



Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

*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 09/30/2025

Submitted by:

Eun Jeong Cha, ejcha@illinois.edu
Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Collaborators / Partners:

N/A

Submitted to:

TRANS-IPIC UTC
University of Illinois Urbana-Champaign
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TRANS-IPIC Quarterly Progress Report (Section 1 – 7, 5 pages max.):

Project Description:

1. Research Plan - Statement of Problem

The durability and long-term performance of bridge infrastructure are increasingly threatened by environmental stressors, such as temperature fluctuations, extreme weather events, and varying precipitation patterns. Precast concrete (PC) bridges, which represent a significant portion of the U.S. bridge inventory, are particularly vulnerable to environment-induced deterioration mechanisms like thermal cracking, corrosion, and moisture-induced damage. Despite these recognized risks, current bridge condition prediction models largely overlook the long-term influence of environmental factors. This critical limitation leads to underestimated deterioration rates and unreliable forecasts of future bridge conditions.

To address this gap, this research aims to develop an environmentally-informed, data-driven bridge condition prediction and projection model. The proposed model will integrate historical bridge performance data, regional environmental observations, future projections, and traffic data, enabling the forecasting of future bridge conditions under different projected scenarios. The goal is to enhance the understanding of how environmental stressors will impact the durability and service life of PC and other bridge types, and to provide transportation agencies with a practical tool for proactive maintenance planning and risk mitigation.

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

Objective 1: Development of an Environmentally-Informed, Data-Driven Bridge Condition Estimation Model

Task 1.1: Data Collection and Preparation

This task focuses on compiling and preparing a comprehensive dataset for model development. Data sources include the National Bridge Inventory (NBI), National Bridge Elements (NBE), historical environmental records from NOAA, traffic data from state Departments of Transportation (DOTs), and other relevant datasets. Particular attention will be given to identifying and processing key variables representing cumulative environmental effects such as temperature fluctuations, precipitation, humidity, freeze-thaw cycles, and extreme weather events. The data will be cleaned, standardized, and formatted to ensure high quality and consistency across all datasets for subsequent modeling.

Task 1.2: Model Development

This task will develop the core predictive models for estimating bridge condition ratings as a function of environmental variables as well as bridge characteristics and traffic loads. Both traditional statistical methods (e.g., ordinal logistic regression) and advanced machine learning techniques (e.g., Random Forests, Support Vector Machines) will be explored. The models will be tailored to address the specific deterioration mechanisms of PC, reinforced concrete (RC), and steel bridges. The goal is to provide interpretable models for insight into key environment-structure interactions while also leveraging machine learning for enhanced predictive performance.

Task 1.3: Model Performance Testing

Once the models are developed, their performance will be rigorously evaluated using split-sample validation (training and testing datasets). Model accuracy will be assessed using metrics such as root mean square error (RMSE), R^2 , and confusion matrices. Sensitivity analysis will be conducted

to quantify the contribution of individual environmental variables to bridge deterioration. The validated models will serve as the foundation for projecting future bridge conditions under varying environmental conditions.

Objective 2: Bridge Condition Projection for Case Study Location

Task 2.1: Selection of Case Study Location

A case study region will be selected to apply the developed model. The selection will be based on the availability of reliable bridge data, regional environmental projections, and vulnerability to long-term environmental stressors. The task will involve compiling local projections (e.g., downscaled projections from NOAA, NASA, or DOE) under multiple scenarios (e.g., SSP1–SSP5) to ensure uncertainty is incorporated. The region will represent conditions where environmental impacts on PC bridge infrastructure are expected to be significant.

Task 2.2: Application of the Model and Bridge Condition Projection

The validated model will be applied to the case study region to project future bridge conditions under both current and multiple future environmental scenarios. This task will quantify how long-term environmental stressors alter the deterioration trajectories of PC, RC, and steel bridges in the region. The projections will identify bridges at elevated risk due to environment-induced deterioration and provide actionable insights for developing risk mitigation and maintenance strategies.

Project Progress:

3. Progress for each research task

Task 1.1: Data Collection and Preparation [% completed to date: 100%]

- 1) Finalized preprocessing of the following datasets for modeling:
 - a) National Bridge Inventory (NBI) and National Bridge Elements (NBE) data
 - b) Historical environmental data from NOAA
 - c) Traffic data from state DOTs

Task 1.2 Model Development [% completed to date: 60%]

- 1) The initial model was developed.
 - a) Data
 - i) Year of 2022 dataset was used. The year was chosen because it contained the most data points (around 2,400 PC bridges).
 - ii) Weather data from the nearest national weather station was paired with other bridge data.
 - iii) Predictor variables: Average Relative Humidity, Maximum Temperature, Average Temperature, Minimum Temperature, Average Daily Traffic
 - iv) Response variable: Condition rating
 - b) Model
 - i) A multilayer perceptron (MLP) model and a multinomial logistic regression model were generated using the 9-scale bridge condition ratings. Both of the models achieved a prediction accuracy of about 35% and showed significant prediction bias caused by imbalanced data distribution. To resolve the bias in the model, the following approaches are taken.
 - (1) A model with 3-scale (0-4: P, 5-6: F, 7-9: G) bridge condition ratings was generated, which achieved a prediction accuracy of about 55% and the bias issue was resolved.
 - (2) A weighted sampling technique is under development to further enhance model robustness.

Task 1.3 Model Performance Testing [% completed to date: 50%]

- 1) Performance evaluation is integrated into Task 1.2.
- 2) Current models achieve ~55% accuracy with simplified condition categories.
- 3) Multiple refinements (e.g., weighted sampling, additional variables, different ML architecture) are planned to improve predictive accuracy.
- 4) Model performance was evaluated using the confusion matrix and F1 scores, in addition to accuracy, to account for sample imbalance.

Task 2.1 Selection of Case Study Location [% completed to date: 100%]

- 1) Illinois was selected as the study region, reflecting both regional accessibility and the strength of available datasets.

Task 2.2 Application of the Model and Bridge Condition Projection [% completed to date: 30%]

- 1) Input data collection and preparation for condition projections is in progress.

4. Percent of research project completed

Approximately 50% of the research project has been completed as of this reporting period. Substantial advancement has also been achieved in Task 1.2 (60%), where the initial model was developed, baseline approaches tested, and preliminary solutions to sample imbalance were explored. Task 1.3 has been partially integrated into the model development process (50%), with performance evaluated using accuracy, confusion matrices, and F1 scores. Under Objective 2, Task 2.1 is now complete with Illinois selected as the case study location, and Task 2.2 has progressed to 30% with input data prepared for projections. Progress in Task 1.2 was briefly slowed earlier in the quarter due to team changes, but the project is now on track and progressing steadily toward delivery of the bridge condition estimation model and its application to the selected case study region.

5. Expected progress for next quarter

The next quarter will be the final reporting period, and all remaining tasks are expected to be completed. The focus will be on finalizing model development and validation, completing the case study application, and preparing final deliverables.

Task 1.2 (Model Development):

Finalize development of the predictive models, ensuring both statistical and machine learning approaches are refined for accuracy and interpretability. Any outstanding adjustments for sample imbalance and variable selection will be resolved.

Task 1.3 (Model Performance Testing):

Complete full model validation using holdout datasets. Final sensitivity analyses will quantify the influence of environmental factors on deterioration.

Task 2.2 (Application of the Model and Bridge Condition Projection):

Complete prediction of bridge condition for the Illinois case study region under multiple environmental scenarios. Summarize findings to identify patterns of deterioration risk and provide actionable insights for proactive maintenance strategies.

By the end of the quarter, the project will deliver a fully developed and validated environmentally-informed bridge condition model, along with case study results that demonstrate its application. These outcomes will form the basis for final reports, presentations, and dissemination activities.

6. Educational outreach and workforce development

No new educational or workforce development activities were conducted during this quarter. However, the following activities have been completed or remain under consideration as part of the broader project plan:

a) Participation in the TRANS-IPIC Annual Workshop (April 2025):

The research team presented preliminary findings and methodologies at the TRANS-IPIC annual workshop, engaging with transportation agencies, researchers, and students.

b) Final Project Dissemination:

The final outcomes will be disseminated through a peer-reviewed conference presentation. If the project is renewed, the results will also be presented at the TRANS-IPIC annual workshop in 2026.

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 focusing on civil engineering decision-making.

d) Potential Development of an Educational Game:

The research team is exploring the possibility of developing an educational game to illustrate infrastructure deterioration, environmental impacts, and maintenance decision-making concepts. This activity remains in the conceptual phase and may be considered for integration into undergraduate structural engineering courses and outreach programs such as the WYSE summer camps in the future.

7. Technology Transfer

No new technology transfer activities were conducted during this quarter. The project is, however, expected to generate the following technology transfer products as it progresses:

a) New Bridge Condition Prediction and Projection Model:

A data-driven model integrating environmental variables into bridge condition assessment and projection, specifically tailored for precast concrete and other bridge types under varying scenarios.

b) User Documentation and Training Materials:

A technical report and supporting materials (e.g., user guides, example applications) will be prepared to assist DOTs and infrastructure practitioners in applying the developed model.

These deliverables are planned for completion in later stages of the project and will be shared with relevant stakeholders through TRANS-IPIC workshops, professional conferences, and formal publications.

Research Contribution:

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

No journal or conference papers have been submitted or published during this reporting period. Manuscript preparation is anticipated once model validation and case study results are finalized. Planned publications will acknowledge TRANS-IPIC UTC support and are expected to be submitted to peer-reviewed venues such as ASCE Journal of Bridge Engineering, Journal of Performance of Constructed Facilities, or ASCE Journal of Infrastructure Systems.

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

- Story M., Tripathi J., Cha E.J. Environmentally-Informed Precast Concrete Bridge Condition Modeling. TRANS-IPIC Annual Workshop. Rosemont, IL. April 2025.
- Cha E.J. Environmentally-Informed Precast Concrete Bridge Condition Modeling. TRANS-IPIC Research Highlights Webinar. November 2025.

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.

In addition to the April workshop presentation, the PI will present ongoing project results at the TRANS-IPIC Research Highlights Webinar (November 2025). This webinar will share progress with the wider TRANS-IPIC consortium, helping to broaden the impact and visibility of the 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. These activities will extend the project's reach beyond research audiences and support TRANS-IPIC's broader mission of workforce development and knowledge transfer.

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. = 1
- 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 = 1
 - 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 = 1 (ASCE Committee on Adaptation to a Changing Climate — cross-cutting, not transportation-specific)
 - No. lead = 1 (ASCE CACC Executive Committee, Secretary role)
 - 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