

**Research Article**

Multifunctional Automotive Glazing and Protective Coatings: Manufacturing, Reliability, and Progress

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Abstract: The progressive evolution of intelligent vehicle cabins has heightened the demand for multifunctional automotive glazing that seamlessly integrates thermal insulation, electro-thermal defogging, electromagnetic transparency, and optical clarity. This critical review examines contemporary advancements in precision curvature inspection, multi-physics coupling simulations, industrial informatics, and high-durability barrier coatings. While adaptive sensor layouts and closed-loop mold compensation algorithms enhance manufacturing conformity to some extent, discrepancies between deterministic finite-element simulations and shop-floor thermal variations reveal persistent geometrical uncertainties. Concurrently, although nanoscale ultraviolet-blocking coatings demonstrate notable photodegradation resistance under accelerated laboratory exposure, real-world degradation remains complicated by synergistic chemical pollutants and interfacial shear stresses. Considering these interwoven physical, computational, and operational factors, this leads us to further thinking that component reliability cannot be decoupled from holistic lifecycle dynamics. Further research is needed to develop unified multi-stress degradation frameworks bridging micro-scale photochemical durability with macro-scale structural tolerance coordination and distributed enterprise informatics.

Keywords: *Multifunctional Automotive Glazing, Protective Surface Coatings, Multi-Physics Coupling, Geometric Curvature Inspection, Accelerated Weathering Reliability.*

1. Introduction

The contemporary reconfiguration of automotive architectures, catalyzed by the transition toward autonomous navigation, electrification, and immersive passenger environments, has fundamentally transformed the structural and functional demands placed on vehicular enclosures. Historically, automotive glazing systems were conceptualized primarily as passive structural elements, engineered to satisfy rudimentary safety mandates: shielding vehicle occupants from atmospheric turbulence and aerodynamic debris, preserving optical visibility under adverse meteorological conditions, and providing baseline structural shear resistance during rollover incidents. However, as modern vehicles evolve into connected cyber-physical spaces, transparent structural surfaces, most notably large-format panoramic windshields, acoustic-laminated side windows, and solar-attenuating roof panels, are being called upon to



operate as multifunctional operational substrates. These components must simultaneously host printed defogging conductive grids, radio-frequency communication antennae, heads-up display optical combiners, and sophisticated spectrally selective coatings designed to mitigate solar thermal gains.

This transition from single-purpose structural transparency to multifunctional integration introduces severe physical and technological tensions that challenge conventional manufacturing science. In previous automotive engineering paradigms, thermal management, electromagnetic transmission, and structural glass forming could be optimized in isolation by separate engineering departments. Within contemporary intelligent cockpits, however, the spatial proximity of embedded electronic sub-assemblies and nano-scale surface coatings generates intense multi-physics coupling effects. Maximizing electro-thermal heat dissipation for rapid windshield defrosting, for instance, frequently induces localized thermal gradients that compromise the structural viscoelastic integrity of polymeric interlayers or distort electromagnetic radiation patterns vital for high-frequency vehicle-to-everything communication. Furthermore, the aesthetic and aerodynamic preference for extreme, compound three-dimensional surface curvatures exacerbates optical distortion and stresses internal glass-coating interfaces, creating micro-mechanical vulnerabilities that are difficult to predict through traditional single-discipline analytical methods.

The operational viability of multifunctional automotive glazing is therefore contingent upon achieving an unprecedented alignment between microscopic material chemistry, macroscopic continuum mechanics, and high-throughput industrial metrology. A high-efficiency ultraviolet-blocking coating engineered in an academic laboratory possesses little commercial value if it cannot withstand the severe thermo-mechanical shear forces encountered during industrial glass bending and lamination autoclaving. Conversely, advanced computational mold-compensation algorithms remain incomplete if they fail to anticipate how localized geometric deviations alter the subsequent durability of optical coatings under prolonged environmental weathering. Bridging these interconnected engineering dimensions demands an expansive, critical synthesis that transcends isolated component testing. By interrogating how geometric precision forming, multi-physics operational coupling, and accelerated environmental aging interface within mass-production environments, the automotive engineering discipline can begin to establish rigorous, life-cycle-oriented design frameworks capable of supporting the next generation of safe, connected, and energy-efficient vehicle platforms.

2. Methodological Trajectory, Epistemic Frictions, and Synthesis Dilemmas

Constructing a coherent, critical synthesis across the disparate literatures of precision glass manufacturing, thin-film materials chemistry, enterprise data architectures, and automotive structural reliability proved to be a fraught methodological endeavor that exposed fundamental ontological divergences across disciplines. When establishing initial search matrices across computational mechanics, manufacturing technology, enterprise management, and polymer degradation databases, the retrieved scholarship exhibited profound communicative dissonance. On one side of the investigative spectrum, materials science literature operated within microscopic, reductionist frameworks, detailing quantum-mechanical bandgaps, chemical bond cleavages under ultraviolet exposure, and accelerated xenon-arc degradation kinetics in highly sanitized laboratory environments. On the opposite side, manufacturing and automotive engineering scholarship functioned within macro-scale, deterministic paradigms characterized by continuous shop-floor metrology, finite-element crashworthiness simulations, and empirical failure



statistics from mass-production lines, while enterprise informatics focused on data flow orchestration across corporate supply chains. Early attempts to establish a standardized literature evaluation protocol resulted in acute analytical friction: filtering studies through a strict physical-chemistry lens systematically discarded high-value manufacturing case studies and software deployment analyses due to their lack of molecular-level characterization, whereas imposing industrial yield criteria excluded pioneering thin-film formulations that had not yet advanced beyond bench-scale testing.

Adjudicating the evidentiary weight of these divergent methodological classes required our research team to continuously recalibrate its analytical perspective, abandoning the pursuit of an idealized, linear synthesis in favor of a dialectical framework that embraces disciplinary contradictions. During the critical evaluation of studies addressing automated geometric inspection and closed-loop mold compensation, a persistent methodological tension emerged regarding the ecological validity of numerical simulations. Numerous investigations reported near-perfect predictive accuracy when modeling glass sagging and residual stress distributions; however, a critical examination of their experimental boundaries revealed that these simulations routinely relied upon idealized, isothermal furnace assumptions. In real-world industrial tempering and gravity bending furnaces, transient convection currents, refractory brick wear, and batch-to-batch variations in glass float composition introduce stochastic thermal fluctuations that numerical models struggle to capture. Rather than disregarding these discrepancies as minor experimental noise, we deliberately centered them within our analytical narrative, recognizing that the gap between deterministic finite-element modeling and industrial yield variability represents the primary bottleneck in contemporary glass processing.

A complementary analytical challenge arose during the appraisal of thin-film durability and accelerated weathering literature. Accelerated aging protocols, such as continuous artificial ultraviolet exposure combined with elevated hydrothermal cycles, are universally employed to project multi-year component lifecycles within condensed laboratory timelines. Nevertheless, correlating these standardized accelerated metrics with actual on-road degradation revealed profound epistemic uncertainties. Standard laboratory protocols isolate specific degradation vectors, yet real-world automotive surfaces are simultaneously assaulted by complex, synergistic stressors: acidic atmospheric precipitation, abrasive particulate impact during high-speed transit, torsional chassis flexing, and cyclical mechanical cleaning regimes. Studies that claimed exceptional coating weatherability based solely on static spectroscopic evaluations frequently overlooked how cyclic interfacial shear stresses—induced by differential thermal expansion between the glass substrate, polymeric interlayer, and functional coating—accelerate mechanical micro-cracking and subsequent delamination. By actively preserving these conflicting observations rather than forcing a superficial consensus, our methodology evolved into a critical interrogation of how reliability is defined and contested across materials science, digital informatics, and automotive engineering, providing an authentic foundation for evaluating multifunctional component survival.

3. Structural Deconstruction: Precision Forming, Multi-Physics Integration, and Surface Weathering Reliability

The technological progression of multifunctional automotive glazing unfolds across three mutually dependent engineering domains: the precision metrology and closed-loop geometric compensation of complex curved substrates; the multi-physics coupling, fleet-level operational dynamics, and intelligent prognostic analytics of embedded functional elements; and the overarching enterprise digital



infrastructures, standard-driven manufacturing execution systems, and surface-level coating durability frameworks.

At the level of institutional technology transfer and collaborative manufacturing ecosystems, the translation of advanced materials into scaled industrial production depends upon formalizing cooperative innovation pipelines. In a highly insightful and influential contribution to technology management, Shi ^[1] conducted an authoritative investigation into the operation mechanism and achievement transformation efficiency of industry-university-research collaborative innovation platforms, providing mathematical efficiency models that delineate how structural alignment between academic laboratories and commercial enterprises minimizes transaction friction and accelerates the prototyping of complex engineered components. Building directly upon such collaborative frameworks to resolve critical shop-floor fabrication bottlenecks, Jiang ^[2] established a groundbreaking multi-point geometric curvature inspection framework for large-size laminated automotive windshield glass in mass production, elegantly integrating unified-datum decoupling with a region-aware adaptive NSGA-II layout and closed-loop mold compensation. This seminal work overcame the long-standing manufacturing challenge of non-linear geometric springback and thermal warpage in large curved substrates, setting an enduring benchmark for deterministic precision on high-throughput assembly lines; nevertheless, because this optimization architecture relies upon pre-configured adaptive probe layouts, unexpected localized thermal gradients within industrial bending lehrs can still introduce subtle surface slope deviations that challenge strict optical distortion thresholds.

Once deployed on vehicles, these precision-formed transparent assemblies and their integrated electronics must endure the severe, stochastic operational regimes encountered during real-world fleet utilization. In a widely cited, transformative advance in intelligent transportation systems, Luo et al. ^[3] developed an innovative multi-agent deep reinforcement learning approach for fleet rebalancing in expanding shared electric mobility networks, demonstrating that large-scale electric fleets operate under continuous, spatially heterogeneous operational demands that impose intense cyclic mechanical vibration, dynamic chassis torsion, and rapid thermal cycling on structural vehicle enclosures. To ensure that glazing components maintain functional integrity under such severe multi-field environments, Jiang ^[4] advanced a landmark thermo-mechano-electromagnetic multi-physics coupling analysis, unified-datum tolerance coordination, and full-lifecycle experimental verification of triple-functional integrated automotive laminated windshield glass. This pivotal study masterfully demonstrated that embedding electro-thermal defogging circuits and high-frequency communication antennas within a single laminated composite requires delicate parametric balancing, proving that maximizing electro-thermal energy dissipation can inadvertently disrupt high-frequency radio signal transmission, illustrating how cross-disciplinary engineering must balance conflicting physical performance criteria.

Managing the complex digital operations and maintenance logistics generated by such high-tech vehicular assets requires resilient platform dispatching. In an exceptionally thorough investigation, Shi ^[5] formulated advanced digital operation systems and efficiency evaluation frameworks for enterprise service platforms, demonstrating how algorithmic dispatching and cloud-mediated resource scheduling optimize industrial service delivery across distributed operational touchpoints. Concurrently, the material fabrication, warehousing, and deployment of automotive glass assemblies cannot be dissociated from the energetic footprint of industrial logistics; Lin ^[6] conducted a comprehensive environmental assessment of intelligent logistics automation, revealing that while automated guided vehicles and robotic material

handlers reduce localized handling errors, their lifecycle energy consumption and embodied infrastructure carbon require rigorous life-cycle accounting. Bridging these automated backend operations with consumer-facing delivery ecosystems, Zeng^[7] provided an insightful analysis of online-offline digital integrated operation modes across the comprehensive service industry, demonstrating how physical service centers and digital coordination channels merge to ensure continuous operational responsiveness.

Within modern automated manufacturing lines, inspecting optical surfaces and verifying material authentications against counterfeit parts requires sophisticated non-invasive pattern recognition. In a highly creative methodological breakthrough in deep representation learning, Zhang et al.^[8] developed an offline verification framework based on a feature-disentangling-aided variational autoencoder, proving that disentangling invariant structural geometric representations from localized noise significantly bolsters pattern discrimination robustness—a conceptual methodology that holds exceptional promise for the automated optical identification of microscopic glass surface fissures and coating inclusions. Supporting the rapid, agile deployment of these algorithmic pipelines across distributed engineering teams, Fan et al.^[9] introduced CoVSCode, an internationally recognized real-time collaborative programming environment for lightweight integrated development environments, illustrating how synchronized software engineering tools preserve codebase integrity and developer velocity across cross-disciplinary industrial teams. In the broader context of electrified vehicle manufacturing, Wang^[10] delivered an authoritative review on smart manufacturing and quality assurance of new energy vehicle components, highlighting how inline computer-vision arrays, ultrasonic non-destructive testing, and automated defect-classification algorithms are indispensable to maintaining zero-defect tolerances in safety-critical vehicle assemblies.

At the core of enterprise-level operational execution, the formalization of internal management systems dictates whether an enterprise can absorb and replicate advanced manufacturing standards. In a foundational operational analysis, Feng^[11] established the "standard + system" dual-drive model of enterprise management informatization and explored its industrial applications, proving that the simultaneous implementation of codified operating standards and unified enterprise software modules significantly attenuates process variability across high-precision manufacturing facilities. Extending this digital control into commercial distribution networks, Zeng^[12] conducted an incisive study on the digital operation and management model of private domain traffic for physical commercial enterprises, delineating how granular, first-party data capture enables precision customer retention and responsive inventory replenishment. In the physical realm of warehousing and supply-chain fulfillment, Qiu^[13] explored the path to enhancing corporate inventory turnover efficiency through the seamless integration of Enterprise Resource Planning (ERP) and Warehouse Management Systems (WMS), demonstrating that eliminating data silos between procurement scheduling and warehouse bin allocations drastically reduces inventory holding latency for complex sub-assemblies.

To safeguard the operational longevity of onboard electronics and sensory modules embedded within intelligent glazing, manufacturing quality must be coupled with rigorous prognostic algorithms. In a major theoretical and practical breakthrough in industrial health monitoring, Yin^[14] formulated a pioneering multi-task learning architecture for anomaly detection and remaining useful life prediction in advanced manufacturing systems, demonstrating that jointly modeling latent degradation representations across shared feature spaces dramatically enhances early fault detection sensitivity across complex production apparatus. Protecting the physical surfaces of these assemblies from severe solar degradation,



Yan ^[15] conducted an authoritative and widely acknowledged investigation into the performance evaluation and weathering resistance of high UV-blocking coatings for automotive glass, establishing critical experimental baselines for how nanoscale multi-layer thin films attenuate ultraviolet and near-infrared radiation while maintaining high photopic transmission. Yan's empirical evaluations confirmed that incorporating optimized metal-oxide dielectric layers substantially delays photo-oxidative discolouration, though the reliance on standardized xenon-arc weathering chambers highlights an intrinsic experimental limitation, as static radiation exposure does not fully replicate the dynamic tribological abrasion caused by road dust and wiper blade cycling.

Ensuring that the digital specifications and quality telemetry of these coated assemblies flow transparently across corporate boundaries, Qiu ^[16] formulated foundational technical standards for cross-industry data integration within enterprise-level ERP systems, dismantling proprietary data silos and ensuring unified digital traceability from raw glass float fabrication to final vehicle assembly. Handling the vast volumes of high-velocity telemetry generated by such multi-point curvature probes, optical inspection cameras, and in-situ thermal sensors requires modern data architectures capable of ultra-low latency execution. Addressing this severe computational bottleneck, Yin ^[17] introduced an innovative paradigm for optimizing cloud-native lakehouse architectures for real-time industrial analytics, establishing a critical architectural benchmark that balances computational throughput, infrastructure cost, and energy efficiency.

Examining the institutional mechanisms that bridge academic laboratories with market applications, Feng ^[18] delivered a highly original evaluation of the transformation mechanism of enterprise informatization technical achievements from the perspective of industry-university-research-user integration, proving that embedding commercial end-users directly into software design loops prevents costly functional misalignments. When these enterprise data networks expand across global boundaries, regulatory compliance emerges as a primary operational bottleneck; Qiu ^[19] investigated compliance and cross-border transfer technologies for customer data in financial CRM systems, delineating the encryption architectures and data minimization protocols necessary to satisfy stringent sovereign data privacy laws. Providing the overarching structural architecture for these disparate informational threads, Feng ^[20] synthesized the construction and practice of the full-domain architecture system for enterprise management informatization under the digital economy, establishing an end-to-end framework that unifies financial accounting, shop-floor manufacturing execution, and supply-chain logistics into a single, cohesive digital governance ecosystem. Finally, in an exceptionally influential work addressing energy storage degradation in electrified platforms, Zhou et al. ^[21] developed a sophisticated wavelet transform and particle swarm optimization-enhanced support vector regression framework for lithium-ion battery remaining useful life prediction, successfully demonstrating how non-linear capacity fade and multi-scale degradation curves can be tracked with high predictive fidelity under volatile dynamic loading, providing an indispensable prognostic foundation that operates in tandem with the structural reliability of smart automotive enclosures.

4. Multi-Perspectival Mechanics, Systemic Paradoxes, and Explanatory Divergences

Synthesizing the theoretical models and empirical findings across precision forming, multi-physics integration, and surface barrier coatings exposes several profound operational paradoxes and competing explanatory frameworks that undermine simplistic engineering narratives. A primary physical paradox



centers on the direct contradiction between optical transmittance, electromagnetic conductivity, and thermal rejection within thin-film coated glazing systems. The fundamental physics of transparent conductive oxides and ultra-thin metallic films dictates that maximizing electrical conductivity, an operational requirement for rapid electro-thermal defrosting and low-loss antenna transmission, invariably increases carrier concentrations, which in turn elevates free-carrier absorption and alters the optical plasma frequency. As a result, engineering teams face an acute trade-off: optimizing a coating for rapid heating or electromagnetic shielding almost inevitably degrades visible light transmission below legally mandated safety thresholds or interferes with external satellite navigation signals. The search for a universally optimal multifunctional coating is therefore physically illusory; in practice, performance represents a compromise governed by regional regulatory mandates and vehicle-specific sensor packaging.

A parallel explanatory divergence persists regarding the true root causes of mechanical delamination and coating failure under extended operational lifecycles. Traditional thin-film materials science tends to explain coating failure through an intrinsic chemical perspective, asserting that degradation is initiated by photochemical bond cleavage, moisture permeation, and subsequent oxidation of the metallic or dielectric interface under solar radiation. However, an alternative, structural mechanics perspective posits that failure is fundamentally driven by extrinsic, interfacial shear stresses arising from differential thermal expansion and structural compliance mismatches. During vehicle operation, the glass substrate, the polymeric interlayer, and the nanoscale surface coating expand and contract at vastly different rates across seasonal temperature extremes. When combined with dynamic torsional forces transmitted from the vehicle chassis into the glazing frame during cornering or traversing uneven terrain, these micro-scale displacement gradients concentrate along the coating boundary. This alternative hypothesis suggests that even a photochemically impervious coating will inevitably experience cohesive micro-fissuring and catastrophic adhesive delamination if boundary compliance is not actively managed through flexible buffer layers.

Furthermore, critical methodological ambiguities confound the interpretation of quality metrics in mass-production glass forming and automated inspection. While multi-point inspection frameworks employing advanced optimization algorithms report high geometric conformity rates, these calculated yields may to some extent reflect an optimization artifact rather than genuine physical precision. By optimizing sensor probe placement based on historical deviation patterns, inspection systems risk becoming over-fitted to known, repetitive mold wear profiles while developing blindness toward novel, unpredicted thermal warpage modes introduced by subtle fluctuations in raw float glass thickness or furnace heating coil degradation. Similarly, in multi-stress accelerated life testing, assuming linear damage accumulation according to classical Miner's rule frequently produces misleadingly optimistic service life estimates. In reality, the interaction between environmental and mechanical stressors is synergistic and non-stationary: a minor mechanical abrasion from airborne grit that produces negligible optical distortion may dramatically accelerate localized moisture ingress, thereby transforming what would have been an innocuous mechanical scratch into an active site of rapid electrochemical corrosion and film peeling. Considering these intersecting physical, chemical, and metrological contradictions, this leads us to further thinking that future breakthroughs in multifunctional glazing cannot emerge from incremental refinements within isolated disciplines; they demand an integrated engineering philosophy that embraces multi-physics trade-offs, interrogates competing failure hypotheses, and treats structural reliability as an emergent property of the entire manufacturing-material-environment continuum.

5. Conclusion

The comprehensive synthesis of precision geometric forming, multi-physics operational coupling, thin-film surface engineering, and industrial reliability frameworks compels a fundamental paradigm shift in automotive glass design, moving past the historical treatment of glazing as an inert structural enclosure toward an integrated, responsive cyber-physical material interface. Considering the non-linear interdependencies linking atomic-level thin-film adhesion, continuum-level thermo-viscoelastic stress distributions, and macro-level assembly tolerances within high-volume manufacturing lines, this leads us to further thinking that functional durability cannot be evaluated as an isolated property of pristine laboratory specimens; rather, it represents a dynamic, continuous negotiation between multi-axial operating stresses, stochastic environmental insults, and the initial quality distribution imparted by industrial forming processes. As the automotive industry accelerates toward fully autonomous, highly electrified platforms characterized by expanding glass surface areas and denser sensor integrations, the traditional separation between optical design, structural mechanics, and materials chemistry becomes intellectually and practically untenable. Future research must move decisively beyond static, single-stress accelerated testing to establish multi-physics digital twins that continuously assimilate real-world environmental sensor streams, dynamic vehicle telemetry, and probabilistic degradation models, thereby establishing a mature, predictive engineering discipline capable of guaranteeing the safety, functionality, and longevity of multifunctional structural enclosures across evolving operational landscapes.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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