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 *09/30/2026*

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N/A

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TRANS-IPIC Quarterly Progress Report

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)

Objective 1: Development and Validation of Probabilistic Bridge Condition Projection Models with Uncertainty Quantification

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: 100%]

This task was completed in the previous reporting period. The developed probabilistic bridge condition projection framework provides the basis for the calibration, validation, and reliability-oriented analyses conducted in subsequent tasks.

Task 1.2 Calibration and Validation: [% completed to date: 100%]

1) Calibration and validation of the probabilistic bridge condition projection framework were completed:
    a. Completed performance evaluation of the developed models using accuracy, balanced accuracy, confusion matrices, and F1-score metrics.
    b. Evaluated model performance across both the 3-class and 9-class condition classification formulations.
    c. Assessed model behavior using the expanded longitudinal dataset to evaluate how prior bridge condition states influence predicted condition distributions.
    d. Completed model refinement and validation to establish the probabilistic bridge condition projection framework for subsequent comparative and reliability-based analyses.

Task 2.1 Comparative Analysis of Uncertainty Across Bridge Types [% completed to date: 40%]

1) Comparative analysis of PC and CIP bridge condition projections was initiated:
    a. Completed an initial comparison of PC and CIP bridges based on estimated survival probabilities, evaluating differences in the probability of maintaining specified condition levels over time.
    b. Initiated further evaluation of differences in probabilistic condition projections and uncertainty characteristics between PC and CIP bridges.
    c. Began reviewing existing approaches for relating bridge condition ratings to structural capacity as preparatory work for integrating the developed condition projection models into the reliability-based assessment framework.

Task 2.2 Implications for Asset Safety Assessment [% completed to date: 10%]

1) Initial work was initiated to establish the connection between probabilistic bridge condition projections and reliability-based assessment:
    a. Began reviewing existing approaches for relating bridge condition ratings to structural capacity and resistance.
    b. Initiated evaluation of condition-to-capacity relationships that could be used to translate probabilistic condition projections into probabilistic resistance measures for subsequent reliability analysis.

4. Percent of research project completed

As of this reporting period, the project is approximately 60% completed. Objective 1 has been completed, including development, calibration, and validation of the probabilistic bridge condition projection framework. The completed framework uses the expanded longitudinal bridge inspection dataset and supports both 3-class and 9-class condition formulations, providing the foundation for uncertainty and reliability analyses.

Progress has also been made under Objective 2. Task 2.1 is approximately 40% completed, with an initial comparison of PC and CIP bridges based on estimated survival probabilities completed during this reporting period. Additional analyses of differences in probabilistic condition projections and uncertainty characteristics across bridge types are underway. Task 2.2 has also been initiated, with an initial review of existing approaches for relating bridge condition ratings to structural capacity and resistance. This review will support the subsequent integration of probabilistic condition projections into a bridge reliability assessment framework.

Overall, the project is progressing as planned, with the primary focus shifting from probabilistic condition model development and validation toward comparative analysis of PC and CIP bridges and reliability-based assessment.

5. Expected progress for next quarter

During the final quarter, the research team will focus on completing the remaining activities under Objective 2, including the comparative analysis of PC and CIP bridges under Task 2.1 and the development and application of the reliability-based assessment framework under Task 2.2.

Task 2.1: Comparative Analysis of Uncertainty Across Bridge Types

Building on the completed comparison of PC and CIP bridges based on survival probabilities, the research team will continue comparative evaluation of probabilistic condition projections across the two bridge types. Differences in prediction uncertainty and model calibration between PC and CIP bridges will be evaluated to determine whether uncertainty characteristics differ systematically across bridge types. Comparative results will be summarized using appropriate graphical representations, including survival curves, probabilistic condition projections, and uncertainty visualizations, to characterize differences between PC and CIP bridges.

Task 2.2: Implications for Asset Safety Assessment

We will continue reviewing existing approaches for relating bridge condition ratings to structural capacity and resistance and identify an appropriate condition-to-capacity relationship for the reliability analysis. The selected relationship will be integrated with the probabilistic bridge condition projections to translate projected condition distributions into probabilistic resistance measures. Reliability analyses will be conducted to evaluate how uncertainty in projected bridge condition propagates into reliability indices or failure probabilities and to examine resulting differences between PC and CIP bridges.

6. Educational outreach and workforce development

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

a) ASCE 2027 Abstract:
An abstract is in development for submission to the joint UTC session at the ASCE 2027 Infrastructure & Engineering Experience Conference to disseminate findings from this project.

b) 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.

c) 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 presented the final results of the Year 1 project along with preliminary findings from the Year 2 project at the 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 =1 (ASCE Infrastructure Resilience Division Workshop, September, 2026)
   - 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 = 2

References:

NA