Evaluating Internally Cured High-Performance Concrete Life Cycle Cost Savings in New Jersey Bridges

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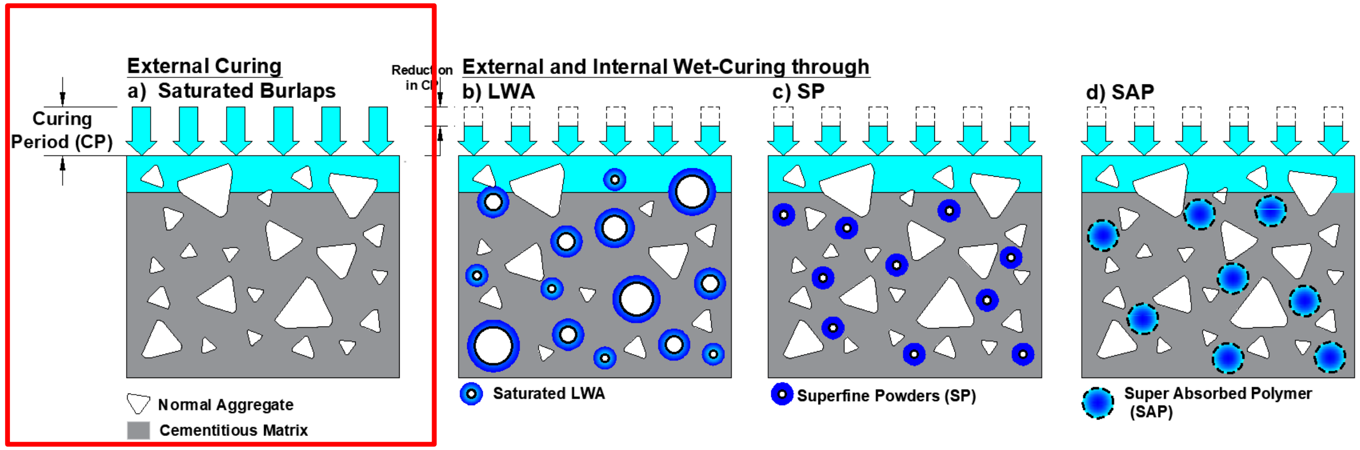
- **Problem:** External curing limits on bridge decks
- Large deck areas → moisture delivery is nonuniform and short lived.
- **Result:** Early shrinkage/cracking, weaker near-surface, poorer abrasion resistance.
- Durability drives life-cycle outcomes (permeability, cracking, rehab timing).

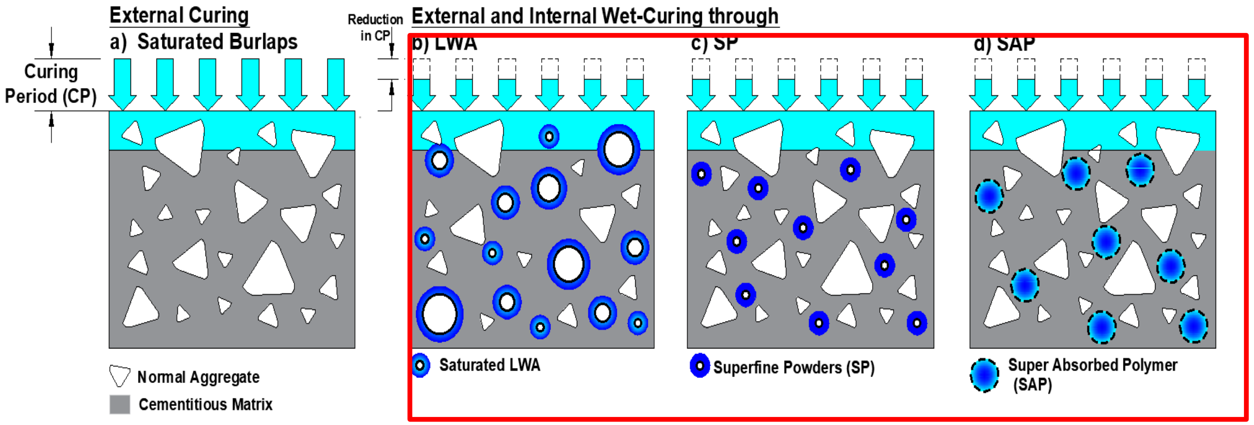


Schematic Description of Curing Process; (a) External Curing (burlap or any equivalent method), External Curing Combined with Internal Curing (b) LWA, (c) SP, and (d) SAP

Extend Service Life of Concrete Bridge Decks with Internal Curing

What is internal curing?

- Add prewetted lightweight fines or superabsorbent polymer that release water internally during hydration.
- Sustains internal humidity → less self-shrinkage and lower permeability.
- Mechanism fits deck reality when external curing is imperfect.
- Delays first crack; extends service life.



Schematic Description of Curing Process; (a) External Curing (burlap or any equivalent method), External Curing Combined with Internal Curing (b) LWA, (c) SP, and (d) SAP

Covered bridge deck during curing.

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Importance of Internal Curing

- Later first crack → later first rehab → fewer total interventions over service life.
- Fewer and later interventions → fewer work zones → lower user/social costs.
- Mechanism aligns with DOT experience: reduced cracking in IC-HPC deployments.
- Use HPIC vs HPC in LCCA to capture service-life and rehab-frequency effects.

Crack in 2 months

Crack in 1 year

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Project Objectives

- Identification of a cost-effective practice of ICC for bridge deck and concrete pavement applications for NJDOT.
- Reviewing other neighboring states' DOT's specifications, lessons learned, and challenges of the current practices for IC-HPC in the US in Phase I
- Conducting a laboratory testing program tailored to evaluate the use of LWA to produce more durable concrete
- Assessing the technical feasibility of implementation of IC-HPC
- **Performing Life Cycle Cost Analysis (LCCA) for the benefits expected. This research is devoted to promoting the application and production of IC-HPC in NJ**

Life-Cycle Cost Analysis (LCCA)

- **LCCA** is an engineering economic analysis tool used to evaluate the total economic impact of different design, material, or maintenance options over the bridge's entire service life.

Why it is important?

- Considers all agency expenditures and user costs throughout the life of an alternative, not only initial investments
- Offers sophisticated methods to determine the economic merits of the selected alternative
- Critical in evaluating **new construction materials/techniques** to quantify durability benefits and account for inherent uncertainty.

Research Overview

In the context of IC-HPC (or HPIC), where enhanced durability aims to reduce shrinkage, cracking, and permeability, LCCA serves as a critical tool to help understand performance benefits into long-term economic value.

The following analysis was conducted to compare **HPIC vs HPC vs Class A concrete**:

- **Deterministic LCCA** for quick assessment
- **Probabilistic LCCA** to consider uncertainties such as service life, discount rate, and unit prices
- **CO2 emission Analysis**: Social Cost of Carbon

Project Level LCCA Model

$$\text{NPV} = \sum_{t=0}^{T} \frac{w_1(AC_t(a_t) - \text{SV}_t) + w_2(TDC_t(a_t, V_t) + VOC_t(a_t, V_t) + CRC_{(t)}(a_t, V_t)) + w_3 \cdot SC_t(a_t, V_t)}{(1+r)^t}$$

- Sums **agency**, **user** and **social** costs over years $t = 0, \dots, T$,
- Uses a scheduled **M&R action** $a_t$each year costs at year $t$depend on a_t.
- Enforces **feasibility** via deterioration/serviceability: if condition falls below a threshold, next-year rehab/replacement is required. **Salvage** at $t = T$.
- Aggregates components with **weights** $w_1, w_2, w_3$to form total NPV.

Key Variables

- t: year when a cost occurs; 0…T where T: analysis period
- r: Discount rate
- a_t: M&R activity at year t (bound by deterioration function f(CR_t),where CR_t: condition at year t
- V_t: AADT at year t (vehicles/day), includes truck share and growth
- Cost functions per year t display direct and indirect costs

Deterministic LCCA: Spreadsheet-Based Tool

- A **spreadsheet-based tool** previously developed by the NYU/RIME research team to integrate life-cycle costs into agency investment decisions is used: Utilized for multiple studies for NJDOT and Missouri DOT in the past
- Estimates **deterministic life-cycle costs** for alternative materials by accounting for costs.
- **Design and cost variables** such as FWHA recommended service life, supplier material costs
- **Traffic and Work-zone variables** such as ADT, Truck%
- Analysis conducted for multiple bridges with various sizes

Project Detail				
Project site:	Interstate-80			
Construction type (Pavement/bridge):	Bridge Deck			
State:	New Jersey			
Milepost from:	61.1901306	To	61.3100552	
Structure Length (feet):	231.9			
Structure Width (feet):	154.8			
Comments:	Bridge built in 1963			

Analysis Option				
Alternatives:	Alternative A:	Class A		
	Alternative B:	HPIC		
Analysis period (years):	75			
Discount rate (%):	3%			
Service Life (years):	Alternative A:	22	Alternative B:	63
Material Unit Price ($/cubic yard):	Alternative A:	235	Alternative B:	285
Construction Unit Cost ($/square feet):	Alternative A:	431.00	Alternative B:	522.70

Spreadsheet Sample Input Interface

Deterministic LCCA: Input Variables

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Design and cost inputs:

Variables such as:

- Structure Size
- Analysis Period (75 years)
- Discount Rate (3%)
- Service Life **(FHWA recommendations):**
  - Class A: 22 years
  - HPC: 40 years
  - HPIC: 63 years
- Material Costs **(obtained from suppliers)**
  - Class A: $230/CY
  - HPC: $260/CY
  - HPIC: $285/CY
- Traffic and bridge data from NBIS database
- Set maintenance and rehab schedule for work zone calculations
- **Traffic and Work-zone Inputs** such as:
  - ADT, Truck %, Annual Growth Rate, Number of Lanes

Sample Bridges from NJ Bridge Database

Deterministic LCCA: Outputs

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Goal: Provide insight on which alternative is better to use

Expected Benefits of HPIC

- Longer service life → Fewer rehabs
- Lower agency cost vs Class A and HPC
- Lower overall social-cost externalities

Example of deterministic LCCA Output (using a bridge on I-80):

- Includes net present value (NPV) of direct (agency) and indirect (user, social) costs

OUTPUT

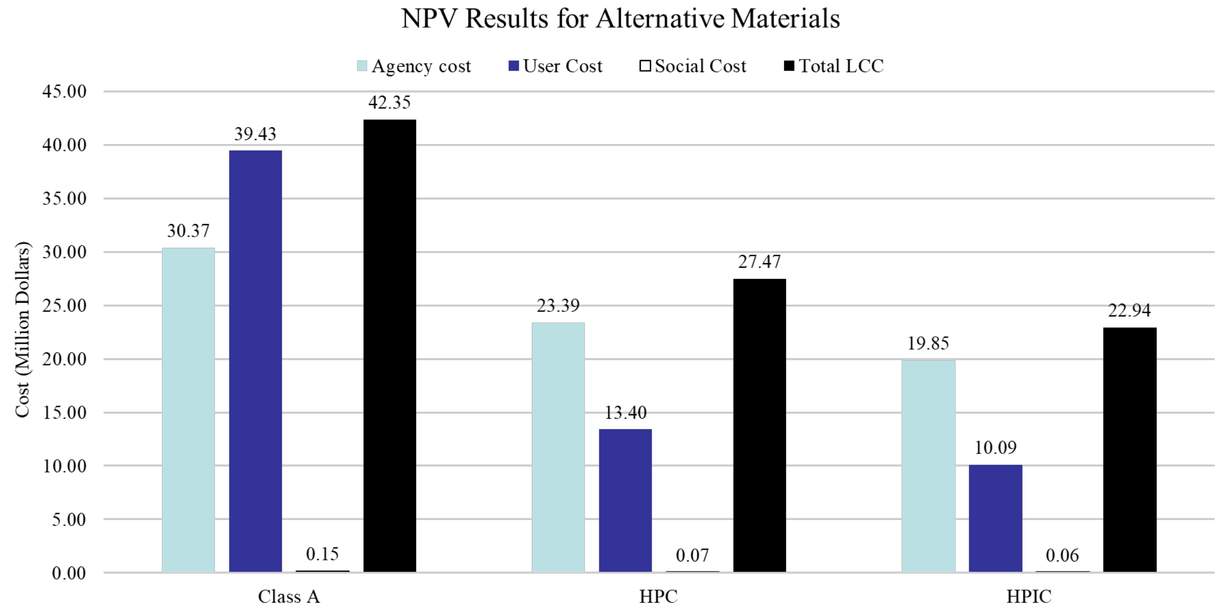
Agency Cost				
Initial Construction Cost ($):	Alternative A:	11,733,001	Alternative B:	14,229,385
Maintenance Cost ($):	Alternative A:	3,218,086	Alternative B:	3,902,785
Rehabilitation Cost:				
(A) Replace the structure (price include demolition&traffic control)($):	Alternative A:	12,288,928	Alternative B:	2,914,612
(B) Approach roadway work (Lump Sum)($):	Alternative A:	614,446	Alternative B:	145,731
(C) Traffic Staging ($):	Alternative A:	2,580,675	Alternative B:	612,069
(D) Preliminary Engineering($):	Alternative A:	1,290,337	Alternative B:	306,034
Total Rehabilitation Cost (s):	Alternative A:	16,774,387	Alternative B:	3,978,446
Salvage Value ($):	Alternative A:	-1,359,598	Alternative B:	-2,258,897
Total Agency Cost ($):	**Alternative A:**	**$30,365,877**	**Alternative B:**	**$19,851,719**
User Cost				
Traffic Delay Cost ($):	Alternative A:	$36,919,008	Alternative B:	$9,453,964
Vehicle Operation Cost ($):	Alternative A:	$2,473,055	Alternative B:	$624,763
Crash Risk Cost ($):	Alternative A:	$42,527	Alternative B:	$8,081
Total User Cost ($):	**Alternative A:**	**$39,434,589**	**Alternative B:**	**$10,086,808**
Social Cost (Environmental)				
CO_2 emission cost ($):	Alternative A:	$153,777	Alternative B:	$65,757
Total Social Cost ($):	**Alternative A:**	**$153,777**	**Alternative B:**	**$65,757**
Total Life Cycle Cost				
Network Present Value ($):	Alternative A:	$42,350,031	Alternative B:	$22,943,519
Recommended Alternative:	Alternative B (New Material)			
Favorite Alternative Benefit:	Agency Cost		34.62%	
	User Cost		74.42%	
	Social Cost		57.24%	
	Total Life Cycle Cost		45.82%	

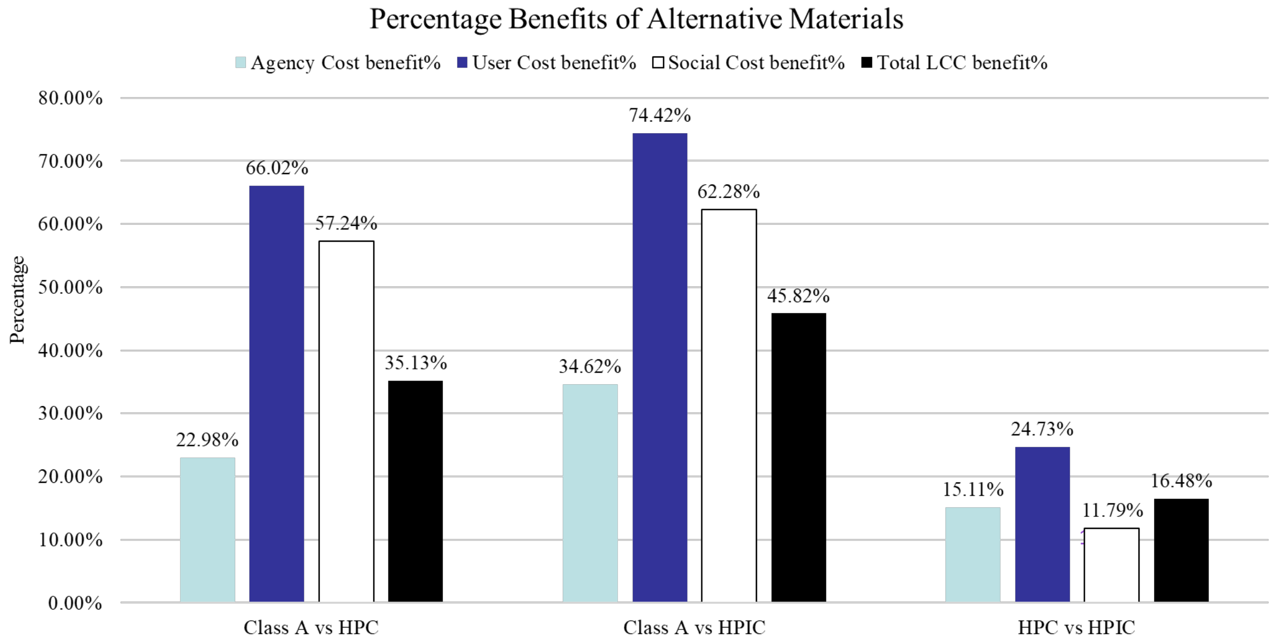
Spreadsheet Sample Output Interface

Deterministic LCCA: Findings

Deterministic LCCA was performed on multiple bridges, and the results are as follows:

- **Cost Savings - <u>HPIC vs Class A</u>:**
- **Agency Cost: 35%**
- User Cost: 60-80%
- Social Cost: 60%
- **Total Cost: 30-50%**
- **Cost Savings - <u>HPIC vs HPC</u>:**
- **Agency Cost: 15%**
- User Cost: 10-40%
- Social Cost: 7-11%
- **Total Cost: 15-25%**
- **Conclusion:** HPIC demonstrates **lower** present values for all costs compared against Class A and HPC.





Probabilistic LCCA: Inputs and Assumptions

Why probabilistic LCCA?

To account for the **uncertainty** associated with the new material HPIC. The uncertainty was evaluated using **Monte Carlo simulations**, which involve repeated random draws from specified distributions of input variables.

Scenario 1 Analysis Inputs:

- **Probabilistic Variable:** Construction unit costs ($/SF) range for all alternatives via triangular distributions (based on NJDOT Cost Estimation Guideline).
  - Example Distribution: HPIC: [min=245, mode=523, max=1192]
- **Deterministic variables:** All other variables from the deterministic analysis remain the same: Service life, material costs, discount rate…
  - Same values used in the deterministic analysis

Probabilistic LCCA: HPIC vs Class A

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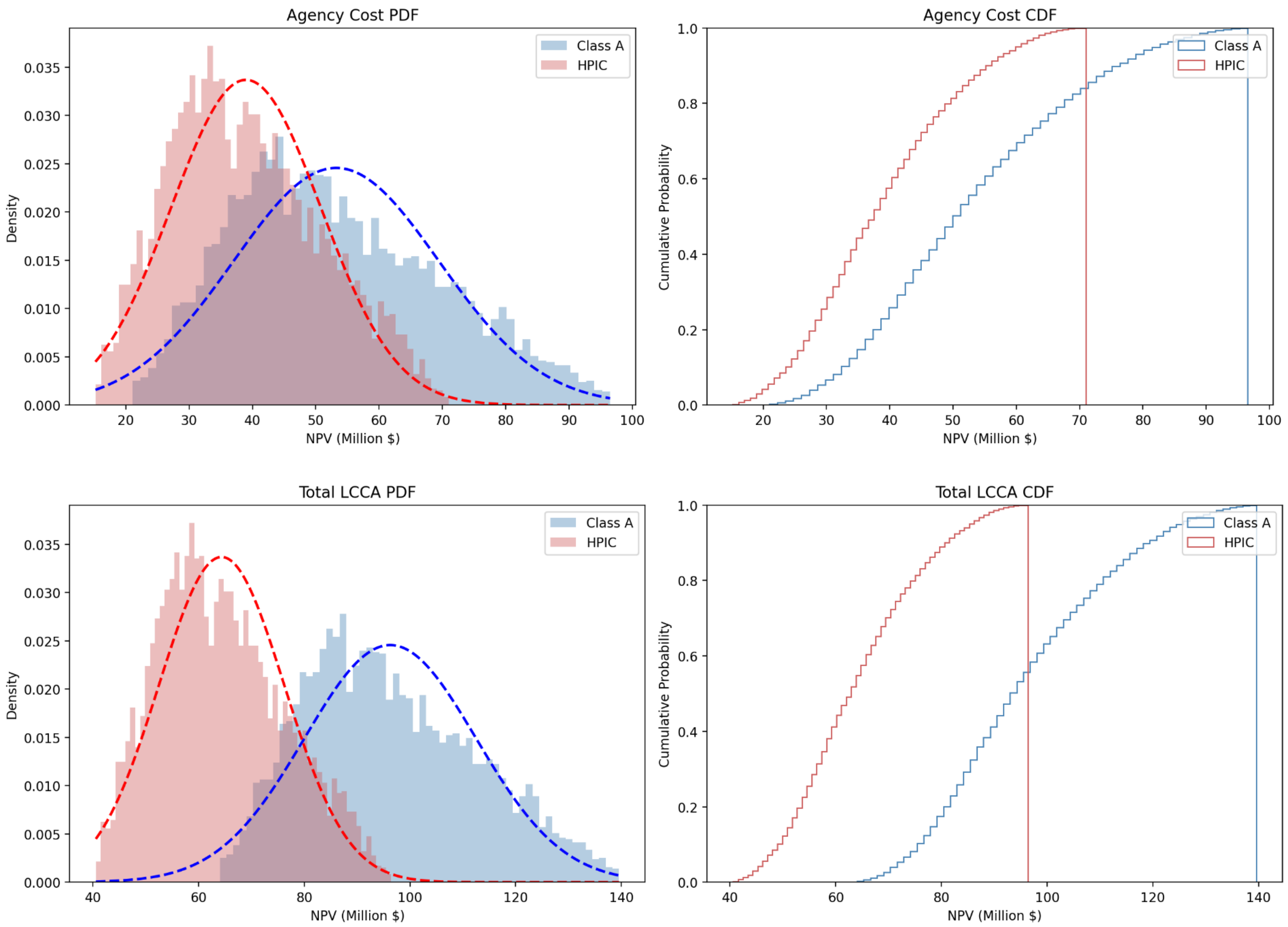
Monte Carlo Simulations (5000 runs) create a distribution of costs based on the defined distributions for input variables.

Key Takeaways:

- **Probability** (HPIC Agency Cost < Class A Agency Cost): **75.3%** and;
- **Probability** (HPIC Total Cost < Class A Total Cost): **94.7%** for all simulated scenarios.
- **Interpretation:** Under modeled **uncertainty**, HPIC's total NPV is lower than Class A in **94.7%** of simulated cases.
- **HPIC is superior against Class A,** as expected.



Probabilistic LCCA: HPIC vs HPC

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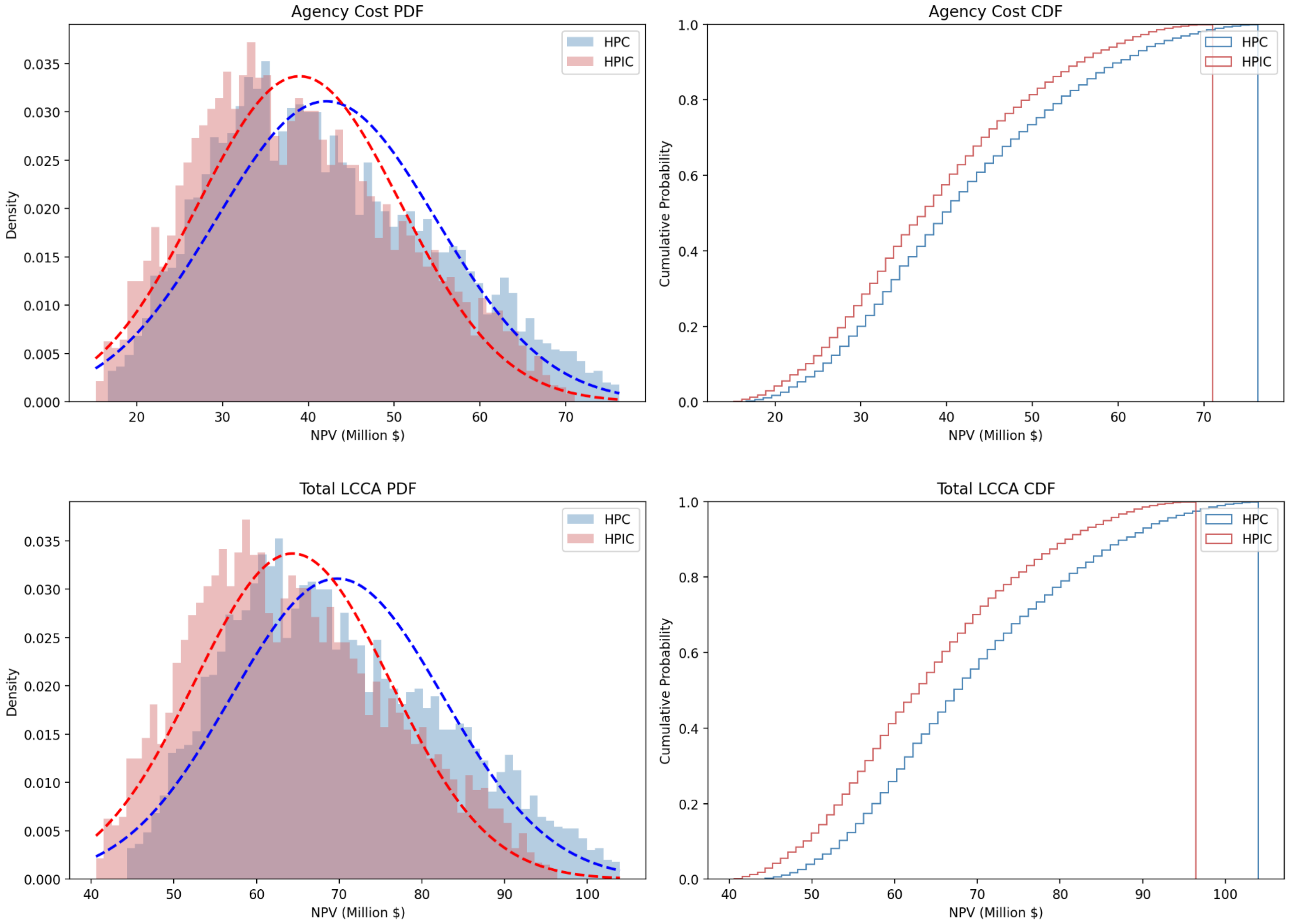
Similar analysis conducted to compare **HPIC against HPC.**

Key Takeaways:

- **Probability** (HPIC Agency Cost < HPC Agency Cost): **56.9%** and;
- **Probability** (HPIC Total Cost < HPC Total Cost): **62.3%** for all simulated scenarios.



Probabilistic LCCA: Uncertainty for Multiple Variables

In addition to the **construction material costs**, probabilistic ranges for **service life** and **discount rates** were considered for probabilistic LCCA.

Scenario 2 Probabilistic Inputs:

- Triangular Distribution Assumption for:
  - **Service Life:**
    - Example Distribution: **HPIC:** [min=60, mode=63, max=70]
  - **Discount rate:**
    - [min=2%, mode=3%, max=5%]
- Deterministic inputs and probabilistic construction unit costs remain the same.

Probabilistic LCCA: HPIC vs HPC

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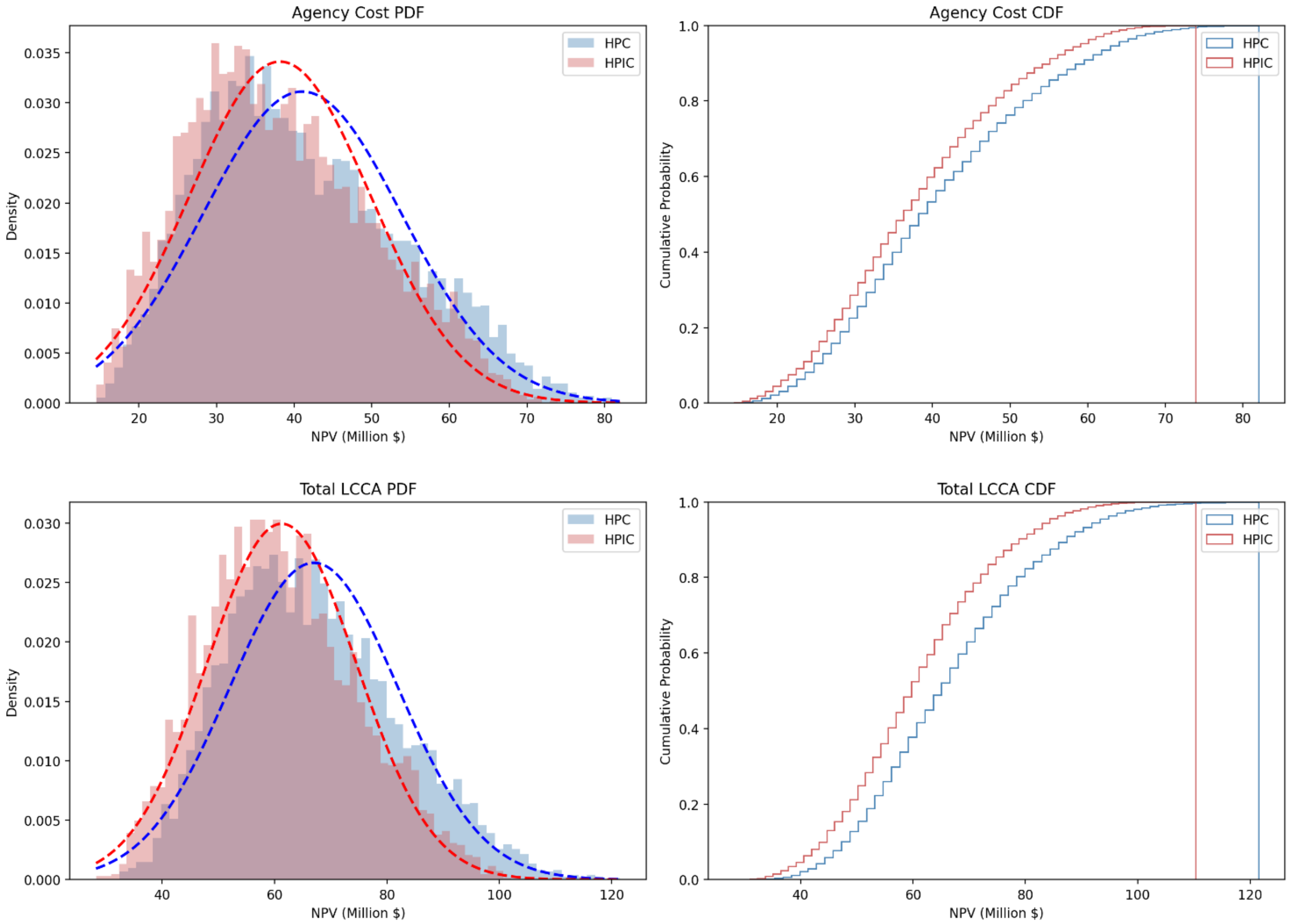
Key Takeaways:

- **Probability (HPIC Agency Cost < HPC Agency Cost): 56.4%** and;
- **Probability (HPIC Total Cost < HPC Total Cost): 62.6%** for all simulated scenarios.

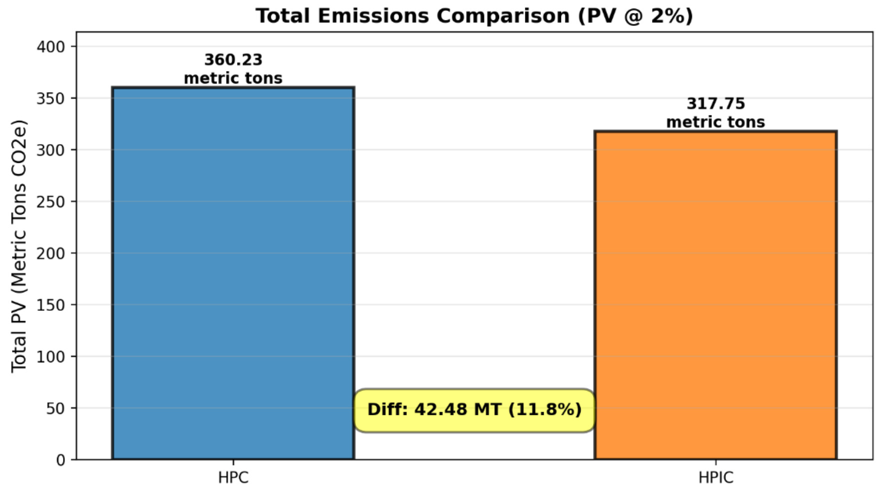
- **Conclusion:** With the addition of uncertainty and probabilistic assumptions, **HPIC still outperforms HPC in most cases.**



CO2 emission Analysis: Social Cost of Carbon

- The social cost of HPIC was also investigated: **Embodied carbon (lbCO2e/CY):**
- HPIC has a **slightly higher** social cost premium.
- Social Cost of Carbon (SCC) was assumed to be:
- Mean: $185.00/metric ton CO2
- 5%-95% Range: $44.00-$413.00/metric ton CO2
- **Conclusion:** Despite the initial extra embodied carbon compared to HPC, **HPIC has a lower SCC value converted to NPV.**
- **11.8% benefits** with 2% discount rate
- **7.3% benefits** with 3% discount rate

Discount Rate:	2%	3%
HPC Emissions (metric tons CO2e):	360.23	320.45
HPIC Emissions (metric tons CO2e):	317.75	297.16
Difference (metric tons CO2e):	42.48	23.29
HPC Social Cost (Mean):	$65,757	$59,621
HPIC Social Cost (Mean):	$58,003	$55,287
Percentage Difference:	**11.8%**	**7.3%**



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Conclusion

- LCCA analysis based on supplier-verified unit costs and FHWA recommendations on service life
- **Deterministic LCCA:**
  - **HPIC < HPC** across various bridges;
  - Savings are observed across all cost types (agency, user, social);
  - Typical ranges:
    - **HPIC vs Class A:** Agency cost saving **≈35%** and total cost saving **≈30–50%** ;
    - **HPIC vs HPC:** Agency cost saving **≈15%** and total cost saving ≈**15–25%**.
- **Probabilistic LCCA:** Monte Carlo simulations over construction-cost, discount-rate, and service-life uncertainty confirm **HPIC has lower costs compared to other alternatives** in most cases
- **Social cost & CO_2:** Despite slightly higher embodied CO_2 per CY, HPIC's longer service life lowers cumulative CO_2; SCC NPV is lower at various discount rates **(~11.8%, ~7.3%).**
- **Overall:** Deterministic and probabilistic evidence together show **HPIC consistently outperforms HPC** in total life-cycle cost.

Future Work

- **Price convergence:** Model HPIC unit cost over time using an experience curve or an exponential approach to the HPC price and test scenarios based on this adoption.
- **SCC uncertainty:** Treat SCC as a distribution and propagate through the emissions inventory.
- **Uncertainty types:** Separate parameter uncertainty (prices, SCC, discount rate) from natural variability (traffic, work zone durations) with a two stage Monte Carlo; report both effects.
- **Discount rate:** Use literature-based priors estimated from guidance and past LCCA; use these in Monte Carlo.
- **Applicability:** Expand the bridge sample across sizes, ADT levels, and regions; verify results under varied traffic and logistics conditions.

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Thank you for your attention.
Questions?

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