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Review Article

Multi-Physics Coupling and Lifecycle Verification of Triple-Functional Laminated Windshield Glass

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***Abstract*:** Triple-functional laminated windshields couple thermal, mechanical and electromagnetic behaviour in ways that single-physics tolerance schemes only partially capture, and datum drift under mass production remains, to some extent, poorly bounded. This study develops a multi-scale framework combining thermo-mechano-electromagnetic coupling analysis with unified-datum tolerance coordination, linked to a closed-loop verification route spanning curvature inspection, adaptive layout optimisation and mold compensation. Treating datum decoupling as purely geometric proved insufficient, since electromagnetic detuning and coating-driven weathering introduced residuals that geometric compensation could not absorb; the framework was revised to admit coupled residuals and bounded coordination. Verification draws on curvature inspection and accelerated weathering, supplemented by RF degradation monitoring and V2X sensitivity testing to probe whether electromagnetic performance survives lifecycle loading. Apparent convergence may reflect compensation artefacts as much as genuine coupling fidelity, and possible biases in inspection sampling warrant further research. Transferability to digitalised enterprise operations and infrastructure governance is discussed as a plausible, though undemonstrated, extension.

Keywords: *Thermo-Mechano-Electromagnetic Coupling; Unified-Datum Tolerance Coordination; Laminated Windshield Glass; Full-Lifecycle Verification; Digital Operational Correlates;*

1. Introduction

The automotive glazing industry has, over the past decade, moved from a component-supply logic toward an integration logic in which a single laminated windshield is expected to carry structural, optical, thermal-management and electromagnetic functions simultaneously. This shift is not merely a matter of adding coatings or embedding antennas; it changes the very object of tolerance analysis, because the quantities that must be held in coordination are no longer purely geometric. A datum that is optimal for curvature conformity may be, to some extent, unfavourable for electromagnetic aperture alignment, and a mold compensation that satisfies optical distortion criteria may perturb the very residual field that antenna detuning is sensitive to. The literature has addressed these concerns in fragments. Multi-physics coupling studies of triple-functional windshields have demonstrated the feasibility of joint thermal-mechano-electromagnetic modelling, yet their verification routes have tended to remain laboratory-scale, leaving the transfer to mass production an open question [1]. Studies of high UV-blocking coatings have produced valuable weathering-resistance evidence, although the extrapolation from accelerated exposure to service life is itself contested, and the coating's dielectric contribution is rarely reported alongside its optical durability [6]. Curvature inspection frameworks for large-size laminated glass have advanced considerably through unified-datum decoupling and region-aware layout optimisation,

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but such frameworks typically treat datum decoupling as a geometric problem, and the possibility that coupled electromagnetic residuals survive geometric compensation has received comparatively little attention.

A parallel body of work, largely outside the glazing literature, offers methodological resources that may be relevant here. Online monitoring of automotive-grade RF power amplifiers under endurance aging has shown that degradation is not monotonic and that apparently stable devices can exhibit late-stage drift [3], a finding that complicates any assumption that a single end-of-line electromagnetic test is sufficient. Automatic sensitivity testing of V2X on-board terminals under multi-working conditions has similarly revealed condition-dependent behaviour that single-condition testing would conceal, and modular multi-scenario simulation platforms for vehicular wireless signals suggest that verification environments themselves must be treated as a design variable rather than a fixed backdrop [23]. Considering these developments together, one is led to ask whether the verification architecture, and not only the glass, should be the object of lifecycle-oriented design.

The present work takes this question seriously while remaining cautious about what can be claimed. Its aim is to develop a multi-scale framework that couples thermo-mechano-electromagnetic analysis with unified-datum tolerance coordination, and to subject that framework to a verification route that spans curvature inspection, adaptive layout optimisation, mold compensation and lifecycle electromagnetic probing. The intention is not to propose a finished production recipe; it is rather to make explicit where the coupling assumptions strain against manufacturing reality, and to identify which of the observed consistencies may be artefacts of compensation rather than evidence of physical fidelity. Whether such a framework can be transplanted to domains as distant as digitalised enterprise operations and infrastructure project governance is a question we raise tentatively, as a possible direction rather than a demonstrated result; the service-platform efficiency work and the infrastructure capital-efficiency analysis each exhibit coordination-under-competing-requirements structures that are analogous in form, though the analogy is structural rather than mechanistic and its practical yield remains to be shown [9].

2. Framework, Datum Coordination and Verification Architecture

The framework is organised around three coupled layers, and the decision to separate them is itself a methodological choice that warrants justification. The first layer treats the thermo-mechano-electromagnetic response of the laminated stack as a coupled field problem; the second layer translates that response into a datum coordination scheme; the third layer constitutes the verification architecture through which coordination claims are tested. Separating the layers allows each to be interrogated independently, which proved important during the work, because failures that initially appeared as coupling errors were later traced to coordination assumptions rather than to the field model.

Within the first layer, the laminate is treated as a layered medium in which thermal gradients, mechanical constraint from the body opening, and electromagnetic aperture behaviour interact. The coupling is deliberately not assumed to be weak; however, neither is it assumed to be fully characterised, since the material parameters that govern dielectric response under combined thermal and mechanical load are, in the available literature, reported with inconsistent conventions. This inconsistency forced a pragmatic decision: rather than seeking a single "correct" parameter set, the framework admits a bounded family of parameter sets and asks whether the coordination scheme remains acceptable across that family. This is, to some extent, a concession—it widens the reported uncertainty—but it also guards against the false confidence that a single calibrated set would have produced.

The second layer, unified-datum tolerance coordination, begins from the recognition that multiple functional requirements compete for datum definition. A single datum cannot simultaneously optimise curvature conformity, optical distortion, and electromagnetic aperture registration, and the coordination problem is therefore one of bounded compromise rather than exact satisfaction. The scheme adopted here decouples the datum into functional sub-data and then re-couples them through a coordination rule that penalises residual transfer between sub-data. An early version of this rule treated the sub-data as strictly independent, on the reasoning that decoupling should be as complete as possible; this proved unsatisfactory, because the residuals did not vanish and instead accumulated in ways that were difficult to attribute. The rule was accordingly revised to permit controlled residual sharing, which is less elegant but more faithful to the observed behaviour. Region-aware adaptive layout optimisation is then applied so that the coordination rule can vary across the glass surface, since the functional demands near the antenna aperture differ from those near the peripheral seal.

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The third layer, the verification architecture, is where the framework is most exposed to criticism. Verification draws on multi-point geometric curvature inspection with unified-datum decoupling, on accelerated weathering evidence for the UV-blocking coating, and on electromagnetic probing that includes RF degradation monitoring under endurance aging and V2X receiving-sensitivity testing under multi-working conditions, with a multi-scenario vehicular simulation platform serving as a complementary environment [27]. Each of these verification streams carries its own limitations. Curvature inspection samples a finite point set and therefore cannot exclude localized deviations between points; accelerated weathering relies on an equivalence assumption between accelerated and service exposure that is convenient but not fully established; and endurance-aging RF monitoring, while informative, observes a small number of units and cannot by itself distinguish design-level from unit-level degradation. These limitations are not treated as reasons to abandon verification but as reasons to interpret convergent findings cautiously. The architecture was also revised during the work: an initial plan to verify electromagnetic performance only at end-of-line was abandoned after endurance-aging evidence suggested that late-stage drift could be missed, and lifecycle probing was inserted instead. This adjustment lengthened the experimental route considerably and introduced scheduling difficulties that had not been anticipated.

3. Coupling Analysis, Datum Coordination and Lifecycle Verification: Process and Observations

The conduct of the work did not follow the sequence in which the framework is presented, and it may be useful to describe the actual path, including its detours. The coupling analysis was begun first, on the assumption that a credible field model would provide the reference against which coordination could be judged. This assumption did not survive contact with the manufacturing data. When the coupled predictions were compared with curvature measurements from production units, the discrepancies were not random but clustered near regions where the datum had been redefined, which suggested that the coordination scheme, not the field model, was the dominant source of mismatch. The order of investigation was consequently reversed: coordination was examined first, and the coupling model was subsequently re-examined with coordination-induced residuals treated as an input rather than an error.

This reversal changed the interpretation of several observations. Consider the curvature inspection results. A straightforward reading is that the revised coordination rule improved conformity, since the point-wise deviations were reduced in the regions where the rule was most active. An alternative reading is that the improvement reflects the inspection's own datum handling, since the inspection itself uses unified-datum decoupling, and a rule that aligns with the inspection's decoupling logic may appear better without being better in service [29]. Both readings are plausible, and the available evidence does not decisively separate them; further research with an independently defined inspection datum would be needed. Similar ambiguity attaches to the mold compensation results. Closed-loop compensation drove the measured deviations toward the target, but compensation is, by construction, fitted to the measured points, and a compensation that fits the inspection cannot be assumed to fit unmeasured regions. The convergence observed should therefore be regarded as bounded evidence rather than proof of coupling fidelity.

The weathering and electromagnetic observations introduced a different kind of uncertainty. Accelerated weathering of the UV-blocking coating produced the expected optical durability, yet the dielectric consequences of coating degradation were not well resolved, and it remains possible that coating changes perturb electromagnetic performance in ways that optical metrics do not register. Endurance-aging RF monitoring showed degradation patterns broadly consistent with the literature, although the small sample size and the unknown prior history of the units limit what can be inferred. V2X sensitivity testing under multi-working conditions reproduced the condition dependence reported elsewhere, and this reproduction is itself informative, because it suggests that the condition dependence is a property of the test architecture as much as of the device; the modular simulation platform further supports this reading by allowing condition sets to be varied systematically. Whether the lifecycle probing sequence adopted here is sufficient to capture the relevant degradation modes is a question we cannot yet answer; the sequence was designed around plausible failure modes, and plausible is not the same as exhaustive.

4. Discussion

The findings invite several interpretations, and it would be premature to settle on one. A first interpretation is that the framework works: coordination improves conformity, compensation reduces deviation, and lifecycle probing captures degradation that

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end-of-line testing would miss. A second interpretation is less flattering, namely that the framework's apparent success is partly an artefact of shared assumptions between design and verification—the same unified-datum logic informs both coordination and inspection, and a coherent but mistaken assumption would propagate through both without being detected. The two interpretations are not mutually exclusive, and the honest position is that the present evidence is consistent with a mixture of both, in proportions that further work may clarify.

This leads us to further thinking about what "verification" means in a multi-physics manufacturing context. The conventional logic treats verification as an independent check on design; in practice, verification instruments embed design assumptions, and the independence is partial at best. The RF and V2X evidence is instructive here. Endurance-aging monitoring and multi-condition sensitivity testing are valuable precisely because they introduce conditions that the design did not anticipate, and their value lies less in confirming predicted behaviour than in exposing condition dependence that the design's own models had smoothed away. A verification architecture that only confirms is therefore of limited use; what is needed is an architecture that is deliberately inhospitable to the design's assumptions, and constructing such an architecture is a design problem in its own right.

The transferability question raised in the introduction deserves a more careful, and more sceptical, treatment than it usually receives. It is tempting to observe that digitalised enterprise operations and infrastructure project governance face analogous coordination problems—competing functional requirements, bounded compromise, verification that is entangled with operation—and to conclude that the framework transfers. Work on enterprise service-platform operation and efficiency evaluation, on industry–university–research collaborative innovation platforms, on platform strategy and industrial resource integration, on ERP–WMS integration for inventory turnover and on ERP cross-industry data-integration standards does indeed display coordination-under-competing-requirements structures [2]; infrastructure governance studies on capital efficiency, engineering–accounting integration, budget-overrun cost governance and principal–agent risk mitigation through joint engineering–financial review display them as well [11]. This temptation should nevertheless be resisted. The analogy is at the level of problem structure, not at the level of mechanism, and structural analogy is a weak warrant for methodological transfer. What may transfer is the discipline of admitting bounded families of parameters and of treating verification instruments as design variables; what is unlikely to transfer is the specific coupling physics. Whether the disciplined version of the analogy yields practical benefit in enterprise or infrastructure settings is, at present, a possible direction rather than a demonstrated one [12].

The limitations of the present work should be stated without softening. The inspection samples a finite point set; the weathering equivalence is assumed rather than established; the RF sample is small; and the coordination rule, though revised to admit residual sharing, still embodies choices that alternative rules might contest. These limitations do not invalidate the framework, but they do bound its claims, and the boundary should be visible to readers who might otherwise over-extend it.

5. Conclusion and Outlook

Read as a whole, the work suggests that the binding constraint in triple-functional windshield manufacturing may lie less in any single physics than in the coordination logic that ties the physics together, and that this logic is entangled with the verification instruments in ways that make independent confirmation difficult to secure; elevating the discussion from component tolerance to verification architecture reframes the practical problem as one of designing instruments that are inhospitable to design assumptions, a reframing whose value extends, tentatively and by structural analogy rather than by mechanism, to digitalised operations and infrastructure governance, where competing functional requirements and bounded compromise are equally familiar; and it points toward future work in which independently defined inspection data, larger endurance samples, and deliberately adversarial verification conditions could begin to separate genuine coupling fidelity from compensation artefact, while the transferability of the disciplined analogy remains an open and, we think, worthwhile question.

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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