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 March 31, 2025

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Collaborators / Partners:
None

Submitted to:
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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 durability, safety, mobility, sustainability, and construction cost, as shown in Figure 1.

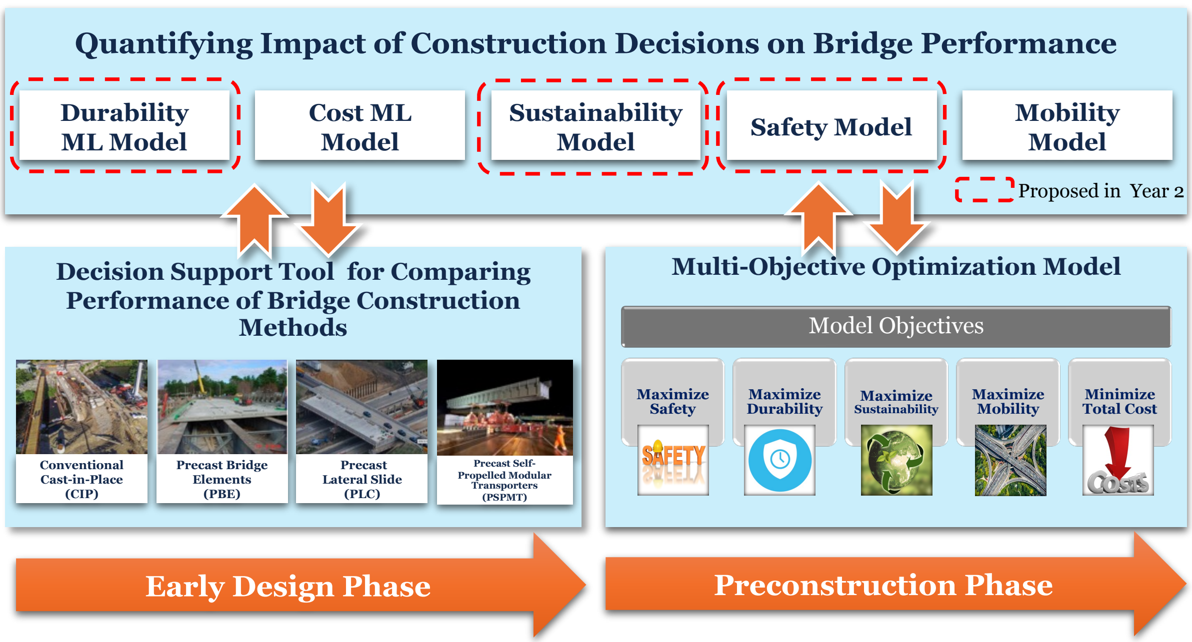

Figure 1. Proposed Decision Support Tool and Optimization Model

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, sustainability, and durability to support 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 durability, safety, sustainability, and mobility while minimizing construction cost.

Project Progress:

3. Progress for each research task

Task 1 Progress [50% completed]. Last quarter, the research team started 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 was started last quarter and is still ongoing. The work in this phase focused on identifying and collecting all bridge related data that have an impact on bridge condition rate 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 will be 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 was started last quarter and is still ongoing. The work in this phase focused 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

The research team will start working on this phase in the next quarter to develop 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, ridge regression, k-nearest neighbors, random forest regressor, and support vector machines that will be trained 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.

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

Task 3 Progress [50% completed]. Last quarter, the research team expanded the multi-objective optimization model developed in year 1 by incorporating the ability to maximize bridge project safety, sustainability, and mobility while minimizing construction cost. The model enables DOTs to generate a set of optimal construction planning solutions for each planned bridge, each offering a unique tradeoff between project objectives.

Last quarter, the research team started and continues to work on the four main phases of the optimization model that focus on (a) identifying all decision variables, (ii) formulating optimization objectives and constraints, (iii) implementing the optimization model, and (iv) analyzing a case study to illustrate the use of the developed optimization model, as shown in Figure 2. The following sections provide an update of the progress made in these four phases.

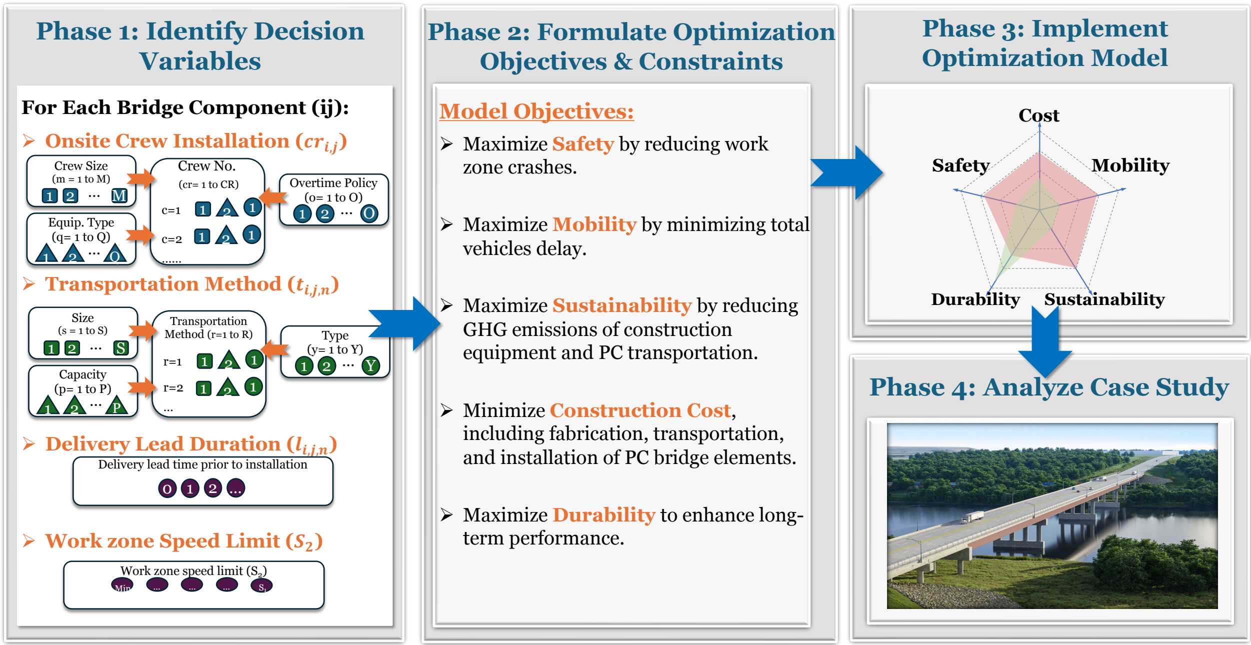

Figure 2. Development Phase of the developed Multi-objective Optimization Model

a. Decision Variables

This phase was fully completed last quarter, and it focused on identifying relevant preconstruction decisions that have an impact on safety, mobility, sustainability, and construction cost of bridge projects. This includes the decisions of selecting from a feasible set of alternatives: (a) an onsite installation crew for each bridge main activity (cr_{ij}), (b) a transportation method for each PC element from prefabrication plant to site ($t_{i,j,n}$), (c) a delivery lead duration prior to installation for each PC element ($l_{i,j,n}$), and (4) work zone speed limit, as shown in Figure 2. It should be noted that the installation crew decision variable (c_{ij}) represents a combined selection of crew size (*m*), equipment type (*q*), and overtime policy (*p*). Similarly, the transportation variable ($t_{i,j,n}$) represents a combined selection of transportation type (*y*), size (*s*), and capacity (*p*), as shown in Figure 2.

b. Model Formulation

This phase is approximately 50% complete. Last quarter, four optimization objectives were formulated that focused on maximizing safety, mobility, and sustainability while minimizing construction costs for planned bridge projects during the preconstruction phase. The first objective function focuses on maximizing safety for both the traveling public and construction workers by reducing work zone crashes. This is achieved using Safety Performance Functions (SPFs) developed by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO), which account for factors such as project duration, work zone length, average daily traffic, and speed limits, as shown in Eq. (1) (Gayah et al. 2024; Kolody et al. 2022). While FHWA provides default SPFs in the Highway Safety Manual (HSM) for various roadway types, state DOTs and research institutions often create their own SPFs tailored to local roadway conditions, crash data, and traffic characteristics. For example, Eq. (2) was specifically developed to predict work zone crashes in Illinois (IL) (Schattler et al. 2020).

$$Min\ (N) = e^{\alpha} * D^{\beta_1} * L^{\beta_2} * ADT^{\beta_3} * e^{\beta_4(S_1 * S_2)} \quad (1)$$

$$N_{IL} = e^{-7.049} * D^{0.904} * L^{0.317} * ADT^{0.486} * e^{-0.0004(S_1 * S_2)} \quad (2)$$

Where N *is predicted number of work zone crashes,* N_{IL} *is predicted number of work zone crashes in IL,* D *is work zone duration in days,* L *is work zone length in miles, ADT is average* *daily traffic, S_1 is speed limit in work zone under normal condition, S_2 is speed limit in work zone during construction, $\beta_1, \beta_2, \beta_3, \beta_4$ are statistical model coefficients, and α is a constant.*

The second objective function focuses on maximizing mobility by minimizing total vehicles delay time. This can be achieved using equations provided by the FHWA in their road user cost calculator tool as shown in Eq. **Error! Reference source not found.** (FHWA 2022).

$$TVD = WDVD + DDVD \tag{3}$$

Where TVD is the total vehicles delay in hours, $WZVD$ is total work zone vehicles delay in hours, DVD is total detour vehicles delay in hours that are affected by total project duration and work zone speed limit.

The third objective function focuses on maximizing sustainability by minimizing greenhouse gas (GHG) emissions of construction equipment and the transportation of precast (PC) elements, as shown in Eq. **Error! Reference source not found.** (Davies et al. 2015; Limsawasd 2016; Patcharachavalit et al. 2023). Emissions from construction equipment are estimated based on operating hours, engine power, and fuel consumption as shown in Eq. **Error! Reference source not found.**, while emissions from transportation are calculated using fuel efficiency and travel distance, as shown in Eq. **Error! Reference source not found.**.

$$Min\ (TPE) = \sum(TEE + TTE) \tag{4}$$

$$TEE = \sum_{i=1}^{I} Dq_i^{cr} * Pq_i^{cr} * Fq_i^{cr} * Eq_i^{cr} \tag{5}$$

$$TTE = \sum_{d=1}^{D}\sum_{t=1}^{T} Co_t^d * (\frac{Di}{Ft_t}) * Et_t \tag{6}$$

Where TPE is the total project emissions, TEE is the total equipment emissions, TTE is the total PC transportation emissions, Dq_i^{cr} is the total hours of equipment operation used by crew cr for activity i (in hours), Pq_i^{cr} is engine power of equipment used by crew cr to install activity i (in horsepower, hp), Fq_i^{cr} is fuel consumption rate of equipment (in gallon per hp-hour), Eq_i^{cr} is CO_2 emissions per gallon of fuel, Co_t^d is number of trips using truck type t on day d, Di is total distance from plants to construction site(in miles), Ft_t is fuel economy of truck type t (in miles per gallon, mpg), and Et_t is CO_2 emissions per gallon of fuel for truck type t.

The fourth objective aims to minimize total construction cost of the planned bridge project including off-site fabrication of PC elements, on-site construction costs, transportation, on-site storage, and assembly of PC elements, as shown in Eq. (4)

$$Min \sum FC + TC + SC + AC + OC \tag{7}$$

Where FC is fabrication cost of all PC bridge components, TC is transportation cost of all PC bridge components from fabrication plant to site, SC is onsite storage cost of all bridge components, AC is assembly cost of all PC bridge components, and OC is onsite cost of all bridge components that are not prefabricated.

c. <u>Model Implementation</u>

This phase is approximately 50% complete. The optimization model is currently being implemented using multi-objective genetic algorithms due to their ability to efficiently explore and identify near optimal solutions in problems with large search spaces within a reasonable computational timeframe (Abdelmohsen and El-Rayes 2018; Al-Ghzawi and El-Rayes 2023; Altuwaim et al. 2021). The model is currently being implemented using the nondominated sorting genetic algorithms II (NSGA-II) and executed with the Distributed Evolutionary Algorithms (DEAP) Python library.

d. Case study

This phase is approximately 50% complete. This phase focus on analyzing a case study to demonstrate the capability of the developed multi-optimization model in the previous phase in optimizing the planning of conventional construction and precast accelerated bridge construction methods during the pre-construction phase to maximize safety, mobility, and sustainability while minimizing the construction cost of planned projects.

4. Percent of research project completed

30% of total project completed through the end of this quarter.

5. Expected progress for next quarter

In the next quarter, the research team will continue developing and evaluating machine learning models to predict the condition and deterioration of bridge projects during the early design phase. Additionally, the team will expand the multi-objective optimization model to incorporate a fifth objective that focuses on maximizing bridge durability during the preconstruction phase.

6. Educational outreach and workforce development

This quarter, the educational and workforce development (EWD) activities focused on continuing to enhance the analytical and research skills of a female PhD student, the lead research assistant. Her work involved collecting and analyzing bridge construction data from various databases and developing machine learning and multi-objective optimization models. Additionally, the research team participated in all TRANS-IPIC Monthly Webinars.

7. Technology Transfer

The research team is currently developing (1) novel machine learning models to predict the condition rates of conventional and precast bridge projects during the early design phase, and (2) a multi-objective optimization model to optimize the planning of bridge projects during the preconstruction phase to maximize safety, mobility, sustainability, and durability 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 and submitted a conference paper, which will be included in the proceedings of the ASCE Construction Research Congress 2025. 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).

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

   The research team is planning to present their preliminary findings at the TRANS-IPIC Workshop on April 22–23, 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.

    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. = One presentation in the ASCE Construction Research Congress (CRC) 2025, Modular and Office Construction Summit (MOC) that is scheduled 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.

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 = None

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 = 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.
   - 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 multi-objective optimization model to optimize the planning of bridge projects during the preconstruction phase to maximize safety, mobility, sustainability, and durability while minimizing construction cost.

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:

Abdelmohsen, A. Z., and K. El-Rayes. 2018. "Optimizing the Planning of Highway Work Zones to Maximize Safety and Mobility." *Journal of Management in Engineering, ASCE*, 34 (1). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)me.1943-5479.0000570.

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