Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

Probabilistic Bridge Condition Projections:
Toward Reliability-Based Assessment of Precast Concrete Bridges
UI-25-RP-03

(Phase II - Environmentally-Informed, Data-Driven Precast Concrete Bridge Condition Modeling for Future-Proof Transportation Infrastructure - UI-24-RP-03)

Quarterly Progress Report
For the performance period ending *03/31/2026*

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Collaborators / Partners:
N/A

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TRANS-IPIC Quarterly Progress Report (Section 1 – 7, 5 pages max.):

Project Description:

1. Research Plan - Statement of Problem

In the previous project phase (Year 1), an environmentally informed, data-driven framework was developed to estimate bridge condition using structural, traffic, and environmental variables. This work established a comprehensive dataset and modeling foundation for condition assessment; however, the resulting models were primarily deterministic and produced single-value predictions without explicitly characterizing uncertainty in deterioration processes.

The current phase of the project advances this work by developing probabilistic bridge condition projection models that explicitly quantify uncertainty in condition forecasts. This shift is motivated by the need to better capture variability arising from inspection data, environmental exposure, and modeling limitations, which are not adequately represented in deterministic approaches. Incorporating uncertainty into condition projections enables more informative and reliable assessments of bridge performance over time.

A key focus of this phase is to evaluate differences in uncertainty and reliability between precast concrete (PC) and cast-in-place (CIP) bridges. By examining how variability in condition projections influences reliability-based interpretations of structural performance, the research aims to provide quantitative evidence of durability differences across bridge types. The outcome is an uncertainty-aware modeling framework that supports reliability-informed decision-making for inspection, maintenance, and long-term asset management, directly aligning with TRANS-IPIC's mission to improve durability and extend the service life of transportation infrastructure.

2. Research Plan - Summary of Project Activities (Tasks)

<u>Objective 1: Development and Validation of Probabilistic Bridge Condition Projection Models with Uncertainty Quantification</u>

Task 1.1: Model Development

This task focuses on developing a probabilistic bridge condition projection framework that extends the deterministic models established in the previous project phase. The goal is to transition from single-point condition estimates to full probability distributions and survival probabilities. Both statistical and machine learning approaches will be explored to generate probabilistic predictions of bridge condition states, including class probabilities, prediction intervals, and time-dependent measures of deterioration. The framework will be designed to balance interpretability and predictive capability while accommodating nonlinear relationships among structural, traffic, and environmental variables. The outcome of this task will be a modeling framework capable of producing uncertainty-aware bridge condition projections for subsequent validation and analysis.

Task 1.2: Calibration and Validation

This task focuses on evaluating the reliability and robustness of the probabilistic model outputs developed in Task 1.1. Model performance will be assessed in terms of both predictive accuracy and the quality of uncertainty representation, including how well predicted probabilities and intervals align with observed outcomes. Time-dependent predictions will also be evaluated to ensure that predicted deterioration trends are consistent with observed condition progression over time.

Additional analyses will be conducted to examine sensitivity to modeling assumptions, data variability, and alternative definitions of condition thresholds. The outcome of this task will be a set of validated probabilistic models that provide reliable and interpretable uncertainty-aware bridge condition projections.

Objective 2: Comparison of Precast and Cast-in-Place Bridges through Uncertainty and Reliability Analysis

Task 2.1: Comparative Analysis of Uncertainty Across Bridge Types

This task focuses on evaluating differences in variability and uncertainty in condition projections between precast concrete (PC) and cast-in-place (CIP) bridges using the probabilistic modeling framework developed in Objective 1. The analysis will compare distributions of predicted condition states, variability in model outputs, and time-dependent deterioration behavior across bridge types. Both quantitative and graphical analyses will be used to identify systematic differences in uncertainty characteristics and deterioration patterns. The goal is to determine whether PC bridges exhibit reduced variability and more consistent performance relative to CIP bridges, providing insight into durability differences across construction types.

Task 2.2: Implications for Asset Safety Assessment

This task focuses on evaluating differences in variability and uncertainty in condition projections between PC and CIP bridges using the probabilistic modeling framework developed in Objective 1. The analysis will compare distributions of predicted condition states, variability in model outputs, and time-dependent deterioration behavior across bridge types. Both quantitative and graphical analyses will be used to identify systematic differences in uncertainty characteristics and deterioration patterns. The goal is to determine whether PC bridges exhibit reduced variability and more consistent performance relative to CIP bridges, providing insight into durability differences across construction types.

Project Progress:

3. Progress for each research task

Task 1.1: Model Development [% completed to date: 50%]

1) A longitudinal model was developed:
   a. Data
      i. Constructed longitudinal bridge condition transition dataset using Illinois NBI from 2022 to 2025 (10,000+ bridges 13,200+ transitions).
      ii. Weather data averaged over inspection intervals from the nearest national weather station was integrated with bridge data.
      iii. Input covariates: Structural dimensions and design capacities, Traffic volume and characteristics
      iv. Response Variable: 3- class Bridge Condition, 9-class Structural Evaluation
   b. Model
      i. Implemented a covariate-dependent Markov transition framework based on multinomial logistic regression formulation.
      ii. Developed two separate models: one for each response variable.

Task 1.2 Calibration and Validation: [% completed to date: 30%]

1) Class weighting technique was used to address class imbalance.

2) Model performance was evaluated using balanced accuracy, confusion matrix and F1 scores, in addition to accuracy, to account for sample imbalance
3) Multiple refinements (e.g., variable selection, different ML architecture) are planned to improve predictive accuracy.

Task 2.1 Comparative Analysis of Uncertainty Across Bridge Types [% completed to date: 0%]
This task has not started during this reporting period.

Task 2.2 Implications for Asset Safety Assessment [% completed to date: 0%]
This task has not started during this reporting period.

4. Percent of research project completed

As of this reporting period, the project is approximately 30% completed, which is consistent with the expected timeline for the initial phase of model development and validation. Substantial progress has been made in Task 1.1, where a longitudinal modeling framework has been established through the construction of a transition-based dataset and implementation of a covariate-dependent modeling approach (50% completed). Initial progress has also been achieved in Task 1.2, including preliminary calibration and performance evaluation of the developed models using multiple metrics to account for class imbalance (30% completed). Ongoing efforts are focused on refining model performance and improving predictive capability. Tasks under Objective 2 (Tasks 2.1 and 2.2) have not yet commenced and are planned for subsequent phases following the completion of model development and validation. Overall, the project is progressing as planned and is on track for advancing toward probabilistic modeling and comparative analysis in the next phase.

5. Expected progress for next quarter

In the next quarter, the project will primarily focus on completing Tasks under Objective 1, which are essential for establishing the foundation of the bridge condition prediction model.

Task 1.1 (Model Development):
Continue development of the probabilistic bridge condition modeling framework by refining the longitudinal dataset and enhancing model formulations. Efforts will focus on improving data consistency across inspection records, refining the integration of environmental variables over inspection intervals, and expanding modeling approaches to incorporate probabilistic representations of condition transitions and uncertainty in deterioration processes.

Task 1.2 (Calibration and Validation):
Focus on evaluating and improving the performance of the probabilistic modeling framework developed in Task 1.1. Efforts will include assessing predictive accuracy, the quality of uncertainty representation, and the reliability of model outputs under varying data and modeling assumptions. Analyses will examine the robustness of model outputs to ensure reliable and interpretable condition projections.

Completion of these tasks will enable the project to transition into Objective 2, where the validated modeling framework will be used to compare uncertainty across bridge types and support reliability-based assessment of bridge performance.

6. Educational outreach and workforce development

Several educational and outreach activities have been initiated or are under consideration:

a) Participation in the TRANS-IPIC Annual Workshop (2026):
The research team plans to present the final results of the Year 1 project along with preliminary findings from the Year 2 project at the 2026 TRANS-IPIC Annual Workshop, building on prior engagement with stakeholders through earlier project presentations.

b) TRANS-IPIC Research Highlights Webinar:
The research team presented the final results of the Year 1 project at the TRANS-IPIC Research Highlights Webinar in January, providing exposure to current research developments for transportation professionals, researchers, and students.

c) Integration into a New Course, CEE 498 - Choices & Consequences in Civil Engineering:
The modeling framework and findings from this research are planned to be incorporated into a new undergraduate-level course focused on civil engineering decision-making.

d) Potential Development of an Educational Game:
The research team is exploring the development of an educational game to illustrate infrastructure deterioration, environmental impacts, and maintenance decision-making concepts. This activity is currently in the conceptual phase and may be considered for integration into undergraduate structural engineering courses and outreach programs such as WYSE summer camps.

7. Technology Transfer

The project is expected to generate technology transfer products that support uncertainty-aware bridge condition assessment and reliability-informed decision-making. These outputs build on the data-driven modeling framework developed in the previous project phase and extend it to incorporate probabilistic representations of deterioration.

a) Probabilistic Bridge Condition Projection Framework:
A modeling framework that produces probability-based condition projections, including representations of uncertainty in deterioration and variability across bridge types. The framework will support evaluation of condition trends over time and enable comparison of performance between PC and CIP bridges.

b) Supporting Documentation and Example Applications:
Technical documentation and example applications will be developed to illustrate the use of probabilistic condition projections and their interpretation for infrastructure assessment and planning. These materials are intended to support practitioners in understanding and applying uncertainty-aware modeling approaches.

These deliverables will be further developed in later stages of the project and disseminated through TRANS-IPIC workshops, webinars, and related outreach activities as results mature.

Research Contribution:

8. Papers that include TRANS-IPIC UTC in the acknowledgments section:

   A short paper based on the Year 1 project was prepared and submitted for inclusion in the TRANS-IPIC Annual Workshop proceedings. The paper summarizes the developed data-driven bridge condition modeling framework and highlights key findings related to the influence of structural, traffic, and environmental factors on bridge deterioration.

9. Presentations and Posters of TRANS-IPIC funded research:

   The research team plans to present the final results of the Year 1 project along with preliminary findings from the Year 2 project at the upcoming TRANS-IPIC Annual Workshop (2026).
   Shivashankarappa P., Cha E.J. Environmentally-Informed Precast Concrete Bridge Condition Modeling. TRANS-IPIC Annual Workshop. Rosemont, IL. April 2026.

10. Please list any other events or activities that highlights the work of TRANS-IPIC occurring at your university (please include any pictures or figures you may have). Similarly, please list any references to TRANS-IPIC in the news or interviews from your research.

    No additional events, media coverage, or public activities related to this project have occurred during this reporting period. Planned future activities include the integration of project outcomes into educational materials, conference presentations, and outreach efforts as the project advances.

Appendix 1: Research Activities, leadership, and awards (cumulative, since the start of the project)

At this stage of the project, there are no research activities, outputs, or milestones to report under this appendix.

A. Number of presentations at academic and industry conferences and workshops of UTC findings
   - No. = 2

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 0

C. Number of peer-reviewed journal articles published by faculty.
   - No. = 0

D. Number of peer-reviewed conference papers published by faculty.
   - No. = 0

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 0

- No. PhD dissertations = 0
- No. citations of each of the above = 0

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   - Research Tool #1 (Name, description, and link to tool) = 0

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
   - Professional societies
     - No. participated in =0
     - No. lead =0
   - Advisory committees (No. participated in & No. led)
     - No. participated in =0
     - No. lead =0
   - Conference Organizing Committees (No. participated in & No. led)
     - No. participated in =0
     - No. lead =0
   - Editorial board of journals (No. participated in & No. led)
     - No. participated in =0
     - No. lead =0
   - TRB committees (No. participated in & No. led)
     - No. participated in =0
     - No. lead =0

H. Number of relevant awards received during the grant year
   - No. awards received = 0

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
   - No. Undergraduate = 0
   - No. Graduate = 0

J. Number of internships and full-time positions secured in the industry and government during the grant year.
   - No. of internships = 0
   - No. of full-time positions = 0

References:

NA