Superlinear Failure Regimes in Single-Use Polyethylene Carrier Bags: Carried-Item Angularity and the Critical Load Threshold in the Driveway-to-Kitchen Transit Corridor

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Abstract

Despite the ubiquity of single-use polyethylene carrier bags in post-industrial grocery logistics, surprisingly little empirical work has addressed the catastrophic yield behavior these vessels exhibit during the driveway-to-kitchen transit corridor (DKTC). The phenomenon — colloquially termed 'the split' — represents a non-trivial failure mode with significant downstream consequences for perishable cargo integrity, yet its stochastic character has resisted systematic characterization since the early field observations of Lindqvist and Hargreaves (2009, Journal of Applied Bag Sciences, 14, 22–31). The present study asks: what is the conditional probability of catastrophic bag failure as a function of gravitational load distribution, ambient temperature, and carried-item angularity? Employing a novel Recursive Tensile Attenuation Protocol (RTAP) across 1,247 instrumented transit events, we report that failure probability increases superlinearly beyond a critical load threshold of $\lambda_c = 4.3$ kg (95% CI [3.9, 4.7]), with angular produce items (e.g., boxed pasta) elevating rupture hazard by 340% relative to spheroidal controls ($p < 0.001$, Cohen's $d = 2.14$). These findings carry immediate implications for municipal bag-thickness ordinances and suggest that current grocery-bagging heuristics are, from a materials-science perspective, empirically indefensible.

1 Introduction

The modern grocery supply chain, from centralized distribution hub to domestic refrigerator, comprises dozens of logistical nodes, each subject to its own risk profile, regulatory framework, and failure taxonomy. Yet it is the final segment — the driveway-to-kitchen transit corridor (DKTC) — that remains, by virtually any empirical measure, the most catastrophically underengineered. Conservative estimates place annual DKTC cargo losses in the United States alone at 2.4 billion individual food items, representing approximately $7.8 billion in spoilage-adjusted replacement cost (Petersen & Olufsen, 2014, *Annals of Domestic Freight Studies*, 29, 114–131). Despite the magnitude of these losses, the DKTC has attracted remarkably little sustained attention from the materials science community, owing in part to what Bergström (2008, *Nordic Journal of Applied Polymer Logistics*, 11, 5–18) termed the "triviality presumption" — the pervasive disciplinary assumption that failure events occurring within 15 meters of one's own front door do not warrant systematic investigation.

The theoretical landscape for plastic film failure under load is, to be sure, not barren. The Nakamura-Voss creep-rupture model (Nakamura & Voss, 2003, *Thin Film Mechanics Letters*, 44, 201–219) provided the first rigorous treatment of time-dependent yield in low-density polyethylene under uniaxial stress, establishing that carrier bags degrade along predictable viscoelastic trajectories when subjected to constant load. More recently, Delacroix (2021, *Comptes Rendus de Rhéologie Domestique*, 18, 33–47) advanced a stochastic thinning hypothesis, arguing that microvoid nucleation in extruded polyethylene is inherently probabilistic, rendering deterministic failure prediction impossible beyond a narrow confidence envelope. Both frameworks, however, share a critical limitation: they model load as a scalar quantity, uniformly distributed across the bag's containment surface. In practice, of course, this assumption is violated with remarkable consistency.

It is here that the concept of the carried-item angularity index (CIAI) becomes indispensable. Originating in Griffith's (1921) foundational work on stress concentration at crack tips and subsequently formalized for irregular contact geometries by Inglis and others, the principle that geometric discontinuities amplify local stress is well established in fracture mechanics. What has not been established — indeed, what has been almost entirely neglected — is the application of this principle to the contact interface between grocery items and the polyethylene film tasked with containing them. A box of penne rigate, with its orthogonal edges and rigid planar faces, produces a radically different stress distribution than a cantaloupe of equivalent mass. The CIAI, introduced here as a dimensionless shape descriptor ranging from 0 (perfect sphere) to 1 (maximally angular prism), provides a systematic means of quantifying this geometric hazard.

The neglect of item geometry in bagging practice may itself be partly cognitive in origin. Kahneman and Tversky's (1979) prospect theory, and in particular their demonstration that individuals systematically misjudge low-probability, high-consequence events, suggests a mechanism: consumers approaching the DKTC appear to employ what we term the *one-trip heuristic* — a strong preference for minimizing transit iterations that leads to systematic overloading beyond the bag's critical load threshold (λ_c). The resulting catastrophic yield behavior is thus not merely a materials phenomenon but a joint product of polymer rheology and bounded rationality.

The present study asks two linked questions: first, whether a critical load threshold λ_c can be empirically identified under ecologically valid DKTC conditions at which catastrophic yield behavior transitions from a low-probability nuisance to a near-certainty; and second, whether carried-item angularity constitutes an independent and practically significant predictor of rupture hazard beyond the effects of mass alone. In this paper, we report findings from 1,247 instrumented transit events conducted under the Recursive Tensile Attenuation Protocol (RTAP), characterize the superlinear failure regime above λ_c, and discuss implications for municipal bag-thickness regulation and consumer risk education.

2 Methods

Apparatus and Transit Environment

All transit events were conducted within a purpose-built driveway-to-kitchen transit corridor (DKTC) analog housed at the Carrier Bag Dynamics Laboratory, University of Uppsala–Satellite Campus. The standardized corridor measured 14.2 meters in length, poured from C30/37 grade concrete at a 2.3°

incline, and was fitted with embedded thermocouples at 1-meter intervals to permit continuous monitoring of surface temperature. Ambient conditions were regulated via a climate-controlled envelope capable of sustaining temperatures between 4°C and 38°C (±0.3°C), calibrated seasonally in accordance with the environmental simulation standards proposed by Kjeldsen and Moriyama (1994, *Proceedings of the First International Symposium on Domestic Load Transport*, pp. 44–59). Four distinct DKTC surface variants — smooth-pour, broom-finished, stamped aggregate, and cracked-with-weed-intrusion — were available on a rotating schedule to capture substrate heterogeneity.

Instrumentation

Each bag was fitted with six piezoelectric strain gauges (Model PZT-4a, Müller Sensortechnik GmbH) affixed at the canonical failure loci identified by the foundational mapping work of Rennert (1987, *Zeitschrift für Verpackungsphysik*, 12, 88–103): the bilateral handle junctions (loci α_1, α_2), the lateral seam midpoints (β_1, β_2), and two interpolated positions along the base weld (γ_1, γ_2). Strain data were sampled at 200 Hz and transmitted wirelessly to a central acquisition unit running a custom implementation of the Oka-Svensson real-time deformation tracker (Oka & Svensson, 2016, *Journal of Instrumented Polymer Testing*, 8, 71–84). From these six channels, the rupture hazard coefficient (ρ_h) was computed at each timestep *t* as:

$$\rho_h(t) = \frac{1}{6} \sum_{i=1}^{6} \frac{\varepsilon_i(t)}{\varepsilon_{\text{crit},i}} \cdot \left(1 + \delta \cdot \text{CIAI}\right)$$

where $\varepsilon_i(t)$ denotes the instantaneous strain at locus *i*, $\varepsilon_{crit,i}$ is the manufacturer-specific critical strain threshold for that locus, and δ is the Pham-Lindström angularity coupling constant, empirically fixed at 0.74 following the calibration procedure of Pham and Lindström (2012, *Applied Bag Mechanics*, 5, 19–30). Catastrophic yield behavior was operationalized as the event $\rho_h(t) \geq 1.0$, corresponding to complete and irrecoverable loss of containment integrity.

Cargo Stimulus Set and Bagging Conditions

A standardized cargo library of 34 common grocery items was assembled, each classified by its carried-item angularity index (CIAI) — a dimensionless shape descriptor computed from the ratio of the item's maximum vertex angle to its minimum radius of curvature, normalized to [0, 1]. Values ranged from $\theta = 0.07$ (cantaloupe, 1.4 kg) to $\theta = 0.94$ (penne rigate, 500 g box). Items were packed into bags according to three ecologically validated bagging strategies: clerk-optimized (heavy-to-light layering with angular items buffered by produce), self-checkout haphazard (randomized insertion order, no geometric optimization), and the single-trip maximal-load condition colloquially designated "everything in one bag."

Sample and Design

A total of N = 1,247 transit events were recorded over 14 months, balanced across the four DKTC surface conditions, three bagging strategies, five bag manufacturers (three national brands, two store-label generics), and two prior-use conditions (virgin vs. one prior use). Gravitational load was varied continuously from 1.0 to 8.5 kg in accordance with the Recursive Tensile Attenuation Protocol (RTAP), wherein each successive transit iteration increased load by $\Delta m = 0.5$ kg until failure or corridor completion (Cox & Oakes, 1984, *Analysis of Survival Data*, Chapman & Hall — adapted here for polymer-film event histories).

Statistical Analysis

Time-to-failure data were modeled using a mixed-effects Cox proportional hazards regression with random intercepts for bag manufacturer and fixed effects for load mass, CIAI, ambient temperature (°C), and bagging strategy. The proportional hazards assumption was evaluated via scaled Schoenfeld residuals; no significant violations were detected (global $\chi^2 = 11.3$, df = 8, $p = 0.18$).

This study was reviewed and approved by the Uppsala Institutional Review Board for Non-Human Materials Research (Protocol 2024-NBM-0047). No sentient organisms were harmed, though an estimated 3,400 eggs were lost during data collection.

3 Results

Critical Load Threshold

The primary analysis revealed a clearly identifiable critical load threshold (λ_c) at 4.3 kg (95% CI [3.9, 4.7]), beyond which the instantaneous hazard function for catastrophic yield behavior transitioned from an approximately linear regime ($\beta = 0.84$, SE = 0.12) to a markedly superlinear one ($\beta = 3.12$, SE = 0.41). This inflection is visible in Figure 1, which plots the smoothed hazard function against total gravitational load across all 1,247 transit events, with the shaded region denoting the 95% pointwise confidence band. The transition is sharp: bags loaded to 4.2 kg exhibited a cumulative failure rate of just 11.4%, while those at 4.5 kg — a mere 300-gram increment — failed at a rate of 38.7%. The nonlinearity was confirmed by a likelihood ratio test comparing the piecewise-linear model against a single-slope null (Δ deviance = 94.6, df = 1, $p < 0.001$). This threshold behavior is broadly consistent with the phase-transition framework proposed by Sørensen and Gupta (2017, *Journal of Catastrophic Polymer Events*, 22, 130–145), though the present λ_c estimate is approximately 0.6 kg lower than their extrapolation from laboratory uniaxial data, a discrepancy we attribute to the ecologically valid multiaxial loading conditions inherent to the driveway-to-kitchen transit corridor (DKTC).

Carried-Item Angularity

The carried-item angularity index (CIAI) emerged as the single strongest predictor of rupture hazard after load mass. Items scoring above 0.70 on the CIAI scale elevated instantaneous hazard by 340% relative to spheroidal controls of matched mass (HR = 4.40, 95% CI [3.21, 6.03], $p < 0.001$, Cohen's $d = 2.14$). Table 1 summarizes hazard ratios by cargo class, rank-ordered by CIAI. Boxed pasta (CIAI = 0.94) occupied the apex of the angularity–hazard distribution, followed by rectangular juice cartons (CIAI = 0.87, HR = 3.72) and rigid cracker boxes (CIAI = 0.82, HR = 3.15). Spheroidal items — cantaloupes, bagged oranges, and cabbages — clustered near the baseline. The magnitude of the CIAI effect exceeded prior estimates by a considerable margin; Taniguchi (2019, *Asia-Pacific Bag Failure Review*, 4, 61–73) reported a hazard ratio of only 2.1 for angular items, likely reflecting that study's use of a static load-hold paradigm rather than dynamic DKTC traversal.

Temperature–Manufacturer Interaction

A significant interaction was observed between ambient temperature and bag manufacturer on the rupture hazard coefficient (ρ_h). Store-label generic bags exhibited a pronounced thermosensitive fragility window between 28°C and 34°C, within which ρ_h increased 2.7-fold relative to the 15°C baseline (interaction term: $\beta = 1.42$, SE = 0.33, $p < 0.001$). National-brand bags, by contrast, showed no significant temperature modulation across the full 4–38°C range ($\beta = 0.09$, SE = 0.11, $p = 0.43$). Figure 2 illustrates the divergent ρ_h trajectories as a function of temperature, stratified by manufacturer class. The differential response is plausibly attributable to variation in polyethylene crystallinity fraction (χ_c), a parameter known to govern thermal softening onset in extruded films (cf. Henriksson & Park, 2015, *Polymer Crystallinity and Domestic Applications*, 19, 204–218).

Bagging Strategy

Bagging strategy exerted a profound effect on median survival time. The “everything in one bag” condition yielded a median time-to-failure of 6.8 seconds post-vehicle-egress, compared with 22.4 seconds for self-checkout haphazard packing and 42.1 seconds for clerk-optimized configurations (log-rank $\chi^2 = 187.4$, df = 2, $p < 0.001$). Pairwise contrasts confirmed that all three strategies differed significantly from one another at the Bonferroni-corrected $\alpha = 0.017$ level.

Prior-Use Fatigue Effect

A secondary but noteworthy finding concerned bag reuse. Bags in the one-prior-use condition exhibited a 22% reduction in λ_c, from 4.3 kg to 3.35 kg (95% CI [2.9, 3.8]), indicating a fatigue-memory effect in which prior loading events permanently attenuate the film’s critical strain capacity. This phenomenon has not, to the authors’ knowledge, been documented in the domestic polymer logistics literature, though it is consistent with the Mullins effect observed in filled elastomers at substantially higher strain amplitudes (Mullins, 1969, *Rubber Chemistry and Technology*, 42, 339–362).

4 Discussion

The superlinear transition in hazard rate observed at the critical load threshold ($\lambda_c = 4.3$ kg) merits careful theoretical interpretation. The abruptness of the failure regime shift — a near-discontinuous escalation in rupture probability across a narrow 0.8 kg band — is inconsistent with the gradual creep-rupture trajectory predicted by the Nakamura-Voss model (Nakamura & Voss, 2011, *Polymer Failure Quarterly*, 33, 71–89) and instead aligns more closely with a punctuated-failure framework. The analogy to self-organized criticality in granular systems (Bak, Tang, & Wiesenfeld, 1987, *Physical Review Letters*, 59, 381–384) is, we believe, not merely heuristic: the polyethylene film matrix under distributed gravitational load appears to accumulate microvoid damage in a manner structurally isomorphic to sandpile avalanche dynamics, with λ_c representing the critical slope at which local failures cascade into catastrophic yield behavior. That this phase transition has gone undetected for decades likely reflects the field’s historical preference for uniaxial tensile testing under laboratory conditions — an approach that, as Farnsworth (2016, *International Review of Carrier Bag Mechanics*, 21, 8–19) conceded, “systematically underestimates the entropic complexity of real-world bag loading.”

The pronounced effect of the carried-item angularity index (CIAI) on rupture hazard deserves particular attention. That a box of penne rigate elevates failure risk by 340% relative to a cantaloupe of equivalent mass suggests that the packaging industry and the carrier-bag industry have evolved under entirely orthogonal selection pressures — a condition we propose terming *antagonistic co-neglect*. Grocery item packaging is optimized for shelf appeal, stackability, and consumer legibility; at no point in the design pipeline, evidently, does anyone evaluate whether a given box geometry will puncture the bag tasked with transporting it. This finding extends the work of Gunnarsdóttir and Pratt (2019, *Journal* *of Retail Containment Ecology*, 7, 103–117), who first hypothesized a "geometric mismatch penalty" but lacked the instrumented DKTC data to quantify it.

The cognitive dimension of these results warrants comment. Consumers approaching the driveway-to-kitchen transit corridor appear to exhibit a systematic overconfidence in bag capacity — the one-trip heuristic — that is consonant with broader findings on miscalibration of subjective probability estimates (Fischhoff, Slovic, & Lichtenstein, 1978, *Journal of Experimental Psychology: Human Perception and Performance*, 4, 330–334). Participants in an unpublished pilot survey (Choudhury & Blix, 2024, manuscript in preparation) estimated their probability of bag failure at approximately 5%, when the observed rate under typical loading conditions exceeded 23%. Whether this bias reflects motivated reasoning, affect heuristic contamination, or simple unfamiliarity with polymer rheology remains an open question.

Several limitations must be acknowledged. The standardized DKTC analog employed here — a 14.2-meter poured concrete corridor at 2.3° grade — does not capture the stochastic perturbations endemic to real domestic environments, including but not limited to uneven pavement topology, pet-related locomotor obstructions, screen-door latch negotiation, and the biomechanical consequences of simultaneously carrying a toddler. Each of these confounds introduces variance that our controlled design necessarily suppresses. Additionally, the present sample excluded reusable polypropylene tote bags, whose failure modes are believed to follow qualitatively different distributions (see Marchetti, 2020, *Sustainable Bag Failure Studies*, 3, 55–62) and thus require independent parametric treatment.

Future work should pursue three complementary trajectories. First, the development of a wearable ρ_h monitoring system would enable real-time rupture hazard estimation during naturalistic DKTC traversals, facilitating ecological momentary assessment at scale. Second, the interaction between CIAI and bagging strategy demands factorial investigation under conditions that include the presently omitted "bag-within-a-bag" redundancy configuration. Third, longitudinal cohort studies tracking individual consumers' loading decisions over time could illuminate whether repeated exposure to catastrophic yield events produces durable recalibration of the one-trip heuristic or merely transient bag-count adjustment.

These findings collectively establish that the rational governance of grocery bag infrastructure requires empirical load standards derived from failure science, not from legislative intuition — a principle with immediate transferability to any domain in which thin polymer membranes mediate the boundary between civic order and domestic chaos.

5 Conclusion

Every civilization is separated from its groceries by a membrane it declines to study. We have shown that this membrane fails not gradually but critically — that there exists a precise weight at which optimism becomes pasta on the driveway. The 4.3-kilogram threshold is not a number to be memorized; it is a boundary condition of domestic life, as fundamental and as routinely ignored as the load-bearing capacity of a promise. Until bag-thickness policy is derived from rupture science rather than from the gut feelings of municipal subcommittees, and until the penne rigate box is redesigned with the faintest awareness that it will one day be placed inside a bag, the driveway-to-kitchen transit corridor will remain what it has always been: the last mile that nobody engineers and everybody walks.

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