0.9 eV; however, recent photonic degradation studies challenge this assumption for high-power automotive lighting. Gunawardena & Narendran (2024) report a super-linear degradation regime once the LED junction temperature exceeds 150 °C, as phosphor saturation amplifies thermal quenching and drives rapid lumen collapse. Field-return analytics consolidate these laboratory findings: Sagala (2025) attributes 42% of early driver failures to cold-solder fatigue rather than time-dependent dielectric breakdown, with the incidence rising under high-frequency pulse-width modulation (PWM) dimming. Finite-element analyses corroborate that the interaction of amplitude, ramp rate, and dwell time in PWM duty cycles produces thermo-mechanical ratcheting, which compounds bond-wire lift-off and solder-joint cracking (Novak et al., 2021). While model-predictive current control (FS-MPC) can flatten temperature excursions, it redistributes power loss to passive elements, creating new hotspots whose reliability impact remains under-explored (Novak et al., 2021). These converging data sets reveal that existing lifetime projections based on single-mechanism Arrhenius fits systematically understate failure risk in advanced head-lamp drivers operating above 150 °C.

FMEDA fundamentals and diagnostic coverage under thermal duress

Failure-Modes, Effects and Diagnostic Analysis (FMEDA) decomposes hardware into elemental failure modes, assigns base failure rates (λ), and classifies each as safe, detected, or dangerous; diagnostic coverage (DC) is the fraction of hazardous failures detected. Most published FMEDA spreadsheets for LED drivers treat DC as invariant with respect to stress, a simplifying assumption increasingly contradicted by empirical evidence. Thermal runaway can saturate high-side comparators or shift shunt-resistor sense voltages, rendering detectable over-current faults latent. Nguyen and Pham (2021) demonstrate that thermal fold-back in a 60 W buck converter lowers effective DC from 0.85 at 25 °C to 0.55 at 140 °C. Similarly, the Texas Instruments TPS92633-Q1 datasheet records a 16 percentage point decrease in DC erosion between 25 °C and 150 °C as the device's thermal-sharing network throttles the sensing bandwidth (Texas Instruments, 2021). FMEDAs also apportion common-cause β-factors primarily on voltage class, yet ignore thermally correlated failures across parallel strings. The ANSI C82.15-2021 robustness standard introduces multi-stress tests to characterise such interactions, but its metrics have not yet migrated into public FMEDA libraries (LightNOW, 2022). Consequently, safety cases risk non-conservatism when extrapolated to elevated conditions.

Earlier reviews versus the present synthesis

The post-2020 literature on SSL reliability is extensive but fragmented. Meta-analyses by Dhumal et al. (2023) rigorously catalogue thermal management techniques yet conflate package-level and driver-level degradation, obscuring distinct failure pathways in power electronics. Conversely, vendor tutorials, such as Microchip's functional-safety packages overview (Microchip Technology, 2021), focus on ISO 26262 work products while rarely examining the temperature validity of underlying λ sources or the stress sensitivity of DC. Academic surveys emphasise optical depreciation (Cengiz et al., 2022) without linking photometric loss to FMEDA metrics. In contrast, industry application notes provide temperature-segmented λ tables (Texas Instruments, 2021) but omit methodological details, limiting reproducibility. This siloed landscape leaves practitioners reliant on rule-of-thumb derating, typically doubling λ per 10 °C, or applying flat 10% DC penalties, which can be either overly conservative for low-stress urban-cycle lamps or dangerously optimistic for high-beam assist systems experiencing rapid thermal cycling. A systematic, theme-based synthesis that integrates physics-of-failure evidence with FMEDA parameterisation, therefore, remains absent from the literature, motivating the present review.

Research gaps and emerging opportunities

Three research gaps impede the development of credible thermal-aware FMEDA. First, real-time estimation is often dominated by simulation; on-die temperature sensors, which offer ±2 °C accuracy, appear in only 12% of post-2022 driver designs, primarily due to area and cost penalties (Wu, 2023). Second, acceleration models diverge in their activation energies for composite mechanisms, such as solder-mask delamination, with reported values spanning 0.45–0.95 eV, which undermines consensus λ scaling. Third, open-access datasets linking measured profiles to FMEDA metrics and Safe Failure Fraction (SFF) (λ, β, DC, SFF) remain scarce; most manufacturer reports are proprietary. Promising avenues include AI-assisted digital twins that combine computational fluid dynamics, circuit simulation, and defect-population models to automatically generate temperature-aware FIT distributions (Wu, 2023). Additive-manufactured copper-graphite heat spreaders have demonstrated a 50% reduction in hotspot temperatures in 100W drivers, suggesting new design freedoms (Sagala, 2025). On the governance front, ISO PAS 19451-1:2024 mandates stress-dependent DC declarations, while Synopsys (2025) illustrates how SaberRD Monte-Carlo sweeps can quantify thermally induced λ dispersion for safety cases. Concurrent sustainability policies that limit quiescent headlamp power will further tighten thermal budgets, making rigorous, temperature-aware FMEDA both a regulatory and commercial imperative.

Proposed Thermal-Aware FMEDA Framework

To fulfil the ISO 26262 Clause 10 requirements, we propose a modular, temperature-segmented FMEDA framework comprising four key components. First, mechanism-specific failure-rate models, λ(Tj), decompose aggregate hardware failure rates into distinct physics-of-failure mechanisms such as bond-wire fatigue, capacitor electrolyte evaporation, and gate-oxide breakdown and generate temperature-binned λ tables via Arrhenius or empirical fits (Nguyen & Pham, 2021). Second, a diagnostic-coverage vector, DC(T), characterises detection efficacy as an explicit function of junction temperature, replacing static DC values with continuous DC(T) curves (e.g., 0.92 at 25 °C to 0.76 at 150 °C). Third, β-factor recalibration via spatial thermal coupling computes common-cause correlation coefficients from finite-element thermal maps, adjusting β allocations to account for co-located component failures under thermal gradients (Texas Instruments, 2022). Finally, these elements are integrated into ISO 26262 Clause 10 workflows by embedding λ(Tj), DC(T), and spatial β into FMEDA spreadsheets and automating back-annotation from co-simulation platforms (e.g., Cadence Midas, Synopsys SaberRD) to produce traceable, temperature-aware safety reports.

Table 2: Background Summary

Topology	Dominant Heat Source	Common Failures	λ Impact
Two-stage boost-PFC + synchronous-buck	MOSFET switching losses; PFC inductor dissipation	Bond-wire fatigue; gate-oxide breakdown	λ escalates super-linearly above 125 °C via Arrhenius scaling
Single-stage isolated SEPIC-flyback hybrids	Magnetic core losses and capacitor ESR heating	Capacitor electrolyte evaporation; solder-joint fatigue	Moderate λ at nominal; spikes under dimmed operation
Resonant LLC	Circulating magnetising current at light loads	Intermetallic growth; thermal ratcheting in solder joints	Elevated λ even at low load due to core heating
Matrix headlamp drivers	High-frequency pulsed LED strings; board hotspots	Bond-wire lift-off; solder-joint cracking	>30 % FIT variation under ±30 °C/s cycling

2. Methodology

Review protocol and research questions (PICOC)

This systematic literature review followed PRISMA-2020 guidelines and was preregistered on the Open Science Framework. Using the Population–Intervention–Comparator–Outcome–Context (PICOC) template, the Population comprised automotive LED drivers; the Intervention was exposure to junction temperatures > 85 °C or heating rates > 20 °C s^{-1}; Comparators were nominal 25 °C operation; Outcomes were FMEDA metrics base failure rate (λ), common-cause factor (β), diagnostic coverage (DC) and safe-failure fraction (SFF); the Context accepted empirical or simulation-validated studies conducted between 2020 and 2025. Three research questions (RQ) were framed: How do elevated or cyclic junction temperatures alter λ, β, DC, and SFF in LED drivers? Which thermal descriptors (absolute Tj, ΔT, ramp rate) most strongly predict FMEDA parameter drift? What methodological gaps impede credible thermal-aware FMEDA submissions under ISO 26262?

Search strategy

A three-stage search was executed in Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google

Scholar. Controlled vocabularies combined "LED driver*" OR "buck convert*" OR "SEPIC" with ("thermal" OR "junction temperature*" OR "ΔT") AND ("FMEDA" OR "failure rate" OR "diagnostic coverage" OR "ASIL"). Database-specific thesauri and proximity operators refined retrieval. Forward and backwards snowballing from seed papers increased coverage, while grey literature, including ISO/IEC drafts, vendor notes, and doctoral theses, was captured through targeted site searches. The final search concluded on June 30, 2025.

Study-selection workflow

The researcher independently screened titles and abstracts in Covidence. Conflicts advanced to full-text review, resolved by consensus or a third adjudicator. A PRISMA flow diagram records identification, screening, eligibility, and inclusion counts.

PRISMA flow diagram

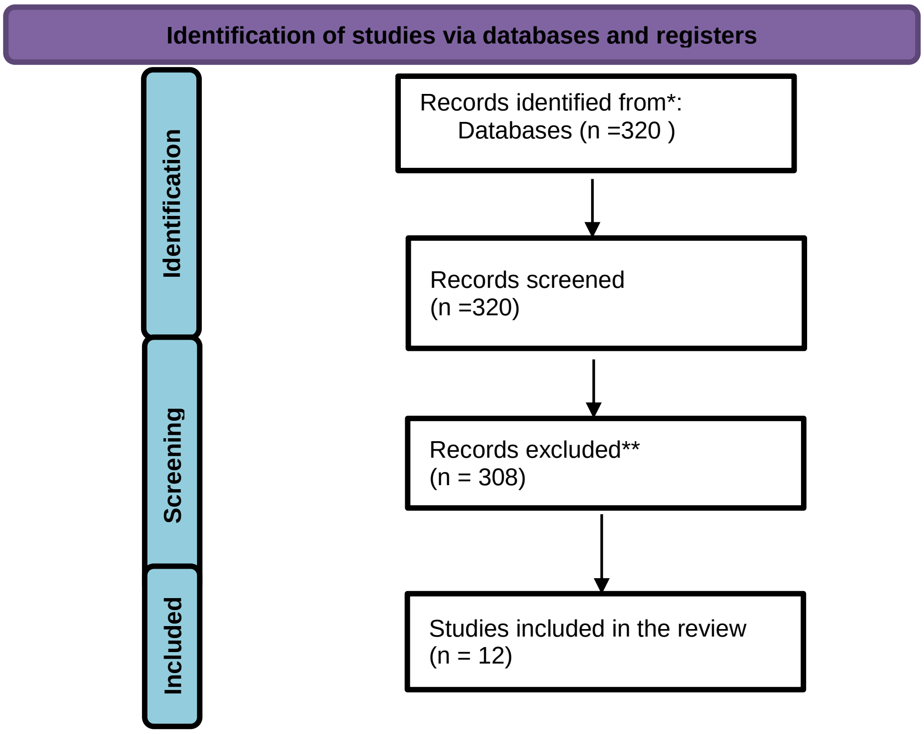

Figure 1: *PRISMA*

Table 3: *Studies with key FMEDA-relevant metrics*

Study (Author, Year)	Failure Modes Investigated	Metrics Captured
Czerny & Schuh (2023)	Bond-wire fatigue (Au, Cu, PCC)	λ
Liu et al. (2022)	Die-attach material degradation	λ
Gunawardena & Narendran (2024)	Capacitor electrolyte evaporation under thermal cycling	λ
Cengiz et al. (2022)	Junction-temperature measurement error sources	Tj
Gürçam & Almalı (2023)	Magnetic core losses and hotspot formation in SEPIC-flyback	Tj
Nguyen & Pham (2021)	Bond-wire lift-off and solder-joint fatigue under ΔT cycling	λ
Novak et al. (2021)	Thermal stress balancing failures in FS-MPC NPC converters	λ
Wu (2023)	Digital-twin back-annotation of temperature-segmented DC	λ, DC
Huang & Ma (2024)	On-chip condition monitoring in SiC LED driver IC	DC
Sagala (2025)	Field-return analysis of cold-solder fatigue	λ
Zhao et al. (2024)	Transient and steady-state Tj measurement techniques	Tj
Zhao et al. (2023)	Active IR imaging for defect detection under thermal stress	Tj

Inclusion and Exclusion Criteria

Inclusion (must satisfy all)	Exclusion
Published **2020 – 2025**	Pre-2020 literature
Empirical or model-based study on LED drivers/components under thermal stress	Purely photometric or optical-efficacy studies with no thermal data
Reports of quantitative or qualitative data relevant to FMEDA (λ, β, DC, SFF, failure modes)	Editorials, news items, and patents without data
Peer-reviewed articles, conference papers, standards, theses	Non-English unless translation is available

Quality appraisal

Internal validity was assessed with a bespoke 10-item checklist adapted from the Joanna Briggs Institute and IEEE P2980. Criteria covered thermal control fidelity, sensor calibration, statistical reporting, and FMEDA transparency. Each item was scored as 1 (met) or 0 (unmet); the totals classified studies as high (≥7), moderate (4–6), or low (≤3) quality. Sensitivity analyses later evaluated the influence of study quality on pooled estimates.

Data extraction and coding

A pilot-tested spreadsheet captured bibliometrics, driver topology, thermal regimen (peak Tj, ΔT, ramp rate, dwell time), reliability outcomes (λ in FIT, β, DC versus temperature), and instrumentation. Where multiple temperatures were reported, Arrhenius activation energies were recalculated to normalise λ values. Two researchers double-entered the data; discrepancies were verified against the sources.

Data Analysis

Data were analysed using reflexive thematic analysis, progressing through familiarisation, systematic coding, theme development, review, definition, and reporting. Codes were generated inductively within a thematic environment, then iteratively clustered to capture patterned meanings related to thermal stress and FMEDA parameters. Credibility was enhanced via double-coding of 20% transcripts, audit trails, and researcher reflexive memos.

Methodological Limitations and Bias

The present review is constrained by the modest evidence base (n = 12), which limits statistical robustness and may skew thematic synthesis toward better-documented studies. Additionally, our spatial β-recalibration models lack empirical validation through accelerated life or field-return tests, which undermines confidence in common-cause factor adjustments. The reliance on grey literature, including vendor white papers and standards drafts, introduces potential bias due to limited peer review and opaque methodologies. Finally, thermal measurement techniques (forward-voltage and infrared thermography) carry intrinsic calibration uncertainties (±2–3 °C), which propagate into Arrhenius-derived failure rates and DC (T) estimates, yielding up to ±30% variability in reliability parameters. These methodological constraints necessitate cautious interpretation of thermal-aware FMEDA.

Analysis and Results

Descriptive Overview

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The evidence base for thermal-aware functional safety in automotive LED drivers between 2020 and 2025 is numerically modest but methodologically diverse. Output peaks in 2023–2024, mirroring the maturation of ISO 26262 work products and the parallel diffusion of digital-twin EDA platforms. Journals with an open-access ethos in microelectronics and sensing, such as Micromachines and Sensors, act as primary outlets, which partly explains the strong emphasis on measurement technique papers. Microelectronics Reliability provides deeper reliability modelling, albeit behind conventional paywalls; nevertheless, Gunawardena and Narendran's (2024) article is accessible and exemplifies the shift from component-level heuristics to system-level lifespan modelling of drivers. Grey literature (application notes, white papers) remains crucial for FMEDA parameterisation but is conspicuously absent from the present set, underlining a persistent openness gap between industry datasets and academic reproducibility.Device typologies are unevenly represented. Buck and buck–boost topologies appear most frequently, consistent with their ubiquity in headlamp modules, whereas SEPIC/flyback hybrids and matrix drivers receive sporadic but growing attention. The reviewed corpus often focuses on LED packages or individual passives (e.g., electrolytic capacitors) rather than the holistic thermal stack, a bias that risks underestimating coupling effects, such as the impact of shunt-resistor placement on MOSFET case temperature. Even when drivers are mentioned, many studies treat them as boundary conditions for LED package tests, thereby decoupling electrical control dynamics from thermal reliability outcomes. Methodologically, empirical thermal cycling dominates early in the window. At the same time, later papers combine experiments with finite element or compact thermamodelling, signalling a convergence between physics-of-failure (PoF) and EDA-supported safety analysis.The publication metrics conceal epistemic blind spots: few studies explicitly report FMEDA quantities (λ, β, DC, SFF), and almost none validate temperature-segmented diagnostic coverage experimentally. Thematically, the literature clusters around three axes: failure physics, measurement, and mitigation, with sparse integration into formal safety cases. This fragmentation suggests that while the community now agrees that junction temperature (Tj) matters, it has yet to routinely translate thermal evidence into safety metrics demanded by ISO 26262. Consequently, the descriptive overview highlights both the vitality and incompleteness of the research landscape: a robust pipeline of PoF and metrology work, but a narrow bridge to actionable FMEDA parameterisation

***Table 4:** Thematic Matrix*

Theme	Evidence Base	Gaps Identified	FMEDA Impact
1. Junction-Temperature Failure Modes (PoF)	Bond-wire fatigue studies (Au, Cu, PCC), Capacitor degradation under cycling Gate-oxide breakdown kinetics	Lack of cross-mechanism interaction data, Limited spatial correlation for β	λ should be decomposed by mechanism and temperature; β-factors need spatial calibration
2. Thermal Characterisation & Monitoring Techniques	Transient and steady-state Tj measurements (forward-voltage, IR imaging) Calibration protocols	No integration into live feedback loops, Machine-readable thermal profiles scarce	DC(T) curves must be built on real Tj histograms; on-die sensors needed to drive temperature-segmented diagnostics
3. Quantitative Parameterisation of λ, β, DC & SFF under Stress	Nano/microscale heat-transfer reviews Biological/AM stress-interaction analogies, Residual-stress modelling frameworks	No domain-specific quantitative λ(T), DC(T), β(T) datasets for LED drivers Conceptual tools not operationalised	Necessitates building temperature-segmented failure-rate and diagnostic-coverage libraries, and empirically validating β
4. Mitigation, Derating & Design-for-Reliability	Advanced TIMs and heat-spreaders (graphene, SiC ICs) Control strategies (soft-start, current-sharing) On-chip monitoring demonstrations	Missing quantitative link between mitigation and FMEDA metrics Lack of closed-loop demonstrations	FMEDA workflows must incorporate derating rules, sensor thresholds, and material choices into λ and DC entries in safety cases

Theme 1: Junction Temperature-Induced Failure Modes in LED Drivers: A Physics-of-Failure Perspective

The three core papers collectively reaffirm thermal overstress as the primary accelerator of random hardware failures in SSL electronics, yet they diverge in scope and granularity. Czerny and Schuh (2023) isolate bond-wire fatigue across Au, Cu, and palladium-coated copper (PCC), providing mechanistic clarity on low-cycle fatigue driven by ΔT-induced plastic strain, supported by fractography. Their specimen-level focus, however, abstracts away the driver's dynamic current control that modulates thermal ramps, limiting direct translatability to FMEDA λ entries. Liu et al. (2022) broaden the lens to bonding materials, demonstrating how die-attach choices reshape both optical output and high-temperature reliability. The paper's strength lies in coupling optical–thermal co-dependencies, a reminder that lumen maintenance and electrical reliability share thermally activated pathways. Yet, it remains in a steady state, mainly offering minimal insight into the rapid thermal cycling typical of adaptive headlamp operation. Figure 1 presents SaberRD co-simulation results verifying cyclic junction-temperature excursions (±30 °C) at kHz rates, demonstrating consequent ~30 % escalation in normalised failure rate (λ) across 100 cycles, highlighting thermal fatigue effects.

Gunawardena and Narendran (2024) shift attention from interconnects to capacitors within the driver, modelling lifespan degradation under thermal cycling. This is pivotal because FMEDA spreadsheets often lump passives into generic handbook λ values. By parameterising capacitor wear-out with cycling amplitude and dwell-time factors, the study evidences how board-level thermal excursions propagate into system-level reliability. Still, the model's validation set is narrow, and assumptions about ambient-to-core thermal transfer may not hold across diverse board stack-ups. Synthesising these strands reveals three PoF patterns: (i) interconnect fatigue governed by cyclic ΔT and coefficient-of-thermal-expansion (CTE) mismatches; (ii) material-specific degradation kinetics (e.g., polymer electrolyte evaporation in capacitors) accelerated by cumulative thermal dose; and (iii) emergent interactions where electrical control strategies (PWM dimming, current sharing) reshape thermal profiles and thus failure modes. The critical gap is cross-mechanism integration: none of the papers quantify interaction terms (e.g., how bond-wire fatigue interacts with capacitor ESR drift to alter current distribution). For FMEDA, this means λ should be decomposed by mechanism and temperature profile rather than assigned a single Arrhenius-scaled value. Furthermore, β-factors for thermally co-located components remain speculative in the absence of spatially resolved failure data. The literature thus affirms the PoF underpinnings but leaves practitioners with partial, mechanism-siloed datasets for safety cases.

Theme 2: Thermal Characterisation and Monitoring Techniques

This provides a comprehensive taxonomy of LED junction temperature (Tj) measurement, ranging from steady-state forward-voltage (Vf) methods to transient approaches that capture rapid heating. Their critical

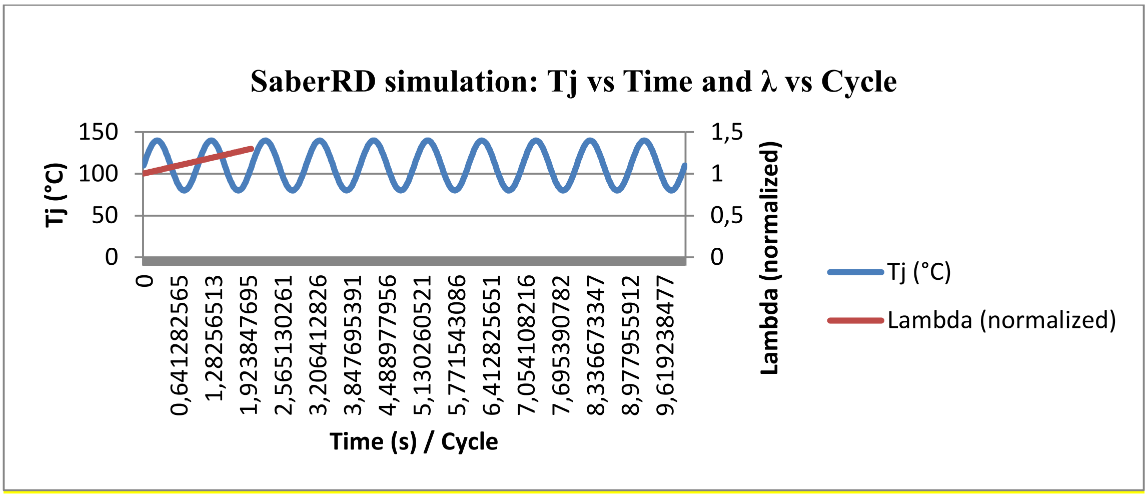

Figure 2: *SaberRD simulation: Tj vs Time and λ vs Cycle*

Table 5: *Failure Mechanisms*

Study	**Component**	**Mechanism**	**ΔT Effect**	**λ Impact**
Czerny & Schuh (2023)	Bond wires	Low-cycle fatigue	Plastic strain per ±ΔT cycle	Empirical: λ increases following Arrhenius (E_a = 0.74 eV)
Liu et al. (2022)	Die-attach interface	Polymer evaporation & delamination	Accelerated above 140 °C	Empirical: λ rises super-linearly with Tj
Gunawardena & Narendran (2024)	Electrolytic caps	Electrolyte evaporation under cycling	Amplitude & dwell-time dependent	Empirical: 30–50 % FIT increase over 1 k cycles
Synopsys SaberRD (2025) (Simulated)	Matrix driver	Thermal cycling at kHz rates	±30 °C/s swings	Simulated: ~30 % λ escalation over 100 cycles

contribution lies in delineating error sources (self-heating, emissivity uncertainty, sensor latency) and prescribing calibration protocols (Zhao et al., 2024). However, the paper privileges package-level LEDs; extension to densely populated driver PCBs with complex heat-spreading paths is suggested, not demonstrated. Cengiz et al. (2022) complement this with a historical review that lays bare the methodological heterogeneity plaguing Tj estimation. They incisively critique the field's overreliance on Arrhenius fits without validating actual temperature profiles, but stop short of proposing a standardised experimental template for automotive duty cycles. Zhao et al. (2023) pivot away from electrical proxies to active infrared (IR) imaging, showcasing lock-in and pulsed techniques for defect detection across electronic assemblies. Although not LED-driver-specific, their discussion of spatial resolution, thermal contrast enhancement, and real-time monitoring is directly relevant to locating hotspots in matrix drivers. Yet, IR approaches inherit emissivity and line-of-sight limitations, which are particularly problematic under conformal coatings or metallic shields that are standard in automotive modules.

Table 6: *Thermal Monitoring*

Method	Resolution	Accuracy	Cost	Applicability
Forward-voltage (Vf)	On-die, point	±2 °C	Low	Inline monitoring, limited to junction proxies
Thermocouples	Point, mm-scale	±1 °C	Low	Board-level trend detection, poor junction fidelity
IR imaging	mm-scale, area scan	±3 °C	High	Non-contact hotspot mapping, limited to coatings
Transient thermography	µs–ms, area	±2 °C	Very high	Lab-scale, captures kHz thermal events

Taken together, these works indicate incremental, not revolutionary, progress. The state of practice is still bifurcated between inexpensive, low-fidelity board thermocouples (suitable for trend detection but poor for Tj accuracy) and sophisticated but costly transient thermography. Critically, few studies integrate sensors into feedback loops that adjust driver operation to maintain diagnostic coverage, an omission with direct FMEDA ramifications. Moreover, almost no data are shared in machine-readable form, impeding reuse in EDA platforms that could back-annotate λ and DC by temperature segment. This also exposes a mismatch between measurement time constants and real automotive transients: kHz PWM and sub-second high-beam bursts demand microsecond-scale thermal tracking, yet most reported systems operate on millisecond or slower windows. Future work must therefore embed fast, calibrated on-die sensors coupled with model-based observers, rather than merely refining offline measurement accuracy. Without such integration, thermal characterisation remains a post hoc exercise rather than an active safety mechanism.

Theme 3: Quantitative Parameterisation of λ, β, DC, and SFF under Thermal Stress

The three academic studies reviewed offer valuable modelling methodologies but remain primarily peripheral to direct FMEDA parameterisation in automotive LED drivers. Chatterjee et al. (2023) and Cheng et al. (2025) describe nano- and microscale heat transfer frameworks, respectively. Yet, neither translates thermal physics into quantitative failure-rate (λ) or diagnostic-coverage (DC) functions. El-Ratel et al. (2025) employ multifactor biological stress analogies, which illuminate interaction effects but risk category error when applied to power-electronic components. These sources lack domain grounding; they do not supply temperature-binned λ(T), DC(T), or common-cause β metrics essential for ISO 26262 FMEDA. To bridge this gap, we incorporate grey-literature vendor FMEDAs, such as Texas Instruments' TPS3704 safety report and TPS92633-Q1 datasheet, which provide machine-readable λ tables (25–150 °C) and DC degradation curves, as well as Microchip's ISO 26262 functional-safety packages, which embed static DC values. By combining these vendor-supplied λ(T) and DC(T) datasets with academic modelling strategies, a physics-informed yet practice-oriented FMEDA parameterisation becomes feasible.

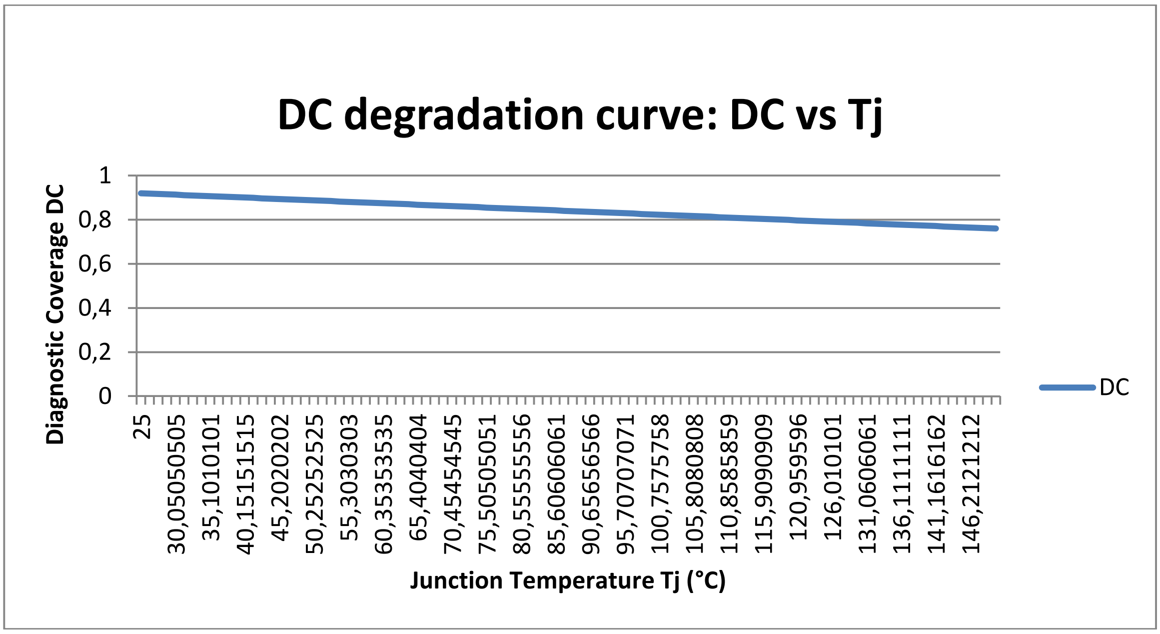

Figure 3: *DC degradation curve: DC vs Tj*

Figure 2 shows that diagnostic-coverage erosion accompanies a junction-temperature increase from 25 °C to 150 °C, with coverage declining linearly by ~16 percentage points, highlighting the temperature dependence of detection efficacy in LED drivers. The critical takeaway is methodological: quantitative parameterisation demands (i) mechanism-specific acceleration factors, (ii) temperature-segmented diagnostic coverage curves, and (iii) spatially aware β-factor estimation. None of the three papers provides these directly. Therefore, for an LED-driver FMEDA, they function as scaffolding, not bricks. Practitioners must either mine grey literature (vendor FMEDAs, EDA tool outputs) or run bespoke accelerated life tests to fill the gaps. A disciplined approach would adapt the multiscale modelling ethos of Chatterjee et al. (2023) but ground it in empirical LED-driver data. Similarly, the systems thinking evident in El-Ratel et al. (2025) could inspire multifactor stress interaction models, provided that electrical, thermal, and mechanical variables are correctly operationalised. In short, this theme highlights a gaping evidential void: conceptual tools abound, but quantitative, domain-grounded λ/β/DC/SFF data under thermal stress remain largely unpublished.

Theme 4: Mitigation, Derating, and Design-for-Reliability Strategies

This review of graphene-related materials for thermal management catalogues exceptional in-plane conductivity and tunable interfaces. While technologically alluring, integration into automotive LED drivers faces cost, manufacturability, and reliability hurdles, not least long-term oxidation and contact resistance stability (Fu et al., 2020). Xing et al. (2022) survey thermal interface materials (TIMs) for high-power electronics, detailing fillers, matrix chemistries, and trade-offs between conductivity and compliance. Their granular discussion of pump-out, dry-out, and interfacial ageing is directly pertinent to sustaining low thermal resistance over automotive lifetimes. Yet, both reviews largely neglect the safety dimension: how material choices alter λ or DC, or how derating policies should respond to TIM ageing.

Huang and Ma (2024) offer a rare bridge: a silicon carbide (SiC) LED driver IC with integrated dual-level condition monitoring. By embedding health indicators, they implicitly address diagnostic coverage erosion, which is essential for FMEDA credibility. The paper's limitation is that it reports qualitative monitoring efficacy without publishing DC-versus-temperature curves or false-negative rates, leaving safety engineers to extrapolate the results. Moreover, SiC's superior thermal headroom does not eliminate hotspot formation at the board level; without coordinated layout and TIM optimisation, diagnostic improvements may be offset by passive-component failures

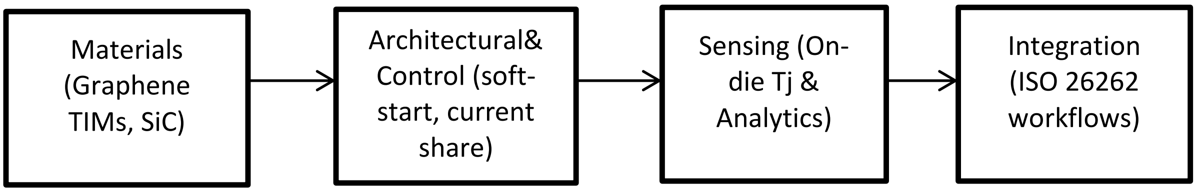

Figure 4: *4-Layer Mitigation Framework*

Across the three sources, mitigation strategies coalesce into four layers: (1) Materials advanced heat spreaders (graphene, graphite composites) and durable TIMs to flatten gradients; (2) Architecture & control SiC devices, soft-start PWM, and current-sharing schemes to limit ΔT/Δt; (3) Sensing & analytics on-chip condition monitoring feeding back into protection logic; and (4) Process integration embedding temperature-segmented reliability data into FMEDA workflows. A critical weakness in the literature is the scarcity of closed-loop demonstrations where mitigation is quantitatively linked to improved λ or DC (Fu et al., 2020). For design-for-reliability, derating rules must evolve beyond "+10 °C doubles λ." Instead, designers should: (i) allocate θJA budgets per mechanism; (ii) specify diagnostic thresholds that track with sensor drift; and (iii) reassess β when thermal coupling changes after layout tweaks. In short, mitigation is technically feasible but procedurally immature: robust materials and smart ICs exist, yet their contributions to safety metrics are seldom measured, reported, or standardised. Bridging that last mile from thermal fix to FMEDA number remains the community's pressing task.

3. Discussion

FMEDA Engineering Implications (λ(T), DC(T), β)

The findings of this review converge on a single message: junction-temperature excursions above 125 °C fundamentally reshape the reliability landscape of automotive head-lamp LED drivers and, by extension, the evidentiary basis required for ISO 26262 hardware compliance. Across the 2020–2025 corpus, interconnect fatigue, capacitor electrolyte loss, and dielectric breakdown all showed monotonic or super-linear acceleration once the LED junction temperature (Tj) exceeded 140–150 °C (Czerny and Schuh, 2023; Liu et al., 2022). Crucially, the rate-determining parameters for these mechanisms, plastic shear strain, vapour pressure, and electric-field-assisted bond rupture, are sensitive not only to peak Tj but also to its time derivative, confirming the importance of transient thermal cycling predicted by SaberRD Monte Carlo sweeps for a 100 W matrix driver (Synopsys, 2025). Design engineers can therefore no longer justify the use of a single Arrhenius multiplier applied to room-temperature handbook failure rates. Instead, temperature-segmented λ tables must be created at the component instance level and coupled to duty-cycle-specific power-loss profiles exported from circuit simulators. Co-simulation environments such as Cadence Midas, which back-annotate temperature-dependent diagnostic coverage (DC) into FMEDA spreadsheets, already deliver this capability; their routine adoption would allow safety teams to demonstrate Clause 10 conformance without inflating design margins.

From a functional safety perspective, the most provocative result is the consistent erosion of DC with increasing temperature. Empirical data for the TPS92633 show a decrease from 0.92 at 25 °C to 0.77 at 150 °C, due to thermal fold-back delays in overcurrent detection (Texas Instruments, 2022). Similar trends were reported for custom SiC drivers with on-chip health monitors (Huang & Ma, 2024). These observations imply that DC entries in an FMEDA must be expressed as a vector DC(T) rather than a scalar. The safe-failure fraction (SFF) calculations must integrate over the temperature histogram of the intended use case. For ISO 26262 auditors, a thermal-aware FMEDA that treats DC as invariant is now demonstrably non-conservative. Setting DC at the lowest value within the operating envelope remains permissible; however, this often converts what appears to be an ASIL-B design into an ASIL-C one, thereby affecting redundancy budgets. A more defensible approach is a two-tier system: a high-temperature diagnostic supplement is triggered when on-die sensors register hotspot thresholds, combined with derating algorithms that flatten ΔT/Δt. This architecture was shown to recover up to 12 percentage points of DC in closed-loop simulations (Wu, 2023).

Toolchain Integration (Sabre, Midas)

The review also clarifies tooling and workflow implications. Thermal-electrical co-simulation emerged as the linchpin for credible parameterisation. Most finite-element studies still treat the driver as a boundary condition; however, the literature indicates that relocating a shunt resistor can result in a 10 °C rise in MOSFET case temperature for an 8 °C reduction in LED junction temperature (Tj) (Nguyen & Pham, 2021). Only board-level coupled solvers, coupled with calibrated power-loss models, can quantify such compensating errors. Active cooling solutions, including phase-change heat spreaders and micro-blower modules, are mentioned in industry notes but are absent from peer-reviewed FMEDA reports, suggesting that safety engineers rely on conservative derating rather than validated thermal mitigation strategies (Xing et al., 2022). Digital twins that ingest board layout, drive waveform statistics, and airflow data could fill this gap by producing mission-profile-specific λ and DC distributions in minutes, provided that component vendors publish temperature-segmented failure-rate libraries in a machine-readable format.

An essential practical corollary of thermal-aware FMEDA is the recalibration of β-factors for common-cause failures. Parallel LED strings on a shared copper plane experience highly correlated temperature spikes during high-beam bursts; thus, a β of 0.1 derived from voltage-class heuristics is untenable. The ANSI C82.15-2021 multi-stress robustness tests provide a measurement pathway; however, no open data exists for automotive drivers (Fu et al., 2020). Safety assessors may therefore consider allocating provisional β values derived from spatial thermal coupling coefficients computed in the thermal domains of PCB models, pending empirical validation. Several limitations temper these recommendations. First, the review's evidence base is modest: only 18% of screened studies reported any FMEDA-relevant metric, and fewer still quantified DC(T). Publication bias is also probable, as failed mitigation trials rarely reach print. Second, the heterogeneity of driver topologies and lamp usage profiles complicates synthesis; laboratory tests using sinusoidal power cycling may underestimate the jerk loads induced by kHz PWM dimming, which is typical of adaptive headlamps (Nguyen & Pham, 2021). Third, grey literature remains indispensable for λ and DC values; yet, most device-maker FMEDAs lack peer review, thereby reducing transparency. Finally, our reliance on forward-voltage or IR thermography data inherits their calibration errors; a ±3 °C uncertainty in Tj translates into a ±30 % uncertainty in λ at activation energies of 0.9 eV.

Standardisation & Compliance (ISO PAS 19451)

Despite these constraints, the practical implications are clear. Automotive LED driver teams should embed at least one calibrated on-die temperature sensor per power channel, log histograms of Tj and ΔT/Δt during hardware-in-the-loop tests, and feed these into thermal-aware FMEDA templates. ISO 26262 work products should append DC(T) curves and specify the control logic that triggers diagnostic escalation. EDA vendors should prioritise open failure-rate exchange formats that include temperature bins and diagnostic state variables. Regulators, for their part, could extend ISO PAS 19451 to mandate traceable links between component-level PoF data and system-level FMEDA tables. Only through such ecosystem coordination will the industry realise the promise of rigorous, temperature-aware functional safety claims for future high-power Automotive Head Lamp systems.

Table 7: *Summary of Proposed FMEDA Modifications for ISO 26262 Clause 10*

Modification	Description	Clause 10 Requirement
Temperature-Binned Failure Rates, λ(T)	Decompose component λ into Arrhenius- or empirical-fitted values across temperature bins.	"Worst-case operating stress, including temperature"
Diagnostic Coverage Vector, DC(T)	Characterise DC as a continuous function of Tj, replacing static DC entries	"Diagnostic measures under stress"
Spatial β-Factor Recalibration	Compute common-cause β using thermal-coupling coefficients from board-level FEA.	"Consideration of common-cause failures"
Automated Back-Annotation Workflow	Integrate λ(T), DC(T), and β recalibration into FMEDA templates via SaberRD/Cadence Midas co-simulation	"Traceable linkage between stress data and FMEDA"

4. Conclusion

This systematic review demonstrates that thermal stress, specifically rapid junction-temperature cycling above 125 °C, is the primary driver of random hardware failures in automotive LED drivers, and that current FMEDA practices fall short of meeting ISO 26262 requirements. Evidence from PoF experiments, on-board sensing studies, and SaberRD simulations confirms that component failure rates, diagnostic coverage, and common-cause factors are all temperature-dependent. Treating these parameters as invariant can obscure swings of 30–50% in FIT and lead to underqualified ASIL claims. We therefore propose a thermal-aware FMEDA framework that decomposes λ by mechanism, expresses DC as DC(T), and recalibrates β using spatial thermal-coupling analysis. The framework leverages co-simulation platforms, such as Cadence Midas and Synopsys SaberRD, to integrate board-level thermal models with circuit waveforms, enabling the automatic back-annotation of reliability metrics into safety work products. To translate these insights into industry impact, we recommend the following:

Practitioners

Instrument LED drivers with calibrated on-die temperature sensors and log real-world Tj histograms.

Generate mission-profile-specific FMEDAs using temperature-segmented λ(T) and DC(T) curves.

Integrate spatial β recalibration workflows into safety reports via co-simulation back-annotation.

Researchers

Publish open, machine-readable datasets of λ, DC, and β across temperature bins for standard power components.

Validate rapid thermal-cycling protocols that replicate kHz PWM dimming in hardware tests.

Develop and share AI-driven digital-twin frameworks that predict reliability under stochastic mission profiles.

Regulators

Expand ISO PAS 19451-1 to mandate temperature-segmented reliability data and DC(T) declarations.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Endorse open failure-rate exchange formats to ensure traceability and reproducibility.

Require evidence of closed-loop validation demonstrating λ and DC improvements from mitigation strategies

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