Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Continuous & Low-cost Inspection of Precast Concrete Bridges using Connected Automated Vehicles (CAVs)
UB-24-RP-01

Quarterly Progress Report
For the performance period ending 09/30/2025

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Collaborators / Partners:
None

Submitted to:
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TRANS-IPIC Quarterly Progress Report (Section 1 – 7, 5 pages max.):

Project Description:

1. Research Plan - Statement of Problem

This project aims to develop a continuous, low-cost data collection system for bridges with precast components prone to reflective cracking. Early damage detection is crucial for durability, but existing inspection methods are costly, primarily when performed continuously. Leveraging existing vehicles on the roads, we propose using vehicle-to-everything (V2X) technologies, where bridges request connected vehicles with standard forward-facing cameras to inspect critical areas. Connected automated vehicles (CAVs) will execute cooperative motion to maximize inspection efficiency. Aggregated data from continuous traffic and inspection results will detect early signs of damage, enabling proactive maintenance. To deliver such a system, a couple of problems need to be tackled: 1) how to design a robust crack-detection algorithm that can work with standard forward-facing cameras with limited focus on the road surface; 2) how to effectively communicate detection requests and results using CV2X communication; 3) how to coordinate the motion of the CAVs to maximize the detection results.

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

This project has two main objectives with six sub-tasks.

Objective 1: Develop sub-components of a cooperative inspection system of road surface cracking between infrastructure and CAVs on the test track on the UB campus.

Task 1.1: Develop a vision-based road cracking inspection algorithm using a vehicle forward-facing camera.

Task 1.2: Update the V2X protocol to enable information sharing between vehicles and infrastructure

Task 1.3: Design cooperative vehicle motion planning control algorithms with V2X information to maximize crack inspection efficiency

Objective 2: Implement and demonstrate the developed cooperative inspection system on a precast concrete bridge in NYS

Task 2.1: Identify ideal precast concrete bridge sites in NYS near the UB Campus

Task 2.2: Deploy and fine-tune the cooperative inspection system at the identified sites

Task 2.3: Deliver a demonstration of the developed system at a pilot site

Project Progress:

3. Progress for each research task

Objective 1 [100% completed]:

Task 1.1 [100%]. This quarter, the research team concluded the crack-detection modeling development. Based on the findings and plan from last quarter, the team has executed a few extra steps in crack detection to mitigate challenges brought by non-ideal vehicle camera views. These steps enable the team to complete Task 1.1 and transition to working on Task 2.2 at bridge sites.

Base Crack Detection Model Selection: Based on a recent survey of crack detection models for vehicular applications [1], the team has identified a popular model with pre-trained weights, DeepCrack [2], as the baseline. The LECSFormer [3] is selected due to its good balance in performance and real-time potential [1]. The team was able to retrain and compare multiple image augmentation techniques that are commonly used in practice. The achieved performance, and we compared it against the baseline over the public datasets, and the results are highlighted in Figure 1. Specifically, on the one hand, we can demonstrate that the augmentation indeed significantly improves the LECSFormer's performance by boosting the F1 score and also making it less sensitive to threshold selection. While

Model	ODS F1	Threshold
DeepCrack (pre-trained, baseline)	0.9089	0.250
LECSFormer	0.8809	0.530
LECSFormer with Augmentation	0.9184	0.680

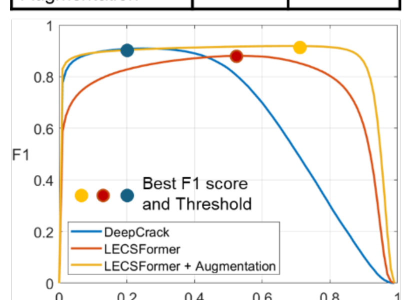


Figure 1 Trained Crack Detection Model Performance on public dataset

this is an improved result compared to last quarter, we still expect degradation in zero-shot performance when deploying to the real bride images. Therefore, the team has proceeded to focus on fine-tuning performance on the actual bridge sites (Task 2.2).

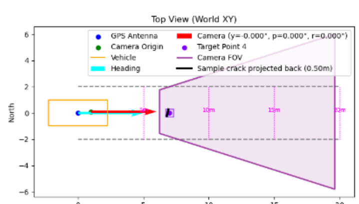
Dynamic Cropping Window. As planned from last quarter, the team has developed a dynamic cropping window determination intended to enhance crack detection performance. The area of interest transmitted by the Bridges will be translated into a cropping window on the camera's field of view. While such translation may be straightforward using a pinhole camera model, the challenges reside in the uncertainties related to camera extrinsic parameters (e.g., yaw, pitch, and roll angles), the vehicle's GPS measurement accuracy, vehicle motion, and other factors. The goal is to acquire cropping windows that 1) include the target crack in the cropping window with high confidence and 2) acquire images where the cropping windows appear with high resolution of pixels for distance translation. In this quarter, the team has implemented these algorithms and achieved satisfactory performance. To be able to get the ground truth of area of interest, a checkerboard is used to mark the potential area of interest. The GPS location could be acquired using a portable RTK GPS antenna. A YOLOv8 model is trained to detect a checkerboard on the ground and mark a bounding box. Distance-IOU [4] is used to evaluate the performance of the cropping window. Furthermore, it is also used to optimize camera extrinsic parameter calibrations, allowing for robust run-time performance of the dynamic cropping window algorithms. In Figure 2 the performance metrics with samples are presented. The reported DIOU score ideally = 1, which indicates that the target area of interest (center of checkboard) should coincide with that of the cropping window. While the performance shows satisfactory results in low-speed scenarios at various locations, the team will continue these calibration efforts to evaluate and improve the parameters as we work on Task 2.2.

$$\text{Optimal parameter} = \underset{\text{Allsamples}}{\arg\max} \sum \text{DIOU}(\text{YOLO Box, Dynamic Cropping window})$$

Statistics	Mean	STD
DIOU score for overlapping	0.86	0.10

Figure 2 Dynamic Cropping Windows Performance

Crack Size Estimation. This quarter, the team has also deployed a crack size estimation based on crack detection results. The estimation is based on a standard pinhole camera model, which is illustrated using a simulated view in Figure 3. The simulated crack is represented by a black line in the area of interest specified (purple square on the road). With proper cropping window logic, the area of interest will be covered, and the crack size can be correctly inferred. When implemented on the real vehicle, it requires proper camera calibration. We leverage the calibration process detailed in the above cropping window logic, and is able to achieve satisfactory results when lighting conditions is favorable and the crack is close to the camera. With these algorithm validated in the simulation and campus setting, the team continuous to refine and test the algorithm on site as we work on Task 2.2.



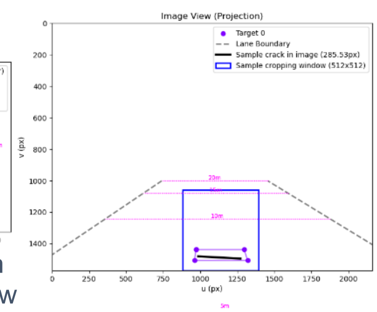


Figure 4 Crack Calculation Illustration in Simulated View

Task 1.2 [100% completed]. This quarter, the research team concluded the C-V2X protocol design and analysis planned for this project, which is designing and quantifying the information sharing between vehicles and infrastructure. The team has enhanced the design for real-time transmission of detection results (images and metadata), as shown in Figure 3. Specifically, a parallel scheme is used where the OBU will transmit a detection in progress status to make sure the RSU is still in range, while in a parallel stream, collect the detection results and packages & release them once the whole process is complete. This updated scheme allows more robust communication between the RSU and OBU in the event of out-of-range loss of package or other unexpected communication failures. The team has conducted field tests on both the campus and at the

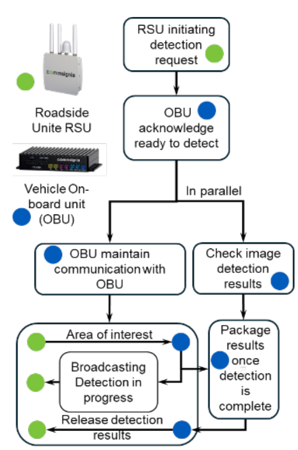


Figure 3 Updated CV2X Communication protocol

bridge site using the latest design, and has quantified the performances. The test on campus focused on bandwidth, and the summary of the sample test is presented in Figure 5. Overall, with the open area and no obstructions (such as trees or buildings), cropped images (300kB) can be transmitted in 5-6 seconds, while cropped image masks (~10kB) can be transmitted within half a second. While such results meet expectations, this implies that the full image detection results (4 MB / image) would not be feasible. Either cropping is needed to show the focus area (could be potentially larger than the area of interest), or other communication techniques (e.g., cellular network). As increasing the communication bandwidth is beyond the scope of this year's project, the team has decided to preserve raw images locally and only report detection measurements and cropped images from the vehicle to the infrastructure. Such strategy will be implemented in Task 2.2 and used in the final demonstration.

Task 1.3 [100% completed]. This quarter, the team has concluded this task on implementing the CV2X-based vehicle motion control on the Lincoln connected automated vehicle (CAV) Platform at UB [5, 6]. The vehicle speed and acceleration would be controlled to maintain performance. This enables speed regulation according to the infrastructure's requested set speed while maintaining safety in traffic. Part of the longitudinal control is included in the accepted paper [6]. The vehicle longitudinal speed can be set to one that enhances crack detection performance by supporting optimal dynamic cropping window determination designed in Task 1.1.

Objective 2 [60% completed]

Task 2.1 [100% completed] In the last quarter, with the help of the NYS DOT team. We have identified one precast bridge candidate (Bridge Bin# 1045890, Google Map) near the UB campus.

Task 2.2 [50% completed]
This quarter, the team has paid a few visits to the bridge site and collected images of bridge deck surfaces. to calibrate and test our platform. See Figure 5 for a series of images collected from multiple sources regarding the same reflective crack spot. While the bridge deck had reflective cracks developed over the years, it was sealed in early September. Due to this maintenance, the demonstration may not be able to detect any cracks. To continue the development and fine-tune effort, the ongoing focus is now shifted to surface crack detection on the main campus site identified from last quarter (Bridge Structure #5511840). The bridge has a reinforced concrete slab, and many visible cracks can be used for both training and testing purposes.

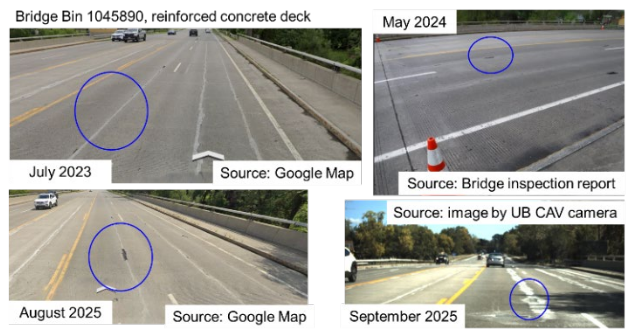


Figure 5 Pilot Bridge Deck Reflective Crack Evolution

Crack detection zero-shot performance. With the collected surface crack image at the bridge candidate, the team tested out the trained LECSFormer crack detection model and reported a regression in performance; see *Figure 6*. This is primarily due to the distribution shift between the training and testing datasets, as the vehicle camera view and surface conditions differ. The team is actively collecting and labelling more vehicle view data on both sites. The dynamic cropping windows algorithm developed in Task 1.1 is also expected to help improve model performance.

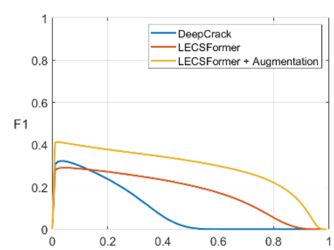


Figure 6 Zero-shot crack detection performance

Communication protocol testing. The team is also validating the communication protocol. The major focus is identifying a feasible transmission time window and assessing the communication quality. In Figure 7, one test run is demonstrated where the vehicle was traveling eastbound with OBU and was expected to inspect the bridge surface. The blue points on the blue curve correspond to instances where basic safety messages (BSMs) were recorded. It started communicating with the RSU around 500 meters before passing the bridge. After passing the bridge, communication between the RSU and the OBU remains possible up to 1km. This means that the

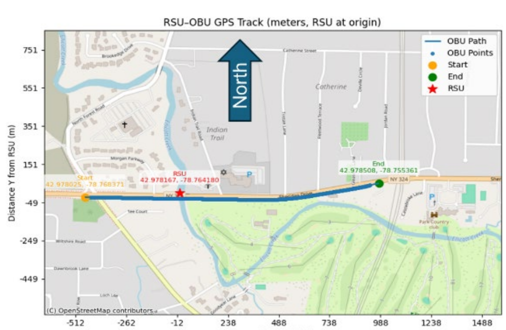


Figure 7 Field Test Communication Performance

transmission of a raw, cropped window image (300 kb or ~6 seconds) is feasible.
The main effort the team has spent on this task has been implementing and optimizing a feasible real-time detection pipeline. Similar to what's being pointed out in the literature [1], the real-time performance of the crack-detection model is, in general, lacking. To mitigate this, the team has been actively exploring robust multi-threading options in the vehicle platform. The team is expected to either solve this issue or find a walk around by the end of October.

Task 2.3 [30% completed] The team has visited the pilot bridge site regularly to investigate and monitor potential crack locations and assess the demonstration plan. Since crack sealing maintenance was conducted at the target bridge site in September to address the reflective cracks, the final demonstrations will help detect any new cracks that may appear. For this reason, the team has decided to stick to the demonstration plan while using the on-campus bridge site as the backup for demonstrations.

4. Percent of research projects completed

With Objective 1 achieved and Objective 2 more than 50% complete, we report that 80% of the total project will be completed by the end of this quarter.

5. Expected progress for next quarter

   For the final quarter, the team will continue working on Task 2.2 and Task 2.3, deploy and fine-tune the inspection performance. The team will deliver the final demonstration in the last quarter and will submit the Final report by December 1st for review.

6. Educational outreach and workforce development

   The funding supported and trained one Ph.D. student, Haosong Xiao, and three master's students, Harsh Bhargava, Rishabh Shukla, and Yamini Ramesh, on connected automated technologies and infrastructure maintenance/inspection protocols.
   The research team actively participated in all TRANS-IPIC Monthly Webinars.

7. Technology Transfer

   N/A

Research Contribution:

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

   H. Xiao and C. R. He, "Safe and Efficient Data-driven Connected Cruise Control," presented at the The 5th Modeling, Estimation and Control Conference (MECC 2025), Pittsburgh, PA, 2025

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

   Delivered the talk titled "Continuous & Low-cost Inspection of Precast Concrete Bridges using Connected Automated Vehicles (CAVs)" at the TRANS-IPIC Research Highlights Webinar on September 26, 2025, as part of the project's dissemination efforts.

10. Please list any other events or activities that highlight 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.

    PI Chaozhe He gave a lightning talk, "*Towards resilient infrastructure with connected automated vehicles*", highlighting the research activities of this project funded by TRASN-IPIC, at the inaugural 2025 SUNY RAISE Workshop: Robotics, Autonomy & Intelligent Systems in Engineering, on August 7th, 2025.

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. = 2

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 1

C. Number of peer-reviewed journal articles published by faculty.
   - No. = 0

D. Number of peer-reviewed conference papers published by faculty.
   - No. = 1

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 1 (December 2024)
   - No. PhD dissertations = 1 (December 2028)
   - No. citations of each of the above = 0 (the MS thesis has not been published yet)

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   - Lab equipment = 1: Portable RSU station for onsite testing.
   -
   - Research Tool = 2:
     - Crack detection algorithm using a forward-facing camera, in development, to be released on GitHub (http://github.com/CHELabUB/crack_detection/)
     - CV2X applications for crack detection and image transmission, in development, to be released on GitHub (https://github.com/CHELabUB/cv2x/)

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 = 1: MAE 502 Vehicle Control Systems (Spring 2025).

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:

[1] N. Ma *et al.*, "Vehicular Road Crack Detection with Deep Learning: A New Online Benchmark for Comprehensive Evaluation of Existing Algorithms," *arXiv preprint arXiv:2503.18082,* 2025.

[2] Q. Zou, Z. Zhang, Q. Li, X. Qi, Q. Wang, and S. Wang, "DeepCrack: Learning Hierarchical Convolutional Features for Crack Detection," *IEEE Trans Image Process,* Oct 31 2018, doi: 10.1109/TIP.2018.2878966.

[3] J. Chen, N. Zhao, R. Zhang, L. Chen, K. Huang, and Z. Qiu, "Refined Crack Detection via LECSFormer for Autonomous Road Inspection Vehicles," *IEEE Transactions on Intelligent Vehicles,* vol. 8, no. 3, pp. 2049-2061, 2023, doi: 10.1109/tiv.2022.3204583.

[4] Z. Zheng, P. Wang, W. Liu, J. Li, R. Ye, and D. Ren, "Distance-IoU Loss: Faster and Better Learning for Bounding Box Regression," *Proceedings of the AAAI Conference on Artificial Intelligence,* vol. 34, no. 07, pp. 12993-13000, 2020, doi: 10.1609/aaai.v34i07.6999.

[5] C. R. He, J. I. Ge, and G. Orosz, "Fuel Efficient Connected Cruise Control for Heavy-Duty Trucks in Real Traffic," *IEEE Transactions on Control Systems Technology,* vol. 28, no. 6, pp. 2474-2481, 2020, doi: 10.1109/tcst.2019.2925583.

[6] H. Xiao and C. R. He, "Safe and Efficient Data-driven Connected Cruise Control," presented at the The 5th Modeling, Estimation and Control Conference (MECC 2025), Pittsburgh, PA, 2025.