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16. Abstract Recent derailment accident that happened in East Palestine, Ohio has drawn huge public attention to railroad system safety. While this accident is under investigation, one of the major contributions to many other derailment accidents is the precast concrete crossties abrasion damage. Concrete crossties can lose concrete sections on portions of the tie bottom and sides during service. Identifying the abrasion damage of precast concrete crossties is critical to extend the railroad service life and prevent potential derailment. This project is a collaboration among Purdue University, Louisiana State University, Rocla Concrete Tie, and CSX. The ultimate goal of this research is to develop mitigation measures to reduce concrete railroad tie section loss at the ballast interface based on expected service life. As a first step to achieve this goal, this project develops a photogrammetry and LiDAR scanning-based precast concrete crossties abrasion damage detection system.		
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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Photogrammetry and LiDAR-Based Precast Railroad Crossties Abrasion Damage Detections
PU-23-RP-04

FINAL REPORT

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Executive Summary (1-page max):

The railroad industry plays a crucial role in freight and passenger transportation. 1,323.2 million tons of cargo and 24.4 million passengers are transported annually in the United States. However, according to statistics from the Federal Railroad Administration (FRA), more than 100,000 train accidents have occurred over the past decade. One of the important factors causing railway accidents is caused by concrete crossties damage or failures. Ensuring the safety and reliability of the railroad system is critical for preventing accidents, protecting human lives, and maintaining the smooth operation of freight and passenger transport.

Railroad tracks are intricate systems mainly composed of rails, crossties, fasteners, ballast, and an underlying subgrade. The main functions of railroad ties include: 1) laid perpendicular to the rails, ties hold the rails upright, and ensure they are spaced at the correct gauge, 2) ties transfer loads to the track ballast and subgrade, and 3) providing resistance against both longitudinal and lateral movements of the rails. Crossties deteriorate over their service life due to various factors, including fatigue from repeated loading and unloading, and exposure to environmental conditions. One of the most frequent failure mechanisms arises in railroads from varying levels of abrasion experienced by the crosstie system at different locations. Therefore, inspecting crossties conditions is an important aspect of maintaining crossties operation life and further railroad transportation safety.

Traditional methods for inspecting crossties involve manual inspection by trained personnel and sensor-based detection. However, the manual inspection approach is costly in terms of labor, and often results in inconsistent accuracy and some cases may put inspectors' safety at risk. Traditional sensor-based detection methods are limited to partial inspections at discrete points and cannot perform comprehensive large-scale inspections of the railroad system. However, some researchers have started exploring the possibility of applying other technologies like 2D images for crosstie inspection (9). Changes in the shape of railroad crossties, such as the deformation of steel ties and the volume loss of concrete ties, are not easily detectable only relying on 2D images. 3D reconstruction including photogrammetry approaches is one of the promising technologies to provide more comprehensive information on structural components such as railroad crossties.

With the advancement in unmanned aerial vehicle (UAV) platforms hardware and software, and image processing algorithm, the UAV-based photogrammetry provides low-cost, efficient, and extensive coverage 3D reconstruction solutions for inspecting dams, bridges, and other large infrastructure. This approach provides a huge potential for railroad crossties conditions inspections. Photogrammetry is a technology that measures and extracts three-dimensional information from a set of overlapping photos. This technology can be used to create accurate maps, and three-dimensional models, and measure the size and shape of objects.

In this project, our team develops a general framework of railroad concrete crosstie inspection methods using UAV-based photogrammetry is introduced. A compact UAV (DJI Mavic 3 Enterprise) is used to collect high-resolution RGB images of railroad crossties for both indoor and outdoor environments. To build a more detailed crosstie model, oblique images and the orthophoto are both applied. Railroad 3D models are reconstructed by applying the Structure from Motion (SfM). AgiSoft software is employed for visualizing and comparing the differences of 3D point cloud models under different conditions.

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TRANS-IPIC Final Report:

The final report is structured as follows:

- Statement of problem

Precast concrete railroad ties are used in heavy-haul rail lines and high-speed rail lines because of their ability to carry large, repeated loads for a very long time. Concrete ties can last 50 years or longer when fabricated properly and the track is properly designed, built, and maintained. When the track has fouled ballast, large curves, or poor subgrade conditions, they can in some cases fail prematurely. Concrete railroad crossties can lose concrete section on portions of the tie bottom and sides during service. This reduction in concrete cross section can result in reduced structural capacity in negative moment regions of the crosstie found in the crosstie center. Railroad ballast uses very hard, durable aggregates to reduce the likelihood of crushing or abrasion damage. Ballast fouling can occur due to many mechanisms. One that has been mentioned by railroads that have experienced abrasion damage is pumping. Hydraulic pressure causes water to rise to the surface, bringing fines from the subgrade and fouling the ballast. Ballast breakdown and fouling can lead to water drainage problems, settlement, uneven support, and a loss of strength in the track structure and result in derailments. As fine particles build-up, some ballast particles lose contact with each other, reducing support. Once the ballast reaches a phase where the ballast particles have very little contact with each other, support for the ties is severely reduced, increasing track deflections during loading. The increased deflection results in large amounts of rubbing of the concrete surface against the ballast, increasing wear rates.

Internationally, concrete has become the primary material for railroad ties in many regions around the world. In North America, the use of concrete railroad ties is steadily increasing, particularly in transit systems and heavy-axle-load freight railways. As the use of concrete railroad ties grows, understanding their conditions, common damage patterns, and maintaining their performance becomes critical. Concrete railroad ties may suffer from different types of damage, including cracks and chemical reactions. The concrete crossties can crack around areas where the fasteners are attached, compromising the stability of the rail. Center and longitudinal cracks due to bending deformation can cause cracks in the center or along the length of the ties, weakening their structural integrity. Chemical reactions, such as alkali-silica reaction (ASR), can deteriorate the concrete, causing expansion and cracking. This reaction occurs when the alkali in the cement reacts with silica in the aggregates, leading to a gel that absorbs water and swells, creating internal pressure and resulting in cracks. These types of damage can significantly change in shape compared to before the destruction, reducing the effectiveness of concrete ties and impacting their performance and lifespan. The concrete crossties' common damages are shown in Figure1.

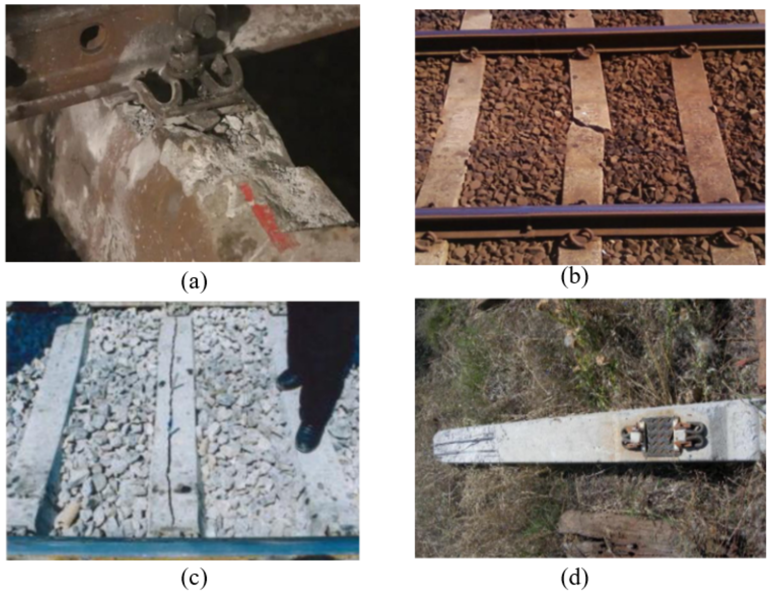

Figure 1 Concrete crossties common damages: (a) cracking around fastener systems; (b) center cracks; (c) longitudinal cracks; (d) chemical damage.

The US railroad industry has been struggling with precast concrete crossties abrasion damage for a long time. Our research team has communicated with multiple class I railroads and all have responded that some of their crossties are facing the abrasion issue. Figure 2 shows abrasion damage on concrete crossties. According to BNSF Railway, crossties abrasion at the ballast interface is a problem of concern for BNSF Railways that often occurs at locations with high moisture and soft subgrades. The Alaska Railroad saw section loss typically at higher speed areas where pumping is a concern. CSX indicated that they had seen this deterioration in locations with and without freezing conditions. To extend the precast concrete crossties service life and ensure railroad safety, there is a strong demand to mitigate the crossties abrasion damage. As it is not practical for the railroad industry to inspect thousands of miles of track to find concrete crosstie abrasion loss manually, an automated, low-cost, mobile, and accurate monitoring approach is urgently needed for the crossties' maintenance and repair.

Figure 2 Concrete crosstie that experienced undercutting abrasion damage, including the exposure of some wires in a section of track in Washington State. (Picture courtesy of BNSF)

Photogrammetry and LiDAR systems have been widely used to monitor infrastructure conditions and defects in service. This method has a long history of use in concrete structures and will be used in this project to measure concrete crosstie thickness non-destructively in track. High-resolution Global Positioning System and Inertial Measurement Unit can provide georeferenced data associated with the crossties conditions.

- Research Plan / Tasks

Task 1: Visit precast concrete crossties damage site

Our team works closely with MxV Rail and Rocla Concrete Tie to understand their demands and experience with abrasion damage of the precast concrete crossties. We visited MxV Rail and discussed with their railroad crossties group to understand the damage pattern of precast concrete crossties and learn their technologies detecting concrete crossties conditions. This trip helps our team understand the damage mechanism and develop an effective system to detect the damages. It provides an excellent sampling of ties from the field to aid in the determination of the prevalence of severe abrasion loss. Our team received three precast concrete crossties donated by MxV Rail. These precast concrete ties shown in Figure 3 will be used as test specimens for our project. We requested three different types of precast concrete ties to represent more real world scenarios.

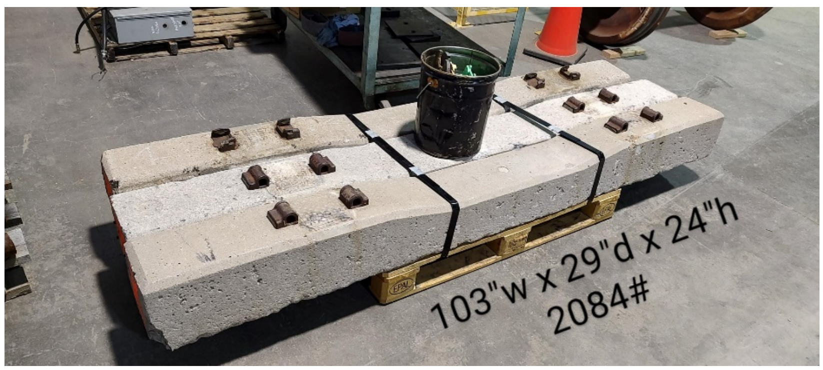

Figure 3 Precast concrete crossties donated by MxV Rail

Task 2: Develop a 3D reconstruction system detecting precast concrete damages

Considering many flexibilities in terms of image resolution, frame rate, and color mode, our team purchased a DJI Mavic 3 Thermal drone and used it to conduct 3D scanning of the concrete ties. DJI Mavic 3 Thermal is equipped with Wide-angle (Equivalent Focal Length: 24mm, 48MP) and zoom-in (Equivalent Focal Length: 162mm, 12MP, 56× Hybrid Zoom) cameras. The cameras have captured high-resolution images for reconstruction of a 3D model with detailed concrete crossties conditions. With the images captured by the drone cameras, we create a series of 3D models of the concrete crossties using Agisoft Metashape Pro software. After the 3D model is created, it will be imported to Cloudcompare software to conduct further analysis to identify the geometry and damage information of the concrete crossties. The 3D model will be used to quantify the concrete thickness and volume changes to determine the abrasion damage levels. The texture information captured by the cameras will be used to locate and identify the surface damage.

Task 3: Validate the system performance in indoor and outdoor environments

Our team has conducted a series of laboratory experiments using a drone-based photogrammetry approach to conduct 3D scanning to sense the concrete crossties conditions. As shown in Figure 3, three concrete ties are stationed on the ground with a 2-foot interval to simulate the practical concrete crossties distribution. The DJI Mavic 3 flied over the concrete crossties along pre-defined paths to take high-resolution video footage and images, which took 15 to 20 minutes. Then the images and videos were imported to Agisoft Metashape to create a high-resolution 3D model (Figure 4). After the 3D model is created, it is analyzed using Cloudcompre software to understand the concrete crossties conditions (Figure 5). We measured the geometry of the concrete crossties and calculated the volume of the concrete crossties to determine their volume loss. We adopted a reference target with all known dimensions to quantify our measurement errors. The discrepancy between the reference target and our 3D model measurements is minimal (Table 1). Then we compared our model results with the actual dimensions of the concrete crossties (Table 2) and the errors are less than 3.33%, which is promising for real application in railroad industry. In addition to the volume loss measurements, our team also quantified the alignments of the crossties which is another critical factor of the railroad safety. The crossties demonstrate good alignments based on the distance between each individual crosstie (Figure 6). In addition to laboratory experiments, our team also conducted a site visit to Madison Railroad company in Indiana to validate our system performance (Figure 7).

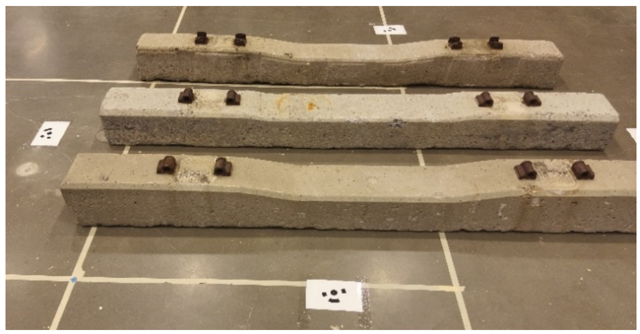

Figure 3 A drone captured concrete crossties image.

Figure 4 3D model created by AgiSoft Metashape via the drone-based photogrammetry.

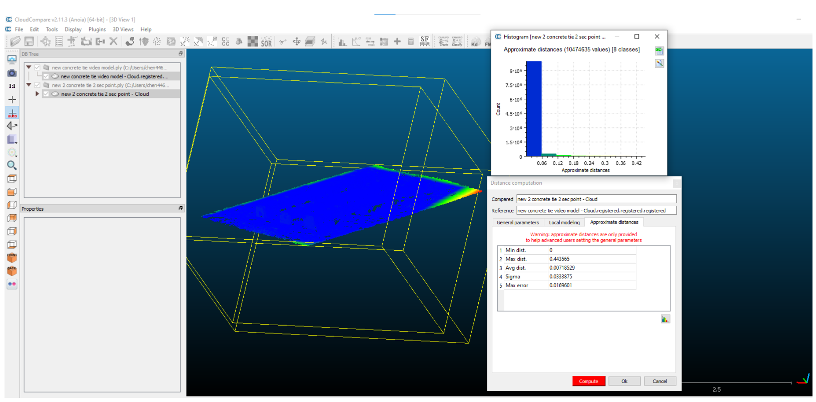

Figure 5 3D model imported to Cloudcompare for further analysis.

Table 1. Rectangular shape volume calculations comparison

Edge No.	A	B	C	D	E	F	G	H	I	J	K	L
$\frac{\lvert Model-Actual \rvert}{Actual}$	0.26%	0.00%	0.26%	0.26%	0.00%	0.00%	0.00%	0.00%	0.26%	0.51%	0.26%	0.51%

Table 2. Concrete crossties volume calculations comparison.

No.	The concrete crossties' model	Model (m^3)	The concrete crossties	Actual (m^3)	Error (%)
1		0.115		0.111	3.3%
2		0.131		0.132	2%
3		0.137		0.137	<1%

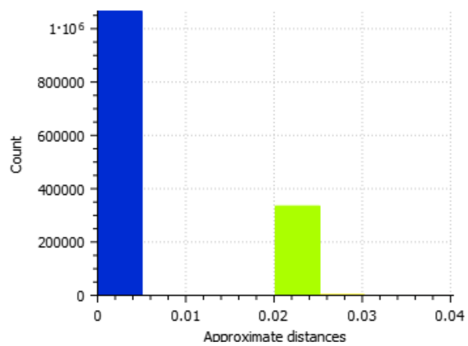

Figure 6 Crossties alignments.


Figure 7 Madison Railroad site visit.

Task 4: Reporting

We submitted all quarterly report on time and received positive feedback from the reviewers. This final report includes all the work we have conducted for this project. Our team is working on paper publications of our completed work.

- Educational outreach activities.

In our CM370 Heavy Civil Infrastructure course at Purdue University, we developed a lecture topic about precast concrete crossties, introduced the damages of concrete crossties, and how to maintain their performance. Students gain the knowledge about the damage patterns of concrete crossties.

Figure 8 The PI taught students during the railroad course.

- Workforce development activities.

None.

- Technology transfer actions.

None.

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

Our team submitted one paper to 2025 TRB convention but received rejection and we are currently working on another journal paper submission about this project.

- Presentations and posters of TRANS-IPIC funded research.

Our team presented at TRANS-IPIC September Workshop Webinar in September 2024.

- Other events or activities that highlights the work of TRANS-IPIC research.

None.

- Any mentions/references to TRANS-IPIC in the news.

None.

- References

[1] You, R., Wang, J., Ning, N., Wang, M., & Zhang, J. (2022). The Typical Damage Form and Mechanism of a Railway Prestressed Concrete Sleeper. Materials, 15(22), 8074.

[2] El-sayed, H. M., Fayed, M. N., Riad, H. S., & Zohny, H. N. (2022). A review of the structural performance of prestressed monoblock concrete sleepers in ballasted railway tracks. Engineering Failure Analysis, 140, 106522.

[3] Shurpali, A. A., Edwards, J. R., Kernes, R. G., Lange, D. A., & Barkan, C. P. (2014). Investigation of material improvements to mitigate the effects of the abrasion mechanism of concrete crosstie rail seat deterioration. Journal of Transportation Engineering, 140(2), 04013009.

[4] Shurpali, A. A., Van Dam, E., Edwards, J. R., Lange, D. A., & Barkan, C. P. (2012, April). Laboratory investigation of the abrasive wear mechanism of concrete crosstie rail seat deterioration (RSD). In ASME/IEEE Joint Rail Conference (Vol. 44656, pp. 99-108). American Society of Mechanical Engineers.

[5] Riding, K. A., Peterman, R. J., Guthrie, S., Brueseke, M., Mosavi, H., Daily, K., & Risovi-Hendrickson, W. (2018, April). Environmental and track factors that contribute to abrasion damage. In ASME/IEEE Joint Rail Conference (Vol. 50978, p. V001T01A009). American Society of Mechanical Engineers.

[6] Alsahli, A., Zarembski, A. M., Palese, J. W., & Euston, T. L. (2019). Investigation of the correlation between track geometry defect occurrence and wood tie condition. Transportation Infrastructure Geotechnology, 6, 226-244.

[8] Sabato, A., & Niezrecki, C. (2017). Full-scale damage detection of railroad crossties using Digital Image Correlation. In International Digital Imaging Correlation Society: Proceedings of the First Annual Conference, 2016 (pp. 117-120). Springer International Publishing.

[9] Wu, Y., Chen, P., Qin, Y., Qian, Y., Xu, F., & Jia, L. (2023). Automatic railroad track components inspection using hybrid deep learning framework. IEEE Transactions on Instrumentation and Measurement, 72, 1-15.

[10] Ravishankar, P., Tokgoz, B. E., Zhang, X., Zhang, J., & Hwang, S. (2021, May). Detecting Defects of Railway Tracks by Using Computer Vision Methodology. In Proceedings of the 2021 IISE Annual Conference.

[11] Zollini, S., Alicandro, M., Dominici, D., Quaresima, R., & Giallonardo, M. (2020). UAV Photogrammetry for Concrete Bridge Inspection Using Object-Based Image Analysis (OBIA). Remote Sens. 12, 3180.

[12] Edwards, J. R., Liang, Y., C Bastos, J., & Dersch, M. S. (2020). Development of a parametric model for the prediction of concrete railway crosstie service bending moments. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 234(10), 1253-1264.