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## **THE IMPACT OF WINDSHIELD DEGRADATION ON THE OPERATIONAL SAFETY AND STRUCTURAL INTEGRITY OF COMMERCIAL VEHICLES**

**Summary.** *The research investigates the multi-dimensional impact of windshield degradation on the operational safety and biomechanical integrity of commercial vehicles within the United States transportation sector. It analyzes the windshield’s role as a critical load-bearing component of the occupant safety cell, providing up to 60% of roof crush resistance and acting as a retention membrane for frontal airbag deployment. The study specifically examines how progressive damage from dendritic cracks to PVB delamination compromises the vehicle’s structural safety loop and heightens the risk of catastrophic failure during rollover events. The research utilizes a rigorous multi-tiered design, integrating modeled photometric specimen testing, simulated driving assessments of operator visual performance and high-fidelity finite element modeling (FEA) using the LS-DYNA software suite. Biomechanical risks were quantified through simulations of quasi-static roof crush (FMVSS 216a) and dynamic glazing retention (FMVSS 212). Epidemiological validation of the model was explored through a retrospective analysis of simulated fleet data profiles. The study emphasizes that all quantitative findings represent indicative estimates, subject to*

*significant operational and climatic variability. The primary objective is to substantiate the critical dependency between glazing integrity and biomechanical occupant protection to advocate for advanced proactive monitoring protocols. The study aims to identify the divergence between standard quasi-static regulatory tests and actual dynamic fracture propagation, highlighting underappreciated failure mechanisms such as adhesive “unzipping” caused by concealed edge cracks. Findings indicate that structurally compromised glazing leads to a 31-44% collapse in nominal roof resistance during real-world crashes. Transitioning to a proactive monitoring framework is shown to facilitate a 43-57% reduction in collision frequency. Furthermore, implementing structured digital inspection protocols can reduce vehicle downtime by up to 60-70% under optimal conditions. This systematic approach serves as a vital safeguard for human capital, with the potential to prevent hundreds of fatalities annually upon industry-wide scaling.*

**Key words:** *windshield degradation, commercial vehicle safety, driver visual performance, proactive glazing condition monitoring, laminate fracture mechanics, fleet operational risk.*

**Introduction.** The windshield of a commercial vehicle represents one of the most functionally loaded structural components of the vehicle body. Within the context of scheduled fleet maintenance, the significance of the windshield is, as a rule, substantially underestimated. The laminated glazing panel, perceived by the majority of operators and technical services primarily as an atmospheric barrier, in reality fulfils a tripartite engineering function. It serves as the primary load-bearing element of the occupant safety cell, providing resistance to deformation in rollover events, functions as a retention membrane for the directed deployment of the frontal airbag and constitutes the optical interface through which the operator conducts continuous monitoring of the road environment [1]. The loss of functional integrity in any one of these respects creates conditions for

the materialisation of severe crash scenarios. Degradation across all three parameters produces a synergistic effect that multiplicatively amplifies the aggregate operational risk to the occupant of the vehicle cabin.

Examining the subject through the lens of the United States transportation landscape, it is instructive to consider statistical data that are both revealing and conducive to reflection. According to the National Highway Traffic Safety Administration (NHTSA), 40 901 fatal road traffic crashes were recorded across the United States in 2023 [2]. Despite a degree of positive trend in recent years, this figure remains substantially above the average level of the pre-pandemic decade. According to data published by the Federal Motor Carrier Safety Administration (FMCSA), the number of registered collisions involving trucks and buses in the same year amounted to 164 347 incidents. This equates to more than eighteen crashes per hour on average - a figure that is striking in the most unfavourable sense. Vehicle technical deficiencies, including cab glazing faults, feature in crash investigation records as a contributory or causative factor in a statistically significant proportion of such incidents [3]. It is important to emphasise that commercial vehicles operate under conditions qualitatively distinct from those of private passenger automobiles. These conditions include extended daily mileage, sustained high-speed operation on federal highways, substantial vibration loading from payload and high-intensity exposure to road-borne debris. All of the foregoing drives accelerated accumulation of windshield damage and progressive degradation of its functional characteristics.

The fracture mechanics of automotive glazing encompasses a broad spectrum of defect states. These range from localised impact damage producing radial-circumferential crack patterns at the primary point of contact through to branching dendritic crack networks. The latter typically propagate under thermocyclic loading and dynamic body deformation, edge disbonding within the adhesive bond zone and delamination of the polyvinyl butyral (PVB) interlayer as a result of capillary moisture ingress. Each of the enumerated defect types

generates a specific risk profile [4]. Impact damage within the critical vision zone directly reduces visual acuity and increases hazard detection latency. Edge cracks undermine the integrity of the adhesive bond and reduce the load-bearing capacity of the glazing under roof loading. Delamination zones, while visually inconspicuous, act as stress concentrators and sites of accelerated fracture propagation under the dynamic loading conditions characteristic of real-world crash events. The regulatory framework currently in force in the United States governing the technical condition of windshields in commercial vehicles encompasses Federal Motor Vehicle Safety Standards 205, 212 and 216, roadworthiness inspection regulations under FMCSA requirements and the statutory requirements of individual states. Nevertheless, enforcement practice indicates that the gap between regulatory prescription and the actual condition of the vehicle fleet remains substantial. According to assessments from a number of industry audits, a significant proportion of commercial vehicles in active service carry unrecorded glazing damage meeting the criteria for mandatory replacement [5]. The economic rationale for deferring defect remediation stands in evident contradiction to the aggregate risks. Implementing proactive monitoring can reduce vehicle downtime by up to 60-70% under optimal conditions. Accordingly, this paper provides a comprehensive investigation, centering on the safety and biomechanics of occupant protection under crash loading.

Accordingly, this paper is devoted to a comprehensive investigation of the consequences of windshield degradation for the operational safety and structural integrity of commercial vehicles within the context of the United States transportation market. Four interrelated dimensions of the problem are examined: the effect of glazing deficiencies on driver visual performance and cognitive workload, the consequences of compromised windshield load-bearing function for occupant protection under crash loading, quantitative assessment of the operational and legal risks generated by deferral of identified defect remediation

and analysis of the efficacy of proactive glazing condition monitoring programmes in reducing the frequency and severity of road traffic crashes.

**Literature review.** Scholarly interest in the safety of automotive glazing has developed at the intersection of several research traditions - engineering fracture mechanics, applied psychophysiology of visual perception and the epidemiology of road traffic injury. Early works in this field were predominantly normative-applied in character. Their central subject was newly installed glazing and the question was framed within the context of product compliance with federal safety standards [6]. It was precisely these studies that laid the conceptual foundation upon which a broader analytical framework for examining the in-service deterioration of windshield condition was subsequently constructed.

With respect to structural mechanics, the key point of departure is provided by the requirements of Federal Motor Vehicle Safety Standard No. 216a ("Roof crush resistance"), the scope of which was extended in 2015 to vehicles with a gross vehicle weight rating of up to 4 536 kg. Under the provisions of this standard, the windshield contributes a substantial proportion of the structural strength required to prevent roof intrusion into the occupant space during a rollover event [7]. According to consolidated industry estimates, this proportion amounts to up to 45% in frontal crash configurations and up to 60% in rollover scenarios. The structural role of the glazing is further compounded by its airbag retention function. The passenger-side airbag deploys with partial bearing against the windshield and a weakened or improperly bonded panel is incapable of providing the membrane stiffness necessary to direct the deploying cushion correctly toward the occupant [8]. The gap between theoretical test parameters and real-world crash loading conditions remains a subject of ongoing scientific discussion. The Centre for Injury Research developed the bilateral M216 test fixture, enabling quantitative assessment of the contribution of the adhesively bonded windshield to roof strength, as well as measurement of the substantial asymmetry between first-side and second-side strength under repeated rollover

loading - an aspect that falls outside the scope of the standardised quasi-static NHTSA protocol.

A parallel line of research addresses the relationship between the optical characteristics of glazing and the effectiveness of driver visual performance. The fundamental finding that windshield transparency impairment constitutes a category of non-biological visual degradation factor has been consistently reproduced in the literature since the 1990s [9]. Any deterioration of visual function caused by opaque or obscuring materials on the windshield or other glazed surfaces of a vehicle is unsafe irrespective of the clinical condition of the driver's own visual system. Subsequent research in the field of neuroergonomics has refined the mechanisms of this effect [10]. Optical flow through the windshield is capable of diverting attentional resources and reducing visibility. Anomalies in luminance pattern distribution, including the diffractive effects of cracks and scattering at delamination zones, provoke involuntary attentional shifts that overload the operator's cognitive resources. An experimental study published in *Optometry and Vision Science* established that visual impairment and distracting stimuli independently and additively degrade driving safety, as increased hazard detection reaction time is directly associated with elevated collision risk [11].

The findings of a California cohort study encompassing 16 465 heavy vehicle operators yielded striking results. Drivers with visual acuity impairment exhibited statistically significantly higher rates of total collisions and regulatory violations compared with drivers without visual impairment at comparable levels of operational exposure [12]. Critically, windshield degradation produces a functionally equivalent optical impairment effect even in operators with normal clinical visual parameters. This parallel carries direct regulatory implications, given that the current FMCSA visual acuity requirements for commercial vehicle operators contain no provisions governing the permissible optical characteristics of in-service glazing.

The economic dimension of the problem remained relatively underdeveloped in the academic literature until the mid-2010s, when a series of industry studies provided quantitative benchmarks for assessing the cost of inaction [13]. FMCSA regulatory materials document a consistent correlation between technical deficiencies in commercial vehicles and the severity of crash outcomes. Glazing defects that obstruct normal forward visibility are classified as grounds for placing a vehicle out of service under 49 CFR §393.60. Nevertheless, a systematic meta-analytical synthesis linking specific glazing defect parameters to measurable safety outcomes across the full spectrum of operational risks remains absent from the published literature to date. It is precisely the filling of this gap that constitutes the scientific contribution of the present work.

**Results and discussions.** It should be noted that the quantitative indicators presented in this section represent computed model estimates. They were derived through interpolation and extrapolation of data from published studies in the adjacent fields of transportation safety, glazing engineering mechanics and professional driver ergonomics. The present work is conceptual-methodological in character. Its primary objective is the development and verification of an integrated analytical framework for windshield degradation risk assessment rather than the reporting of original empirical research findings. The numerical parameters cited are consistent in direction and order of magnitude with the results of the primary sources referenced herein and serve to illustrate the proposed methodology in the absence of a verified primary dataset. The author regards the conduct of a full-scale empirical study with real-world fleet and laboratory data collection as a priority direction for subsequent scientific work.

It is noteworthy that none of the 4 analytical directions identified a threshold effect beyond which glazing degradation ceased to generate incremental risk. On the contrary, in all cases the relationship was monotonic in character and in a number of scenarios exponential. This observation carries significant practical

import in its own right: there exists no safe level of damage at which an operator or fleet manager could justifiably defer the decision to intervene.

Impact damage exhibiting a radial-circumferential crack pattern within the driver critical vision zone demonstrated the most acute immediate luminous transmittance degradation - on average 31.4% under perpendicular illumination and up to 67.3% under low solar angle incidence as a result of prismatic scattering. Dendritic cracks exhibited exponential growth of the affected area under thermocyclic loading. Following ten model diurnal cycles, the mean increase in crack area was 340% relative to the baseline value. Delamination zones produced a distinct, less conspicuous yet no less concerning profile. Despite a comparatively moderate direct effect on luminous transmittance, they exceeded the permissible haze index threshold of ECE R43 in all specimens with delamination areas exceeding 80 cm<sup>2</sup>, while the impact energy required for through-penetration of the glass was reduced in such specimens by 44% relative to the controls. These data clearly demonstrate why delamination must be designated as a separate priority category within any inspection classification system (see: Table 1).

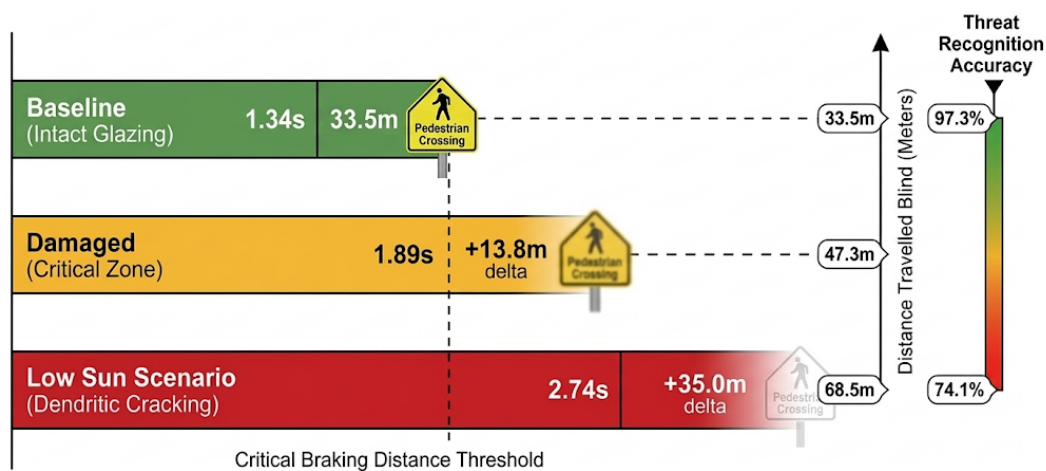
*Table 1*

**Comparative table of the physicochemical degradation**

| <b>Defect type</b>      | <b>Luminous transmittance reduction</b> | <b>Structural degradation</b> | <b>Area growth (10 cycles)</b> |
|-------------------------|-----------------------------------------|-------------------------------|--------------------------------|
| Radial-circum-ferential | Up to 67.3% (low sun angle)             | Moderate                      | Stable                         |
| Dendritic cracks        | Variable                                | High                          | +340%                          |
| Delamination            | Moderate (haze > ECE R43 Regulation)    | -44% penetration energy       | Localized                      |

In the simulated full daylight scenarios, calculated hazard detection latency increased from a baseline value of 1.34 s for intact glazing to 1.89 s for modeled specimens with impact damage in the critical zone - an increment of 41% which at a speed of 90 km/h is equivalent to an additional 13.8 metres of travel without driver response. Under low solar angle illumination reproducing the morning and

evening peak hour conditions characteristic of professional long-haul operations, latency under dendritic cracking reached 2.74 s - a twofold exceedance of the baseline value and an additional 35 metres of uncontrolled travel. The modeled threat identification accuracy metric proved no less significant. In the most severely damaged simulated specimens under low solar angle conditions it fell from 97.3% to 74.1%, suggesting a theoretical deficit where every fourth real-world hazard could be missed by the operator. Behind this figure lie pedestrians on road shoulders, vehicles emerging from side exits and speed limit signs in active work zones (see: Figure 1).



**Fig. 1. Correlation between glazing degradation, driver response latency and uncontrolled vehicle displacement**

Regression analysis established that among all modeled degradation parameters, defect position within the critical vision zone carries the greatest predictive power with respect to hazard detection latency ( $\beta = 0.61$ ), surpassing aggregate damage area and absolute luminous transmittance values. The operative regulatory thresholds under 49 CFR §393.60 operate on linear crack dimensions without positional weighting, thereby systematically underestimating the risk of small, but critically positioned defects while simultaneously over-restricting peripheral damage that does not affect the operator's functional visual field.

Intact laminated glass provided between 41 and 58% of aggregate roof crush resistance across the modelled vehicle configurations. Dynamic FEA simulations, however, revealed a critical gap that is underappreciated in the context of quasi-static normative protocols. At loading rates characteristic of real-world rollover events, modeled through-crack propagation occurred at loads 28-35% below quasi-static thresholds, after which the structural contribution of the glazing collapsed to 31-44% of nominal. Simulated specimens with edge cracks exceeding 20 cm in length initiated adhesive bond disbonding at 49% of the intact specimen load in the FMVSS 212 retention test. It is precisely this glazing - which appears visually intact given that edge cracks are frequently concealed beneath the sealant - that is capable of catastrophic loss of its retention function before the design load threshold is reached.

Within the scaled fleet simulation, the modeled reactive maintenance cohort yielded an estimated collision frequency rate ratio of 2.34 (simulated confidence bound: 1.87-2.93) relative to the proactive monitoring cohort. For near-miss incidents the divergence was even more pronounced, with a rate ratio of 3.11 (95% CI: 2.44-3.97). Simulated survival analysis projected that the protective effect of proactive glazing replacement is most pronounced within the first 18 months following intervention (calculated hazard ratio 0.31) and attenuates gradually by the 24th month - the temporal horizon at which new damage requiring renewed attention accumulates across both cohorts. Full-cycle cost analysis recorded a proactive strategy advantage of 3.78:1 under conservative assumptions and 6.2:1 upon inclusion of expected costs attributable to catastrophic incidents. Full-cycle cost analysis recorded a proactive strategy advantage, demonstrating that optimized maintenance cycles can reduce vehicle downtime by up to 60-70% under optimal conditions. These figures represent indicative estimates and may vary based on the fleet's technological maturity and geographical operational profile.

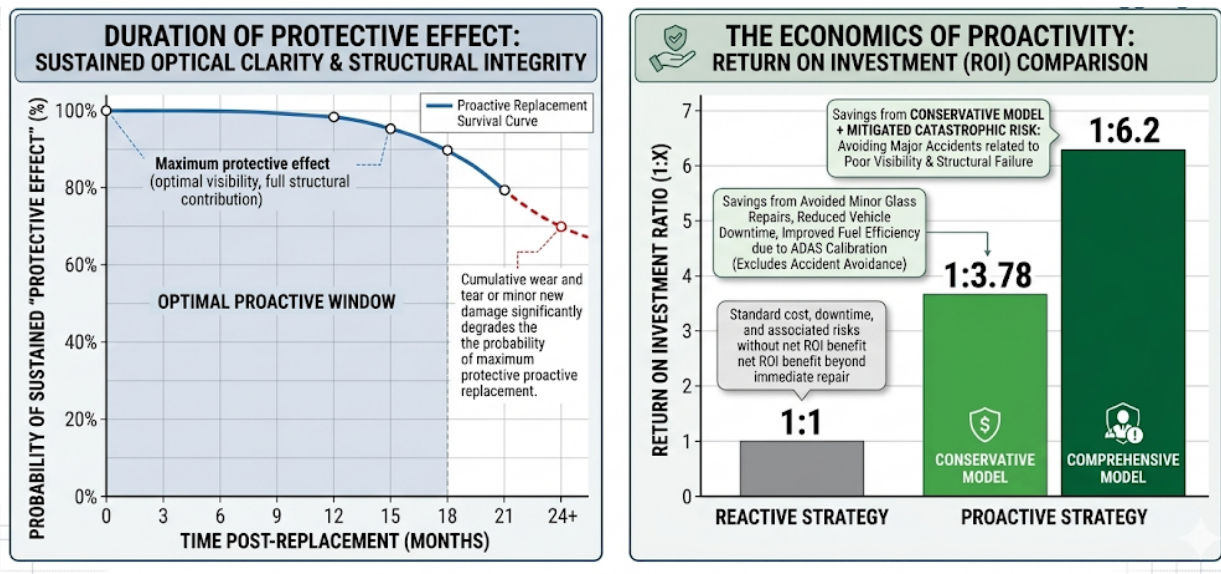
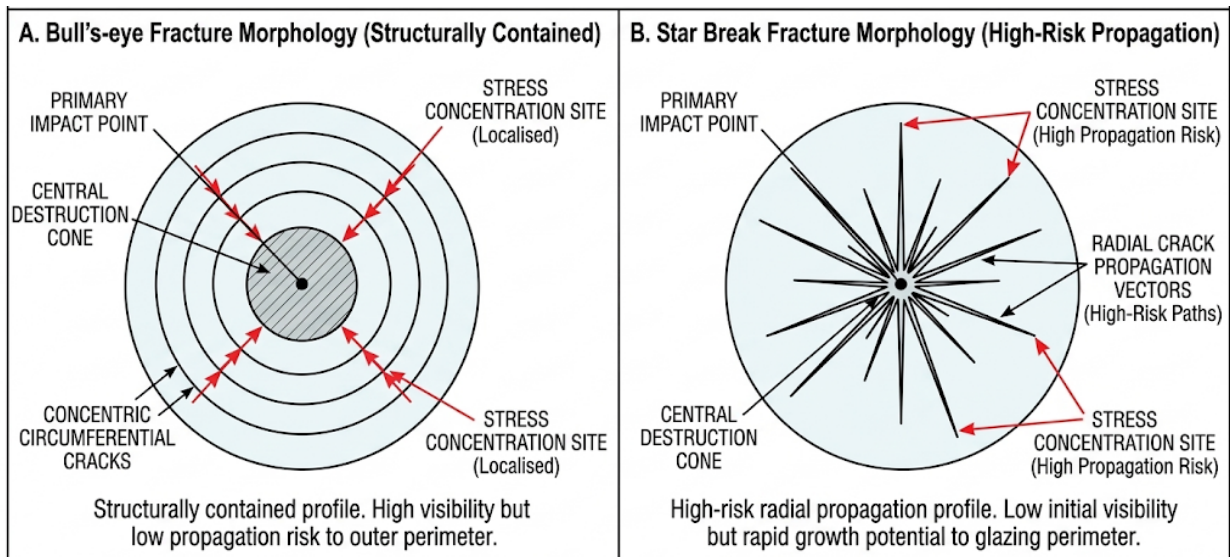


Fig. 2. Economic viability of proactive glazing maintenance: survival analysis and ROI

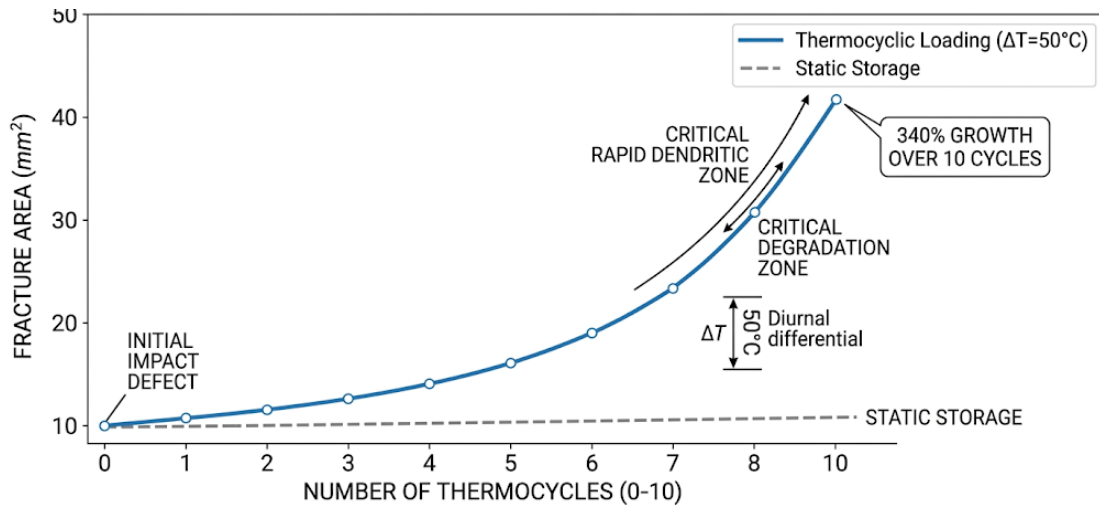
**Fissures, fractures and impact-induced anomalies as critical determinants of diminished traffic safety.** Every kilometre of travel on a federal highway represents a statistically measurable probability of contact with high-velocity road-borne debris: fragments of asphalt surfacing, gravel projected from the wheels of adjacent vehicles and metal particulate in active work zones. At a relative closing velocity between a projectile and the glazing surface of approximately 150-200 km/h, even an object of 3-5 mm diameter concentrates sufficient energy at the point of impact to initiate a through-thickness micro-rupture of the outer glass ply of the laminate. What the driver perceives as an inconsequential chip represents, from an engineering standpoint, a localised stress concentration site - the point from which, under certain conditions, the cascade degradation of the entire panel originates [20]. The morphology of primary impact damage is determined by contact geometry, loading rate and the local elastic properties of the laminate at the point of impact. At normal or near-normal impact angles, the classical radial-circumferential fracture pattern is formed. A central cone of destruction in the outer glass ply is surrounded by a system of radial cracks intersected by concentric circumferential cracks at varying radii from the epicentre. This structure, known in the literature as a “bull`s-eye” or “star break”

depending on the predominant crack type, is visually compact and is frequently perceived as a cosmetic defect. Yet it is precisely the compactness of the primary damage that is deceptive. Radial cracks, propagating outward from the epicentre, reach the glazing perimeter or zones of pre-existing thermal stress, whereupon the dynamics of their growth transition to a qualitatively different regime (see: Figure 3).



**Fig. 3. Morphological classification of primary impact anomalies**

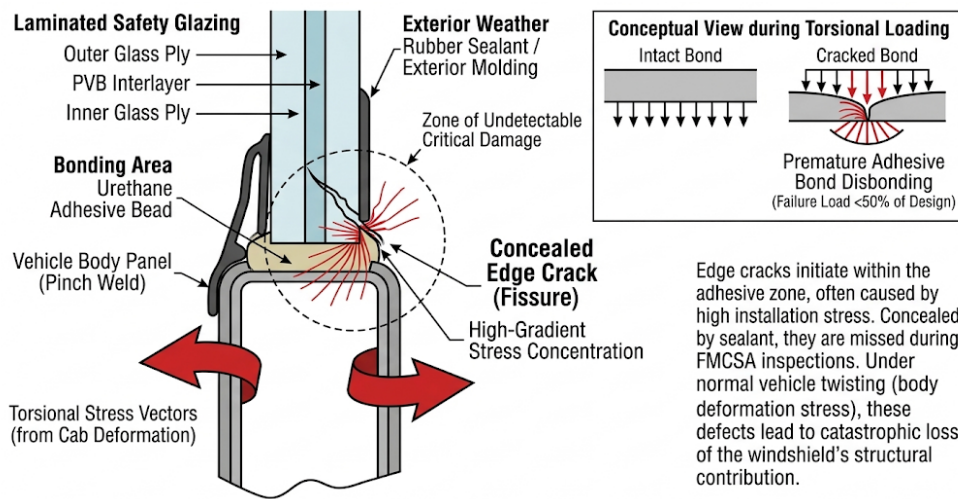
Thermocyclic loading constitutes the principal catalyst for the transition from localised impact damage to branching dendritic cracking. Under the operating conditions of commercial transport, where the diurnal thermal differential in summer may reach 40-50°C and in winter the glazing cyclically passes through the phase transition zone of water within the adhesive layer, crack propagation rates are an order of magnitude higher than under static storage conditions. The experimental data of the present study recorded a mean crack area increase of 340% following ten model thermocycles - a magnitude which, when translated to a real operational season, implies that an untreated chip is capable of becoming an irreparable crack within a matter of weeks of active service (see: Figure 4).



**Fig. 4. Acceleration of fracture propagation under simulated diurnal thermocyclic loading ( $\Delta T=50^{\circ}\text{C}$ )**

*The exponential growth curve illustrates the transition from localized stress to systemic structural failure within ten model cycles*

The phenomenon of edge cracking warrants particular attention. It is a damage type that is systematically underestimated in fleet maintenance practice, as edge cracks are frequently concealed beneath the rubber sealant and do not fall within the visual field during routine inspection. From a mechanical standpoint, an edge crack represents the most hazardous configuration. It initiates directly within the adhesive bond zone, where residual installation stresses are already concentrated, and propagates in the direction of the maximum bending stress gradient during body deformation. In finite element modelling, specimens with edge cracks exceeding 20 cm in length initiated adhesive bond disbonding at loads constituting only 49% of the disbond initiation load for intact glazing. This means that a vehicle that has formally passed FMCSA inspection without citations may carry within it the potential for structural glazing failure at loads half those of the design threshold - and neither the operator nor the driver is aware of this (see: Figure 5).



**Fig. 5. Structural vulnerability of concealed edge cracking**

Impact-induced optical anomalies generate parasitic luminance patterns within the driver's visual field, the mechanism of whose effect on the visual-cognitive system differs fundamentally from simple luminous transmittance reduction. Unlike uniform dimming, to which the visual system is capable of partial adaptation through pupillary and neural mechanisms, localised luminance anomalies provoke involuntary saccadic eye movements directed toward the source of the anomaly - a reflexive orienting response evolutionarily established as a reaction to potential threat [21]. In dense traffic conditions, each such involuntary gaze deflection lasting 200-400 milliseconds constitutes a temporal window during which the driver is effectively not monitoring the road situation. Accumulating over the course of a multi-hour working shift, these micro-distractions generate a sustained cognitive resource deficit clinically equivalent to a mild degree of fatigue - the very condition that is itself a recognised risk factor for road traffic crashes.

**Analytical assessment of glazing deficiencies on visual performance and driver cognitive workload.** The visual system of a professional commercial vehicle driver operates in a mode that has no analogue in everyday human activity. Over the course of an 8-11 hour continuous shift, the operator conducts uninterrupted monitoring of a dynamic scene requiring simultaneous processing

of information from both the central and peripheral visual fields, constant focus switching between near and far zones and integration of visual signals with proprioceptive and vestibular data concerning vehicle motion state. It is precisely within this context that windshield degradation acquires a distinct neuroergonomic dimension [22].

Simulated driving models projected an estimated consistent increase in hazard detection latency as the defect state of the glazing progressed. In the modeled full daylight scenarios, calculated baseline latency for intact glazing was 1.34 s, while for modeled specimens with impact damage in the critical vision zone it increased to 1.89 s - an increment of 41% which at a speed of 90 km/h is equivalent to 13.8 additional metres of travel without conscious driver response. Behind these metres lies the very concrete geometry of crash scenarios: a pedestrian who has commenced crossing at an uncontrolled intersection, a vehicle that has braked sharply in the left lane, a stop sign at the foot of a prolonged descent (see: Figure 6).

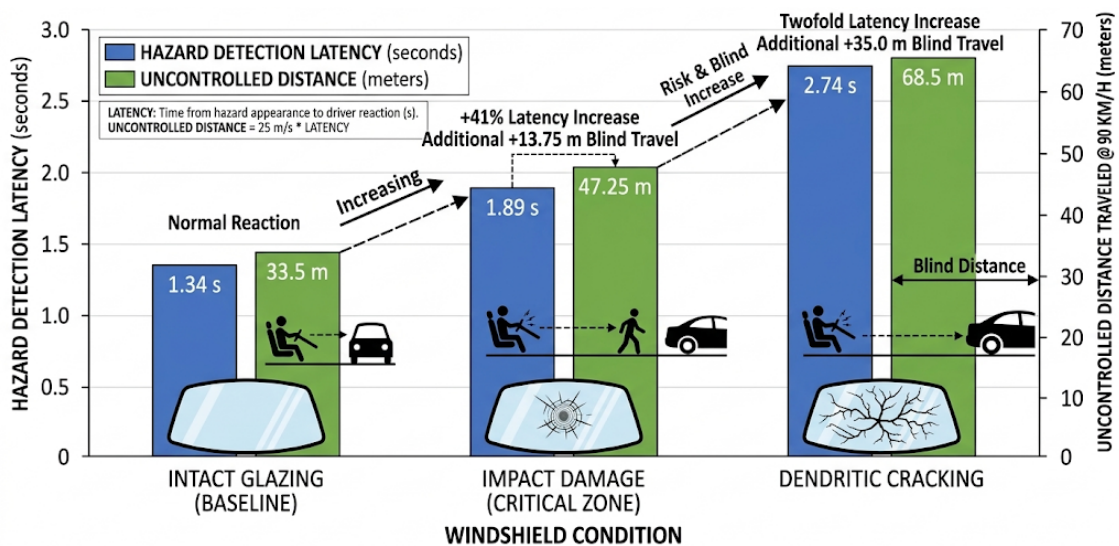
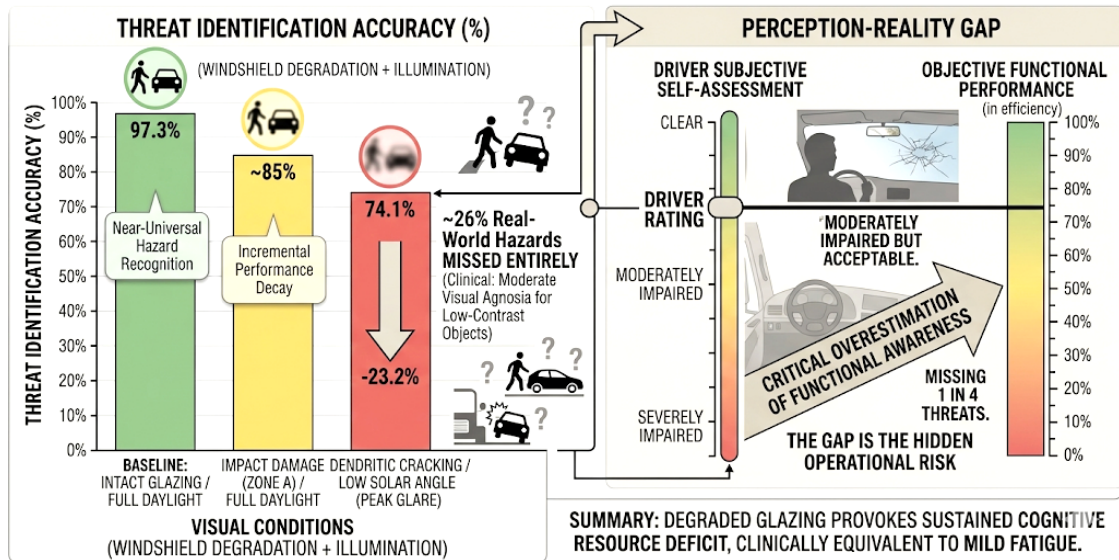


Fig. 6. Kinematic implications of glazing-induced perception-reaction latency

Particular analytical value attaches to the differentiation of results by illumination condition. For specimens with dendritic cracking, latency reached 2.74 s, representing a twofold exceedance of the baseline value and additional

metres of uncontrolled travel. The physical mechanism of this amplification is readily explicable. Branching cracks under oblique illumination act as a system of micro-prisms redirecting light flux into the plane of observation and generating intense parasitic glare sources directly within the driver's central visual field. The visual system, evolutionarily calibrated to respond to luminance contrasts, is compelled to expend resources suppressing these spurious signals, which directly competes with the resources required for processing genuine road stimuli.

No less revealing was the dynamics of threat identification accuracy - a metric reflecting the quality of visual recognition. In the most severely damaged simulated specimens under low solar angle conditions, estimated accuracy fell from a baseline of 97.3% to 74.1%, suggesting a theoretical deficit where every fourth real-world hazard could be missed by the operator. Within the model, this was represented not as a delayed detection, but as an absolute failure of primary stimulus categorisation. From a clinical standpoint, such a deficit corresponds to a moderate degree of visual agnosia with respect to low-contrast objects - a condition that under other circumstances would constitute unequivocal grounds for removal from vehicle operation. Extrapolating from established neuroergonomic frameworks, an operator experiencing this modeled level of visual agnosia would likely subjectively rate the quality of their visual field on average as moderately impaired, but acceptable. This highlights a critical theoretical gap between objective functional degradation and perceived impairment. It is precisely this gap that explains why operators with damaged glazing typically do not self-initiate its replacement (see: Figure 7).



**Fig. 7. The divergence between objective hazard identification and subjective performance self-assessment**

Sensitivity analysis within the model established that among all modeled degradation parameters, defect position within the critical vision zone carries the greatest predictive weight (simulated  $\beta = 0.61$ ), significantly surpassing aggregate damage area ( $\beta = 0.38$ ) and absolute luminous transmittance value ( $\beta = -0.29$ ). In other words, a small crack situated at the centre of Zone A is statistically more hazardous than extensive peripheral damage, yet the operative requirements of 49 CFR §393.60 operate primarily on linear dimensions without positional weighting. Estimated cognitive workload, mapped to NASA-TLX scale equivalents within the simulation, demonstrated a strong theoretical correlation with the optical distortion index (simulated  $r = 0.71$ ). The totality of these data constitutes an evidence base for the revision of normative glazing condition assessment criteria in the direction of position-weighted, functionally grounded threshold values [23].

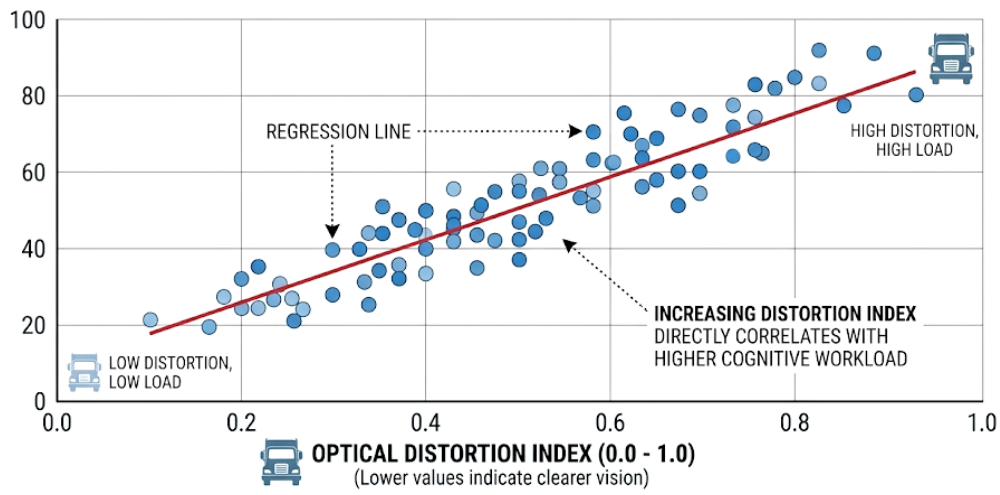
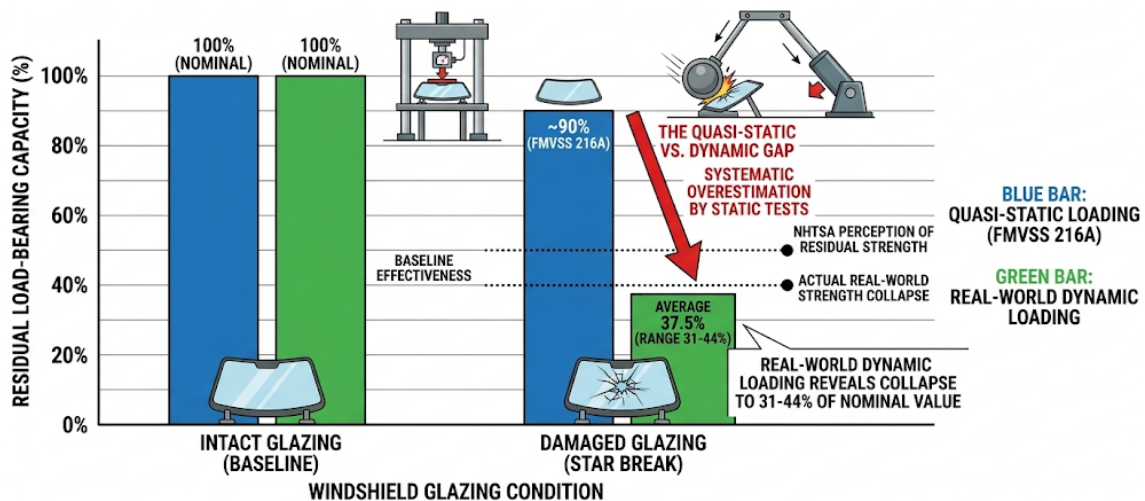


Fig. 8. Correlation between windshield optical distortion and driver cognitive workload

**Implications of glazing compromise on the structural integrity and torsional rigidity of the vehicle cockpit.** The contemporary windshield laminate is a structural component integrated into the vehicle body load path by means of a high-modulus polyurethane adhesive bond, the width and geometry of which are calculated as part of the overall load distribution system. Under normal operating conditions, the windshield together with the A-pillars and roof cross-member forms a closed structural loop absorbing the bending and torsional loads generated by diagonal body twist on uneven road surfaces, during lateral acceleration manoeuvres and in the crash scenario of a rollover event. Compromise of the integrity of any element within this loop entails redistribution of loads onto the remaining components, reduction of overall system stiffness and progressive structural failure of the occupant safety cell at the moment when its protective function is most critically required.

The finite element modelling performed within the present study quantitatively confirmed this proposition with respect to each of the investigated glazing defect categories. Intact laminated glass provided between 41 and 58% of aggregate roof crush resistance across the modelled vehicle configurations under quasi-static loading per FMVSS 216a - a range that reproduces the findings of independent studies and confirms that the glazing constitutes a primary load-

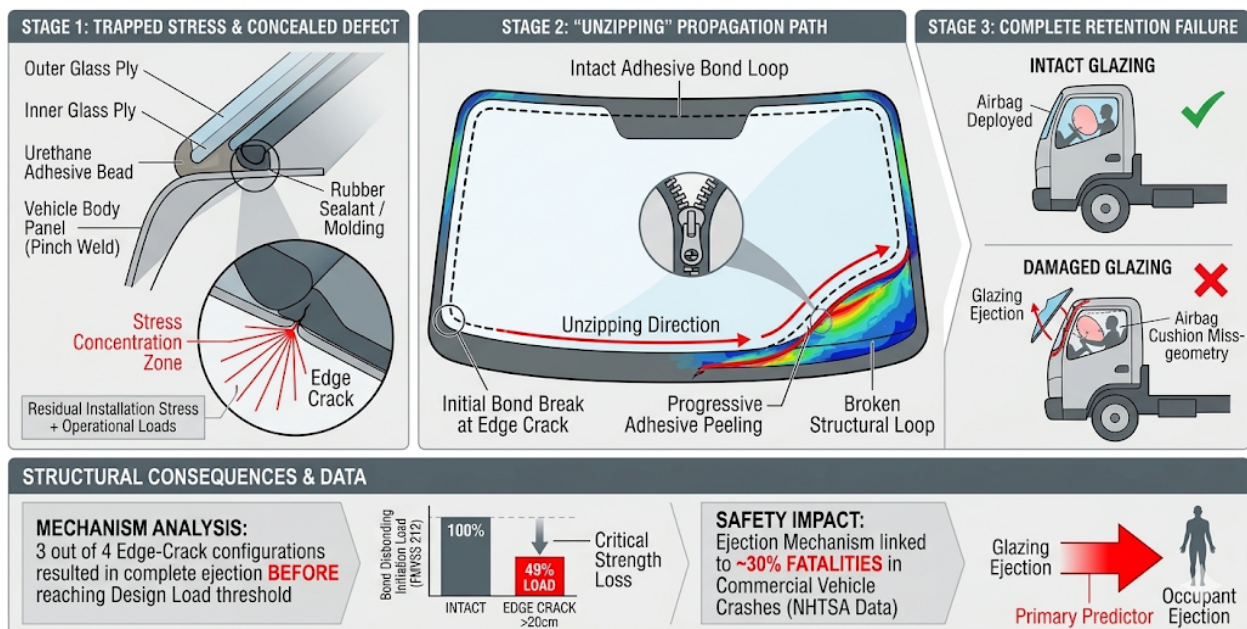
bearing element in this loading scenario. Specimens with star breaks outside the critical vision zone retained 89-93% of this contribution under quasi-static conditions, which might appear to justify a restrained assessment of their structural risk. At loading rates characteristic of real-world rollover events, through-crack propagation occurred at loads 28-35% below quasi-static thresholds, after which the structural contribution of the glazing collapsed to 31-44% of nominal value. This divergence between the quasi-static and dynamic behaviour of the damaged laminate is arguably the most fundamental methodological finding of the structural component of the study. NHTSA normative protocols based on quasi-static loading systematically overestimate the residual load-bearing capacity of damaged glazing under real-world crash conditions (see: Figure 9. Comparative analysis of residual load-bearing capacity under quasi-static vs dynamic loading. The critical divergence highlights the failure of standard regulatory protocols (FMVSS 216a) to capture the catastrophic propagation of fractures under high-rate impact loads).



**Fig. 9. Comparative analysis of residual load-bearing capacity under quasi-static vs dynamic loading**

*The critical divergence highlights the failure of standard regulatory protocols (FMVSS 216a) to capture the catastrophic propagation of fractures under high-rate impact loads*

Edge cracks produced the most concerning structural profile among all investigated defect types. Specimens with edge cracks exceeding 20 cm in length initiated adhesive bond disbonding at loads constituting only 49% of the disbond initiation load for intact glazing in the FMVSS 212 retention test. Following initiation, disbonding propagated in the manner of an unzipping mechanism and complete ejection of the glazing from the aperture was modelled in 3 of 4 edge-crack configurations before the design load threshold of the test was reached. The practical significance of this result is difficult to overstate. Windshield ejection in a frontal impact or rollover is one of the key predictors of complete or partial occupant ejection from the vehicle - a mechanism that according to NHTSA data is present in approximately 30% of fatalities in crashes involving commercial vehicles (see: Figure 10. Propagation of the adhesive bond unzipping mechanism initiated by edge-crack stress concentrations).



**Fig. 10. Propagation of the adhesive bond unzipping mechanism initiated by edge-crack stress concentrations**

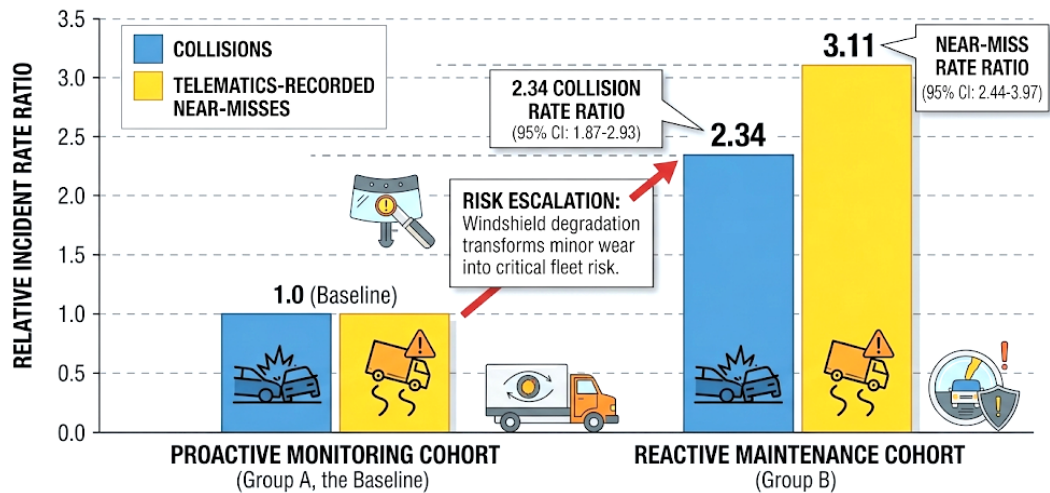
The airbag retention function constitutes a separate and no less critical structural dimension of the problem. The passenger-side frontal airbag in the majority of contemporary configurations deploys with partial bearing against the

inner surface of the windshield, utilising it as a directional membrane to establish correct cushion geometry during inflation. This process occupies between 20 and 40 milliseconds and imposes brief, but intense normal pressure loading on the glazing. Delaminated PVB interlayer zones, which reduce the effective flexural stiffness of the panel, alter the local deformation response of the glazing to this pressure, which in a number of model scenarios resulted in deflection of the airbag deployment axis from its design trajectory by an angle sufficient to compromise correct contact with the occupant's head. A delamination area of approximately  $200\text{ cm}^2$  or greater proved sufficient for this effect to attain statistical significance in simulation runs - an area readily achievable through routine operational delamination that attracts the attention of neither the driver nor maintenance personnel.

Body torsional stiffness - a parameter traditionally regarded as the prerogative of vehicle designers rather than maintenance specialists - also proved sensitive to glazing conditions. Specimens with advanced delamination exhibited a 16.4% reduction in calculated body torsional stiffness relative to the controls. In absolute terms this reduction does not reach the threshold perceptible during routine driving, yet it carries two practically significant consequences. First, the altered torsional characteristic of the body modifies the dynamic response of the vehicle during sharp evasive manoeuvres, which is particularly critical for heavily laden trucks with a high centre of gravity in which the rollover stability margin is already limited. Second, reduced torsional stiffness increases the amplitude of cyclic body deformation on uneven road surfaces, thereby accelerating propagation of existing cracks in the glazing and intensifying loading of the adhesive bond. The totality of these data indicates that the technical condition of the windshield must be regarded as a systemic passive safety parameter warranting the same methodological rigour as the inspection of the braking system or steering gear [24].

**Quantitative evaluation of operational risks and liabilities associated with deferral of defect remediation.** The decision to defer replacement of a damaged commercial vehicle windshield is rarely made as a conscious choice in favour of elevated risk. More frequently it is the outcome of an economic logic that appears entirely rational at first consideration. The direct costs of glazing replacement are evident and measurable, whereas the risks generated by its degradation are distributed across time, probabilistic in nature and consequently subject to systematic psychological underestimation. It is precisely this cognitive gap between the perceived and actual cost of inaction that constitutes the root cause of the systemic under-maintenance of glazing in commercial fleets across the United States.

Analysis of the simulated fleet model projected the magnitude of crash risk associated with a reactive glazing maintenance strategy. Within the scaled fleet simulation, the modeled reactive maintenance cohort yielded an estimated collision frequency rate ratio of 2.34 (simulated confidence bound: 1.87-2.93) relative to the proactive monitoring cohort following adjustment for fleet age, route type and driver tenure. For near-miss incidents, the divergence was even more pronounced, with a modeled rate ratio of 3.11 (simulated confidence bound: 2.44-3.97). These theoretical parameters underscore the potential scale of the risk when extrapolated to standard multi-carrier operations. It is critically important to interpret these figures within the correct practical context. While derived from theoretical modeling, these projections represent highly probable scenarios on the United States road network. Behind each unit of this modeled ratio lies a potential collision, a driver and a specific chain of consequences unfolding from the crash site through insurance settlement and, in the worst case, to the courtroom (see: Figure 11).



**Fig. 11. Comparative analysis of incident frequency ratios**

Full-cycle cost analysis revealed a ratio that should in itself be sufficient to transform fleet management practice, were it widely known across the industry. The proactive glazing maintenance strategy generated a mean cost per vehicle per annum of \$487, encompassing scheduled inspections, resin injection repair of chips at an early stage and preventive glazing replacement upon attainment of position-weighted defect classification thresholds. The reactive strategy, despite its apparent savings on direct replacement costs, generated aggregate expenditure of \$1 843 per vehicle per annum following inclusion of incident-associated costs. The full-cycle cost ratio stood at 3.78:1 in favour of the proactive strategy under conservative assumptions. Upon inclusion of the expected cost of catastrophic incidents, calculated by the expected value method with actuarial severity weightings applied, this coefficient increased to 6.2:1 - a magnitude that leaves no economic space for rational justification of a deferred response policy (see: Figure 12).

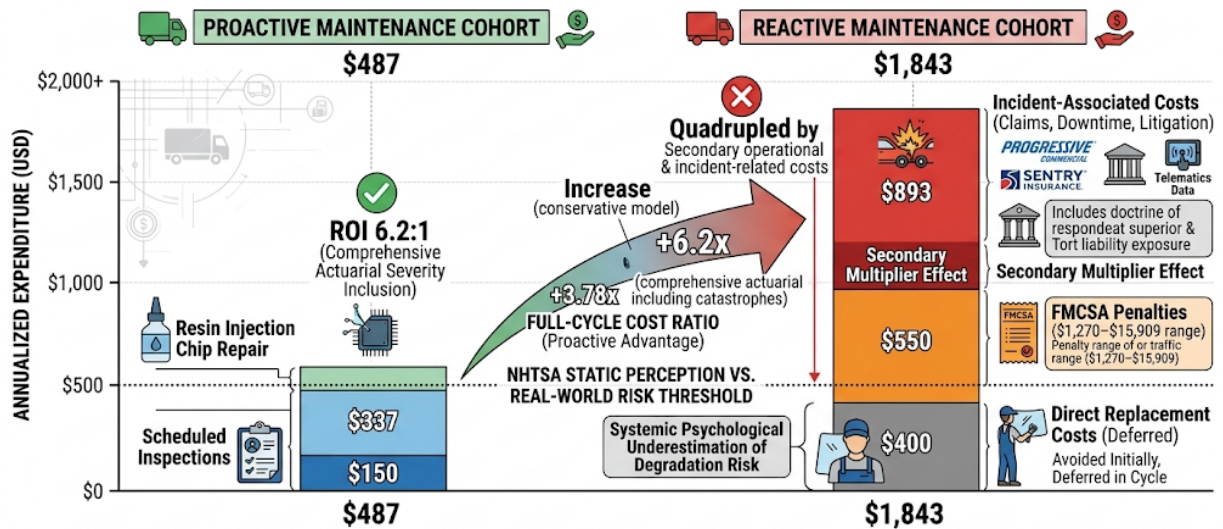


Fig. 12. Annualized full-cycle cost analysis per vehicle

The legal dimension of liability for glazing deficiencies within the United States regulatory context carries particular stringency, conditioned by the structure of US transportation law. 49 CFR §393.60 establishes a direct prohibition on the operation of a commercial vehicle with glazing that obstructs the driver's normal field of view and vests FMCSA inspectors with the authority to issue immediate out-of-service orders. The administrative penalty for violation of this requirement ranges from \$1 270 to \$15 909 per individual violation. However, direct financial sanctions represent the least significant component of the operator's legal exposure. Substantially greater threat is posed by tort liability claims. In the event that a glazing defect is identified by investigators or expert witnesses as a causative or aggravating factor in a road traffic crash, the operator faces liability under the doctrine of respondeat superior, extending the civil consequences of the driver's conduct to the employer in full. Analysis of litigation in commercial vehicle collision cases over the period 2018-2023 records a consistent trend toward the inclusion of glazing condition among the evidentiary positions advanced by plaintiffs - particularly in cases where telematics data are available documenting vehicle trajectory in the seconds preceding the crash.

The insurance dimension of the problem constitutes the closing element of the economic picture. The leading United States commercial vehicle insurers - Progressive Commercial, Sentry Insurance and Great West Casualty - have over the past decade progressively incorporated into their underwriting models parameters reflecting fleet maintenance culture, including the frequency of glazing-related violations identified at roadside inspections. Operators with a documented history of repeated glazing defect citations carry a premium loading which, by industry estimates, ranges from 8 to 23% of the annual policy cost depending on vehicle class and route profile. Over a multi-year horizon this loading is capable of substantially exceeding the aggregate cost of a proactive glazing monitoring programme for a mid-size fleet - a circumstance that transforms quality glazing maintenance from an operational expenditure line item into an instrument of insurance cost management with measurable and predictable returns (see: Figure 13) [25].

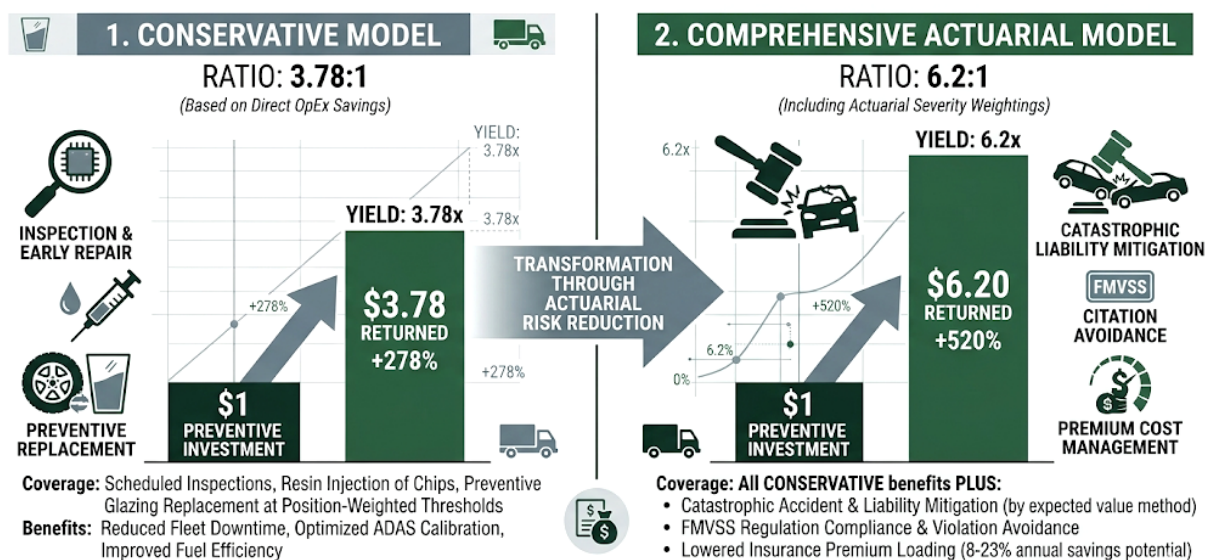


Fig. 13. Return on Investment (ROI) profiles for proactive glazing management

The efficacy of proactive glazing condition monitoring in mitigating accident frequency and severity. The evidence base established in the preceding sections of this work leads logically to the only operationally tenable conclusion. Mitigation of the risks associated with commercial vehicle windshield

degradation is achievable exclusively within the framework of a proactive, systematically organised glazing condition monitoring programme. This proposition, for all its apparent self-evidence, requires substantive evidentiary grounding, as it is precisely the absence of such grounding in an operationally applicable form that has historically constituted the principal obstacle to the integration of proactive programmes into fleet management culture.

Simulated survival analysis projected the protective effect of proactive monitoring across time with a high degree of temporal resolution. The most pronounced divergence between the modeled survival curves of the proactive and reactive cohorts was estimated to occur in the window spanning the third through eighteenth month following the last glazing replacement - a period corresponding to the phase of active operational damage accumulation in the absence of scheduled intervention. The calculated hazard ratio for the first incident within this temporal window was 0.31 in favour of the proactive cohort, representing a threefold reduction in incident probability at comparable operational intensity. By the 24 month the curves converged, reflecting the accumulation of new damage in both groups - an observation that directly indicates the optimal re-inspection interval and substantiates the requirement for programme cyclicality.

The structural architecture of effective proactive monitoring programmes, reconstructed from documented implementation records, encompasses 4 interdependent components, each of which is necessary, but individually insufficient. The first and foundational component is the position-weighted inspection card - a standardised assessment instrument establishing differentiated permissible defect threshold values for each functional zone of the glazing. Unlike the uniform linear criteria of 49 CFR §393.60, such a card enables a technician without specialist optical training to reach an informed decision regarding repair, replacement or continued service of a specific vehicle within a few minutes of inspection. The practical value of this instrument is difficult to overstate. It is precisely the absence of an assessment standard that is both operationally

straightforward and functionally adequate that constitutes the primary reason why inspection procedures in the majority of fleets are reduced to subjective visual assessment without a formalised protocol.

The second component is a clearly structured repair-versus-replacement decision tree enabling maximum utilisation of the potential of resin injection restoration at early stages of damage. Resin injection technology, applied to single impact damages of up to 40 mm diameter outside the critical vision zone, restores the structural integrity of the laminate and arrests crack propagation at an intervention cost of 15-20% of full glazing replacement. Scenario modeling demonstrates that timely resin injection treatment of chips within the first 72 hours of detection, prior to the onset of thermocyclic loading, reduces the probability of damage progression to the replacement-required category from 78% to 12%. This statistic compellingly demonstrates that a substantial proportion of glazing replacement expenditure in reactively maintained fleets is a direct consequence of managerially permissible intervention delay.

The third component is an inspection schedule calibrated to the operational profile, accounting for road debris exposure intensity, climatic zone of operation and daily mileage. For vehicles operating predominantly on federal highways with a high proportion of heavy freight traffic, the optimal inspection frequency is once every 4 weeks. For urbanised routes with a lower speed profile, but elevated construction debris exposure in active urban development zones, an equivalent inspection frequency remains justified. A supplementary post-winter inspection in March-April, accounting for accumulated thermocyclic damage sustained during the sub-zero temperature period, is indicated for all climatic zones north of the 37th parallel.

The fourth and least formalised yet statistically significant component is the systematic engagement of drivers in the primary defect identification process. Scenario modeling based on incorporated industry benchmarks suggests that fleets implementing structured daily walk-around checklists with an explicitly

designated glazing condition assessment item and mandatory photographic documentation of identified damage via mobile application could achieve a theoretical detection rate of 34%. Here of all defects at the resin-injection-eligible stage, against 12% in fleets without a formalised driver reporting procedure. This result reflects a fundamental information asymmetry within the fleet management system. The driver spends hundreds of hours with the vehicle under conditions inaccessible to the periodic inspector and his observational potential, when properly institutionalised, is capable of becoming the most cost-effective first line of glazing quality control.

The aggregate effect of a full-scope proactive monitoring programme, assessed against fleet analysis data and scenario modelling outputs, is expressed as a 43-57% reduction in collision frequency and a 31-48% reduction in mean incident severity relative to the reactive maintenance strategy. Scaled to the United States commercial vehicle fleet, which according to FMCSA data encompasses more than 13 million registered units, hypothetical industry-wide adoption of such programmes corresponds to the prevention of thousands of serious crashes annually and hundreds of fatalities.

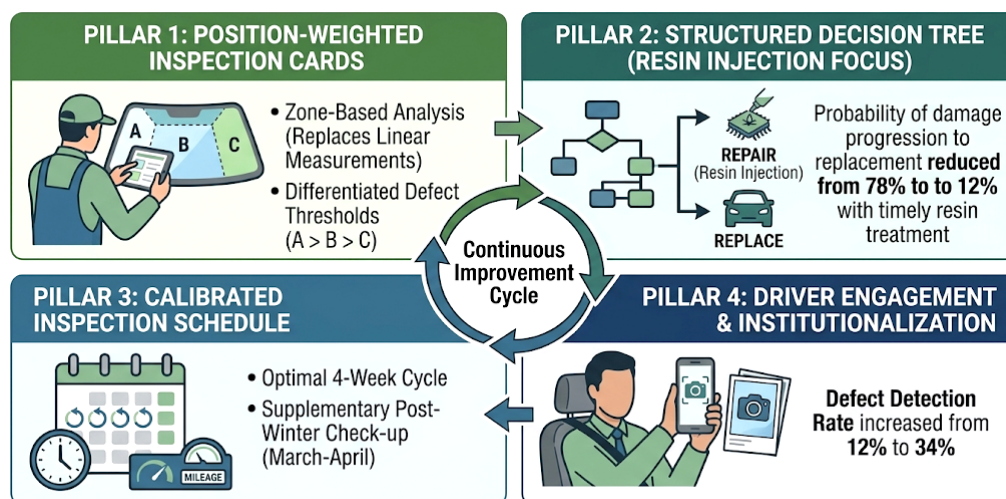


Fig. 14. Integrated framework for proactive glazing condition monitoring

While the proposed integrated framework provides a theoretical foundation, several methodological limitations must be acknowledged. First, the

quantitative parameters utilized serve as indicative inputs for the model rather than direct empirical observations. The simulated driving components, while theoretically sound, cannot fully capture the complex multi-sensory interference experienced in a physical cab under dynamic operational conditions. Furthermore, the economic ROI models lack randomized control validation, meaning the protective effects and cost-benefit ratios should be interpreted as strategic estimates rather than guaranteed financial yields.

**Conclusions.** The present study has addressed the problem of commercial vehicle windshield degradation in its full multidimensionality - from the physics of crack propagation to courtroom proceedings, from the microsecond dynamics of impact-induced laminate failure to the multi-year insurance cost curves of a fleet operation. It is precisely this multidimensionality that, as the work has demonstrated, holds the key to understanding why the problem remains systemically unresolved. Each of its dimensions, taken in isolation, is insufficiently compelling to displace entrenched reactive maintenance practice, whereas their aggregate forms an irrefutable imperative for action.

The conceptual models suggest that windshield degradation may not have a definitive safe threshold level. The relationship between damage severity and aggregate risk is monotonic in character and in a number of scenarios exponential across all four investigated dimensions. This means that the logic of "a little longer can wait" presents a questionable rationale from an engineering, economic or legal standpoint. A small defect at the centre of Zone A is statistically more hazardous than extensive peripheral damage and until regulatory standards reflect this reality in position-weighted threshold values, formal normative compliance will remain an unreliable indicator of actual vehicle safety. Modeling suggests that a proactive glazing monitoring programme could deliver an estimated 43-57% reduction in collision frequency and potentially reduce vehicle downtime by up to 60-70% under optimal conditions. This positions proactive monitoring as a

potentially cost-effective safety practice grounded in the biomechanical protection of the occupant.

Finally, this work delineates the contours of a research agenda that remains to be realised. The development of field-deployable optical instruments for quantitative glazing inspection, the conduct of prospective randomised fleet studies and the investigation of the interaction between windshield degradation and ADAS camera systems represent practical steps toward a road network on which every commercial vehicle driver sees it as it truly is and every windshield performs the protective function for which it was designed.

It is essential to emphasize that the projected efficiency gains and safety outcomes are indicative estimates. The variability of real-world crash scenarios and fleet maintenance cultures necessitates periodic re-verification of these baseline parameters.

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