Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Optimizing Maintenance Decisions for Precast Concrete Bridges

UI-25-RP-04

Quarterly Progress Report

For the performance period ending 6/30/2026

Submitted by:

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Collaborators / Partners:

None

Submitted to:

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Project Description:

1. Research Plan - Statement of Problem

The American Society of Civil Engineers (ASCE) reports that approximately 56% of the nation's 623,000 bridges are in fair or poor condition that caused substantial safety risks and traffic delays for millions of daily users. This has been caused by the lack of funding for the rehabilitation and reconstruction of aging bridges which created a $191.3 billion rehabilitation backlog and a $373 billion funding gap over the next decade (ASCE, 2025; FHWA, 2025). To address this pressing challenge, federal and state departments of transportation (DOTs) need to optimize the use of limited funding and budgets for the rehabilitation of aging bridges to maximize their overall performance and durability. This presents federal and state DOTs with several challenges, including how to (1) optimize maintenance and repair decisions for precast concrete bridges; (2) maximize durability of precast concrete bridges; (3) minimize bridge maintenance costs; and (4) generate and analyze trade-offs among these bridge optimization objectives. To address these challenges, this research will develop robust multi-objective models and a user-friendly decision support tool for optimizing maintenance decisions for precast concrete bridges. This perfectly aligns with the TRANS/IPIC mission of "providing gains in durability, safety, and economy as well as reducing environmental impact and resources required for repair and replacement" (TRANS-IPIC, 2025).

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

Task 1: Identify all relevant decision variables representing maintenance actions for precast concrete bridge components throughout the user-specified planning horizon.

Task 2: Formulate objective functions to quantify the impact of the identified maintenance decision variables on critical optimization objectives, including extending bridge durability by maximizing its condition rating and minimizing bridge maintenance costs.

Task 3: Model all practical constraints that affect this multi-objective optimization problem to fully represent all limitations confronting state DOTs such as annual budgetary restrictions, resource availability, and bridge performance requirements.

Task 4: Implement the formulated model using various optimization techniques, including Mixed-Integer Programming (MIP), Genetic Algorithms (GA), Ant Colony Optimization (ACO), and Constraint Programming (CP).

Task 5: Evaluate the computational efficiency and effectiveness of the implemented models using several case studies of varying sizes and maintenance funding levels to illustrate their capabilities in prioritizing and optimizing maintenance and repair decisions for precast concrete bridges.

Task 6: Develop a practical decision support tool (DST) that integrates the developed models and friendly graphical user interface (GUI) to facilitate the use and adoption of the research development by State DOTs and bridge planners.

Project Progress:

3. Progress for each research task

Task 1 Progress: [100% completed]. During this quarter, the research team completed the first research task that focused on Identifying all relevant decision variables representing maintenance actions for each precast concrete bridge component throughout the user-specified planning horizon. For example, a binary decision variable ($X_{b,i,j,r}$) was defined to represent the selection of maintenance action j for each component i of bridge b during time period r of the planning horizon (Betz et al. 2024). These decisions can be represented by selections from a set of alternative maintenance actions such as no action, preventive maintenance, minor repair, rehabilitation, or replacement/major reconstruction.

Task 2 Progress: [100% completed]. During this quarter, the research team completed the second research task that focused on formulating objective functions to quantify the impact of the identified maintenance decision variables on key optimization objectives, including maximizing bridge durability and minimizing total maintenance cost. For example, the impact of alternative maintenance decisions on maximizing the condition rating of individual bridge components such as decks and superstructure are quantified using the FHWA condition rating scale ranging from 0 to 9 (AASHTO 2025; FHWA 2025), as shown in Eq. (1) and (2). The durability objective function maximizes the weighted post-maintenance condition ratings of bridge components while penalizing condition ratings that fall below a specified threshold. The post-maintenance condition rating is calculated by adding the improvement associated with the selected maintenance action to the pre-maintenance condition rating, subject to a maximum rating of 9, as shown in Eq. (2). Similarly, the maintenance cost objective function is formulated to minimize the total cost of selected maintenance actions by summing the costs of selected actions across all components and time periods, as shown in Eq. (2).

$$Max\ Durability = Max \sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{r=1}^{R}\left(CR_{b,i,j,r}^{Post} \quad W_i - \lambda\left(max\left(0, CR_i^{th} - CR_{r,i,j}^{Post}\right)\right)\right) X_{b,i,j,r} \tag{1}$$

$$CR_{b,i,j,r}^{Post} = min(CR_{b,\,i,r}^{pre} + \Delta\, CR_{b,i,j,r},\ 9) \tag{2}$$

$$Min\ Total\ Maintenance\ Costs = Min \sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J} MC_{b,i,j,r} * X_{b,i,j,r} \tag{3}$$

Where $CR_{b,i,j,r}^{Post}$ represents post-maintenance condition rating of component i of bridge b, resulting from maintenance decision j in time period r, W_i represents importance weight of component i , λ represents penalty coefficient for condition ratings below the threshold, CR_i^{th} represents minimum acceptable condition-rating threshold for component i, $CR_{b,\,i,r}^{pre}$ represents condition rating of component i of bridge b before apply any maintenance decision in year r , $\Delta\, CR_{b,i,j,r}$ represents improvement in the condition rating of component i of bridge b due to the selection of maintenance decision j in time period r. $MC_{b,\,i,\,j,\,r}$ represents the maintenance cost of component i of bridge b due to the selection of maintenance decision j in time period r.

Task 3 Progress: [100% completed]. During this quarter, the team completed the third research task that focused on modeling all practical constraints that affect this multi-objective optimization problem to fully represent the limitations confronting state DOTs such as annual budgetary restrictions, resource availability, and bridge performance requirements. These constraints ensure that the optimization model generates only feasible and implementable maintenance solutions within the specified budget and the limited availability of maintenance and rehabilitation crews. For example, only one maintenance decision j can be selected for each component i of bridge b in any year r, as shown in Eq. (5). Similarly, the total maintenance cost for all components $(i = 1\ to\ I)$ of all bridges $(b = 1\ to\ B)$ in year r must be less than or equal to the maximum budget available in this year $Budget_r$, as shown in Eq. (6). In addition, the total required maintenance resources (e.g., crews) for all selected actions in year r must not exceed the available resources in that year, as shown in Eq. (7). Furthermore, the overall bridge performance must satisfy minimum condition requirements to ensure acceptable service levels, as shown in Eq. (4).

$$\textstyle\sum_{j=1}^{J} X_{b,i,j,r} = 1 \qquad \forall\, b, i, r \tag{5}$$

$$\sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J} MC_{b,i,j,r}\, X_{b,i,j,r} \ \le\ Budget_r \ \ \forall\, r \in \{1,2, \dots R\} \tag{6}$$

$$\sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J} RC_{b,i,j,r} * X_{b,i,j,r} \leq Resource_r \ \forall\, r \in \{1,2,\dots R\} \tag{7}$$

$$CR_{b,i,j,r}^{Post} \geq CR_i^{th} \qquad \forall b,i,r \tag{8}$$

Where $Budget_r$ represents the total available maintenance budget in year r, $RC_{b,i,j,r}$ represents the required resource (crews) for applying action j to component i in year r, $Resource_r$ represents the total available resources in year r.

Task 4 Progress: [50% completed]. During this quarter, the research team initiated the fourth research task, which focuses on implementing the formulated maintenance optimization model using various optimization techniques. To accomplish this, the research team developed machine learning (ML) models to accurately predict the initial condition ratings of bridge components, including bridge decks, prior to the application of any maintenance actions. These predicted condition ratings serve as the baseline for evaluating and quantifying the impact of alternative maintenance decisions on bridge durability. The development process of the ML models focused on four stages: (1) collecting bridge deck data from the National Bridge Inventory (NBI); (2) preprocessing the collected data and splitting the dataset into training and testing datasets; (3) developing six ML models for predicting the condition rating of concrete bridge decks; and (4) evaluating and validating the performance of the six developed ML models using the testing dataset, as shown in Figure 1. The research team summarized the findings from the development of these machine learning (ML) models in a peer-reviewed manuscript, which was accepted for publication in the *ASCE Journal of Construction Engineering and Management* on June 25, 2026.

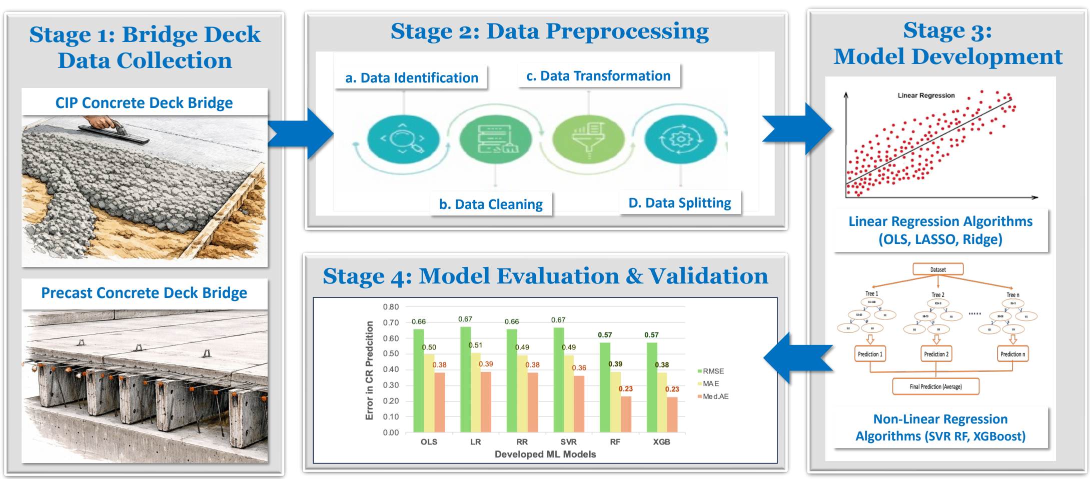


Figure 1. Development stages of ML models for predicting condition rating of concrete bridge decks

Task 5 Progress: [0% completed] (Not Started).

Task 6 Progress: [0% completed] (Not Started).

4. Percent of research project completed

50% of total project completed through the end of this quarter.

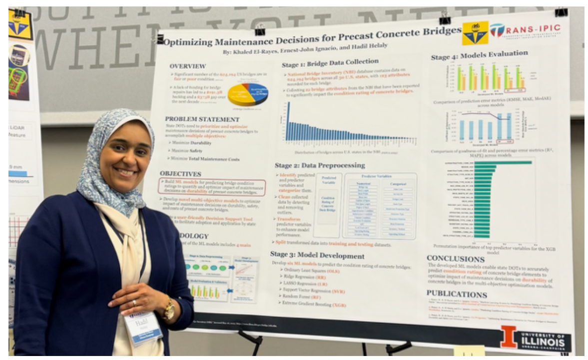
5. Expected progress for next quarter

In the next quarter, the research team will finalize the fourth task, which focuses on implementing the formulated maintenance optimization model using various optimization techniques. Additionally, the team will initiate the fifth task, which involves evaluating the computational efficiency and effectiveness of the implemented models through case studies of varying sizes and maintenance funding levels. These case studies will be used to demonstrate the models' capabilities in prioritizing and optimizing maintenance and repair decisions for precast concrete bridges under different budget constraints and operational conditions.

6. Educational outreach and workforce development

This quarter, the educational and workforce development (EWD) activities focused on enhancing the analytical and research skills of a female PhD student serving as the lead research assistant on this project. Her work involved collecting and analyzing bridge construction data from multiple databases and developing multi-objective optimization models. Additionally, the research team participated in all TRANS-IPIC monthly online webinars and attended the 2026 TRANS-IPIC Workshop on April 14, 2026, in Rosemont,IL to learn about cutting-edge technologies in precast concrete construction and present the preliminary findings of this research project during the poster presentation session, as shown in Figure 2.

(a) Research team attending the 2026 TRANS-IPIC workshop



(b) Research team presenting their preliminary findings at the 2026 TRANS-IPIC workshop

Figure 2. Research team attending the 2026 TRANS-IPIC workshop in Rosemont, IL

7. Technology Transfer

The research team developed six novel machine learning (ML) models to predict the condition rating of concrete bridge decks using the National Bridge Inventory (NBI) database, which is the largest bridge inventory database in the United States. Additionally, the team is developing novel multi-objective optimization models and a user-friendly decision support tool to optimize maintenance decisions for precast concrete bridges.

<u>Research Contribution:</u>

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

The research team submitted a manuscript titled "*Machine Learning Models for Predicting Condition Rating of Cast-In-Place and Precast Concrete Bridge Decks*" to the *ASCE Journal of Construction Engineering and Management*, where it was accepted for publication on June 25, 2026. Additionally, the team submitted a manuscript to TRANS-IPIC for publication in the proceedings of the 2026 TRANS-IPIC Workshop, as follows:

- Helaly, H., K. El-Rayes, and E. J. Ignacio. 2026a. *Machine Learning Models for Predicting Condition Rating of Cast-In-Place and Precast Concrete Bridge Decks*. Accepted for publication in the *ASCE Journal of Construction Engineering and Management* on June 25, 2026.
- Helaly, H., K. El-Rayes, and E. J. Ignacio. 2026b. "Predicting Condition Rating of Concrete Bridge Decks." In *Proceedings of the 2026 TRANS-IPIC UTC Workshop*.

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

The research team presented the preliminary findings of this research project at the 2026 Annual TRANS-IPIC UTC Workshop on April 14, as shown in Figure 2 and Figure 3.

- El-Rayes, K., E. J. Ignacio, and H. Helaly. 2026. “Optimizing the Planning of Precast Concrete Bridges.” Poster presentation at the 2026 TRANS-IPIC UTC Workshop.

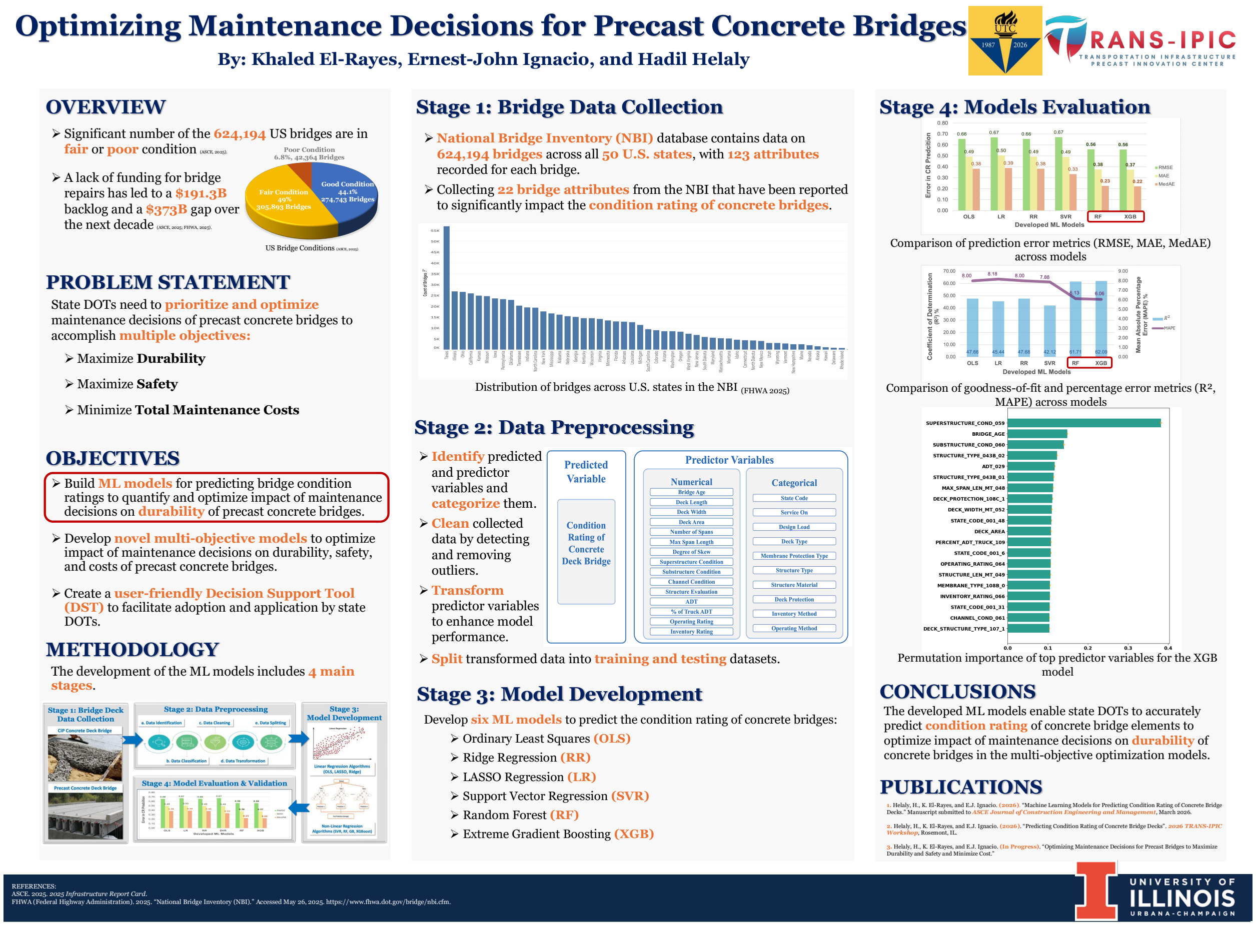


Figure 3. Poster presenting the preliminary results of the TRANS-IPIC research (El-Rayes et al., 2026)

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.

None.

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

A. Number of presentations at academic and industry conferences and workshops of UTC findings
   - No. = 1: One poster presentation at the 2026 TRANS-IPIC Workshop held on April 14, 2026, in Rosemont, IL.

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 1: One manuscript was submitted to the *ASCE Journal of Construction Engineering and Management* in March 2026 and was accepted for publication on June 25, 2026.

C. Number of peer-reviewed journal articles published by faculty.
   - No. = One manuscript was published at the ASCE *Journal of Construction Engineering and Management* in May 2026 based on outcomes of UTC funded projects.

D. Number of peer-reviewed conference papers published by faculty.
   - No. = One manuscript was submitted to TRANS-IPIC for publication in the proceedings of the 2026 TRANS-IPIC Workshop.

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 0
   - No. PhD dissertations = One ongoing PhD dissertation by Hadil Helaly
   - 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: Six novel machine learning (ML) models were developed to predict the condition rating of concrete bridge decks using the National Bridge Inventory (NBI) database.
   - Research Tool #2: Novel multi-objective optimization models for planning maintenance decisions of precast concrete bridges (ongoing).
   - Research Tool #3: A user-friendly graphical user interface (GUI) designed to facilitate the use and adoption of the developed optimization models by State Departments of Transportation (DOTs) and bridge planners (ongoing).

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 = One award was received by Hadil Helaly (lead research assistant) — the 2025 TRANS-IPIC Outstanding Student of the Year, recognized at the Council of University Transportation Centers (CUTC) Awards Banquet during TRB 2026.

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
   - No. Undergraduate = 2
   - No. Graduate = 2

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:

AASHTO Manual for Bridge Evaluation (MBE). 2025. *Bridge Design Manual*.

ASCE. 2025. *2025 Infrastructure Report Card*.

Betz, T., K. El-Rayes, and M. Grussing. 2024. "Multiyear Facility Maintenance Optimization." *Journal of Performance of Constructed Facilities*, 38 (2). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/jpcfev.cfeng-4678.

FHWA (Federal Highway Administration). 2025. "National Bridge Inventory (NBI)." Accessed May 26, 2025. https://www.fhwa.dot.gov/bridge/nbi.cfm.

Transportation Infrastructure Precast Innovation Center (TRANS-IPIC). 2025. "Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)." Accessed July 22, 2025. https://trans-ipic.illinois.edu/index.asp.