UTC-Semi-Annual Progress Report

Tier 1 University Transportation Center on Improving Rail Transportation Infrastructure Sustainability and Durability

Rail TEAM

University of Nevada Las Vegas
Virginia Polytechnic Institute and State University
University of Delaware

Submitted to

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UTC Semi-Annual Progress Report

1. ACCOMPLISHMENTS

Major goals and objectives of the program

The goals of this program are to conduct research, promote education, and facilitate technology-transfer activities to improve the sustainability and durability of railroad infrastructure in the United States. Forecasts call for the U.S. economy to continue to grow and for freight travel to remain steady or increase slightly. Thus, railroads will have an even larger role in the future in meeting this demand. In turn, the increased use will expedite the deterioration of railroad systems. The need for faster transfer of goods and people will necessitate high-speed rail transportation, as has occurred in all developed and developing countries around the world. High-speed rail transportation will place far higher demands on maintaining and sustaining the rail infrastructure, which can only be accommodated through advanced technologies, such as those detailed within the goals and objectives of this DOT-UTC.

The first objective of this program focuses on four research areas that are critical to railroad system operations and safety:

- Asset management and performance assessment
- Condition monitoring, remote sensing, and use of GPS
- Application of new materials and technologies
- High-speed rail (HSR) construction methodologies and management

Virginia Polytechnic Institute and State University (Virginia Tech) focuses on condition monitoring, remote sensing, and the use of laser-based and GPS-based systems. The University of Delaware (UD) focuses on asset management and performance management using big data (data analytics) techniques and on the application of new materials, analytic models, and technologies. The University of Nevada Las Vegas (UNLV) is engaged in technologies and construction methodologies to better enable further development and implementation of HSR in the U.S.

The second objective of the program is to improve the development of the workforce and rail education in the U.S. by 1) offering related undergraduate and graduate courses for engineering students; 2) establishing certificate programs suitable for the new generation of engineering students and young professionals who wish to engage in the rail industry; and 3) providing short courses suitable for practicing engineers who wish to hone their skills. All three partnering universities are thus engaged in complementary activities that range from STEM activities to the introduction of railroad-specific undergraduate and graduate courses, workshops, and professional development seminars.

The third objective of this program is to develop and conduct professional activities to disseminate the results of the research to industry and academia. Examples of these activities are organizing and attending conferences, seminars, and workshops. We will also write and submit articles for publication in various journals.

Goal accomplishments

Continuing active research projects

Our consortium universities have continued 18 research projects in this reporting period, i.e., four at Virginia Tech, seven at the University of Delaware, and seven at the University of Nevada Las Vegas. Significant advances have been made in each project. The progress of the projects is described below.

VT-1: Energy Harvester Tie for Providing Access to Electric Power in Remote Locations. We successfully field tested the prototype energy harvester tie (EHT) that was developed for this project on the revenue service track in close collaboration with one of our industrial partners, Norfolk Southern. The tests went well. The NS crew was able to install the EHT on the track without any issues, under our supervision. During a period of six weeks, we were able to be present trackside to monitor the performance of the tie and record the amount of energy harvested by the passing trains. The data indicates that the EHT can provide an average of 15 Watts of power for every axle that passed over it. For example, a long train with 150 railcars and 4 axles per car would amount to 9000 Watts of power. If the energy is stored and retrieved with 50% efficiency, the harvester yields approximately 4.5 KW of usable power per train. This amount of energy can sufficiently operate electronics and trackside instrumentation such as strain gages, accelerometers, LiDAR systems, and similar devices. It may even be able to operate small trackside devices without relying on external batteries or solar panels, as is the case for many of the trackside devices that the railroads operate.

After six weeks of being installed on the track, the harvester developed a minor mechanical issue that necessitated removing it and fixing the problem in the lab. The removal from the track was as routine as the EHT installation. We have fixed the minor mechanical failure that had developed with some of the fasteners in the harvester. The redesigned harvester has been re-assembled and tested in the lab and is currently awaiting receiving approval from Norfolk Southern for re-installation on the revenue service track.

VT-2: Application of Doppler LiDAR Sensors for Assessing Track Gage Widening in Curves and Locations with High-lateral Forces. As noted in our past reports, the Association of American Railroads (AAR) is providing cost-sharing for this project through its research and development organization, MxV Rail (formerly known as TTCI). During this reporting period, we made major advances in achieving one of the major goals of the project, testing Virginia Tech's LiDAR system on a test track. The tests were conducted over one week in early August at the Transportation Technology Center (TTC) in Pueblo, CO, in close coordination with MxV Rail. All the objectives of the tests were achieved successfully. We were able to test the LIDAR system on the High Tonnage Loop (HTL) at TTC in multiple loops at speeds ranging from 10 to 40 mph, and we were able to install the system on a heavily loaded gondola and test it for the duration without any issues. Two locations on the track, one on a tangent and another one in a curve, were set up to emulate a track with weak lateral restrain by removing the track spikes over approximately 12 feet. A third location in a curve was used as "control" with the intent to compare the results for the weak and control sections to determine the LiDAR system's effectiveness in measuring any gage widening due to the laterally weak track.

We are currently in the process of analyzing the test data and video images captured during the tests. The first phase of the data analysis task is intended to be completed by the end of 2022 and follow-up work is to be conducted in 2023, as part of this project. The follow-up data analysis in 2023 will include completing the analysis of an extensive amount of revenue service track data that we collected in 2021 as part of this project and our collaboration with MxV Rail (at the time called TTCI).

VT-3: High-precision Evaluation of the Effect of 3rd Body Layers on Rail, Including Top of Rail Friction Modifiers. The evaluation of the effects of 3rd body layers on reducing rolling traction and braking continued during this reporting period. The test evaluations were performed using the high-precision Virginia Tech-Federal Railroad Administration (VT-FRA) roller rig at the Railway Technologies Laboratory (RTL). The tests with Top-of-Rail Friction Modifiers (TORFM) that railroads use to control the rolling friction between the wheel and rail were extended to include other natural contaminants such as water, oil, and even grease. The tests performed in this reporting period were beyond those we had conducted and reported in the past. The amount and application methods of the contaminants were improved to better control the repeatability and accuracy of the experiments.

The results support our earlier findings in that the agents (i.e., water, oil, and grease) reduce the wheel-rail traction and braking ability to varying degrees, directly correlated to their rate of depletion and lubrication. For instance, water evaporates within a brief period after it is applied. Hence, although water reduces traction by nearly 70 – 80% upon its application, it allows traction to restore to the unlubricated level as soon as it dries. In contrast, agents such as oil and grease have significantly higher lubrication capacity and slower depletion rate. As such, not only do they significantly reduce traction (by as much as 90%) but also sustain the diminished traction for longer periods of time. The tests indicate that traction does not return to the unlubricated level for the duration of the tests. Additionally, the test results show that excessive lubrication can result in stick-slip dynamics between the rail and wheel, which is detrimental to the train's ability to generate traction and braking forces, as well as the longevity of the wheel and rail. Tests with larger amounts of oil and grease resulted in slip marks on the roller surface that resemble similar marks seen on the track in the field at times. Such marks can result in further damage to the top of the rail due to rolling contact fatigue.

VT-4: Automated Inspection of out-of-sight Under-train Equipment. Our testing with the remotely controlled Track Crawler Robot (TCR) is designed for recording video images of trains undercarriage in locations that are out of plain sight continued in this reporting period. As indicated in our past reports, the TCR is fitted with GoPro® cameras and can travel the length of a train in between the rails without interference. The inspections are intended to be done in sidings or train yards when the train is stationary. Ultimately, the goal is to equip the TCR with imaging systems beyond GoPro® cameras, depending on the needs of the user (railroads) such as thermal imaging systems, sonars, etc. It has been suggested that the TCR imaging and inspection ability would also be of interest for security purposes to both the railroads (for high-value assets such as tank cars) and government agencies such as the TSA and U.S. Army. Although we have not yet evaluated such applications, we intend to do so in the future.

The tests proved that the TCR can be operated reliably and effectively for undercarriage inspection at up to 10 mph. The cameras installed onboard the TCR, however, experience considerable vibrations at higher speeds. This resulted in the video images blurring at speeds above 1.5 mph. Although one can argue that such speeds would be sufficient for the type of inspections that the TCR is intended for, we aim to improve the image quality to enable operation at higher speeds, potentially 3-4 mph. Our initial assessment for using cameras other than GoPro® has proven challenging because of both the larger size and cost of the alternative cameras. Alternatively, we are pursuing potentially isolating the GoPro® cameras from the TCR chassis to reduce vibration transmission from the rough surface on which the TCR travels to the cameras. This task is currently underway. We intend to have an initial design concept by the end of 2022. The installation and evaluation of the isolation system for improving image quality at higher TCR speeds will most likely extend into 2023.

UD-1: Development and Validation of a New Generation Rail Wear Model Using Emerging Big-Data Analytic Techniques. This project is ongoing, and work continues on Phase II of the rail wear model. Amtrak has restated their interest in this rail wear model and will be providing additional data for the analysis activity. This includes transverse rail profile data that were collected for over10 years from annual inspections for approximately two miles of track. The data were used to develop two-dimensional wear rates, and we are now working on predicting the evolution of the profile based strictly on its past performance, after a delay due to the coronavirus (during which Amtrak was not able to provide data support). Work is now progressing on the prediction of the transverse rail profile, based on historic changes in the transverse profile using the 2DARIMA modeling approach developed previously under this activity. This approach treats the transverse Cartesian data as time series with adjoining weighting functions that constrain adjacent growth. Data are now being used to train an AI based analysis model. Amtrak has resumed active cooperation and the team is working with Amtrak on this activity. A paper based on this research was presented at American Railway Engineering and Maintenance of Way Association Annual Conference, Denver, CO, August 2022.

UD-2: Load Transfer from Track to Bridge Structure on Curves. This activity has been concluded, and a paper was published in February 2021 in The Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. The project began in September 2019, and it addresses the issue of the transfer of thermal longitudinal rail forces from the track to the structure of the bridge on a curved track. The design of a railway bridge is significantly different from the design of a conventional highway bridge because of the additional loading on the bridge due to the behavior of the track structure under vehicle and thermal loading. This difference is enhanced on curves, i.e., where the bridge supports a track that has a curvature. This research focuses on the effect of thermal forces on welded rail in the curves of bridge structures. The presence of a curve results in this force having both lateral and longitudinal components. Both theoretical models were developed based on fundamental research by S. Timoshenko and by A. D. Kerr as well as a finite element model, and there was excellent agreement when the results were compared. An UTC Report was submitted in January 2021, and a journal paper was published in 2021 by the Journal of Rail and Rapid Transit.

UD-3: Track Geometry Models Using the "Small Data" Algorithm. This project has concluded, and a paper is scheduled to be presented at the annual meeting of the Transportation Research Board in 2022. The activity addressed the use of "small data" algorithms to model the geometry of railway tracks. The quality of the track geometry is correlated directly to the safety, reliability, and ride quality of the vehicles. Therefore, the performance of the track is affected considerably when its geometry deviates from the specified limits due to the weight of the loads it carries and continuous usage. The analysis of track geometry data allows for the prompt application of preventive and corrective maintenance measures, such as tamping, to increase the lifespan of the track and provide higher speeds for trains, thereby optimizing the performance of the track. The first section of this research focuses on the implementation of Approximate Bayesian Computation (ABC), also known as the likelihood-free method, to estimate the parameters of track degradation models for track maintenance. The second part of this research compares the ABC models to Bayesian non-parametric models (Gaussian Processes) to select the best model of track degradation. An UTC Report was submitted in February 2020, and a paper entitled "Approximate Bayesian Computation for Railway Track Geometry Parameter Estimation" has been accepted for publication by the Journal of Rail and Rapid Transit.

UD-4: Effect of Adjacent Poor Ties on the Life of Wood Crossties. This research activity is ongoing, and one paper was published in the May 2021 edition of the Journal of Transportation Infrastructure Geotechnology as well as an article on the research published in Railway Track & Structures in October 2021. A presentation was also made at the Big Data in Railroad Maintenance Planning conference of December 2021. A new paper has also been submitted recently to the Journal of Transportation Infrastructure Geotechnology in September 2022. This activity continues in order to study the effect of adjacent tie conditions on the life of a railroad crosstie using automated crosstie inspection taken from the same track over multiple years. This approach takes into account the dynamic changing of the conditions of adjacent ties to predict the life of the rail and develop improved models of the ties' longevity more accurately. The project currently focuses on the interaction of the degradation rates over time, as well as the iterative process that describes how changing the support condition impacts the middle and adjacent ties. The development of a closed-form expression that describes the deterioration behavior of wood ties as a function of the degradation rates of adjacent ties is underway. Then, a data science approach will be used to develop the relationships identified in the closed form solution, to include the relationship between tie condition and load distribution, and the corresponding relationship between load distribution and degradation rate. Additional tie condition data has been obtained to now include data from approximately 100,000 crossties over the five-year period from 2016 to 2021. This activity aims to provide a method to predict and model the lives of ties based on dynamically changing support conditions as defined by the changing conditions of adjacent crossties.

UD-5: Risk Modeling of Grade Crossing Accidents. This project has been completed, and a follow-up activity is being considered. This activity utilized the national grade crossing inventory database and other readily available demographic data to develop a Bayesian Network to predict optimal crossing protection and accident/collision risk. An exposure metric was developed based on the densities of both train and highway traffic. This metric, along with other variables, was employed in the development of the Bayesian Network to define the protection level required for an individual crossing based on the historic performances of similar crossings, and it predicts the probability of collisions between trains and vehicles on the road.

UD-6: Random Forest-Based Covariate Shift in Addressing Non-Stationarity of Railway Track Data. This activity has been completed, and a paper was published in the ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 2021. This project addresses the accuracy issue for automated track geometry measurement vehicles, specifically the limitations due to the likelihood of the non-stationarity of the gathered data due to external influences. The effect of non-stationarity may lead to the wrong representation of track conditions, thereby increasing the possibility of false outputs from the model. In this study, supervised Machine Learning (ML) methods were used to detect the geometric data's non-stationarity. The methods included Random Forest, Logistic Regression, and Support Vector Machine. The researchers varied the train-test and validation ratio in phases to ascertain the accuracy of each of the Machine Learning methods and their adaptability to different distributions. In the first phase, both the Random Forest and the Support Vector Machine had accuracies of 97.1%, and the Logistic Regression had an accuracy of 96%. In the second and third phases, the Random Forest method produces better results than the other supervised learners, with 97% and 97.1% accuracy, respectively. Similarly, for validation, the Random Forest performed better than the other classifiers with a 98% accuracy rate. Conclusively, the application of the developed models indicated that the Random Forest model provided a more effective approach for detecting the non-stationarity of track geometry data.

UD-7: Topological Data Analysis and Track Geometry Data. Topological data analysis (TDA) is a data-driven approach that involves studying high-dimensional data without assumptions or feature selections. For many complex data sets, especially monitoring railway tracks, the number of possible hypotheses is large, and generating useful hypotheses becomes difficult. The data can be streamed in high dimensions, which can cause the "curse of dimensionality" problems. There is a need to extract robust, qualitative information and gain insight into the processes that generates the data initially. Compared with traditional principal component analysis (PCA), t-distributed stochastic neighbor embedding (t-SNE), and cluster analysis, TDA more effectively detects large and small patterns in data. Thus, the main objective of the project is to apply TDA to various track geometry data and to develop a new approach, i.e., an invariant approach to traditional TQI, that can be more effective.

UNLV-1: Mobile 3D Printing of Rail Track Surface for Rapid Repairment. In this reporting period, a segment of worn rail was welded and tests on the repaired rail have been conducted. At the same time, the rolling contact fatigue tester has been under construction, which is near completion. A dissertation was written based on the work in this project and one presentation was given at a conference.

UNLV-2: High-speed Rail Access Charge for the XpressWest of Nevada. A final report has been prepared for this project in this reporting period.

UNLV-3: Development of Acoustics Technology to Detect Transverse Defects in Rail at High-speed (220 mph). The research team continued the investigation to improve the performance of the machine-learning (ML) approach in predicting the existence of defects in rails. However, after evaluating various ML architectures and hyper-parameter settings on the HTL dataset, the prediction accuracy did not significantly improve. As a causal study, the team started investigating the quality of the field test data sets. The team performed pencil lead break (PLB) tests, which are commonly considered reliable simulations of acoustic emission (AE), to evaluate the signal attenuation at different locations. PLB tests are conducted on the rail web; three sets of bone-conduct sensors are placed near the testing spot (i.e., on the rail, the train's wheel above the testing spot, and the train's suspension frame). The field test results indicate that the interface between the rail and the train's wheel would significantly attenuate the signal: The PLB signals collected from the train's wheel and suspension frame can hardly be observed, while the signals from the rail web presented significant patterns. The PLB field tests indicate that the current data acquisition (DAQ) system, which is mounted on the train frame, might have difficulty collecting AE signals properly (even if a 60 dB pre-amplifier is applied). Therefore, the team planned to change to the air-coupled sensor and place the new sensor above the rail surface to capture the AE signals more effectively and with less attenuation. Currently, the team is modifying the DAQ system for applying the air-coupled sensor. More field tests will be performed once the new DAQ system is set up.

UNLV-4: Development of a Platform to Enable Real-Time, Non-disruptive Testing and Early Fault Detection of Critical High Voltage Transformers and Switchgears in High-Speed Rail. The team has successfully employed the Tektronix API and RSA 306 to recursively scan radio frequency (RF) signals from 100 MHz to 3 GHz with a step size of 40 MHz. The entire data acquisition and processing (DAQP) system (i.e., Intel NUC, RSA 306, and antenna) can now periodically record the scanned signal data into .r3f file with simple spectrum information included (e.g., center frequency, power spectrum, etc.) Each scanning and recording iteration (i.e., 100 MHz to 3 GHz) can take about 100 ms. The .r3f file can be decoded offline into a .csv file that contains raw data in the time domain. The DAQP system is now able to detect a 315MHz signal and a Bluetooth signal (i.e., about 2.45 GHz) over -30 dBm within a one-foot range. The team is still looking for other testing scenarios for on-site tests and/or all frequency range tests at longer distances. Meanwhile, the team is also optimizing the program to reduce the data size and the time cost of each scanning iteration to avoid possible data loss/missing rate. In summary, the team has achieved a DAQP prototype to record raw signal data from 100 MHz to 3 GHz and is able to run simple spectrum analysis in real-time to detect signals of specific frequency.

UNLV-5: Non-Propriety Ultra-High-Performance Concrete (UHPC) for Ballast-Track High-speed Railroad Sleepers. During this period, flexural and stirrup reinforcements were purchased. Formwork for five 8-feet span ties were constructed. Reinforcement caging for the five rail ties were assembled. Strain Gauges at the critical location of the reinforcement were installed. A 10 cubic feet mortar mixer was rented. During the first week of October, all five railway ties were cast. Presently, the ties are being cured. A testing program has been devised and is slated to begin in late November. The actual test setup is being outsourced for fabrication.

UNLV-6: Development of UAV-Based Rail Track Irregularity Monitoring and Measuring Platform. The team has explored multiple methods to fuse IMU sensor data with LiDAR PCD frames, but the measurement accuracy remains unsatisfactory under dynamic testing scenarios. The team is trying to figure out whether we can recover or achieve the absolute level planar after data fusion, without which it will be extremely challenging to measure the irregularities of cross-level and warp in rail geometries. The team is still searching for alternative approaches.

Meanwhile, the team is also fusing data from IMU and GPS/GNSS with LiDAR PCD frames for image registration, based on the simultaneous localization and mapping (SLAM) technologies. By doing so, the UAV does not need to fly high altitude (> 10 meters, which will significantly decrease the cloud point density on rails and thus degrade the rail detection accuracy) to expand LiDAR's field of view (FOV) to include long rails (i.e., > 62 feet) in each PCD frame to measure the rail profile. Instead, PCD frames may be stitched and extended, and rail profiles and curves are measurable for long rails. Currently, the image registration algorithm works well under urban area (e.g., with buildings, trees, cars, etc.), but due to the lack of features (e.g., specific planar, corners, etc.) at and/around rail tracks, accurate image registration is difficult; the team is developing and fine-tuning our algorithms to overcome this problem.

UNLV-7: Efficient Railway Analysis Using Video. Benchmarking of three different state-of-the-art semantic segmentation algorithms (FRRN-B, HRNet-OCR, and SFSegNets) has been completed on the RailSem19 public railroad dataset to characterize the segmentation quality and processing time using GPU and CPU. Our current work addresses implementation of the networks on lower-powered devices or single-board computers (SBCs) such as the Raspberry Pi or Nvidia Jetson. Initial tests show the Raspberry Pi is not powerful enough for the segmentation networks and the Jetson needs to be used for GPU speedup. A locomotive camera system package is in development for unattended data collection with the Nevada Southern Railway Inc. in Boulder City of Nevada.

Initiating new research programs

None to report in this period.

Upgraded education opportunities

We continue to have plans to offer a distance learning graduate course, entitled "Rail System Dynamics." The research involvement, however, has proven to make the planning and development of the course more challenging than initially anticipated. Upon its implementation, the course will be made available to the University of Delaware and UNLV graduate students in an online format. The students at each university will receive credit toward their graduate degrees from their home institutions.

The University of Delaware offered four railroad courses one in the Fall of 2022; CIEG 418/618 Railroad Engineering and three in the Spring of 2022; CIEG 317 Introduction to Railroads, CIEG 414/614 Railroad Geotechnical Engineering and CIEG 417/617 Railroad Safety and Derailment Engineering. At UNLV, two courses were offered in the Spring and Fall semesters in 2022, i.e., CEE 470/670 High-speed Rail and CEE 460/660 Introduction to Railway Transportation. More than 20 graduate and undergraduate students attended each course.

Opportunities for training and professional development

Virginia Tech hosted the 2nd Symposium on Infrastructure Diagnosis and Prognosis on May 23-24, 2022, in Hotel Roanoke, a historic railroad hotel in Roanoke, Virginia. The symposium was a resounding success. It brought together more than 60 practitioners and scientists from the industry, academia, and government agencies. Five technical sessions with three panelists in each session were organized during the 1.5-day event, with ample opportunity for the participants to interact and exchange ideas in a more relaxed social setting. Additionally, we are considering conducting a one-half-day working session on rail neutral temperature in conjunction with the ASME Joint Rail Conference on April 9, 2023, in Baltimore, MD. This effort is in its early stages of planning, and we hope to be able to list it in our future reports.

The University of Delaware's Professional Engineering Outreach provides professional courses for practicing railroad and transit professionals. These professional development courses include the new Continuous Welded Rail-Rail Neutral Temperature course (July 2021), with other recent professional development courses, such as Application of Emerging Data Science Techniques for Railway Maintenance Planning, Rail Grinding and Rail Maintenance, and Rail Industry Growth for Increased Long-Term Profitability.

The Big Data in Railroad Maintenance Conference takes place in December each year at the University of Delaware, and the Conference is co-sponsored by the RailTEAM UTC. This Conference addresses the growing use of data analytics in the planning and management of railroad maintenance, and it usually has more than 200 attendees from railroads, transit systems, railway suppliers, data analytic companies, and academia. The 2022 conference is scheduled for December 14-14, 2022, at the University of Delaware, Newark DE campus.

Results disseminated

Our efforts in preparing three reports on our past projects have been delayed due to other project commitments. Nonetheless, we intend to complete these reports before the end of March 2023 and share them with the DOT through RailTEAM's lead university, UNLV. We have been prolific in making the results of our research known throughout the industry and among our industrial partners. We made two presentations at the RailTEAM Symposium in May on VT-2 and VT-4 projects. Additionally, we made a presentation regarding VT-3 to the ICRI working group, an international group interested in wheel-rail interface issues. We have had two online meetings with Norfolk Southern to report the findings of our Energy Harvest Tie testing (VT-1). Similar online meetings have been held on two occasions with the AAR's MxV Rail on VT-2. Our projects' results have been disseminated to the industry and government agencies.

At the University of Delaware, we are currently preparing three reports on our past projects that we will share with the DOT through the lead university, UNLV. A new presentation is scheduled for the 2022 Big Data at the University of Delaware on December 14-15, 2022. Additionally, we made three presentations at the ASME Joint Rail Conference that took place virtually on April 20-21, 2022. We have also had Zoom and in-person meetings with researchers and engineers from

FRA and some of our industrial partners, such as Amtrak, Norfolk Southern and AAR's Transportation Technology Center, Inc. (TTCI).

The University of Delaware conducted two major activities to disseminate results to industry and academia. The next Big Data conference will take place December 14-15, 2022, in live format, and will include presentations concerning the UTC projects that are being conducted at Virginia Tech and the University of Delaware. The University of Delaware maintains contact with industry partners and its own railway advisory board to present the results of the UTC project. In the UD Railway Advisory Board meeting in December 2021, the results of the UTC project were presented from several UTC sponsored projects. The next UD Advisory Board is scheduled for December 13, 2022.

In addition, Amtrak has rejoined the rail wear project, and is again supporting that activity with rail wear data and is interested in utilizing the results in their rail maintenance management program. This Amtrak activity was suspended for almost two years due to Covid but has recently been reinstated. A paper based on this wear project was presented at the August 2022 AREMA technical conference.

UNLV gave two presentations at the RailTEAM Symposium in May 2022 based on their work on 3D printing and access charge to high-speed rail. A dissertation on 3D printing application to repair worn rail was completed and stored in the UNLV library electronically which researchers all over the world can access remotely.

Plan for the next reporting period

Virginia Tech's efforts in completing the current four projects it is undertaking will continue to completion in 2023, as noted earlier. The University of Delaware and UNLV will also plan to continue their research and educational activities through the end of the current UTC contract. Both universities are offering railroad-related courses in the fall 2022 semester, and plan to continue their course offerings in the spring 2023 semester.

2. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Organizations involved as partners

Both Norfolk Southern (NS) and MxV Rail serve as industrial partners in our research projects. During this reporting period, we had a great amount of interaction with NS, resulting in planning, installing, and successfully testing the VT's energy harvester tie on the NS track at a location in Christiansburg, VA. Additionally, we had extensive collaboration with MxV Rail, the R&D arm of the Association of American Railroads (AAR), resulting in extensive tests at their test facility in Pueblo, CO in August. As reported in the past, AAR is providing $154,300 of matching funds for VT-2. The requested information about AAR's matching funds is:

- Organization Name: MxV Rail or Association of American Railroads (AAR)
- Location of Organization: Pueblo, Colorado

- Partner's contribution to the project (identify one or more): Financial Support for $154,300. Extensive engineering support (approximately ½ man-year in total during this reporting period)

At the University of Delaware, Phase II of the rail wear project will have new data and technical support from Amtrak's Engineering Department (Philadelphia, PA) as well as ongoing support and data from CSX Transportation in Jacksonville, FL. Results will be presented to Amtrak upon completion for incorporation in their maintenance management activities.
The requested information about Amtrak's matching funds is:

- Organization Name: National Railroad Passenger Corporation (Amtrak)
- Location of Organization: Philadelphia, PA
- Partner's contribution to the project (identify one or more): Financial Support for $95,437 plus engineering support and provision of data for use in the activity.

Nevada Southern Railway Inc. (NSRI) has continued to provide support for our research projects at UNLV. In this reporting six months, they met with our researchers about collecting video data using their locomotive and their track. Tests on the acoustic sensors were also conducted using a rail car they own on their track. The NSRI identified the geometric data to be provided to our UAV project team. In addition, they agreed to use their shop to host our rolling contact fatigue tester, which required high voltage power. It implies that we will contact our rolling contact fatigue tests for our 3D printing project at their facility.

Other collaborators or contacts involved

None to report during this reporting period.

3. OUTPUTS

Output performance measures

We have the following three output performance measures: (1) number of publications in peer-reviewed conferences or journals, (2) number of invention disclosures filed estimated, and (3) number of provisional or utility patent applications filed. In this reporting period, we have four publications including one Masters' thesis and one Ph.D. dissertation, which is at the target 3-4 per six months. One invention disclosure was filed by Virginia Tech, which is more than the target 0-1 per six months. UNLV filed a patent based on their work on 3D printing for repairing worn rail, which is more than the target 0-1 in six months.

Publications, conference papers, and presentations

The presentations and publications developed by our UTC team in this reporting period are as follows:

Publications

1. Pan, Y., Zuo, L., and Ahmadian, M., A Half-wave Electromagnetic Energy-Harvesting Tie towards Safe and Intelligent Rail Transportation, Applied Energy, 313(4):118844, May 2022. (https://doi.org/10.1016/j.apenergy.2022.118844). UTC support acknowledged. (Virginia Tech)
2. Soufiane, K., Zarembski, A. M., and J. W. Palese, The Contribution of Crosstie Condition as Represented by Local Track Stiffness to the Wheel Load Distribution, submitted to Journal of Transportation Infrastructure Geotechnology, August 2022. UTC support acknowledged. (University of Delaware)
3. Mortazavian, E., Mobile 3D Printing of Rail Track Surface for Rapid Repair, Ph.D. Dissertation, Department of Mechanical Engineering, University of Nevada Las Vegas, August 2022. UTC support acknowledged (University of Nevada Las Vegas)
4. Qiu, L., Development of UAV-Based Rail Track Geometry Irregularity Monitoring and Measuring Platform Empowered by Artificial Intelligence, Department of Electrical and Computer Engineering, University of Nevada, Las Vegas, May 2022. UTC support acknowledged (University of Nevada Las Vegas)

Books or other non-periodical, one-time publications

None

Other publications, conference papers and presentations

1. Michael, M. and Ahmadian, M., Improving Trackside Inspection of Rolling Stock Using a Track Crawler Robot: A Step Toward Better Diagnosis and Prognosis of Railcars, Railroad Infrastructure Diagnosis and Prognosis Symposium – RailTEAM UTC, Roanoke, VA, May 2022. UTC support acknowledged. (Virginia Tech)
2. Radmehr, A. and Ahmadian, M., Early Diagnosis of Track Stability through Non-contact LiDAR Measurements and Unsupervised Machine Learning Algorithms, Railroad Infrastructure Diagnosis and Prognosis Symposium – RailTEAM UTC, Roanoke, VA, May 2022. UTC support acknowledged. (Virginia Tech)
3. Zarembski, A. M., Palese, J. W., and Nguyen, M., Forecasting Track Geometry Degradation Using GPR Based Ballast Condition, American Society of Mechanical Engineers Joint Rail Conference 2022, April 2022, Baltimore, MD. UTC support acknowledged (University of Delaware)
4. Palese, J. W. and Zarembski, A. M., Predicting Rail Transverse Profile Shape Using 2D ARIMA Modeling, American Railway Engineering and Maintenance of Way Association Annual Conference, Denver, CO, August 2022. UTC support acknowledged (University of Delaware)
5. Attoh-Okine, N., Theory Guided Data Science and Railway Informatics, Railroad Infrastructure Diagnosis and Prognosis Symposium – RailTEAM UTC, Roanoke, VA, May 2022. UTC support acknowledged (University of Delaware)

6. Palese, J. W., A Data Driven Approach to Predicting Rail Transverse Profile Shape, Railroad Infrastructure Diagnosis and Prognosis Symposium – RailTEAM UTC, Roanoke, VA, May 2022. UTC support acknowledged (University of Delaware)
7. Zhiyong "John" Wang, 3D Printing Rail Surface for On-Site Repair, University of Nevada Las Vegas (UNLV), Railroad Infrastructure Diagnosis and Prognosis Symposium – RailTEAM UTC, Roanoke, VA, May 2022. UTC support acknowledged (University of Nevada Las Vegas)
8. Kaseko, M. and Boyapati, K., Development of a Framework for Determination of Access Charges on a Shared High-Speed Rail (HSR) Corridor Using VISSIM Simulation, UTC support acknowledged (University of Nevada Las Vegas)

Policy Papers

None to report

Website

We have purchased the "railteam.org" web domain for the RailTEAM UTC. It was used for the RailTEAM Symposium in May 2022. The participants were able to download the technical program, register for the symposium, and get lodging information through the railteam.org webpage. Additionally, Virginia Tech maintains its website for publicizing its research activities. Many of the DOT-UTC initiatives have been included at the Center for Vehicle Systems and Safety's new website (https://www.cvess.me.vt.edu), The Railway Technologies Laboratory (RTL) website (https://www.me.vt.edu/rtl-2/), as well as RailTEAM's webpage (https://www.unlv.edu/railteam).

The University of Delaware has continued to highlight the railway research and educational activities in its Railroad Engineering and Safety Program website (railroadengineering.engr.udel.edu/). UNLV routinely updates the RailTEAM website with information from partnering universities.

Technologies or techniques

Virginia Tech's energy harvesting tie presents a novel and innovative technology that can bring railroad transportation many benefits. This novel technology was developed due to RailTEAM's efforts. Similarly, the Track Crawler Robot (TCR) developed by Virginia Tech provides a unique all-terrain platform that is being tested for the first time for its intended railroad safety and security applications. Finally, as documented in the past, Virginia Tech's efforts have resulted in significant advances in the application of LiDAR technology for railroad applications. The advances made in LiDAR technology have not only raised the industry's awareness but have also made them more comfortable with adopting LiDAR systems for their way practice maintenance.

The University of Delaware has developed noteworthy maintenance models. One is the method/model for predicting the wear life of railway rails, and it was presented at the 2022 American Railway Engineering and Maintenance of way Association Annual Conference, Denver

CO, August 2022. A second model is a new approach to predicting the development of rail defects and the associated fatigue life of rail, recently published (2021) in *The Jo*urnal of Rail and Rapid Transit, an internationally recognized railway journal. A third model determines life of timber crossties as a function of varying support condition, presented at the American Railway Engineering and Maintenance of Way Association Conference, September 2020, the Railway Tie Association's annual technical conference in November 2021, and was published in *The Journal of Transportation Infrastructure Geotechnology* in 2021. A new paper, with more recent research results has been submitted to The Journal of Transportation Infrastructure Geotechnology in September 2022.

UNLV has been developing a 3D printing technology to repair worn rail on site. Instead of replacing the worn rail, it can be repaired and can continue to provide service. This technology will save significant maintenance costs for the railroad industry. Another technology that UNLV is developing is the inspection of track irregularities such as gauge and curves using LiDAR and UAV technology. This technology can replace the labor extensive track inspection using the current inspection cart. The other technology monitors the pantograph strip that receives electricity from overhead wires to high-speed rail trains. This strip constantly touches the wire and wears out quickly. This monitoring technology can tell the extent the strip is worn out in real time, which provides information as to the time to replace the strip. We also found that PTV Vissim, a highway traffic simulation software, can simulate the operation of high-speed rails, which provides a way to evaluate them.

Inventions, patent applications, and/or licenses:

Virginia Tech has one patent filed: Kinetic Energy-Harvesting Device for Powering and Charging Railway and other Applications, USPTO Application No. 17719971, filed on April 13, 2022.

UNLV is preparing a patent file on 3D printing: Additive Manufacturing System and Method for Railroad Rail and Wheel Repair, September 2022.

4. OUTCOMES

Passage of new policies, regulation, rulemaking, or legislation

The University of Delaware is working with Amtrak to develop new tools for improved management of rail maintenance, particularly in the area of worn rails, because it is a major maintenance cost area.

Increases in the body of knowledge

Many of the technologies that we are developing are expected to have tangible outcomes that will make rail transportation safer and more operationally efficient. For instance, the energy harvesting tie in VT-1 provides the ability to integrate sensors and monitoring electronics in the track to continuously monitor its condition and alert track engineers when there are track anomalies or failures that could cause derailments. Similarly, for VT-4, the Track Crawler Robot will be able to monitor train undercarriage conditions and assess any deficiencies or pending failures that require intervention, to eliminate unscheduled maintenance that could cause major interruptions to train schedule and traffic flow. The VT's LiDAR system in VT-2 can provide an earlier indication of track lateral instability and gage widening so that the track crew has more time to schedule maintenance to circumvent the track deficiency. This not only causes less interruption to the traffic flow but also prevents the deficiency to progress to become a costly catastrophic failure. These are all examples of how RailTEAM’s research projects are expected to create actual outcomes to benefit U.S. rail transportation.

The research at the University of Delaware addresses new generation data analytic tools to increase the amount of railroad inspections and operations data and the development of new relationships between performance, component degradation, and safety. Current research activities already address this in the following areas, i.e., degradation of crossties (sleepers), wear of railway wheels, wear of railway rails, railway rail fatigue, track geometry degradation, and forecasting derailments.

We do not know whether LiDAR on UAV can measure track irregularities that required high accuracy. Our UAV projects demonstrates that track irregularities can be measured with LiDAR mounted on UAV, which is a knowledge breakthrough, providing a direction for a new way to inspect track effectively.

Improved processes, technologies, techniques, and skills in addressing transportation issues

All RailTEAM’s projects are undertaken with the intention of improving processes and technologies that will address one of the most critical rail transportation issues, track, and train maintenance. For instance, Virginia Tech’s VT-3 project is developing better lubrication processes that can improve track friction management, toward more fuel efficiency and less wheel/rail wear. The energy harvesting tie in VT-1 and LiDAR system in VT-2 will lead to more advanced track maintenance monitoring and diagnostic technologies.

The research performed by the University of Delaware provides new analytical tools to address key issues in rail transportation. These include degradation/failure mechanisms for both track and vehicle components, specifically ties, wheels, rails, track geometry, and CWR on bridges, which represent critical cost, maintenance, and safety areas.

Our project at UNLV on 3D printing technology can reduce maintenance cost significantly.

Enlargement of the pool of trained transportation professionals

Virginia Tech's Railway Technologies Laboratory is planning a special recruiting event for the rail transportation industry, in conjunction with the VT-AREMA student chapter. This event is primarily intended to provide direct access by some of the key companies in the U.S. rail transportation to recruit some of the most talented undergraduate and graduate students at Virginia

Tech. The students are pre-selected based on their academic qualifications, extra-curricular activities, and diversity to pair up with the rail companies in an event that provides them a personal experience with the engineer and human resource professionals from the attending companies. The main intent of this recruiting event is to enlarge the pool of trained transportation professionals.

The railroad program at the University of Delaware trains working professionals who earn UD's Graduate Certificate in Railroad Engineering. The program includes professionals from Amtrak, SEPTA, the U.S. Navy, and numerous consulting groups and international railways.

UNLV has been working with professionals in high-speed rail agencies on education and research to enlarge the pool of trained transportation professionals.

Adoption of new technologies, techniques, or practices

Our projects all use new technologies, techniques, and practices. We are at the leading edge of the application of many of these technologies in practice. Although interesting technologies are often studied in the laboratory, they fall significantly short of practical solutions that help the industry. Our projects have successfully bridged this gap.

Three of the RailTEAM's projects at Virginia Tech successfully undertook field testing of prototype systems in revenue service or on test tracks. During this reporting period, we achieved revenue service testing of the energy harvester tie (VT-1), track testing of the LiDAR system (VT-2), and rail yard testing of the track crawler robot (VT-4). This was in an attempt to cover some of the lost ground in field testing our systems during the Covid Pandemic era in 2020 and 2021, as reported in our past semi-annual reports. We remain somewhat behind with our field testing, and it is expected that one or two years of extension will be needed for the current program at Virginia Tech to fully recover the lost time due to the Covid shutdown.

The University of Delaware's rail wear forecasting methodology is shared with Amtrak, which is currently working with UD to apply this methodology to its current rail wear analysis and rail replacement planning tools as part of the maintenance planning programs at UD. The University of Delaware's methodology to predict the rate of wheel wear and identify "bad actor" cars that generate excessive wear (and possibly excessive levels of lateral force) has been shared with New York City Transit (NYCT), the largest transit system in the United States. NYCT is examining how it can be incorporated into their maintenance and safety programs. The work has significant potential for both maintenance and safety since it addresses railway wheels and the point at which they are removed from service for either maintenance or replacement (safety).

UNLV has developed a few technologies that have the potential to be adopted in practice. For example, the 3D printing technology to repair worn rails may be quickly adopted, evidenced by the high citation rate of the relevant papers produced from our project.

Outcome performance measures

Two outcome performance measures proposed by our RailTEAM are: (1) number of citations of research papers in technical journals and conference proceedings, and (2) number of news media coverage. During this reporting period, our research papers were cited 59 times, 10 for Virginia Tech, 8 for UD and 11 for UNLV, which is more than 3 to 5 times the amount we targeted. Unfortunately, we do not have any news media coverage during this reporting period. Hopefully, more news media coverage will come up in the next reporting period.

5. IMPACTS

Impact on the effectiveness of the transportation system

Most of the research conducted under this UTC has resulted in field-proven and tangible results that will result in safer and more reliable rail transportation in the U.S., mainly reducing the likelihood of costly derailments and accidents. As accidents in the railway industry draw public attention, improvements in approaches to safety have a direct impact on society's perception regarding the safety of using new and emerging technologies. The impact of technologies under development at the RailTEAM UTC is related directly to improving track-maintenance practices. The U.S. railroads collectively spend billions of dollars on track and rolling stock maintenance. Even small improvements (say 4 or 5%) in maintenance practices yield significant cost savings, beyond saving lives and raising the public's confidence and reception of rail transportation. The technologies in which we are engaged at Virginia Tech (LiDAR, energy harvesting, train inspection robots, and others) promise to bring significant cost savings and improved railroad safety. The cost savings are due to the improved fuel efficiency that result from the better understanding and management of friction, the ability to detect failed components and malicious out-of-sight packages, and early detection of any pending track failures before it is too late.

The University of Delaware's UTC sponsored research on rail wear is being applied on Amtrak, and specifically Amtrak's Northeast Corridor, in rail replacement planning, a key part of Amtrak's track maintenance program. The University of Delaware is working with Amtrak to collect additional rail profile data for continued efforts on Phase II of the rail wear research project. Amtrak also provides guidance on the practical application of the methodology, as well as data limitations. As this model becomes fine-tuned and validated, we expect implementation on many major U.S. rail systems, including freight railways, passenger and commuter railways, and rail transit systems.

As reported previously, the University of Delaware extended the method it developed to predict the rate of wheel wear. The railways can directly apply models to predict the wearing of railway wheels and predict when to perform maintenance to extend life (e.g., wheel truing) or replace them. NYCT is examining how to incorporate this information in the company's maintenance and safety programs.

A new method of predicting the development of rail fatigue defects by the University of Delaware examines the use of Parametric Bootstrapping for the Weibull Analyses. This bootstrapped method provides reasonable estimates track segment defect rates with no prior defect data, allowing for far more data analysis and accounting for in-maintenance planning efforts, thus increasing the rail forecasting effectiveness.

A model has been developed for the determination of lateral thermal forces on curves, including curves on bridges, and this will allow the accurate prediction of these forces that can affect the load on bridge structures due to constrained thermal expansion in continuously welded rail. The Journal of Rail and Rapid Transit has recently published a paper concerning this information (February 2021).

Finally, a model has been developed that addresses the issue of the accuracy of data for automated track geometry measurement vehicles, specifically the limitations due to the likelihood of non-stationarity of the gathered data due to external influences. The effect of non-stationarity may lead to the wrong representation of track conditions, thereby increasing the possibility of false outputs from the model. This work thus results in increased data accuracy from track geometry car measurements.

UNLV's access charge project will directly impact the construction decision of XpressWest, which is considering building a high-speed rail from Las Vegas to Los Angeles. XpressWest did not consider this access charge when initiating their project.

Impact on the adoption of new practices

Virginia Tech's track and field testing of the LiDAR system, the energy harvesting pre-production tie, and the Track Crawler Robot prototype have all contributed to increasing the confidence in the commercial success of these technologies, beyond the immediate research by the RailTEAM UTC. If successfully deployed, these technologies will have a significant impact on improving railroad engineering practices. For instance, the LiDAR system in VT-2 can be adopted for in-situ measurement of track gage widening onboard a locomotive or Hyrail truck. This would enable detecting and fixing sections of the track with low lateral strength before they lead to costly derailments. Similarly, the commercialization of the energy harvester tie in VT-1 will enable a seamless and practical means of accessing power in places where such power is currently unavailable. This will be a critical and enabling technology for integrating sensors and smart devices on the track, which will have several significant advantages. The track Crawler Robot in VT-4 would yield means of train inspection that is currently only available through highly sophisticated and costly systems.

It is expected that 3D printing technology that can repair worn rails onsite will change railroad maintenance practice. Currently, worn rails are removed from the railroad track and replaced with new ones. Due to the 3D printing technology that can repair worn rails on site, the worn rails will not need to be removed from the track. This practice will save the cost of removing and discarding the worn rail, thereby reducing the railroad operating cost significantly.

Impact on the body of scientific knowledge

The knowledge gained in VT-3 regarding the effect of contaminants on traction has had measurable improvements in the basic science of how a railroad wheel interacts with the rail. The scientific knowledge gained in this regard has been significant enough that leading peer-reviewed journals have accepted our publications. Some of the technologies we are working on have scientific and practical applications beyond rail transportation. For instance, LiDAR technology can assess roadway surface conditions. The Track Crawler Robot can also be used for under-train inspection by the Department of Homeland Security and the U.S. Army.

The University of Delaware has developed approaches and methodologies to maintain the railroad infrastructures that are readily adaptable in the areas of highway pavement and airport runway research and analysis.

Impact on the development of transportation workforce development

The RailTEAM projects continue to provide the education and training necessary for careers in the rail transportation industry, producing highly sought after undergraduate and graduate students. As mentioned earlier, we not only provide the training and education that ensure the success of our graduates in the rail transportation industry, but also provide career planning and recruiting events that connect them with the leading rail companies, such as the career fair that has been planned for November 9, 2022.

UNLV has been teaching courses on railroad and high-speed rail. The undergraduate and graduate students who took these courses have opportunities to join the work forces to, plan, design and construct high-speed rails in the U.S. Some new employees at the current high-speed rail projects have been seeking professional development related to their projects.

Impact performance measures

We have two performance measures for impact: (1) number of stakeholders requesting RailTEAM expertise in the application of research products and/or results and (2) number of results transferred to companies, adoption of new practices, or the initiation of new startups. We have three requests from stakeholders for RailTEAM expertise, two to Virginia Tech and one to UD, which exceeds our target one per year. Virginia Tech and UD, each has one research result transferred to companies, which is also above our target one per year.

6. CHANGES/PROBLEMS

No changes in approach.

Actual and anticipated problems or delays

We have mostly recovered from the interruptions caused by the COVID-19 Pandemic, which mainly affected the field testing that we had planned for 2020 and 2021. Although the field testing and test track evaluation that we were able to conduct during this reporting period has enabled us to gain some ground on the delays caused by the shutdown during 2020 and 2021, we anticipate that more time beyond the current conclusion of the RailTEAM contract will be needed to complete the tests. As such, we would like to request a two-year no-cost extension to the end of September 2025.

The change in our testing schedule has had some impact on expenditures by delaying them. There have been no significant changes in the use or care of human subjects, vertebrate animals, and/or biohazards. In addition, no change has occurred in the location of the primary performance site from the original proposal.

7. SPECIAL REPORTING REQUIREMENTS

Our UTC project complies with the Research Project Requirements and Submission of Final Research Reports.