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 *06/30/2025*

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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

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: 50%]

1) Identified a baseline modeling approach.
2) The general model structure is under development.
3) A preliminary analysis has been conducted to understand the dynamics of bridge condition change in the dataset.
4) The graduate student is actively exploring the methodology and acquiring the coding skills necessary for implementation.

Task 1.3 Model Performance Testing [% completed to date: 0%]

This task has not started during this reporting period.

Task 2.1 Selection of Case Study Location [% completed to date: 70%]

1) Narrowed down to the top candidate region based on data quality and relevance.
2) Initiated acquisition of projections for the selected location.

Task 2.2 Application of the Model and Bridge Condition Projection [% completed to date: 15%]

Prepared input data framework for condition projections.

4. Percent of research project completed

Approximately 40% of the research project has been completed as of this reporting period. Major progress was made in Task 1.1 (now complete), and foundational work for Task 1.2 is underway (50%). Task 1.3 has not yet started. Work under Objective 2 has continued steadily, especially with narrowing down the case study region. **Overall, the project is on schedule** and progressing steadily toward the development of the environmentally-informed bridge condition model and its application to the selected case study region.

5. Expected progress for next quarter

In the next quarter, the project will primarily focus on completing Tasks 1.2 to 1.3 under Objective 1. Completion of these tasks will enable the project to transition into Objective 2, where the validated model will be applied to the selected case study region to project future bridge conditions.

Task 1.2 (Model Development):
Advance model development under Task 1.2 by completing the implementation of the baseline model. Conduct further analysis to evaluate model structure, variable importance, and predictive performance.

Task 1.3 (Model Performance Testing):
Conduct model testing and validation using holdout datasets. Performance will be evaluated using appropriate statistical metrics.

6. Educational outreach and workforce development

This project is still in its early stages, and several educational and outreach activities have been conducted or are under consideration:

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

The project is 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. Publications are expected in future reporting periods as the model development and case study application progress.

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

   The research team presented preliminary findings at the TRANS-IPIC Annual Workshop (April 2025).

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

    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. = 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 =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