Internalizing Environmental Risk: Insurance Design and Firm Behavior in Hazardous Industries

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Motivation: Mispricing Environmental Risk

The Market Failure

- **High Stakes:** Median cleanup costs $ > $\100,000$; Uniform Premium $\bar{P}$ mute incentives.
- **Theory:** Strict liability only internalizes risk if priced ($P_i \propto Risk_i$) (Shavell, 1982).

The Technological Friction

- **Legacy Fleet:** High-risk single-walled tanks persist (48% of stock).
- **Cost Barrier:** Safer double-walled tanks cost ~60–90% more (GAO, 1987).

The "Texas Experiment" (1999)

- **Shock:** Policy forces 100% of owners into risk-rated private market.

Research Question & Contribution

Research Question
Does replacing Uniform Premium public insurance with risk-based pricing induce firms to internalize environmental damages?

Contribution 1: Mechanism
I show that firms respond to insurance premiums not just by exiting, but by **substituting capital**.

- *Result:* High-risk tanks are scrapped; low-risk tanks are retained.

Contribution 2: Policy I demonstrate that privatizing liability reduces leak probability by **XX pp**.

- *Implication:* Market pricing can be a substitute for direct regulation.

Preview of Findings

1. Acceleration of Closures

Transition to risk-based pricing increased annual closure rates of single-walled tanks by 2–3 percentage points.

2. Technology Substitution (Not Just Exit)

Closures shifted from market exit to **on-site replacement**:

- Exit probability (conditional on closure): **Decreased** (~10 pp).
- Replacement probability: **Increased** (~10 pp).

3. Environmental Improvement

Probability of a reported leak **fell** by ~1 percentage point.

- *Note:* Represents near-total elimination of pre-policy baseline risk for this group.

Institutional Context: The Texas Experiment

The Policy Shock (1999)

- **Pre-1999:** Texas operated a Uniform Premium public fund (similar to 18 control states).
- **Post-1999:** Fund closed; all owners forced into private market or self-insurance.

The Treatment (Private Pricing)

- **Actuarial Step Function:** Premiums ratchet up at specific tank ages (e.g., 20, 30 years).
- **Tech Surcharge:** Single-walled tanks face strictly higher base rates.

Identification Strategy

Difference-in-Differences (DiD) comparing Texas incumbent facilities to those in 18 states retaining public funds.

Regulatory Context: 1990–2025

1. Federal Baseline (Technical Rules Constant)

Identical EPA mandates for Texas & Controls:

- **1998: Hard Deadline** — All non-compliant tanks must close or upgrade.
- **2005: Energy Policy Act** — Mandates 3-year inspections & secondary containment.

2. Texas Divergence (Financial Rules Change)

The insurance regime splits in 1999:

Period	**Control States**	**Texas**
Pre-1999	Public Fund ($\bar{P}$)	Public Fund ($\bar{P}$)
1999	*Status Quo*	**SHOCK: Fund Closing**
Post-1999	Public Fund ($\bar{P}$)	Private Market (P_{it})

Key Takeaway Technical mandates moved in lockstep; only Texas privatized liability, exposing owners to market prices.

A Dynamic Model of Tank Closure

The Agent's Decision

The Choice

Each period t, the facility chooses: $d_t \in \{\text{Maintain}, \text{Close}\}$

The Trade-off

- **Maintain:** Earn net revenue, pay insurance premiums.
- **Close:** Exit market and recover scrap value κ (liquidity of land).

Flow Utility (Maintain)

$$u(a) = \underbrace{R}_{\text{Net Revenue}} - \underbrace{C_j(a)}_{\text{Insurance Premium}}$$

Simplifying Assumption: Full Coverage

Firms face environmental risk solely as an *ex-ante* cost (premium), not an *ex-post* shock (deductible).

The Dynamic Problem

The Bellman Equation

$$V(a) = \max \left\{ \underbrace{u(a) + \beta \mathbb{E}[V(a') \mid a]}_{\text{Value of Maintaining}}, \quad \underbrace{\kappa}_{\text{Scrap Value}} \right\}$$

The Continuation Value (V_{cont}) The value of keeping the tank active today to preserve the option of operating tomorrow:

$$V_{cont}(a) = u(a) + \beta \mathbb{E}[V(a') \mid a]$$

Optimal Stopping Rule

$$\text{Close if} \quad V_{cont}(a) < \kappa$$

The Policy Lever: Insurance Regimes

1. **Uniform Premium Pooling (F)**
   - **Premium:** Constant $\bar{P}$.
   - **Incentive:** Zero marginal cost of aging.

$$\frac{\partial C}{\partial \text{Age}} = 0$$

2. **Risk-Based Pricing (RB)**
   - **Premium:** Rises with risk $h(a)$.
   - **Incentive:** Positive marginal cost of aging.

$$\frac{\partial C}{\partial \text{Age}} > 0$$

The Benchmark: Social Value & Market Failure

Social Planner's Objective (SOC) Internalize *all* damages, including health externalities (E).

$$u_{SOC}(a) = R - h(a) \cdot \Big(\underbrace{L}_{\text{Remediation}} + \underbrace{E}_{\text{Health Damages}} \Big)$$

The Unpriced Externality

- **Market Failure:** Liability (L) covers cleanup but misses health impacts (E).
- **Evidence:** USTs generate significant unpriced health costs (Marcus 2021).
- **Result:** Risk-Based is **Second Best**. It captures L but ignores E.

$$V_{RB} > V_{SOC}$$

The Efficiency Gap

1. Fact: Asset Depreciation

Rising leak risk causes tank value to strictly decrease in age ($V'(a) < 0$).

- *Economic Friction:* The regime determines if private incentives align with this social decay.

2. Inefficient Retention (Uniform Premium)

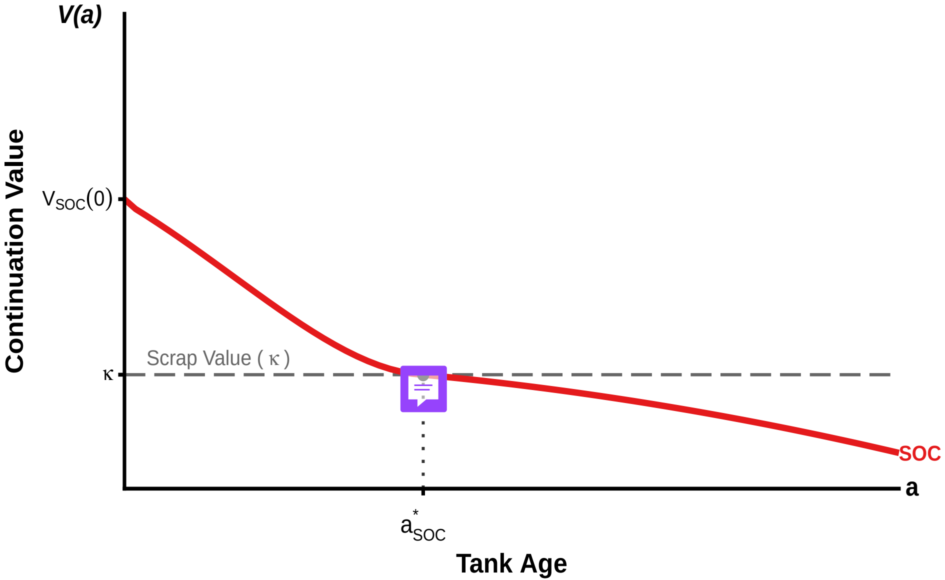
- **Mechanism:** Static costs ($\bar{P}$) $\implies$ Zero marginal cost of aging.
- **Result:** Firm ignores risk; retains asset longest (a^*_{FF}).

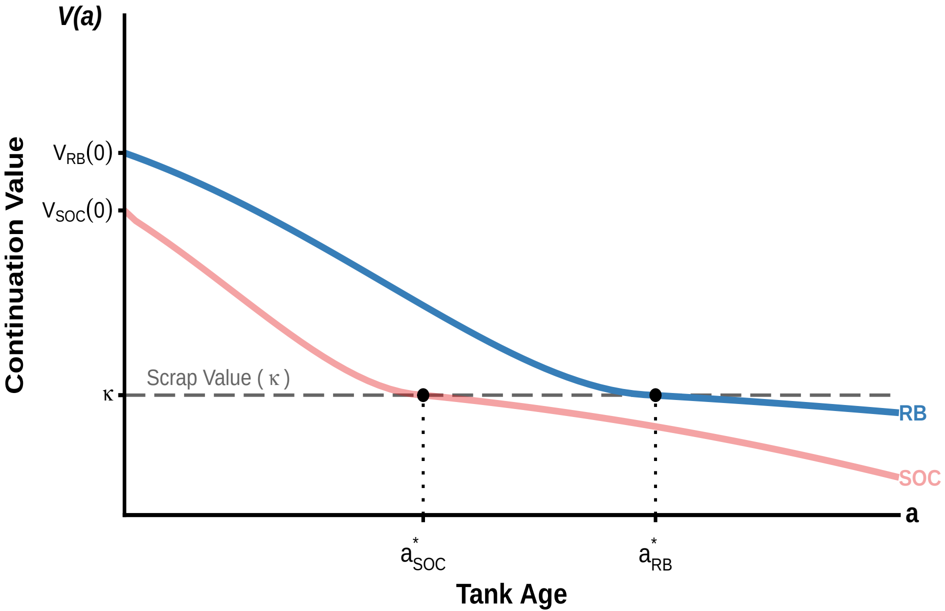
3. Partial Correction (Risk-Based)

- **Mechanism:** Rising premiums ($h(a)L$) $\implies$ Positive marginal cost of aging.
- **Result:** Accelerated exit (a^*_{RB}), yet strictly $> a^*_{SOC}$ due to unpriced health costs.

The Ordering

$$a^*_{SOC} < a^*_{RB} < a^*_{FF}$$


V(a)
Continuation Value
$V_{SOC}(0)$
Scrap Value (κ)
κ
SOC
a
a^*_{SOC}
Tank Age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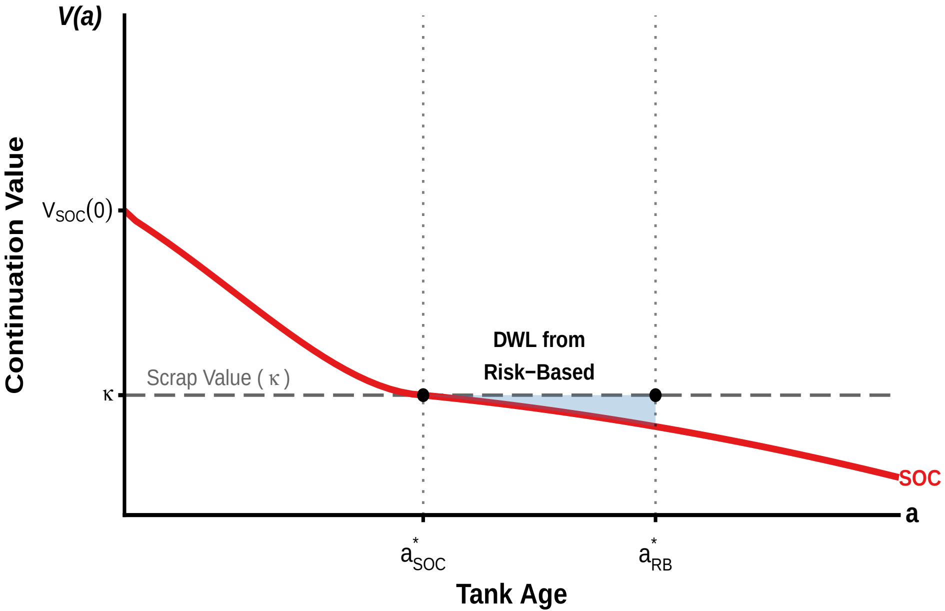
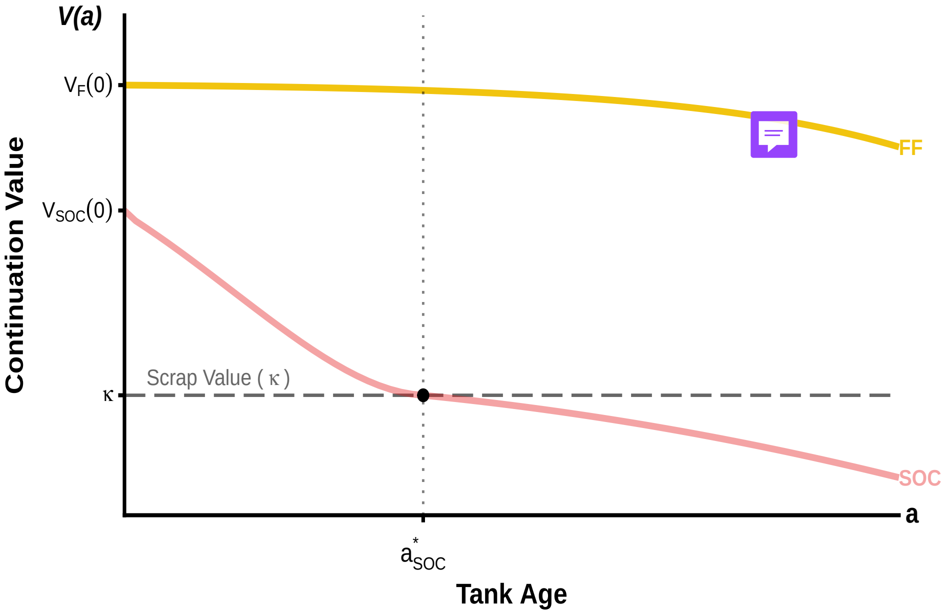
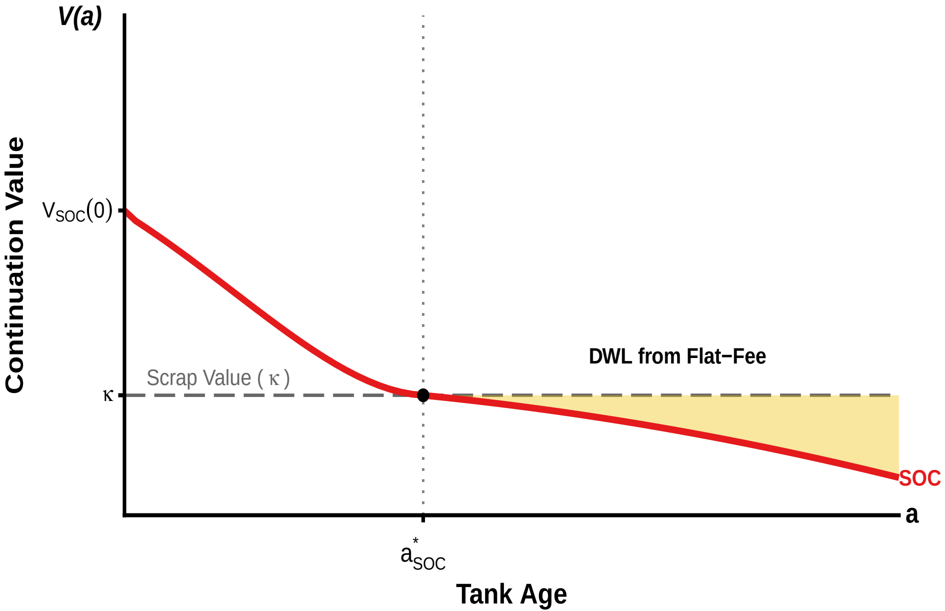
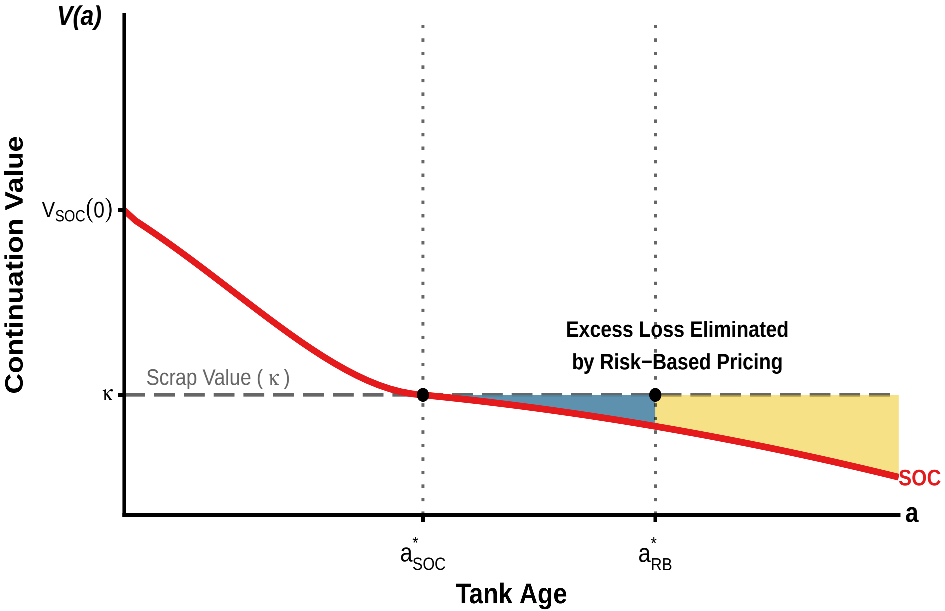

V(a)
Continuation Value
$V_{SOC}(0)$
Scrap Value (κ)
κ
DWL from
Risk−Based
SOC
a
a^*_{SOC}
a^*_{RB}
Tank Age



V(a)
$V_F(0)$
$V_{SOC}(0)$
κ
Continuation Value
FF
Scrap Value (κ)
SOC
a
a^*_{SOC}
Tank Age


V(a)
Continuation Value
V_SOC(0)
κ
Scrap Value (κ)
DWL from Flat−Fee
SOC
a
a*_SOC
Tank Age


V(a)
Continuation Value
$V_{SOC}(0)$
κ
Scrap Value (κ)
Excess Loss Eliminated
by Risk−Based Pricing
SOC
a
a^*_{SOC}
a^*_{RB}
Tank Age

From Theory to Empirics

H1: Risk Selection (The Mechanism) Theory: Risk-based pricing steepens the optimal stopping curve.

- **Metric:** The *Closure Hazard Gradient* (Slope).
- **Prediction:** The marginal effect of risk factors on the hazard rate increases.
- **Test:** $\beta_{Tx \times Post \times Risk} > 0$ in a **Cox Proportional Hazards Model**.

H2: Correction of Misallocation (The Level) Theory: The regime shift flushes the accumulated backlog of inefficient capital ($a^*_{FF} \gg a^*_{RB}$).

- **Metric:** The *Aggregate Closure Probability* (Level).
- **Prediction:** A discrete jump in the extensive margin of exit.
- **Test:** $ATT > 0$ in a **Facility-Level Linear Probability Model**.

What about the Pollution?

The Empirical Challenge

Observable leak counts (LUST) conflate **true risk** with **measurement effort**.

1. The Detection Effect (Reporting $\uparrow$)

- **Monitoring:** Insurers mandate inspections $\rightarrow$ detection of *existing* leaks.
- **Closure:** Mandatory site assessments $\rightarrow$ discovery of *historical* contamination.
- *Outcome:* Short-run spike in reported incidents.

2. The Prevention Effect (True Risk $\downarrow$)

- **Selection:** High premiums force inefficient, high-risk tanks to exit.
- **Upgrade:** Single-walled tanks replaced with double-walled tech.
- *Outcome:* Long-run decline in leak probability.

Net Result: A safer tank fleet, initially masked by increased reporting.

Reduced Form Evidence

Data: Baseline Risk Profile (1999 Incumbents)

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Characteristic	Texas (Treated)	Control States	Relevance
Capital Stock (H2)			
Mean Tank Age	XX.X yrs	XX.X yrs	*Potential Backlog*
% Pre-1980 Vintage	XX.X%	XX.X%	*Inefficient Retention*
Risk Factors (H1)			
% Single-Walled	**XX.X%**	**XX.X%**	*Primary Risk Proxy*
% High Risk ($>$20y)	XX.X%	XX.X%	*Actuarial Threshold*
Facilities	*XX,XXX*	*XX,XXX*	

Identification: Risk Selection (H1)

Model 1: Structural Hazard Gradient (The Slope) To test if pricing risk alters behavior (H1), we estimate a Cox Proportional Hazards model with risk interactions:

$$h_{jt}(t) = h_0(t) \exp\left(\beta_1(\text{TX} \times \text{Post}) + \boldsymbol{\beta_2}(\text{TX} \times \text{Post} \times \textbf{Risk}_{\textbf{jt}}) + \mathbf{X}_{jt}\gamma\right)$$

Specification Details

- **Target (β_2):** Tests if the closure hazard *steepens* for high-risk tanks (Age > 20, Single-Walled).
- **Inference:** Stratified by county $h_{0c}(t)$; Clustered by state ($G = 19$).

Identifying Assumption

No Differential Sorting: The correlation between tank risk (e.g., age) and closure probability would have remained constant relative to controls absent the policy shock.

Identification: Misallocation Correction (H2)

Model 2: Reduced Form DiD (The Level) To test if the regime shift clears the inefficient backlog (H2), we estimate the aggregate extensive margin response:

$$Y_{it} = \beta_{\mathbf{1}}(\mathsf{TX}_{\mathbf{i}} \times \mathsf{Post}_{\mathbf{t}}) + \alpha_i + \delta_t + \mathbf{X}_{it}\gamma + \varepsilon_{it}$$

Specification Details

- **Outcome (Y_{it}):** Binary Closure Indicator (1 = Closed any tank in year t).
- **Target (β_1):** Tests for a level shift (intercept) in the exit rate.
- **Inference:** Wild Cluster Bootstrap (Webb-6 Weights).

Identifying Assumption

Parallel Trends: In the absence of the insurance reform, the trend in closure rates in Texas would have evolved in parallel to the control states.

Identification Verification: Hazard Parallel Trends

[PLACEHOLDER: Dynamic Hazard Ratio Plot] **The Test:** We plot the hazard ratio (β_t) for the interaction TX $\times$ Year$_t$ $\times$ Risk.

Results H1: The Mechanism (Risk Selection)

The "Risk Gradient" (Slope Effect) Testing if pricing risk accelerates the exit of high-risk capital.
[PLACEHOLDER: Model 2 Hazard Table (Risk Interactions)]

Identification Verification: Aggregate Parallel Trends (H2)

[PLACEHOLDER: Event Study Plot (Closure Probability)]

Results H2: The Aggregate Response (Misallocation)

The "Backlog Flush" (Level Effect)
Testing the correction of inefficient retention ($a^*_{FF} \gg a^*_{RB}$).
[PLACEHOLDER: Model 1 Regression Table (Extensive Margin)]

Identification: Aggregate Environmental Response

Specification: Dynamic Event Study To establish the aggregate effect of the policy on leak reporting, we estimate the dynamic difference-in-differences specification:

$$Y_{it} = \alpha_i + \delta_t + \sum_{k=-5}^{10} \beta_k \cdot (\mathbb{1}[t - 1999 = k] \times \text{TX}_i) + \varepsilon_{it}$$

Components

- **Outcome (Y_{it}):** Count of **New LUST Reports** filed in facility i in year t (Inverse Hyperbolic Sine).
- **Coefficients (β_k):** Measures the differential leak rate in Texas relative to controls k years from the policy shock (omitting $k = -1$).

Results: Aggregate Environmental Outcomes

[PLACEHOLDER: LUST Event Study Plot]

Mechanism 1: The Detection Channel

Hypothesis: The spike is driven by "Revealed Leaks"—historical contamination discovered solely because the tank was forced to close.

Specification: Conditional Logit on Closure

$$P(Y_j = 1 \mid \text{Close}_j) = \Lambda\left(\alpha + \beta_1(\text{TX}_j \times \text{Post}_j) + \mathbf{X}_j\gamma\right)$$

Outcome Definition (Y_j)

- **Revealed Leak:** Binary indicator $= 1$ if a leak report is filed for tank j within the **decommissioning window** (0–5 years post-closure).
- **Population:** Restricted to *closed* tanks.

Interpretation

- $\beta_1 > 0$ **(Odds Ratio > 1):** Texas closures are significantly more likely to reveal contamination than control closures.
- **Implication:** The policy forces the internalization of *latent* stock externalities.

Mechanism 2: The Prevention Channel

Hypothesis: Conditional on remaining active, the "surviving" fleet is safer due to the exit of high-risk tanks (Selection) and upgrades (Retrofit).

Specification: Cause-Specific Operational Hazard

$$h_{jt}^{\text{leak}}(t) = h_0(t) \exp\left(\beta_1(\text{TX} \times \text{Post}) + \mathbf{X}_{jt}\gamma\right)$$

Outcome Definition (h_{jt})

- **Operational Leak Hazard:** The instantaneous probability of a leak occurring while the tank is *active* (operating).
- **Competing Risk:** Tank Closure is treated as a competing event (censoring the operational leak observation).

Interpretation

- $\beta_1 < 0$ **(Hazard Ratio < 1):** The active fleet in Texas has a lower risk of failure than the control fleet.
- **Implication:** The long-run effect of the policy is an improvement in environmental safety (Prevention).

Reduced Form Summary

Hypothesis	Outcome	Estimate	Interpretation
H1 (Slope)	Single-Walled Hazard	**+XX.X %**	Risk Selection (Mechanism)
H2 (Level)	Annual Closure Rate	**+XX.X pp**	Correction of Misallocation
Outcome	Reported LUSTs	**+XX.X %**	Detection > Prevention (Short Run)

Structural Model [Simulated Data]

The Agent's Decision Problem

State Space $x = (A, w, \rho)$

- **Age (A):** 9 bins (0-5y ... 40y+).
- Risk $h(A)$ rises w/ age.
- **Wall (w):** Single vs. Double.
- **Regime (ρ):** Uniform Premium vs. Risk-Based.

Choice Set

1. **Maintain ($d = m$)**
   - Pay premium $p(x)$, face risk $h(x)$.
   - Next: $A \to A + 1$ (stochastic).
2. **Close ($d = c$)**
   - Permeanltly Close Tank.
   - Payoff: Scrap value κ.

Timing

1. Facility observes state x_t and shock ε_{it} (Type I EV).
2. Chooses d_{it} to maximize expected discounted value ($\beta = 0.95$).

Bellman Equation & Flow Utility

Optimal Stopping Problem

$$V(x) = \max \left\{ \underbrace{u^m(x) + \beta \mathbb{E}[V(x')|x, m]}_{\textbf{Maintain (Continuation)}}, \quad \underbrace{\kappa}_{\textbf{Close (Scrap)}} \right\} + \sigma\varepsilon$$

Flow Utility (Normalized)

$$u^m(x) = \underbrace{1}_{\textbf{Revenue}} - \underbrace{\gamma_{\mathbf{p}} \cdot p(x)}_{\textbf{Premium}} - \underbrace{\gamma_{\mathbf{r}} \cdot h(x) \cdot L}_{\textbf{Liability}}$$

Scaling & Interpretation

- **Numeraire:** Annual net revenue is normalized to $\psi = 1$.
- **Unit Interpretation:** - Estimated parameters $\{\kappa, \gamma\}$ are expressed in **multiples of annual revenue**.
  - A value of $\gamma_{\mathbf{r}} = 0.5$ implies the marginal liability risk is equivalent to 6 months of revenue.

Identification of Parameters

Which Variation Identifies Which Parameter?

Parameter	Interpretation	Source of Variation
κ	Scrap Value	Average facility exit rate (Unconditional Levels)
$\gamma_{\mathbf{p}}$	Premium Sensitivity	Cross-sectional premium jumps across (A, w, ρ)
$\gamma_{\mathbf{r}}$	Liability Sensitivity	Variation in deductible sizes & coverage limits

Estimation Protocol

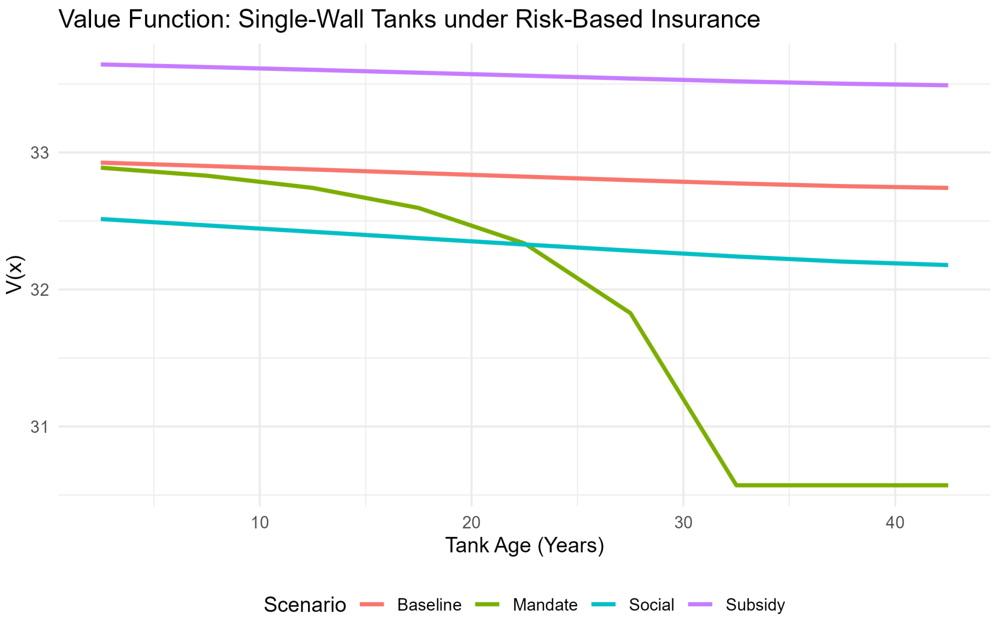
- **Algorithm:** Nested Pseudo-Likelihood (NPL) {(Aguirregabiria & Mira, 2007)}
- **Standard Errors:** Facility-level block bootstrap ($B = 999$).
- **Sample:** [Insert N] facilities observed quarterly (20XX-20XX).

Estimation Results [Simulated Data for Demonstration Only]

Parameter	Estimate	SE	Interpretation
$\hat{\kappa}$	6.25	(0.84)	Scrap value (annual revenue units)
$\hat{\gamma}_{price}$	−1.20	(0.31)	Firms dislike premiums (Price Elastic)
$\hat{\gamma}_{risk}$	1.00	(0.22)	Near-perfect private internalization

Interpretation

- **Price Sensitivity ($\gamma < 0$)** Firms respond strongly to premium hikes ($p < 0.01$).
- **Risk Neutrality ($\gamma \approx 1$)** Owners fully internalize *private* costs (deductibles), implying the remaining distortion is purely the **external** damage.



Value Function: Single-Wall Tanks under Risk-Based Insurance
V(x)
33
32
31
10
20
30
40
Tank Age (Years)
Scenario
Baseline
Mandate
Social
Subsidy

Counterfactual Design

Four Policy Scenarios

#	Scenario	Implementation
1	**Baseline**	Status quo (TX: RB, Controls: FF)
2	**Social Optimum**	$\gamma_{risk} \times 2$ (internalize externality)
3	**Closure Subsidy**	$\kappa +$ Subsidy (pay to close)
4	**Mandate**	Force closure if $A \geq 30$ & Single-Walled

Welfare Metrics

- Average closure probability
- Expected leak risk: $\mathbb{E}[h(x) \cdot P(\text{maintain}|x)]$
- Social loss: Private loss $\times$ externality multiplier

Counterfactual Results: Closure by Policy

PLACE HOLDER FOR COUNTERFACTUAL FIGURE

Counterfactual Comparison

Welfare Summary

Scenario	Avg Close Rate	Δ vs Baseline	Leak Risk	Δ Risk
Baseline	4.2%	—	1.8%	—
Social Opt	8.1%	+3.9 pp	0.9%	−50%
Subsidy	6.5%	+2.3 pp	1.2%	−33%
Mandate	5.8%	+1.6 pp	1.4%	−22%

Ranking: Social Optimum $>$ Subsidy $>$ Mandate $>$ Baseline

Conclusion & Policy Implications

Findings

1. **Risk-based pricing works** +2–3 pp closure rates (DiD)
2. **Mechanism is upgrading, not abandonment** Retrofit substitution
3. **Welfare-improving but not First Best** Gap to Social Optimum remains

Policy Recommendations

- Risk-based insurance dominates Uniform Premium pooling
- Targeted **closure subsidies** for high-risk tanks can close remaining welfare gap
- **Mandates** are less efficient (distort margins not requiring intervention)

Broader Implication Market-based environmental regulation can outperform command-and-control when behavioral elasticities are sufficient.