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RESEARCH BRIEF

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Data-Driven Inspection Planning for Utah Culverts Using Federated Learning

the ISSUE

Transportation agencies have increasingly turned to machine learning (ML) to enhance the effectiveness of infrastructure asset management. However, limited local inventory data often hinders building accurate and reliable ML models. Additionally, data privacy and ownership concerns discourage agencies from sharing raw datasets. Many state departments of transportation (DOTs) face challenges in managing culverts due to limited inspection data and privacy concerns.

the RESEARCH

This research explores the use of federated learning (FL) to enhance predictive modeling for culvert condition assessment, enabling collaborative data usage while preserving data confidentiality across multiple state DOTs. This research aimed to enhance culvert condition prediction for the Utah Department of Transportation (UDOT) using FL. UDOT faces significant challenges in managing its more than 47,000 culverts due to limited inspection data. Traditional ML models require large, diverse datasets for accurate predictions, but DOTs often struggle with data scarcity in their inventories. Additionally, privacy concerns prevent data sharing between organizations.

The methodology involved collecting culvert inventory data from UDOT and five other state DOTs. The data were preprocessed to standardize inspection ratings and incorporate environmental features such as soil properties. Four ML models were compared: a local Utah model (Utah-CL), a synthetic data-augmented model (Utah-SMOTE), a centralized model using data from all states (ALL-CL), and the proposed FL model (ALL-FL). Artificial neural networks (ANNs), a powerful algorithm for learning complex patterns, were used as the base model. For data augmentation, SMOTE was employed to address class imbalance in tabular data. FL enabled collaborative model training without sharing raw data, ensuring compliance with privacy regulations. Instead of exchanging sensitive data, only learning weights were shared and aggregated to update a global model, maintaining privacy while improving prediction accuracy.

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the FINDINGS

The research showed that FL significantly improved culvert condition prediction for UDOT despite limited data. The FL model achieved an accuracy of 80.4%, closely matching the performance of the centralized model trained on data from all ALL-CL, while outperforming the local Utah-CL and Utah-SMOTE. The FL model also showed higher precision and recall compared with the local models, particularly in identifying high-risk culverts. Notably, FL maintained strong predictive performance without compromising data privacy, as it only shared model weights rather than raw data. This approach proved effective in overcoming the challenges of data scarcity and privacy concerns, offering a scalable solution for infrastructure asset management. The findings highlight the potential for FL to enhance predictive modeling in transportation systems, enabling collaborative training without violating data privacy regulations.

the IMPACT

This research provides a scalable, privacy-preserving solution for improving culvert condition prediction, enabling transportation agencies to make more data-driven, proactive maintenance decisions. By leveraging FL, UDOT and other state DOTs can collaborate without sharing sensitive data, enhancing predictive accuracy while maintaining compliance with privacy regulations. The implementation of FL can improve infrastructure management, optimize resource allocation, and enhance the overall safety and longevity of transportation networks, potentially saving millions in maintenance costs over time.

For more information on this project, download the Main report at https://www.ugpti.org/resources/reports/details.php?id=1259

For more information or additional copies, visit the Web site at www.ctips.org, call (701) 231-7767 or write to Center for Transformative Infrastructure Preservation and Sustainability, Upper Great Plains Transportation Institute, North Dakota State University, Dept. 2880, PO Box 6050, Fargo, ND 58108-6050.

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