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 3/31/2026

Submitted by:

Khaled El-Rayes, Professor UIUC, elrayes@illinois.edu
Ernest-John Ignacio, Teaching Assistant Professor UIUC, eignaci2@illinois.edu
Hadil Helaly, Research Assistant UIUC, hadil@illinois.edu

Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Collaborators / Partners:

None

Submitted to:

TRANS-IPIC UTC
University of Illinois Urbana-Champaign
Urbana, IL

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 bridge safety and load capacity; (3) maximize durability of precast concrete bridges; (4) minimize bridge maintenance and life-cycle costs; and (5) 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, as shown in Figure 1.

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, improving bridge safety by maximizing its load capacity, and minimizing bridge maintenance cost, as shown in Figure 1.

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, as shown in Figure 1.

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), as shown in Figure 1.

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, as shown in Figure 1.

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, as shown in Figure 1.

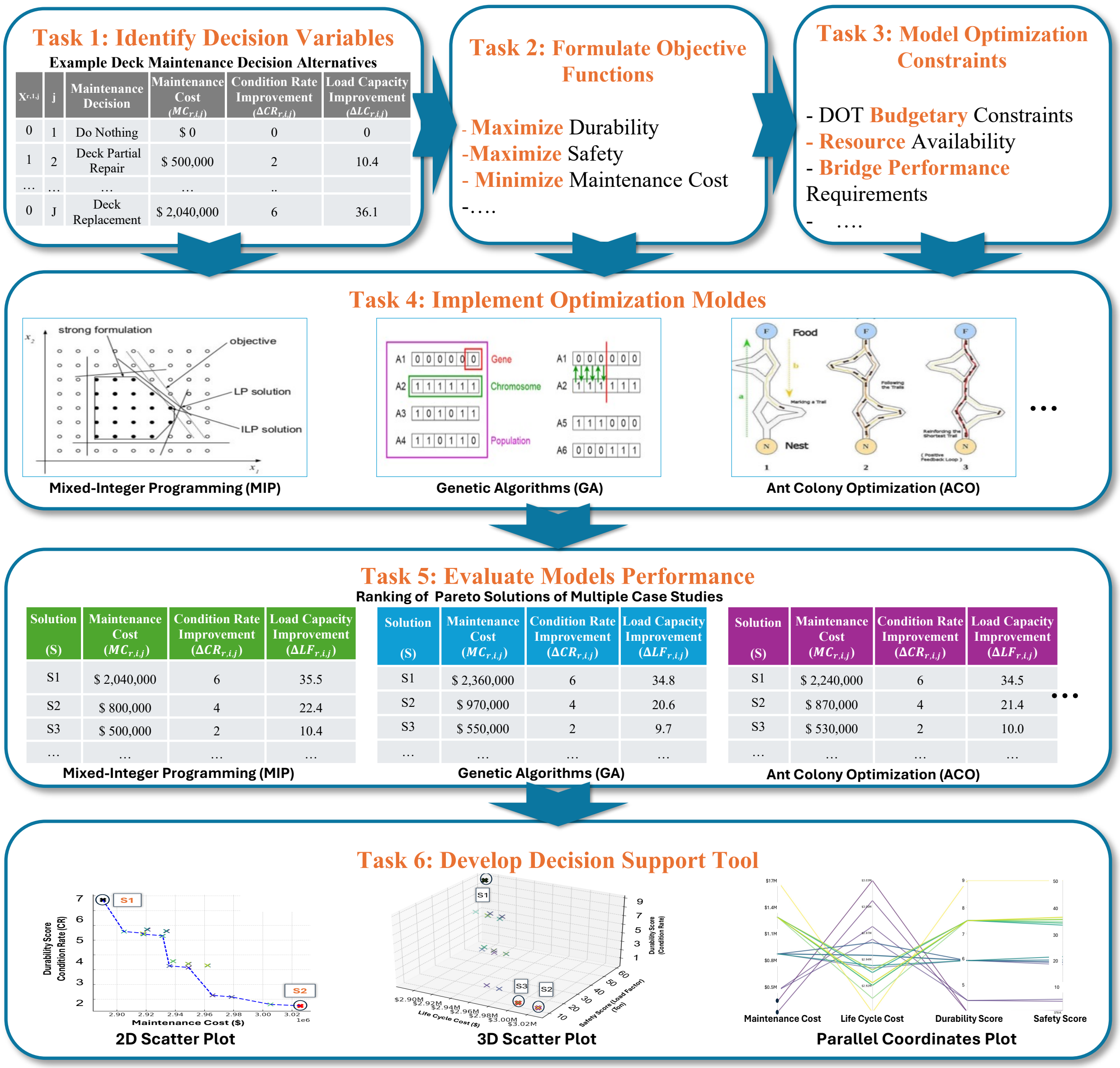

Figure 1. Research Tasks

Project Progress:

3. Progress for each research task

Task 1 Progress [80% completed]. This quarter, the research team worked on 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 ($X_{r,i,j}$) can be used to represent the selected maintenance decision j for each bridge component i during time period r of the planning horizon, as shown in Figure 1 (Betz et al. 2024). These decisions can be represented by selections from a set of alternative maintenance actions such as no maintenance, partial repair, full repair, partial replacement, or full replacement.

Task 2 Progress: [80% completed]. This quarter, the team worked on the second research task that focused on formulating objective functions to quantify the impact of the identified maintenance decision variables on critical optimization objectives, including enhancing bridge durability by maximizing condition improvement, improving bridge safety by maximizing load capacity, and minimizing total maintenance cost. For example, the impact of alternative maintenance decisions on enhancing the condition rating of individual bridge components such as decks and superstructure can be quantified using the methods provided by Betz et al. (2024) on a scale that range from 0 to 9 (AASHTO 2025; FHWA 2025), as shown in Eq. (1). Similarly, the effect of alternative maintenance decisions on improving bridge load capacity can be quantified using the load capacity (LC), which represents the permissible load level that a structure may safely carry based on its structural capacity and condition (AASHTO 2025; FHWA 2025), as shown in Eq. (2). The impact of maintenance decisions on minimizing total maintenance costs can also be quantified by summing the costs of selected actions across all components and time periods, as shown in Eq. (3).

$$Max\ Durability = Max\ Bridge\ Durability\ Improvment = Max \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{J} \Delta CR_{r,i,j}\ X_{r,i,j}\, W_i \tag{1}$$

$$Max\ Safety = Max\ Bridge\ Load\ \ Capacity\ Improvement = Max \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{J} \Delta LC_{r,i,j}\ X_{r,i,j}\ V_i \tag{2}$$

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

Where $\Delta CR_{r,i,j}$ represents improvement in the condition rating of bridge component i due to the selection of maintenance decision j in time period r; W_i represents relative importance weight of bridge component i; $X_{r,i,j}$ represents a binary decision variable equal to 1 if maintenance decision j is selected for component i in period r, and 0 otherwise; $\Delta LC_{r,i,j}$ represents the improvement in load capacity of bridge component i due to the selection of maintenance decision j in time period r, measured in metric tons, V_i represents the improvement in load capacity of bridge component i, and $MC_{r,i,j}$ represent the maintencance cost of bridge component i due to the selection of maintenance decision j in time period r . For example, the binary selection of $X_{2,1,2} = 1$ represents a decision to maintain deck component $(i = 1)$ through partial repairing/ patching $(j = 2)$ during the second period $(r = 2)$. This action increases the bridge condition rating from 3 to 5 $(CR_{2,1,2} = 2)$, raises its load capacity from 33.3 tons to 43.7 tons $(\Delta LC_{2,1,2} = 10.4\ tons)$, and costs $500,000, as shown in Figure 1.

<u>Task 3 Progress:</u> [75% completed]. This quarter, the research team worked on 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 bridge component i in any year r, as shown in Eq. (4). Similarly, the total maintenance cost for all bridge elements $(i = 1\ to\ I)$ in year r must be less than or equal to the maximum budget available in this year $Budget_r$, as shown in Eq. (5). 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. (6). Furthermore, the overall bridge performance must satisfy minimum condition requirements to ensure acceptable service levels, as shown in Eq. (7).

$$\textstyle\sum_{j=1}^{J} X_{r,i,j} = 1 \qquad \forall\, r, i \tag{4}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} MC_{r,i,j}\, X_{r,i,j} \ \le\ Budget_r \ \ \forall\, r \in \{1,2,\dots R\} \tag{5}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} RC_{r,i,j} * X_{r,i,j} \leq Resource_r \ \forall\, r \in \{1,2,\dots R\} \tag{6}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} \Delta CR_{r,i,j} * W_i * X_{r,i,j} \leq CR_r^{min} \ \forall\, r \in \{1,2,\dots R\} \tag{7}$$

Where $Budget_r$ represents the total available maintenance budget in year r, $RC_{r,i,j}$ 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, CR_r^{min} represents the minimum acceptable bridge condition level in year r.

Task 4 Progress: [0% completed] (Not Started).

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

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

4. Percent of research project completed

25% 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 first three tasks that focus on identifying decision variables, formulating objective functions, and defining optimization constraints. Additionally, the team will start working on the fourth task, which involves implementing the formulated model using various optimization techniques.

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. 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 plans to attend the 2026 TRANS-IPIC Workshop on April 14, 2026, in Rosemont, IL, to learn about cutting-edge technologies in precast concrete and present the preliminary findings of this research project during the poster presentation session.

7. Technology Transfer

The research team is currently developing novel multi-objective models and a user-friendly decision support tool to optimize maintenance decisions for precast concrete bridges.

Research Contribution:

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

The research team submitted one manuscript to the TRANS-IPIC on March 27, 2026, for publication in the 2026 TRANS-IPIC Workshop.

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

The research team is planning to present the preliminary findings of this research project at the TRANS-IPIC Workshop on April 14, 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 is scheduled for the 2026 TRANS-IPIC Workshop 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 *Journal of Construction Engineering and Management, ASCE* in March 2026 based on outcomes of UTC funded projects.

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 = 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: Novel multi-objective optimization models for planning maintenance decisions of precast concrete bridges (ongoing).
    - Research Tool #2: A friendly graphical user interface (GUI) to facilitate the use and adoption of the developed optimization models by State 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 = 1
        - 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.

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