Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Optimizing the Planning of Precast Concrete Bridge Construction Methods to Maximize Durability, Safety, and Sustainability (Phase II)
UI-23-RP-05

Quarterly Progress Report
For the performance period ending June 30, 2025

Submitted by:
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Collaborators / Partners:
None

Submitted to:
TRANS-IPIC UTC
University of Illinois Urbana-Champaign
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Project Description:

1. Research Plan - Statement of Problem

The American Road and Transportation Builders Association reported that 36% of all U.S. bridges required major repair work or replacement (ARTBA 2023; FHWA 2024). To address this, the US federal government enacted the Infrastructure Investment and Jobs Act in 2023 that invests over $300 billion in replacing and repairing America's aging roads and bridges (The White House 2023). This presents DOTs with a number of challenges including how to (1) accurately predict the condition of aging conventional cast-in-place and precast bridges to improve their durability and extend their life; (2) analyze and compare during the early design phase the durability, safety, mobility, sustainability, and construction cost of alternative bridge construction methods including conventional cast-in-place, precast bridge elements or systems, precast lateral slide, and precast self-propelled modular transporter, for each planned project based on its specific conditions and requirements; and (3) quantify and optimize during the preconstruction phase the impact of important construction decisions on multiple objectives including safety, mobility, sustainability, and construction cost, as shown in Figure 1.

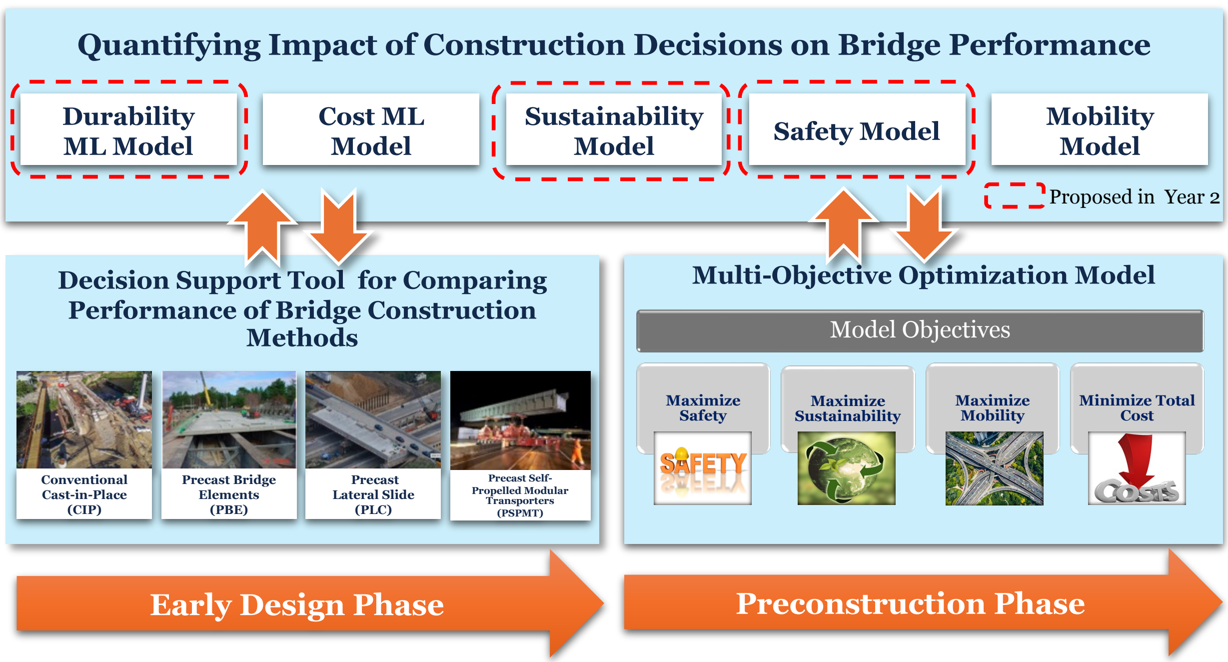


Figure 1. Proposed Decision Support Tool and Optimization Model

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

Task 1: Develop novel machine learning models to accurately predict the condition rates of both conventional cast-in-place and precast bridges based on a wide range of variables including bridge age, length, design type, average daily traffic, and design load.

Task 2: Create a practical decision support tool (DST) that can be used by DOT planners during the early design phase to analyze and compare the durability, safety, sustainability, mobility, and construction cost of conventional cast-in-place and precast bridges.

Task 3: Expand the developed multi-objective optimization model in the first year to include safety and sustainability to support State DOTs during the preconstruction phase in identifying optimal bridge construction decisions such as delivery day, transportation, and on-site installation of bridge PC modules to enhance safety, sustainability, and mobility while minimizing total construction cost.

Project Progress:

3. Progress for each research task

Task 1 Progress [60% completed]. Last quarter, the research team continued working on the first research task that focused on developing novel machine learning models for predicting the condition rates and deterioration of conventional and precast bridges during the early design phase. The development of these models focused on the following four main phases.

a. Data Collection

This phase is still ongoing and is focusing on identifying and collecting all bridge related data that have an impact on bridge condition rate and deterioration using the database of the National Bridge Inventory (NBI) (FHWA 2024). This NBI database contains related data such as bridge condition rate, age, length, width, span length, number of spans, and average daily traffic for over 600,000 bridges in the United States. The collected data is currently being used to develop novel machine learning models for predicting the condition rate of conventional and precast bridges during the early design phase.

b. Data Preprocessing

This phase is still ongoing and is focusing on preprocessing the raw data that was collected in the previous phase to ensure its quality and usability. This was accomplished in five main steps that focused on (1) identifying predicted and predictor variables, (2) categorizing predictor variables to categorical and numerical variables, (3) cleaning collected data by detecting and deleting outliers, (4) transforming predictor variables to enhance their performance in the machine learning models, and (5) dividing the transformed data into training and testing sets.

c. Model Development

This quarter the research team started working on this phase that focused on developing different novel ML models to predict the condition rates and deterioration of conventional and precast bridges using ML algorithms such as extreme gradient boosting, multilayer perceptron neural networks, k-nearest neighbors, random forest, and support vector machines using the training dataset (Chen and Guestrin 2016; Fabian Pedregosa et al. 2011)

d. Model Evaluation

This phase is planned to start after the completion of the model development phase. The performance of the developed ML models will be evaluated using the testing set by comparing their predicted values to the true values. This validation analysis will be conducted using four primary metrics: (1) mean absolute percentage error (MAPE), (2) mean absolute error (MAE), (3) median absolute error (Med AE), and (4) root mean squared error (RMSE).

Task 2 Progress [0% completed] (Not started).

Task 3 Progress [100% completed]. The research team has completed the development of a multi-objective optimization model to support State DOTs in generating and analyzing optimal trade-offs among the four key objectives of maximizing safety, mobility, and sustainability while minimizing total cost of precast bridge construction projects. The development of the optimization model focused on the following three main phases, as shown in Figure 2.

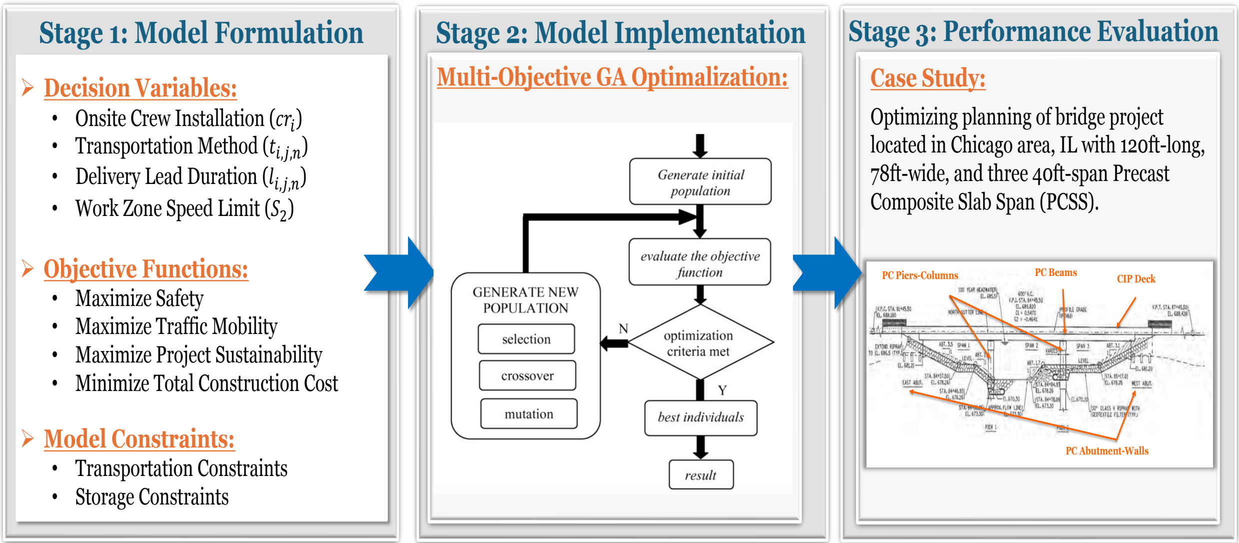


Figure 2. Development stages of multi-objective optimization model

a. Model Formulation

This stage focused on formulating a novel multi-objective optimization model for identifying optimal construction planning decisions for precast bridge construction projects. This was achieved in three main steps that focused on: (i) identifying all relevant decision variables including work zone speed limit (S_2), crew selection (Cr_i) for each bridge activity i, and delivery lead days $(l_{i,j,n})$ prior to installation day, and the transportation method $(t_{i,j,n})$ of each precast element n of section j in activity i; (ii) formulating objective functions to maximize safety, mobility, and sustainability while minimizing total construction cost; and (iii) modeling all practical constraints related to the transportation and onsite storage of prefabricated elements.

b. Model Implementation

This stage focused on implementing the optimization computations of the formulated model. This was executed in Python using the Nondominated Sorting Genetic Algorithm II (NSGA-II) and four supporting modules: (a) scheduling module that generates a construction schedule to comply with crew availability, job logic, and crew work continuity; (b) transportation module that creates a practical and cost-effective plan for transporting all precast bridge elements to the construction site with the least number of truck trips and transportation cost; (c) cost module that calculates the cost of each generated solution based on the formulated cost objective function; and (d) performance module that estimates safety, mobility, and sustainability scores.

c. Performance Evaluation

This stage focused on analyzing a case study of a bridge construction project in Illinois to evaluate the performance of the developed optimization model and demonstrate its capabilities in optimizing the planning of precast bridge construction projects. In this case study, the model generated a set of 35 optimal solutions, where each represents a unique and optimal trade-off among the four optimization objectives, as shown in Figure 3.

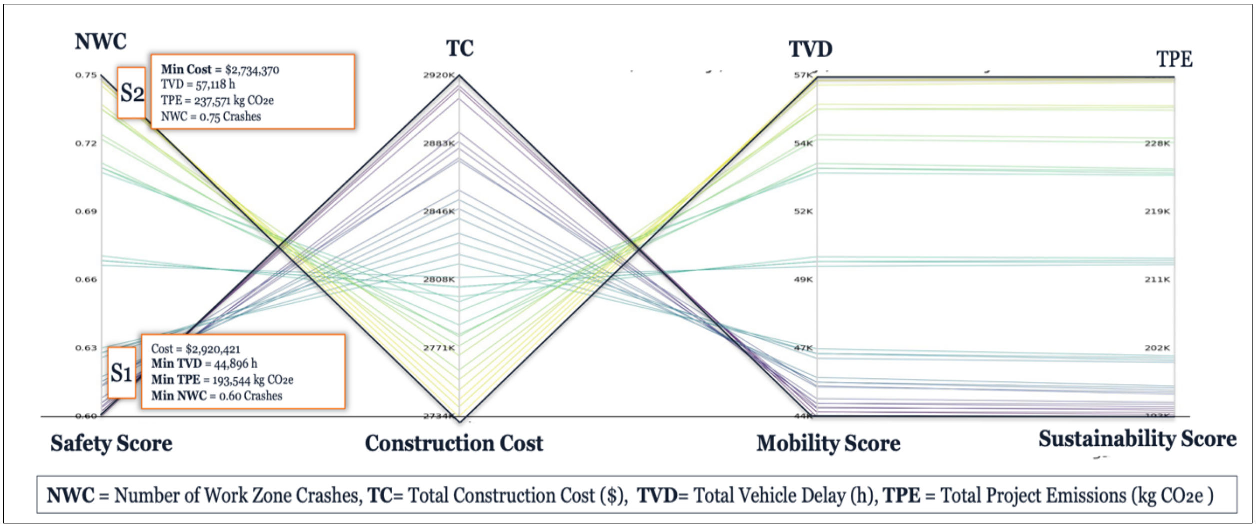


Figure 3. Parallel coordinates plot of optimization objectives

4. Percent of research project completed

53% of total project is completed through the end of this quarter:

Task 1: 60% completed.
Task 2: 0% completed (not started).
Task 3: 100% completed.

5. Expected progress for next quarter

In the next quarter, the research team will continue working on developing and evaluating machine learning (ML) models to accurately predict the condition rate and deterioration of bridge projects. Additionally, the team will start creating a practical Decision Support Tool (DST) that integrates both the ML models developed last year for predicting construction cost and the newly developed models for predicting bridge condition. This tool will enable comprehensive analysis and comparison of durability, safety, sustainability, mobility, and construction cost for conventional cast-in-place and precast bridges during the early design phase.

6. Educational outreach and workforce development

The educational and workforce development (EWD) activities this quarter focused on: (1) continuing to enhance the analytical and research skills of a female PhD student, the lead research assistant, in collecting and analyzing bridge construction data from various databases and developing machine learning and multi-objective optimization models; (2) developing educational modules for two construction engineering courses (CEE 421 and CEE 526), which the PI and Co-PI teach to over 120 students annually; and (3) attending the TRANS-IPIC monthly webinars.

7. Technology Transfer

The research team is currently developing (1) novel machine learning models to predict the condition rates of bridge projects during the early design phase; (2) a practical decision support tool (DST) to analyze and compare the durability, safety, sustainability, mobility, and construction cost of conventional cast-in-place and PC bridges during the early design phase, and; (3) a multi-objective optimization model to optimize the planning of bridge projects to maximize safety, mobility, and sustainability, while minimizing the total construction cost.

Research Contribution:

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

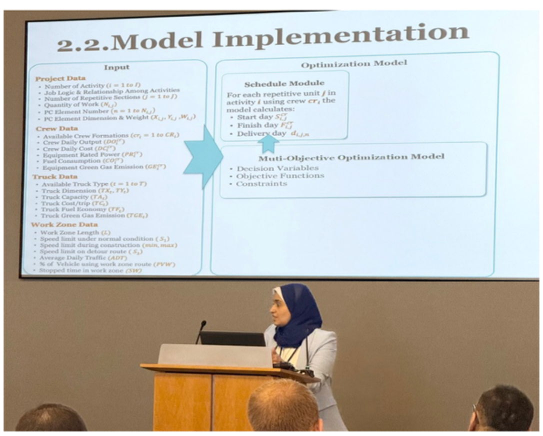
The research team successfully published two papers in leading construction engineering and management journals; submitted a conference paper, which will be included in the proceedings of the

ASCE Construction Research Congress 2025; and is currently preparing a new journal manuscript for submission. The publications are as follows:

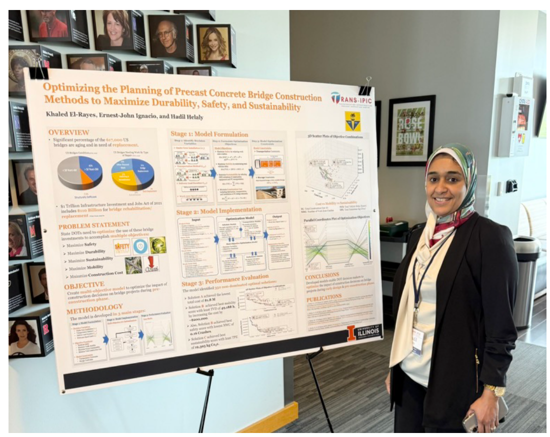
1. Helaly, H., K. El-Rayes, E.J. Ignacio, and H. J. Joan. (January 2025). “Comparison of Machine Learning Algorithms for Estimating Cost of Conventional and Accelerated Bridge Construction Methods During Early Design Phase” Journal of Construction Engineering and Management, ASCE. https://doi.org/https://ascelibrary.org/doi/10.1061/JCEMD4.COENG-15934.
2. Helaly, H., K. El-Rayes, and E.J. Ignacio. (February 2025). “Predictive Models to Estimate Construction and Life Cycle Cost of Conventional and Prefabricated Bridges During Early Design Phases.” Canadian Journal of Civil Engineering. https://doi.org/10.1139/cjce-2023-0493.
3. Helaly, H., K. El-Rayes, and E.J. Ignacio. (July 2025). “Machine Learning Models for Estimating Construction Costs of Conventional and Accelerated Bridge Construction Methods” ASCE Construction Research Congress (CRC) 2025, Modular and Office Construction Summit (MOC).
4. Helaly, H., K. El-Rayes, and E.J. Ignacio. (In Progress). “Multi-Objective Optimization of Precast Bridge Construction Projects”

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

The research team presented their preliminary research findings in four venues including (1) an oral presentation on April 22, 2025, during the first day of the TRANS-IPIC Workshop; (2) a poster presentation on April 23, 2025, during the second day of the workshop; (3) an online presentation during the TRANS-IPIC monthly webinar on May 21, 2025; and (4) an upcoming presentation at the ASCE Construction Research Congress (CRC) 2025, Modular and Offsite Construction (MOC) Summit in July 2025, as shown in Figure 4.



(a) The research team presenting their preliminary findings on the first day of the TRANS-IPIC Workshop 2025



(b) The research team presenting their preliminary findings on the second day of the TRANS-IPIC Workshop 2025

Figure 4. The research team attending the second annual TRANS-IPIC workshop in Rosemont, IL

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. = Four presentations including (1) oral presentation on April 22, during the first day of the TRANS-IPIC Workshop 2025; (2) poster presentation on April 23, during the second day of the TRANS-IPIC Workshop 2025; (3) online presentation during the TRANS-IPIC monthly webinar on May 21, 2025; (4) upcoming presentation at the ASCE Construction Research Congress (CRC) 2025, Modular and Offsite Construction (MOC) Summit in July 2025.

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = Two published peer-reviewed papers that were published in (1) Journal of Construction Engineering and Management, ASCE in January 2025, and (2) Canadian Journal of Civil Engineering in February 2025. Additionally, the research team is currently preparing a third journal manuscript for submission.

C. Number of peer-reviewed journal articles published by faculty.
   - No. = Two published peer-reviewed papers that were published in in (1) Journal of Construction Engineering and Management, ASCE in January 2025, and (2) Canadian Journal of Civil Engineering in February 2025.

D. Number of peer-reviewed conference papers published by faculty.
   - No. = One peer-reviewed conference paper in the ASCE Construction Research Congress (CRC) 2025, Modular and Office Construction Summit (MOC) that is scheduled in July 2025

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = None
   - No. PhD dissertations = One ongoing PhD dissertation by Hadil Helaly
   - No. citations of each of the above = two citations of the published journal papers listed in Section C.

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   - Research Tool # 1= six developed machine learning models to estimate the construction cost of conventional and precast bridge projects during the early design phase.
   - Research Tool # 2= multi-objective optimization model to optimize the planning of bridge projects to maximize safety, mobility, and sustainability, while minimizing construction cost.
   - Research Tool # 3= ongoing machine learning models to predict the condition rates and deterioration of bridge projects during the early design phase.
   - Research Tool # 4= ongoing practical Decision Support Tool (DST) to facilitate the use of the developed machine learning models by state DOTs and bridge planners during the early design phase to analyze and compare the durability, safety, sustainability, mobility, and construction cost of conventional cast-in-place and precast bridges.

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
   - Professional societies
     - No. participated in = One at the ASCE Construction Research Congress (CRC) 2025, Modular and Office Construction Summit (MOC) that is scheduled in July 2025
     - No. lead = None
   - Advisory committees (No. participated in & No. led)
     - No. participated in = None

- No. lead = None
- Conference Organizing Committees (No. participated in & No. led)
  - No. participated in = None
  - No. lead = None
- Editorial board of journals (No. participated in & No. led)
  - No. participated in = None
  - No. lead = None
- TRB committees (No. participated in & No. led)
  - No. participated in = None
  - No. lead = None

H. Number of relevant awards received during the grant year
- No. awards received = None

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
- No. Undergraduate = 3
- No. Graduate = 4

J. Number of internships and full-time positions secured in the industry and government during the grant year.
- No. of internships = None
- No. of full-time positions = None

References:

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