Technology Scan Summary Report for Advancements in Railway Research

for Transport Canada

Prepared by MxV Rail

P-24-004

April 02, 2024

MxV Rail
A subsidiary of the Association of American Railroads
Pueblo, Colorado USA
www.mxvrail.com

Disclaimer:

Acknowledgements

MxV Rail

Project Manager

Christopher Pinney

Subject Matter Experts

Mr. Benjamin Bakkum

Dr. Yin Gao

Dr. Silvia Galvan-Nunez

Dr. Duane Otter

Mr. Alan Polivka

Dr. Anish Poudel

Mr. Brian Smith

Mr. Tony Sultana

Dr. Stephan Wilk

Dr. Matthew Witte

Editorial Services

Susanna Tobias

Transport Canada

Project Manager

William Anthony

Table of Contents

List of Figures

List of Abbreviations and Acronyms

Abbreviation/ Acronym	Meaning
AC	Alternating current
ACO	Ant Colony Optimization
AAR	Association of American Railroads
AI	Artificial intelligence
ALTRIOS	Advanced Locomotive Technology and Rail Infrastructure Optimization System
ANFIS	Adaptive neuro-fuzzy inference systems
ANSI	American National Standards Institute
ATCS	Advanced train control systems
ATI	Automated track inspection
ATO	Automated Train Operation
BEL	Battery-electric locomotive
CARE	Community, Analysis, Response, and Evaluation
CBTC	Communications-based train control
CFD-DEM	Computational fluid dynamics-discrete element method
CNG	Compressed natural gas
CNN	Convolutional neural network
CPKC	Canadian Pacific Kansas City
CTA	Cognitive Task Analyses
CWR	Continuous-welded rail
DAS	Distributed Acoustic Sensing
DoS	Denial of Service
DOT	Department of Transportation
DTL	Diode–transistor logic
ETCS	European Train Control System
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
EIC-PRT	Employee-in-Charge Portable Remote Terminal
EMS	Energy management systems
ERP	Effective radiated power
ETC	Enhanced Train Control
EO-PTC	Enhanced Overlay PTC
FMB	Full Moving Block
GA	Genetic Algorithm
GHG	Greenhouse gas
GNSS-RTK	Global Navigation Satellite System-Real-time kinetic positioning
GPR	Ground Penetrating Railroad
HBD	Hot box detectors
HEP	Human error probability
HIPS	Host intrusion prevention systems
HMI	Human-machine interface
HRCTC	Higher Reliability and Capacity Train Control
ICD	Interface Control Documents
InSAR	Interferometric Synthetic Aperture Radar
ITC	Interoperable Train Control
LAN	Local area network
LDS	Location determination system
LiDAR	Light Detection and Ranging
LNG	Liquified Natural Gas
LP	Liquid propane

LRV	Light rail vehicle
MITM	Man-in-the-middle
MOTES	Mobile Telematic Systems
NCHRP	National Cooperative Highway Research Program
NDE	Nondestructive evaluation
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NTSB	National Transportation Safety Board
OBRD	Onboard Broken Rail Detection
OEM	Original equipment manufacturers
PSF	Performance shaping factors
PSO	Particle Swarm Optimization
PTC	Positive Train Control
PTL	Positive Train Location
QMB	Quasi-Moving Block
QRA	Quantitative risk assessment
RF	Radio frequency
RGHRP	Railway Ground Hazard Research Program
RIoT	Rail Internet of Things
RISC	Rail Information Security Committee
ROI	Return on investment
SEPTA	Southeastern Pennsylvania Transportation Authority
SME	Subject matter expert
SPAR-H	Standardized Plant Analysis Risk-Human
TADS	Trackside acoustic detector systems
TC-IC	Transport Canada's Innovation Centre
TG	Track geometry
THD	Truck Hunting Detectors
TPD	Truck Performance Detectors
UAV	Unmanned aerial vehicle
UP	Union Pacific
WILD	Wheel impact load detectors
WPD	Wheel Profile Detector

1.0 INTRODUCTION

In late 2023, Transport Canada's Innovation Centre (TC-IC) requested MxV Rail's support in developing a technology scan of emerging railway technologies. Designed to focus on technological advancements in long-haul freight and inter-city passenger rail, this technology scan included a review of technology references from around the world and Canadian industry stakeholder views on technology trends and important research opportunities. The objective of the technology scan is to provide information to the Canadian Rail Research Advisory Board and support the development of TC-IC 2025–28 Research, Development, and Deployment (RD&D) Work Plan. Figure 1 illustrates an emerging technology (hydrogen fuel cell locomotive) identified in the technology scan as being developed to address railway decarbonization strategies.

Figure 1. CPKC hydrogen fuel cell locomotive

2.0 RESEARCH THEMES SUMMARIES

Transport Canada and MxV Rail SMEs scanned technology references from around the world and gathered industry stakeholder perspectives from Canadian Class I railroads, short line railroads, and academic research institutions based on eighteen research themes representing emerging technologies in the railway industry (see Appendix A). Using SME knowledge, information from the Canadian stakeholder interviews (see Appendix B), and technology scan references (see Appendix C), the research themes have been developed into individual summaries, each containing a current landscape and opportunities for future research section.

2.1 Track and Infrastructure Inspection Technologies

2.1.1 Current Landscape

Ensuring the safety of railway infrastructure is crucial, and regular inspections are necessary to monitor and detect anomalies that may lead to damage. Researchers are considering a variety of inspection techniques for conducting track inspections at different development stages. These techniques include ultrasound, phased array ultrasound, electromagnetics, thermography, machine vision, 3D Light Detection and Ranging (LiDAR), photogrammetry, unmanned aerial vehicles (UAVs), Drone-Based Digital Image Correlation, Distributed Acoustic Sensing (DAS), and track geometry measurement systems that use lasers, accelerometers, cameras.

Despite the development of computer-aided track inspection technologies, manual inspections continue to be the current predominant inspection method, especially in the search for missing or broken track components. Despite being the main inspection method, manual inspections can be both subjective and challenging due to the logistics of performing detailed inspections at speed (revenue service or hi-rail). Typically, human inspectors conduct visual inspections and document any defects found through field measurements and visual observations. The data is usually recorded in paper-based forms that must be well-organized to support future inspections. In addition, such processes may be limited by 1) the experience and knowledge of the inspector and 2) the location of the area to be inspected, especially for larger structures like railway bridges.

Recently, machine-based and automated track inspections (ATIs) have been explored to augment human inspections. Nondestructive evaluation (NDE) techniques have been widely implemented in rail and wheel inspections, and these techniques continue to improve in detecting material failure in track components. Additionally, ATIs for track geometry (TG) measurements make it possible to improve track inspection in a more efficient and effective manner. Railroads seek to increase automated TG measurements and reduce periodic visual track inspections. In addition, researchers have investigated using machine vision inspections (e.g., drone-based imaging and image processing technologies) and providing consistent, automated, and less-biased inspections. By leveraging artificial intelligence (AI), machine learning, and deep learning approaches, such as convolutional neural networks (CNNs), researchers are trying to develop a fast, accurate, easily operated, and low-computation track inspection method that uses imaging technology. In addition, the use of the digital twin concept is also being considered for the complete management of railway infrastructure, which is believed to offer continual asset monitoring and life cycle assessment by incorporating sensors and inspection information into the digital twin.

These technologies present several opportunities for efficient and effective track inspections. Some of the relatively mature technologies used for monitoring track infrastructure, such as NDE, continue to evolve, while other technologies (ATI, AI-based, digital twin) are still in the early stages of development. Overall, the inspection technologies present new horizons and opportunities for future research that can help achieve accident-free rail transportation.

2.1.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Development, testing, and validation of advanced NDE techniques, such as phased array ultrasound, laser ultrasound, infrared thermography, etc.	Rail inspections for detecting and characterizing internal anomalies are primarily conducted using a traditional ultrasonic testing method. Advanced NDE methods present newer horizons and opportunities for future research that can help achieve accident-free rail transportation.	The research outcome can provide information on the performance of advanced NDE techniques and shed light on their limitations in revenue service implementation. The outcome of the research can inform the reliability of the new NDE methods for rail inspections in real-world scenarios.	Enhanced rail inspection techniques and procedures using appropriate tools can lead to enhanced rail safety. The research can equip stakeholders, in particular railways, with strong diagnosis tools to both detect internal faults and prevent accidents
Integration of other NDE technologies such as ultrasonic, radiographic, and optometric, with automated track geometry measurement system (ATGMS)	There are a few research projects that have been conducted on ATGMS and its capabilities regarding automated fault detection in rails, but there is a lack in research in evaluating the use of multiple technologies for optimal fault diagnosis.	The outcome of this research can inform the optimal sets of technologies that can be integrated with ATGMS, which enables identifying faults that advanced track geometry measurement systems cannot detect single handed.	Optimal autonomous inspection system enhances rail safety and provides scientific evidence for supporting regulatory bodies and policy makers. The tool can help railways enhance supply chain resiliency by planning for corrective maintenance.
Development, testing, validation, and improvement of drone-based monitoring technologies for track and infrastructure inspection	There are research projects focused on rail infrastructure using drones with optical machine-vision cameras and LiDAR for mapping rail infrastructure objects and surfaces. These technologies use image processing to detect rail flaws and broken tracks.	This research informs the best practices for flying over rail infrastructure, setting up automated mapping, and developing stabilization and image enhancement methods. Another value proposition of this research is improved data analysis to perform optimal fault diagnosis and capture rail faults.	This tool has the potential to assist rail inspectors with rail and infrastructure inspection. The tool can also help railways to support effective and reliable track maintenance
Implementation and enhancement of remote rail track monitoring technologies using distributed acoustic sensing in revenue service environment.	Literature suggests acoustic sensing based on fiber-optic technology along railroad tracks allows for anomaly detection. However, further research is required to	The outcome of this research can 1) shed light on the performance of acoustic sensing and fiber-optics technology in a revenue service environment and 2)	The technology can be used by railways as a fully remote anomaly detection tool to both support effective and reliable track maintenance and

	enhance the performance of such a system with the focus on improving signal-to-noise ratio and the reliability of technology in revenue service-type environments.	develop signal and data analysis processing methods that assist in detecting anomalies.	reduce the number of incidents.
Development of training modules for railway personnel, conductors, and inspectors to use and leverage AI-based failure diagnosis technologies.	There are several inspection technologies that can leverage AI to identify faults along rail tracks. However, there is a lack of training modules or learning materials to instruct railway personnel and rail inspectors on the use of these tools.	The outcome of this research is development of training modules for railway personnel and inspectors on the efficient use of inspection tools that leverage AI.	The training modules help rail personnel effectively use AI-based track inspection technologies, leading to enhanced rail safety and fewer incidents. The training modules can help rail inspectors with enhanced and smoother inspection procedures.
Optimizing and fine-tuning the AI models for broader applications in railroad condition monitoring, considering different types of infrastructure and environmental conditions.	There are several current research projects investigating the performance of AI-based tools in track inspection, but very few projects considered different environmental and infrastructure conditions.	The outcome of this research is the creation of tools that are designed for a broader range of environmental conditions and that can effectively perform a safety inspection.	The research can help railways identify track faults in different environmental conditions leading to safer operations and fewer accidents with regard to track faults.
Research on smart trains with multiple onboard sensors and data fusion.	There are several research projects investigating the use of on-board sensors, such as Sonar, machine-vision cameras, air-coupled ultrasonic transducers, and accelerometer- coupled AI/ML algorithms. These concepts are only demonstrated in controlled laboratory settings or on smaller track sections.	The proposed concept can potentially be operated at revenue speeds, with real-time data acquisition and processing capabilities, highlighting the concept of a “smart train.”	The research can help railways identify track faults in different environmental conditions, thereby leading to safer operations and fewer accidents with regard to track faults
Onboard broken rail detection using electromagnetics.	The concept was tested in both laboratory and field environments. The test results proved the viability of Onboard Broken Rail Detection (OBRD) with the transmission coil successfully inducing detectable signal in the	The outcome of this work can provide a valuable understanding on how to eliminate crosstalk between Tx and Rx coils, how to add frequency selectivity to the shunts in the test setups, carrying out track	Onboard broken rail detection using electromagnetics presents unique advantages to PTC and or CBTC systems in identifying rail breaks.

	rail. Additionally, data analysis of alternating current (AC) track impedance was conducted to provide insight on trends for impedance variables with varying frequencies and under different environmental and ballast conditions.	impedance characterization over a longer section of track, and developing a breadboard and prototype of the system for testing.	

2.2 Equipment and Rolling Stock Inspection Technologies

2.2.1 Current Landscape

Mature wayside inspection technologies include wheel impact load detectors (WILD), Truck Performance Detectors (TPD), Truck Hunting Detectors (THD), Wheel Profile Monitors (WPD), hot box detectors (HBD), acoustic detector systems (TADS), and hot and cold wheel detectors. These technologies are mature in the sense that the systems are commercially available and installed in great numbers throughout the North American rail network. All are monitored through the Association of American Railroads (AAR) committee structure with shareable data centralized through Railinc. Commercial contracts and intellectual property agreements limit the data details that can be shared, but there is still a substantial amount of information being warehoused. Research to address the systems interdependencies between the data available from different detectors (e.g., how wheel profile wear per railcar correlates with truck performance detector data) would likely add intelligence to maintenance practices, and ultimately, to safety.

Emerging technologies are those technologies that either have limited commercial applications or are still in the development stages. Examples of emerging technologies would include machine vision systems capable of imaging the entire railcar at track speed. Full-train inspection portals are showing up on the network, but the software analytics for fully automated inspection are still evolving. Thermal vision inspection systems for locomotives are also under development. BNSF railroad is leading much of this development. The concept of full-train thermal imaging is an area ripe with research opportunities. Cracked wheel and cracked axle detection are being actively researched both in North America and worldwide. For example, China is using piezo-based ultrasonic automated wheel inspection systems. This technology was evaluated for use in North America, and the evaluation led to research using electromagnetic acoustic transducers. On-board sensing technology is in its infancy in North America and requires much additional research. A commercial consortium known as RailPulse is now monitoring equipment with on-board sensors operating on the network. The AAR is sponsoring the ongoing development of Mobile Telematic Systems (MOTES) through a technology advisory group with representatives from the industry and supply community.

2.2.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Software and analytics development to improve the utility of the data. Historical data is accumulating in large volumes across the industry.	The application of machine learning techniques to analyze and extract insights from historical rail data.	Advanced data analytics tools for rail operations, predictive maintenance algorithms, and decision-support systems to optimize rail network performance.	Providing tools to analyze and use historical data effectively, leading to improved decision making, operational efficiency, and predictive maintenance capabilities.
Conventional analytic approaches can be applied for data mining	The use of data mining techniques to identify trends in rail operations	Enhanced AI algorithms for machine vision inspection	Improving the accuracy and efficiency of rail inspection systems,

to reveal trends and for training AI algorithms. AI is evolving rapidly across the industry and is being applied to improve the accuracy of existing machine vision inspection systems. Much of the performance research in this field is proprietary and closely guarded by the owners for competitive purposes.	and the development of AI-powered predictive maintenance models.	systems, data mining tools to uncover trends in rail operations, and improved predictive maintenance models for rail infrastructure.	enabling predictive maintenance, and enhancing the overall safety and reliability of rail operations.
Development of validation and calibration procedures for wayside and on-board sensors. This leads into the larger issue of standardization and regulation of automated inspection systems across north America.	Development of sensor calibration methods for railway applications, the standardization of automated inspection systems, and the regulatory framework for deploying these systems.	Standardized procedures for sensor calibration, regulatory guidelines for automated inspection systems, and improved wayside and on-board sensing technologies for rail safety and maintenance.	Enhancing the accuracy and reliability of sensor-based inspection systems, leading to improved safety, efficiency, and compliance with regulatory standards.

2.3 Fire Risk Monitoring and Mitigation Technologies

2.3.1 Current Landscape

Experts found numerous emerging fire risk technologies that may apply to Canadian railway rights of way and equipment operations. Because of climate change conditions around the world and particularly in Canada, fire risk research is an evolving area of interest. The current landscape of fire risk monitoring and mitigation for railway operations in Canada relies mainly on individual railroad operating rules and regulations set forth by Transport Canada.

Locomotives represent the highest equipment fire risk while railcar braking operations, bearings, and wheels (e.g., slide flats) create additional risk factors. Modern freight locomotives and railcars do not have equipment to detect and automatically report fires in a real-time scenario, therefore they rely primarily on manual inspection or wayside detection (e.g., hot bearing detectors) notifications for mitigation and monitoring of equipment. The development of machine vision applications with camera-based systems used to inspect the various components on railcars and locomotives has advanced, and the systems are being implemented on the railway network in North America. A thermal image acquisition module that provides accurate spatial visualization of locomotive and railcar undercarriage heat propagation is under development. This module can be integrated with existing systems already deployed in North American and may provide additional inspection capabilities related to fire risk monitoring and mitigation.

Performance specifications for tank cars carrying hazardous materials can be found in 49 CFR 179 – Hazardous Materials Regulations. Liquefied natural gas (LNG)/compressed natural gas (CNG), propane (LP)/ammonia, and methanol are transported in approved tank car designs (e.g., Department of Transportation [DOT] 113, DOT 112, and DOT 117 designs). Rule 49 CFR 179 currently allows the transport of LNG by rail, but the puncture resistance of the DOT-113C120W9 design has not been fully established.

For passenger equipment, water mist systems using on-board fire detection sensors have been shown to work well in enclosed locations, such as locomotive engine rooms and passenger spaces. It is not currently known through research and testing how a water mist fire suppression system would survive in major accidents or derailments where there is potential for physical damage to the systems, or how the system would perform when fires start on the exterior of the locomotive or passenger railcars.

High fire risk track maintenance activities include rail grinding, cutting, and welding. Currently, the assessment of fire risk conditions (e.g., weather conditions, topography) for planning and the use of welder tents, fire prevention, and suppression trains with water and fire-retardants based on application conditions, all provide a vital role in fire risk mitigation. There is not an industry standard for fire risk ground condition susceptibility mapping (e.g., UAVs, satellites) or advanced track materials (e.g., fire retardant coatings) for track right of way and land adjacent to railway track.

2.3.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Mapping/imaging technologies using UAVs and satellite to evaluate high risk fire areas on railroad rights of way.	Mapping/imaging systems capable of detecting high risk areas without human oversight is a new technology area for railroads. Currently, a platform designed to provide early detection and prevention of forest fires (WildFireSat) is being developed in Canada.	Correlation of ground imaging/mapping information with conventional ground condition data for practical decision making can help determine the cohesiveness of current railroad fire risk operating practices with the information these new technologies provide.	The proposed research has the potential to provide faster, more detailed geospatial information than current practices on ground conditions to mitigate fire risk. Improved information related to 1) forecasting to proactively identify upcoming risk areas and 2) communicating this information to operating personnel to enable planned actions per operating procedures can be enhanced.
Fire retardant coatings for infrastructure, such as bridges and ties in high-risk fires areas.	Currently, most railroads have fire retardant products that can be added to water tanks and applied to the right of way infrastructure along with water for fire prevention. There also have been developments in the pretreatment of railroad wood products with fire-retardant intumescent coated mesh. The coating is designed to protect wood in case of fire by forming a protective barrier that stops the spread of flames.	Fire retardant products can be further developed and evaluated to determine practical applications for fire risk mitigation. Materials with higher fire risk, such as wood, should be evaluated under real operating scenarios (e.g., distance, ground conditions, and temperature ranges) to determine feasibility. Understanding the life cycle effects of the fire-retardant coating as well as the effects on railroad wood components vs. conventional components.	Increased infrastructure safety in high-risk fire areas. Possible reduction in the application of conventional fire-retardant products (e.g., labor, material, mechanized equipment) during high-risk fire seasons.
Machine vision camera-based inspection systems (wayside portals) with undercarriage thermal image acquisition modules.	Commercial tests have evaluated locomotives instrumented with onboard thermocouples and data loggers to record real-time temperatures for the	This system has the potential to deliver early and reliable fault detection for several critical freight and passenger railcars mechanical	There are wayside portals implemented on the Canadian railway system that can integrate thermal image undercarriage inspection systems.

	driveline components of the locomotives. Results showed a good correlation between the undercarriage thermal image module and onboard temperature measurements, suggesting a strong potential for using thermal scanning technology to monitor the major driveline components of locomotives.	components, such as rotors, wheels, and traction motors. Improving the accurate spatial visualization of heat propagation (thermal images) of locomotive and railcar undercarriages.	The primary benefit of this technology may be the increased inspection cycles of locomotive undercarriages during real-time operations as a preventative fire mitigation measure.
Safety and reliability testing of onboard water mist fire suppression sensor systems for locomotives and passenger railcar systems.	Research has been focused mainly on the feasibility and applicability of water mist systems to the rail environment and how they can be used in passenger railcars and locomotives. These systems are used in the rail environment on a much larger scale internationally, mainly in European countries. European trainsets are mainly equipped with systems in the passenger compartments. North American systems are designed for the locomotive engine compartment.	Safety and reliability testing of water mist fire suppression system designs with onboard sensors. Crash test simulations may provide valuable information into 1) how these systems would survive in major accidents or derailments where there is potential for physical damage to the system, or 2) how the system would perform when fires start outside the locomotive or passenger railcars.	Exo, a Canadian based public transit, currently has water mist fire suppression systems that are exclusively locomotive. Generally, when fires propagate to the interior of the locomotive or passenger car, it is possible that a water mist system 1) could have reduced the impact of fire and smoke on passengers (e.g., smoke inhalation and egress time) or 2) could have reduced damage caused by the fire incident. Testing scenarios to determine safety and reliability of the systems may support the implementation (new builds/retrofits) of onboard sensor fire monitoring technology systems.
Improved tank car designs to mitigate the potential safety risk of fires occurring from a derailment (transport of LNG by rail).	Existing models have been developed with techniques for tank car puncture assessment under various impact conditions to the DOT-113C120W9. Evaluation of relative performance to other designs can be referenced in report	There is a current rule that allows transport of LNG by rail, but the puncture resistance of the DOT-113C120W9 design has not been fully established. Additional testing may provide a better specification (design) to reduce risk of building a	Reduce the fire risk of HazMat releases for LNG transport. Prevent potential casualties from derailments. Reduce liability costs for railroads.

	DOT/FRA/ORD-13/17. Reference/refinement of the existing constitutive model for cryogenic ASTM A240 304.	fleet of LNG tank cars with insufficient puncture resistance, requiring changes in future rule making and obsolescence.	

2.4 Flooding/washout Risk Monitoring and Mitigation Technologies

2.4.1 Current Landscape

The SMEs observed multiple research areas related to flooding/washout risk monitoring and mitigation. One research area in-particular that has the potential to provide value to railway planning, with further research, is climatic forecasts on a regional basis across Canada. Current research shows that climatic forecasts are becoming more regional, but additional detailed studies are still required for the research to be useful for any localized analysis.

There are multiple monitoring technologies for flooding/washout risk monitoring, such as satellite, UAV, LiDAR, and real-time monitoring. Each of these technologies has its benefits and limitations, but each has shown significant improvements over the past decade and will continue to do so. In general, progress has been based on improved technology and data processing algorithms, but both have limitations of scale and currently have difficulty being applied on a system-wide basis due to installation and material costs and large amounts of data collection and processing. As these technologies progress, justifying their application on a system-wide basis should expand as well.

There have been limited numerical studies into flooding/washouts because these studies often require a coupled computational fluid dynamics-discrete element method (CFD-DEM) analysis that is extremely complicated and computationally expensive. Recent advancements in the theory and computational abilities have started to make these analyses more practical, but a stronger fundamental understanding of input properties would be required before these analyses could be become mature. Risk-assessment studies have been performed (e.g., Amtrak), but there is a lack of quantifiable values on the force side (flood elevation, water force) and strength side (washout resistance) that may make decisions on remediation difficult.

2.4.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
The development of regional climatic models that forecast changes in heat/cold/precipitation in different areas of Canada.	Amtrak and Canadian Pacific Kansas City (CPKC) have looked at regional climatic models (Amtrak) or had consultants perform their own (CPKC).	The data collected from these models could be used for culvert/drainage design and risk-assessment and the identification of changing risk regions.	Optimal culvert designs could be established, minimizing the risk of track washouts. Using forecasted regional data for flood and washout risk assessments/ mitigations can increase the safety of railway operations and focus efforts where needed.
Continue researching how satellite (e.g., Interferometric Synthetic Aperture	A small range of studies have been conducted using a combination of satellite	Data collected from the technologies can be used to inform flood/washout risk	Optimal inspection methods will lead to enhanced safety, minimized

Radar [INSAR]), UAV, and LiDAR technology can be used to address a range of flooding/washout concerns. This may include development of algorithms or techniques.	images, UAV, and LiDAR technology for flood monitoring and water inspection.	management and mitigation with benefits such as providing real-time information.	infrastructure damage, and more efficient operations.
Physical monitoring devices that provide real-time alerts are already available. These technologies may or may not need additional documents and support.	Some research has been done on water level sensors and flood monitors to enable remote monitoring.	Improved alert systems and use of alert systems in a system.	Improve safety of railroad network.
Modeling the washout process is difficult and still requires fundamental research and testing. Modeling includes categorizing 1) the various "washout" mechanisms (what causes the washout) and 2) the important parameters that influence washouts, and quantifiable numbers to represent forces and track strength, including general values or a detailed list depending on the embankment material and strength properties.	Some research has been conducted on modeling the washout process, including a model for railway ballast washout and idealization of ballast for dynamic characteristics.	Understanding the washout process and how it impacts railway infrastructure will allow for mitigation measures to be established and put in place.	This research can inform the safe design of railway track and embankment to reduce the impact of washouts. For example, quantify how various remediations would improve embankment strength and reduce risk of washouts. Data from the models can inform industry of best practices for washout mitigation and management.
Development of tools or framework to assess flooding/washout risk.	There has been a BNSF pilot study on washout risk.	The goal of this tool or framework would give guidance regarding the important parameters for washouts and allow railroads to rank locations.	The most at-risk locations would be identified and prioritized for increased safety measures.

2.5 Geohazard Monitoring/Mitigation Technologies

2.5.1 Current Landscape

Using geohazard monitoring/mitigation technologies for landslide prediction is extremely difficult, especially in remote mountainous areas. There are a range of technologies and techniques that can monitor/detect landslides (e.g., InSAR, UAV, global navigation satellite system-real-time kinetic positioning [GNSS-RTK], borehole inclinometers/piezometers). Each technique has its own strengths and limitations, and dataset combinations have often been used in past research projects. For large networks, satellite InSAR appears to be the most promising method because it allows monitoring of locations with consistent satellite coverage without a human site visit. The number of locations is growing with the ever-increasing number of satellites, but it remains difficult to interpret InSAR movements and quantify large datasets using only an overhead view. In addition, InSAR will likely be one of many methods used in railroad landslide monitoring programs. The UAVs have the benefit of viewing a terrain from multiple angles and the ability to set specific flight paths, but this method requires a site visit, and it may be limited by weather conditions and regulations. The GNNS-RTK technologies are able to continuously monitor sites and capture physical slope movements, but they are limited by only having a single location per instrument and difficulties uploading or collecting data. All the listed technologies are anticipated to become more advanced in their capabilities in the next decade. Due to various limitations of each single technology, combining datasets provides the most accurate assessment but doing so requires an amount of effort likely reserved for only a few high-risk locations. Satellite technology may be used for a large-scale desk study that identifies a manageable number of more specific locations for site visits and additional instrumentation. The Canadian Railway Ground Hazard Research Program (RGHRP) appears to be a world leader in the development and use-cases of these technologies, including case studies in the Assiniboine River Valley and Thompson River.

Other measurements that may have certain applications but are less matured for geohazard monitoring are fiber optics and other sensor systems that are often already installed in railway track for other purposes. For rockfalls detection/prediction, LiDAR, UAVs, and other technologies have shown significant advancement in the past decade. These methods are often not currently able to be implemented at-scale, and there are parallel efforts to develop frameworks that can identify high-risk locations across a subdivision/network.

2.5.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Support and develop algorithms that can monitor/detect/predict geohazards. This may require additional site locations and datasets.	Research has compared the performances of swarm-based algorithms such as Particle Swarm Optimization (PSO), Ant Colony	Development of an algorithm that can process data and serve as an early detection system for geohazards.	The development of sophisticated algorithms can provide rail operators with valuable data and insights, enabling more informed decision-making regarding route

	Optimization (ACO), and Genetic Algorithm (GA)-optimized adaptive neuro-fuzzy inference systems (ANFIS) in the spatial prediction of landslides. These methodologies can be adapted and applied to the rail industry for geohazard detection and prediction.		planning, infrastructure investment, and risk management.
Support and continue to advance technological advancements in the wide range of monitoring technologies (InSAR, UAVs, GNSS-RTK).	Studies have used remote sensing technologies, such as InSAR, LiDAR, and UAVs for monitoring terrain deformation, identifying potential landslide areas, and assessing the extent of damage after a geohazard event.	Specify the type of technology that will be used, identify the geohazard of interest, and come up with an integration of said technology in a geohazard monitoring application.	Improved geohazard monitoring can significantly enhance the safety of rail operations by providing early warnings of potential hazards, reducing the risk of derailments, and ensuring the safety of passengers and freight.
Development of tools or framework to assess geohazard risk. The goal of this tool or framework would be to give guidance for the important parameters for geohazards and allow railroads to rank locations to help identify the most at-risk locations.	Development and operation of geohazard management programs focused on risk-based rock fall rating systems for railway operators, such as the program developed by BGC Engineering for CN Rail	Establish a mapped, risk-level based database of railroad locations that can serve as guidance for railroads to determine navigation procedures or risk mitigation measures.	The tools or frameworks will provide rail operators and stakeholders with valuable data and insights to make informed decisions regarding infrastructure investment, maintenance, and risk management.

2.6 Technologies for Managing Cold Weather Operational Challenges

2.6.1 Current Landscape

Due to significant safety and operational challenges, winter conditions and cold temperatures can negatively affect the performance of both railway infrastructure and rolling stock. Managing winter operational conditions is vital to maintaining a fluid and safe railway network. Recent technological developments show great potential in helping railway operators overcome these challenges. The technology scan references for this theme can be grouped into three general sub-themes: 1) railway infrastructure under winter conditions, 2) passenger rail operations in winter environments, and 3) brake system performance and safety for freight trains.

Research has shown success in long-term monitoring of continuous-welded rail (CWR) by measuring lateral displacements of the track in curves using a sensor type that resists low temperatures and measurement drifts. Field monitoring of frost heave formation and numerical modeling was carried out to observe the effect of culverts on frost zones, frost heave and thaw softening, and their impact of culverts on the wheel/rail interface. The studies, which have been concluded, were contained to a single site under well-maintained track. It is unknown how the method would perform for lower-class tracks, indicating the need for further study. Compared to real-time monitoring of the track substructure, vehicle-mounted ground penetrating radar (GPR), and the ability to conduct mobile measurements across the railway network, has proven cost effective in the identification of frost heave sources. Mechanisms of frost penetration under railway embankments, protective snow fence strategies, and a literature review on icing effects on railways provide insights for winter mitigations. A thawing-guided drainage system to prevent icicles in old railway tunnels was developed and fabricated in the lab. Testing showed this system was effective against icicle buildup, but no plan was mentioned to make the system available commercially. A review of construction techniques summarized modern methods for reducing the environmental impact of railway construction on permafrost. Studies on thermal-moisture-mechanical behaviors and thermoelectric heater systems offered solutions for mitigating icing on track components. Researchers developed rolling stock designs to reduce winter icing and ballast splashing. While studying brake systems, researchers found that the braking distance increased with ice buildup on the brake shoe and abnormal disc wear could be reduced by optimizing train driving strategy.

Most of this research was not conducted in Canada, raising questions about its applicability to Canadian winters. There are information gaps in understanding 1) the effect of cold temperatures on non-contact ultrasonic rail flaw testing, 2) the root cause of icing on railway infrastructure, 3) the autonomous detection and effective mitigation of compressed air leaks on trains. An emerging technology to prevent undesired train movements, such as the automatic parking brake, has yet to be thoroughly tested by the railway industry. Further research is needed to address brake system performance degradation, especially in extreme cold temperatures.

2.6.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Brake system performance and safety for freight trains			
Acoustic brake system leakage detection should be validated on a larger variety of equipment types. The detection system should also be tested in uncontrolled field environments to assess its feasibility for wider adoption.	A proof-of-concept system to autonomously detect compressed air leaks on moving trains was developed and a small amount of data was collected.	System validation and further testing in uncontrolled field environments could lead to wider adoption.	A better understanding of and detection method for air brake leakage could lead to safer, more efficient locomotive operations.
Other leakage detection methods should be investigated. A literature review should be conducted to summarize the current best practices from other industries that rely on pressurized pneumatic systems.	A proof-of-concept acoustic brake system leakage detection method was studied.	Understanding the best practices and identifying the present gaps in information could lead to more targeted studies and tests.	More advanced leakage detection methods can increase safety in locomotive operations.
Research and tests on methods to prevent undesired movement from brake cylinder leakage in cold temperatures are needed. Potential devices should be tested both in the laboratory and on trains.	Transport Canada is conducting cold weather air brake research in collaboration with NRC. Data regarding the performance of air brakes in temperatures ranging from 0°C to -40°C has also been collected.	Help industry and government determine a common performance specification and understand potential operational issues.	Could lead to regulations or best practices that will increase the safety of rail operations in cold weather.
Railway infrastructure under winter conditions			
Assessment of measurement techniques, such as comparing the performance of different sensor types by measuring the same curves, to monitor lateral track displacement in sharp curves should be conducted in the Canadian environment. The data can be	Previous research has been done on the remote monitoring of continuous welded rail on curves in cold temperatures. An online monitoring system and mathematical model of ultrasonic stress detection was studied.	Optimal measurement techniques can be determined for measuring track displacement in sharp curves due to cold weather.	Understanding the effect of cold weather on track displacement can help the industry determine at risk areas and ensure safe locomotive operations.

compared against track geometry car measurements to see if noticeable curvature changes are recorded.			
Existing data from curve measurement and frost heave monitoring research should be analyzed to find trends and early warnings, potentially with the help of advanced statistical methods such as machine learning. Frost heave monitoring techniques developed outside Canada should be validated in Canada.	Research conducted in Canada at the VIA Rail test site for long-term frost heave monitoring should be expanded to validate their findings and applicability in various locations and under different axle-load environments.	A better understanding of the frost development mechanism and its impact on safety and performance of train operations.	Industry and government will better understand the effects of frost heave on track geometry, allowing mitigation measures to be determined and safety to be increased.
Further finite element model development is needed to understand better the root cause of tie plate icing and its mitigation. The thermoelastic heating system could be tested as one potential solution to this problem.	An investigation into tie plate/ice jacking was conducted by Transport Canada and MxV Rail.	This could result in a better understanding of the mechanisms causing tie plate icing and the use of modeling to provide the means to predict the occurrence of tie plate icing.	Understanding the effects of tie plate icing can help guide the industry's winter preparedness and remediation methods, both of which will lead to safer operations.
The effect of cold temperatures on non-contact ultrasonic rail flaw detection accuracy needs to be better understood. One way this can be achieved is by conducting measurements on a much larger rail sample in the field and in the environmental chamber. The feasibility of methods to mitigate the effects of cold temperatures on ultrasonic sensors could also be studied.	A study was conducted by Transport Canada and MxV Rail on ultrasonic rail flaw parameters in extreme cold temperatures.	Better understanding of temperature effects on ultrasonic rail flaw detection could result in a better calibration method of ultrasonic rail flaw detection in the winter that results in more accurate detections.	Railway infrastructure managers will be able to detect rail flaws in cold temperatures with higher accuracy, leading to more targeted remediation and improve safety.
Methodologies to reduce snow and ice buildup along railway infrastructure can be investigated. A starting point could be adapting	Research includes an assessment on old railway tunnel icicle prevention, de-icing catenary wires, and an investigation on snow	Developed methods and mitigation measures to reduce snow and ice accumulation along railway infrastructure.	Increased safety and efficiency of locomotive operations.

foreign research methodologies into the Canadian winter environment and assessing their merits.	accumulation on bogies.		
Passenger rail operations in winter environments			
Snow and icing shields could be installed on Canadian passenger rolling stock to compare their effectiveness against vehicles that did not have these installations.	There is research on anti-snow structures, such as deflectors and wheelset snow shields.	Knowledge of the effectiveness of snow and icing shields and how they impact rolling stock operations.	Could lead to more efficient rail operations.
Stopping distance tests and long-term brake disc monitoring due to abnormal wear in winter conditions should be conducted in Canada.	Some research has been performed on abrasive wear of brake discs.	An understanding of the effect of the staged driving strategy on safety and methods to reduce abnormal brake disc wear.	Addressing abnormal abrasive wear due to winter conditions will lead to more consistent braking and train control in winter conditions.
Novel catenary and trolley wire deicing systems proposed in the research reviewed should be installed in Canadian environments to validate their effectiveness.	Previous research has been based on the use of heaters.	This method provides an alternative method of deicing trolley wire.	This method will lead to a decrease in energy consumption of deicing and contribute to industry decarbonization efforts.

2.7 Technologies for Subgrade Stabilization

2.7.1 Current Landscape

From geotextiles (e.g., geogrid, geocells, various geotextiles, such as Tracktex or Mirafi) to drainage (e.g., trench drains), a wide range of technologies provided by multiple manufacturers, distributors, and consultants are available for subgrade stabilization (e.g., grout, polyurethane, geospikes, rail piles). Each technology comes with benefits and drawbacks (e.g., improve subgrade strength versus add confinement versus barrier layer), and different technologies may be suitable in different situations depending on the issue root cause, the issue severity, the allowable track time, the track access, and the cost, among other considerations.

While there is a range of available products and most of these products are mature technologically, there are gaps in guidance regarding 1) which product would be appropriate for a particular situation and 2) the effectiveness and longevity of each product. Most of this information is provided by the vendors themselves, and it can be difficult for railroad agencies to compare different technologies and have reliable data to make decisions.

2.7.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
A scan of the information from various railroad agencies (freight, passenger, transit) to identify common subgrade issues the railroads currently experience to understand the current technologies those agencies employ along with specific needs.	Limited existing research.	Guidance for more targeted research and insight into specific hurdles that must be crossed to make promising technologies implementable.	Improved documentation and knowledge of technologies can better justify use and reduce subgrade issues.
Guidance on industry-accepted identification of subgrade issues, best practices, and tradeoffs of different subgrade technologies.	MxV Rail has an internal document summarizing subgrade issues and various remediations. Much other research focuses on one or two technologies.	Improved railroad decision making regarding subgrade.	Reduced risk of subgrade issues
Testing, instrumenting, and documenting different subgrade stabilization in a track environment.	MxV Rail summarized a 30-year long test looking at different applications to stabilize weak subgrades (geocell, Hot-Mixed Asphalt) and worked with Class 1 railroads	Improved railroad decision making regarding subgrade	Reduced risk of subgrade issues

	on two specific issues (ballast pocket and flooded cut) and monitored the benefits of the remediations (geogrid and various barrier geotextiles). MxV Rail is currently monitoring five technologies to reduce mud spots with another Class 1 railroad (unpublished). There is a general lack of third-party documented research on performance.		

2.8 Enhanced Train Control

2.8.1 Current Landscape

Enhanced Train Control (ETC) systems are being developed to enhance the capabilities of the train operators, to reduce human error, and to improve the safety of both passenger and freight railway operations in Canada. The ETC technologies can alert the train crew to danger and, at their highest functionality, slow or stop a train to prevent a collision or derailment.

The ETC will be a communications-based train control (CBTC) system, critically dependent on dependable connectivity among fixed and mobile segments. Otherwise, when operating in the highest functionality mode, ETC can stop trains unnecessarily. Redundant diverse communication media are required to achieve the necessary level of dependability. Communications must also employ cybersecurity to avoid compromising safety.

The minimum required CBTC functionality varies from country-to-country due to differences in objectives, needs, and constraints. The Interoperable Train Control (ITC) Positive Train Control (PTC) system can be leveraged because it is the most widely deployed CBTC system in the United States (U.S.), and it is already installed on many Canadian locomotives that operate across the border since they must be interoperable.

Advanced CBTC modes such as Enhanced Overlay-PTC (EO-PTC), Quasi-Moving Block (QMB), Full Moving Block (FMB), and Automated Train Operation (ATO) add functionality that can significantly improve both the railway throughput and the average velocity along with increasing safety.

The National Transportation Safety Board (NTSB) and the Federal Railroad Administration (FRA) have identified certain classes of human error that PTC (and therefore, potentially ETC) could mitigate, including:

- Preventing train-to-train collisions during restricted speed operations.
- Automatically returning PTC to the active mode following switching operations (or alternative means of collision protection during switching operations).
- Eliminating the possibility of human error when identifying the track occupied by a train (e.g., during initialization) in multiple track territory.
- Eliminating the risk of miscommunication between dispatchers and roadway workers in charge when establishing working limits and PTC protection.

CBTC is a complex distributed real-time safety-critical system requiring sophisticated testing. The technology scan references and opportunities for future research fall into four general sub-themes: 1) existing solutions that can be leveraged, 2) critical communications issues, 3) required or minimum essential functionality, and 4) unique testing needs.

2.8.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Existing solutions that can be leveraged. The needs, requirements, and constraints for ETC should be compared with ITC PTC specifications and Interface Control Documents (ICDs) to identify commonalities and prioritize gaps. Based on the gap analysis, potential solutions should be proposed and assessed.	Experience and specifications resulting from historical use of ITC PTC on multiple U.S. freight railroads.	ETC requirement specifications that are optimized toward the specific needs of Canadian railroads.	Maximization of ETC return on investment (ROI) by minimizing the amount of new developments and safety certifications required while meeting critical unique needs.
Existing solutions that can be leveraged. The potential cost vs. benefits of energy management systems (EMS) should be evaluated in the context of Canadian railroad applications. EMS assists drivers or directly controls throttle and brake to save fuel and to manage in-train forces.	Performance results from historical use of EMS with ITC PTC on multiple U.S. freight railroads.	Interoperability and performance standards for EMS systems and their integration with ETC.	Maximization of ETC/EMS ROI by minimizing the amount of new development required while meeting unique needs. Increasing the fuel-efficiency of train operations across multiple railroads. Reducing equipment wear and damage by reducing in-train forces.
Required or minimum essential functionality. The potential cost vs. benefits of integrating a dispatch movement planner/scheduler with EMS pacing should be evaluated in the context of Canadian railroad applications.	Historical performance results from historical use of a movement planner together with PTC (e.g., from NS Railroad's experience).	Assessment of ROI from integrating a dispatch movement planner/scheduler with EMS pacing.	Optimal train movement planning integrated with EMS and real-time train location reporting can improve fuel efficiency and reduce rail network congestion.
Required or minimum essential functionality. Potential advanced train control modes that can increase the ROI and the safety of ETC should be assessed when specifying the	Reports and specifications from Higher Reliability and Capacity Train Control (HRCTC) and ATO projects.	Estimate of ROI from incorporating ETC into each of the following advanced operating modes: EO-PTC, QMB, FMB, and ATO.	Solutions that can increase railroad safety, increase capacity, increase network velocity, increase productivity, reduce headways, and reduce delays.

functional requirements for ETC.			
Required or minimum essential functionality. The following safety enhancements should be assessed when specifying requirements for ETC: • Collision prevention at restricted speed • Non-overridable enforcement of stop at entrance and modifiable speed restrictions for work zones • Automated track discrimination in all multi-track scenarios.	Reports, specifications, and test results (in some cases) on QMB, FMB, Employee-in-Charge Portable-Remote-Terminal (EIC PRT), and Positive Train Location (PTL).	Assessment of ROI from providing the cited safety enhancements to ETC.	The potential enhancements cited, if incorporated into ETC, can protect against additional forms of human error, thereby increasing railroad safety.
Critical communications issues. Evaluate/compare private vs. commercial networks, open vs. proprietary waveforms / protocols, dedicated vs. shared vs. unlicensed radio frequency (RF) spectrum, and terrestrial vs. satellite in terms of performance, cost, and interoperability among railroads (domestic and below the border).	Historical performance of ITC PTC radio communications systems used in the U.S. (dedicated PTC radio, WiFi and cellular) as well as mobile communications systems available in Canada.	Assessment of the adequacy of existing coverage and infrastructure (towers, satcom, power source, backbone) along tracks in Canada. Identification of what is most feasible to add – means to operate where coverage (terrestrial) or visibility (satcom) is low.	Determination of the most cost-effective solution to achieve the required highly reliable and interoperable communications on Canadian railroads.
Critical communications issues. Survey RF propagation prediction and message traffic load models to identify best suited for ETC.	Propagation models used by cellular companies have benefited from far more development funding than railroads can provide. A message traffic load model has been developed specifically for ITC PTC and applied (by MxV Rail) to the radio network design in all large U.S. urban areas based on historical and predicted train operations. These	Determine the best suited existing propagation model(s) to predict required quantity, locations, effective radiated power (ERP), and frequency of fixed ETC radio sites. Determine whether any modifications to the message traffic load model are necessary to support ETC.	Avoidance of cost to develop new propagation and message traffic load models for ETC.

	models have been used to achieve successful deployment of ITC PTC.		
Critical communications issues. Trade off train location determination system (LDS) solutions regarding Canadian railroad needs.	Historical performance and costs of GNSS-based LDS (ITC PTC) vs. Balise-based LDS (European Train Control System [ETCS])	Assessment of performance and costs (ROI) of GNSS vs. Balise-based train positioning and identification of associated options for ETC.	Selection of solution that offers low life cycle cost while meeting critical system performance requirements.
Critical communications issues. Assess potential cybersecurity threats to ETC comms and GNSS for the present and foreseeable future. Determine the level and type(s) of solutions needed to protect ETC against the potential threats (e.g., authentication, encryption, key management, spatial discrimination [via antennas]).	Information (e.g., from actual incidents in more than just railroads) on the increasingly sophisticated potential jamming/denial of service and spoofing threats. Historical performance of various candidate threat mitigations. Available GNSS vulnerability test bed (at MxV Rail).	Design of functions and equipment to detect, log, analyze & mitigate the threats (real time vs. post). Identify which messages require encryption vs. those only needing authentication. Test results under various jamming and spoofing scenarios to optimize key parameters.	Cost-effective cybersecurity threats mitigations.

2.9 Technologies for Increasing Grade-Crossing Safety

2.9.1 Current Landscape

Numerous studies on technology used to detect and monitor grade crossing obstructions (e.g., trespassers, crossing violations, stalled vehicles, etc.) have been and are being conducted to improve safety and reduce incidents. These studies are primarily focused on the ability to detect instances where a person or object is 1) within the limits of a rail crossing and 2) at risk of being struck by rail traffic (freight, passenger, or transit). The studies have primarily been proof-of-concept in nature to determine whether machine-vision based equipment is a viable option for collision prevention at grade crossings. Information gaps exist regarding connecting these devices to current safety warning and/or dispatcher/train systems. There is limited practical application for these technologies due to train stopping distances, the inability to quickly remove stalled or high-centered vehicles from crossings, and the potential for false alarms. Fully deployed detection/warning systems are not currently in use on a large scale. Also, due to costs and lack of existing infrastructure, many of the technologies available and currently being researched have power and communication requirements that make application in remote areas potentially difficult. While the detection of crossing violations and near-miss events has been achieved, the prevention of crossing violations altogether remains unresolved. While detecting obstructions and crossing violations is a step toward achieving greater industry safety, the prevention of crossing violations and obstructions/trespassing can and should be a topic of continued investigation.

In Europe, the use of connected vehicle technology is being deployed to provide in-vehicle warnings and/or prevent a motor vehicle from entering the crossing zone. This technology takes a different approach to the human factor problem or eliminates the human factor completely. In the U.S., for at least three years now, some railroads have been working in conjunction with the WAZE navigation application to provide users of the app with warnings near railroad grade crossings. A couple railroads working in this area include Metro-North and Southeastern Pennsylvania Transportation Authority (SEPTA) (commuter lines in the New York City and Philadelphia areas, respectively.)

In terms of improving grade crossing safety, grade separations and crossing closures, as well as sight-distance improvements, also need to be considered. Both a cost-benefit analysis of these improvements and traditional warning systems are covered in the current Federal Highway Administration (FHWA)/FRA methodology (GradeDec) and an ongoing National Cooperative Highway Research Program (NCHRP) project to update that methodology.

2.9.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Continued investigation and development of detection systems with a focus on deployment of fully functional	Extensive preliminary research on machine vision, cameras, LiDAR, etc., to detect	Better detection algorithms and technologies for vehicles stuck or stalled on crossings, possibly	Reduce grade crossing incidents involving stuck or stalled vehicles, possibly pedestrians.

systems in areas with known problem crossings.	objects in crossing zones.	also for pedestrians lingering at crossings.	
Development of system interfaces for warning systems needs to be continued and integrated into existing railroad warning and alert systems already in use.	Tends to be supplier driven. Limits on how many accidents can be prevented due to train stopping distances, etc.	Better detection systems for vehicles stuck or stalled on crossings, possibly also for pedestrians lingering at crossings.	Reduce grade crossing incidents involving stuck or stalled vehicles
Expanded research into the human factor side of crossing violations is needed.	Much work done by FRA and more work ongoing.	Better understanding of factors likely to improve grade crossing safety.	Reduce grade crossing incidents involving drivers likely to ignore existing warnings or take extreme risks
Cost/benefit analysis of different violation-deterrence technologies to enable railroads or transit agencies to select the most cost-effective grade crossing enhancements for a crossing based on potential benefit gain.	There is a current NCHRP project focused on updating the factors used for such analysis.	Methods for more efficient allocation of limited resources for improving grade crossing safety.	More efficient allocation of limited resources for improving grade crossing safety.
Development of a modularized detection system that would not only detect potential crossing safety violations but prevent collisions or accidents from occurring once detected and that could be integrated into existing railroad safety systems.	Not aware of any previous work.	See implementation challenges discussed in current landscape.	Limited value proposition at this time due to challenges discussed in current landscape.

2.10 Technologies for Monitoring Trespassing

2.10.1 Current Landscape

Experts grouped technologies into three general sub-themes; 1) video-based technologies for detection, 2) other technologies for detection, and 3) the broader overall topic of trespasser prevention. The video-based trespasser detection systems are primarily wayside-based and employ machine vision systems with neural networks or other AI algorithms. One variation on the video-based system is the use of a thermal vision camera, which can distinguish features that might be hard to detect with conventional video. Wayside vision-based detection systems should be placed at known hot-spot locations to be used most effectively.

A UAV-based system might help identify trespasser hot spots, but the system currently employs manual detection. One video system noted the potential for an on-board application to help identify hot-spot locations. Compared to wayside systems, the constantly changing background presents a challenge to in-motion and on-board video systems due to the additional effort required to indicate trespassers as well as to distinguish trespassers from right-of-way workers. Other detection technologies noted were fiber-optic acoustic sensing and radar. Both technologies seem to require further development compared to the video-based systems. A fiber-optic system is inherently wayside-based only.

All the monitoring and detection technologies share the challenge of making effective use of the findings. An on-board system might help locate trespasser hot spots, although it is likely that railway train operators and maintenance-of-way personnel can already provide such information. Once a wayside system detects a trespasser, either a warning (visual and/or audible) needs to be initiated (especially if a train is in the vicinity) or enforcement needs to be called. In some cases, it might be more cost-effective to install an automated pedestrian crossing.

References covering the broader theme of trespasser prevention provide further information regarding the many other factors and challenges to the implementation of various mitigation strategies, technological or otherwise, that need to be considered. Trespassers, even those with cell phones, are not likely to be using a navigation app such as WAZE that can provide highway-rail grade crossing warnings, and apps such as WAZE or other technology-based detection and/or warning systems are likely to have little or no effect on trespasser fatalities, a significant portion of which are suicides. Recent research indicates the number of suicides as likely to be undercounted, and educational efforts to deter trespassing and raise awareness of the potential dangers of railroad crossings could have the undesired effect of attracting more suicides to railroad tracks. While the various efforts in recent decades have reduced grade crossing incidents and fatalities significantly, challenges to reducing the number of trespassing issues on the tracks remain.

Further investigation into other methods and technologies for trespass prevention should include trespassing deterrence methods, such as thick/thorny vegetation, fencing, and pedestrian underpasses and overpasses. Each method has its respective advantages, challenges, and costs. Urban planning can also play a part by minimizing the placement of popular pedestrian destinations, such as convenience stores, across the tracks from common pedestrian origination sources, such as apartment complexes.

2.10.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Further development of video-based technologies, including on-board and UAV-based technologies is required, in addition to fixed wayside-based systems.	Several studies currently underway.	Better detection technologies for trespassers on railroad right-of-way	Better response to trespasser incursion on railroad right-of-way (pending implementation as noted below)
Next-stage development/implementation of detection technologies to coordinate with enforcement, initiate warnings, or take other appropriate action.	Not aware of any but might be happening with suppliers.	Proposed methods for implementing trespasser detection with existing protocols and systems.	Better response to trespasser incursion on railroad right-of-way.
Continue, reinvigorate, and/or update the Community, Analysis, Response, and Evaluation (CARE) model effort has previously undertaken. Some of the limitations and challenges noted in the previous effort might now be able to be addressed with some of the new tools and technologies available.	Past work on CARE model by TC and FRA.	Efforts will likely include solutions in the enforcement or education spaces, not just engineering.	Reduce frequency of trespassing incidents.

2.11 Development of Tools and Analytics for Risk Assessment

2.11.1 Current Landscape

The SMEs reviewed available research references related to quantitative risk assessment (QRA) for hazardous material transport. The references suggest that, in the transportation industry, QRA is primarily used for public safety and emergency response preparedness. Risk assessment can be grouped into security, emergency response, public safety, and operating safety. The rise in large datasets produced by centralized traffic control, wayside and onboard detection systems increase the available factors that contribute to a QRA model. Other datasets, including transportation routing information, rail incident information, citizen population densities, environmental data (including environmentally sensitive areas or geohazards), grade crossings and usage, and general orders of operation for railroads can provide useful additional information to identify critical factors in a risk assessment.

An example of the use of QRA related to rail operations and safety that used a section of rail in the Canadian Cordillera Mountain range was referenced. The assessment in the example used Monte Carlo simulations to develop a risk probability distribution to estimate the risk to the life of freight train crews operating in this area.

Currently, QRAs are being performed on several platforms with a variety of statistical tools. The tools identified by the probability of promising results include Bayesian Networks and Monte Carlo simulations and supplemental tools like computational fluid dynamics (CFD) models, F/N (frequency of event vs number impacted often as derailments or loss of life) curves, and Event Trees for detailed analysis. These tools are available in Python and R, programming languages commonly used in neural networks, machine learning, and statistical analysis. Other analytic tools are available but not referenced in the technical literature.

2.11.2 Opportunities for Future Research

Three common areas identified in the current landscape section include the following research opportunities:

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
The need for more detailed transport accident information.	QRA relies heavily on accident and incident data of previous occurrences. The available databases of accidents and incidents are often limited in detailed information, leading to a lack of clarity on the cause of incidents.	The incorporation of more detailed information in accident and incident data could strengthen QRA and help to better understand causes of incidents and accidents. It could also help strengthen predictive modeling.	More accurate QRAs leading to safe and more efficient transportation of goods by rail.
Volume of road traffic at grade crossings (intersecting roadway	Annual average daily traffic data (e.g., the total volume of vehicle	The incorporation of better traffic data at grade crossings could	Grade crossings are areas at highest risk of incidents and

systems) could provide improvements to the risk models.	traffic of a highway or road for a year divided by 365 days is widely available. This data could be incorporated in QRA to quantify the risk of grade crossings on the movement of goods.	strengthen QRA and help strengthen predictive modeling.	accidents, and accurately quantifying the risk of transporting goods through grade crossings could improve public safety and ensure the efficiency of rail and road transportation by reducing high risk incidents.
The domino effect of breached freight cars that are modeled with various neural networks could be included into a QRA model for the potential of added risk that could increase the severity of the QRA model results.	There exists a body of research that models the severity of derailments by looking at the potential for damage to cars and breaches that could occur in a loss of containment.	Incorporating tank car damage modeling into QRA could more accurately predict the severity of an incident and the appropriate preventative or mitigative measures.	More accurately understanding the risk severity of transporting goods could help increase public safety.
Written guidelines for input factors that feed the QRA models could aid in producing a repeatable, more accurate, and less biased result. As new information is discovered, the guidelines should be updated to accommodate the new information.	Guidelines for QRA exist and are valuable to support the implementation of assessment methodologies (e.g., the “purple book”). Railways could leverage this guidance to help inform their own QRA efforts.	Incorporation of best practices from QRA guidelines could strengthen QRA for rail transportation.	More accurately understanding the potential risk of transporting goods.
Adding other datasets can be added to most QRA models to determine if additional factors may be identified, i.e., localized weather events, peak and off-peak traffic density changes for citizen movements. Review troubleshooting guides for weaknesses in instructions for multiple related or non-related failure events.	Work to date on QRA in rail transportation has highlighted a lack of data, and an opportunity to input additional data sets to better understand exposure, consequences, and preventative and mitigation measures.	The proposed outcome would increase the comprehensiveness of QRA results and include impacts on additional factors such as sensitive environments and vulnerable communities.	A more comprehensive QRA could result in better public safety.

2.12 Cybersecurity

2.12.1 Current Landscape

The rise in large volumes of data generated by various sources, including, but not limited to, wayside and onboarding inspection systems, signaling systems, and train control systems, as well as the integration of communication-based connected railroad technologies known as the Rail Internet of Things (RioT), has provided significant value to the railroad industry. However, this advancement concurrently poses challenges related to data storage, privacy, data fusion, and cyberattacks. Three main areas were identified in the current landscape of this review:

- Rail cyber-physical systems threats and vulnerabilities.
- North American railroad industry efforts in cybersecurity.
- Cybersecurity measures and mitigation strategies.

The reviewed literature delineates various rail cyber-physical systems and associated threats. The systems encompass the areas of train control, traditional railway signaling, Balise-based data transmission, railway traction power, voltage control, human-machine interface, public address or public information display screens, railway sidetrack, ATO, and CBTC. Among the identified threats are:

- Multiple attacks during electromagnetic interference.
- Denial of service (DoS).
- Unauthorized network access.
- Message modification.
- Man-in-the-middle (MITM) attacks potentially resulting in false data injection, spear-phishing emails, etc.
- Attempts at fraud through corporate identity misuse.
- Scans for information on corporate executives.
- Occasional high-volume or otherwise suspicious activity from foreign internet protocol addresses.
- Compromise of email accounts belonging to shippers or other industry entities.
- Creation of falsified websites as a cyber-criminal activity designed to lure unsuspecting individuals into providing personal and financial information.

2.12.1.1 North American railroad industry efforts in cyber security

The AAR has established the Rail Information Security Committee (RISC) to facilitate the exchange of practices, threats, vulnerabilities, and incident response strategies related to industry-wide information sharing. These strategies include collaboration through the AAR Railway Alert Network, sharing insights with government departments and agencies in select countries responsible for cybersecurity, and benchmarking security against well-established and proven cybersecurity standards.

The report focuses on the role of suppliers and their influence in the cybersecurity of rail systems. The outlined practices provided to suppliers cover areas such as software and services, access control, account management, session management, authentication/password policy and management, logging and auditing, communication restrictions, malware detection and protection, heartbeat signals, and ensuring reliability and adherence to standards.

2.12.1.2 Cybersecurity measures and mitigation strategies

In addressing cybersecurity measures and mitigation plans, the reviewed literature outlines a range of strategies, including intrusion detection/prevention systems, firewalls, host intrusion prevention systems (HIPS), authentication, secure file transfer protocol, log collection, encryption, dedicated equipment, and the implementation of a physical "air-gap," among other approaches. The description of supplier life-cycle security programs is designed to establish a framework for developing products with fewer weaknesses and vulnerabilities. These programs focus on identifying and remediating potential weaknesses and vulnerabilities before the installation of software and systems in the customer's environment.

The literature also explores cyber risk management methodologies for RIoT, providing guidance to stakeholders and encompassing key components, such as identifying threat sources, the technical decomposition of architecture and components, prevention, and detection, as well as mitigation and recovery strategies. Lastly, the research presents a model-based cybersecurity analysis, integrating inputs from the security analysis on system components, potential attacks, and attacker models into a comprehensive goal, system, and attacker graph. The findings show that deploying firewalls is highlighted as an effective way to protect critical local area networks (LANs) from compromise.

2.12.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Resilience and disaster recovery planning.	Collaborative initiatives in North American railroads as part of the RISC, as well studies in risk assessment and vulnerability analysis.	Opportunities for North American railroads to evaluate the security profile and take action as needed.	Railroads can expect to encounter robust cyber threats, so there is a need to evolve security programs given the dynamic risk environment and the potential for increasing the use of technology for safe and more efficient operations.
The research also suggests that the railroad freight industry needs to use today's technologies as the	Overview of rail technologies and how these developments had consideration in cyber threats, risk	Opportunities exist for North American railroads to improve their cybersecurity practices by	This can support the early identification of threats and vulnerabilities as well as the design and

foundation for more innovation to further enhance the safety and security of the network.	assessments and their components, and communication nodes and links.	collaborating with vendors during the design phase of railway technology development. This collaborative approach can enable the integration of cybersecurity measures into the design process, ensuring that security considerations are prioritized from the outset.	implementation of prevention and mitigation strategies for cyber threats.
Machine learning for threat detection involves exploring the application of machine learning algorithms for anomaly detection, e.g., anomalies in signaling systems, advanced train control systems (ATCS), wayside and onboard detection systems, and positive train control (PTC), among others.	This is an emerging research area with very limited information available. Some initial efforts have focused on identifying system vulnerabilities to unexpected disruptions through the application of deep learning techniques.	Opportunities for North American railroads to expand the research and applications of using machine learning methods for threat detection.	With large amounts of data collected from multiple technologies in the railroad, using machine learning approaches can help support the development of models to identify threats.
Conduct comparative analyses of the different model results with independent studies from previous risk assessments.	Literature in this area is very limited at the time of the review, and the studies focused more on the framework design without a formal comparison with other approaches.	Opportunities for North American railroads to identify the strength and weaknesses of different models so researchers and practitioners can better understand which cybersecurity aspects are more effectively addressed by each model.	Allow benchmarking of different model performances against industry standards or support the creation of new standards. Also, it can help support the enhancement of cybersecurity resiliency strategies.

2.13 Human Factors

2.13.1 Current Landscape

New systems and technologies are frequently being introduced to improve railroad safety, efficiency, and productivity. New systems perform duties including CBTC, energy management, situation awareness enhancement, improving worker safety in yards and work zones via wearable technologies, remote inspections to improve defect detection, helping yard workers avoid uncontrolled movements, driver assistance, steps toward automation, etc. New technologies include AI, track or object sensors, and exoskeletons. These systems and technologies generally require human interaction for monitoring, for providing information and for handling anomalous situations. Operating procedures and human-machine interface (HMI) designs that minimize human errors in interacting with these systems can be critical to avoiding negative impacts on railroad safety and operations. Training, experience, workload, fatigue (including its relation to level of automation), and declining situational awareness of operators and other actors (e.g., highway vehicle drivers) are also relevant factors.

Studies performed for railroad and other industries in other countries have produced relevant human factors information, identification of issues, probabilities, conclusions, mitigations, and analysis methodologies. In many cases, systems developed and deployed in other countries can be leveraged to save development costs and facilitate interoperability. However, differences in objectives, operating rules, environment, infrastructure, and language may prevent direct adoption. The SMEs identified opportunities for future research that fell into three general sub-themes: 1) human factors analysis methods, 2) specific topics for human factors analysis, and 3) existing solutions to leverage.

2.13.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
The example PTC Cognitive Task Analyses (CTA) results referenced can provide a starting point for performing CTAs regarding the "actors" who will interface with Enhanced Train Control (ETC) in Canada. The CTA process can also be applied to other new technologies, such as EMS.	The Standardized Plant Analysis Risk-Human (SPAR-H) hazard risk assessment method has been developed and refined on research projects by the U.S. Nuclear Regulatory Commission (NRC). It has been successfully applied previously in safety case development for railroad systems.	The SPAR-H method can be applied directly to new railroad systems to quantify human error probability (HEP) as qualified by performance shaping factors (PSF) and possible error propagation.	The analysis will provide a quantitative indication of where there would be unacceptable risk. Based on that scientific assessment, mitigations (e.g., ways to improve the HMI) can then be devised and the risk reassessed to verify that the solutions are adequate.
Research on mistrust/under-reliance or over-reliance on safety and productivity/automation	Research on human error analyses and ways to improve the HMI for locomotive driving and train	Probability of human errors vs. probability of machine errors in executing each critical function need to be	The results will indicate focus areas and solutions used elsewhere to reduce the risk associated with

systems is recommended. Training is needed to ensure operators are depending on these systems to the appropriate extent.	handling associated with cab automation has been conducted for the U.S. DOT and the FRA. Other organizations referenced have researched human factor issues such as wearable vests, highway crossings, driver fatigue, situation awareness, and relevant non-railroad issues.	jointly assessed along with their level of correlation to ensure the composite human-machine process has sufficiently low probability of error. Takeover performance should be analyzed, e.g., in the transition from autonomous to manual operations in emergency situations.	human errors and ways to increase situational awareness. Resulting human factor improvements can increase railroad safety and reduce operator fatigue.
Human engineering is required to accommodate differences in objectives, operating rules, environment, infrastructure, and language so an existing system can be modified accordingly.	Systems have been developed and deployed in other countries, and these systems can be leveraged by Canadian railroads to save development costs, increase safety, and facilitate interoperability.	Train control, driver assist, situation awareness enhancers, wearable vests, crossing protection, and cab automation systems need to be adapted for Canadian railroad operating methods and rules. Interoperability standards need to be developed for EMS.	The results of the proposed work are necessary to avoid conflicts and ambiguities between equipment and operating methods and rules that could otherwise result in negative operational and safety impacts.

2.14 Low Carbon Fuels

2.14.1 Current Landscape

Current developments in low carbon fuels, additives, and engine technologies demonstrate the potential efficiency and emissions benefits from using technologies for controlling engine heat rejection, blends of standard diesel and hydrogen, or various feedstocks of renewable energy sources and biodiesels. Other developments that may have emission benefits include nano-particle fuel additives and the addition of post-treatment technologies in concert with fuel changes. Initial tests have been performed using several alternative fuels and small-scale engines in controlled environments. If these or other fuels are to be used in the rail environment, they will require further investigation on the large-bore, medium-speed diesel engines of the railroads. For these alternative fuels to be of full benefit to the industry, their use will require consideration across the large number of engine families and an understanding of the impacts on the rail environment and fuel storage infrastructure.

While increasing fuel efficiency and reducing emissions is a stated target of introducing alternative fuels, end users include the goal of ensuring minimal impacts to normal railroad operating efficiencies during the transition and in future use. With that in mind, gaps exist in almost every alternative identified because only limited research has been conducted. Gaps include, but are not limited to: 1) impacts of alternative fuels on wear and interaction with engine lubrication; 2) understanding/identifying risks associated with operations and/or performance if fuel quality/consistency is not maintained; 3) impacts of environmental conditions (temperatures, moisture, etc.) for candidate fuels within the current fixed fueling infrastructure, diode–transistor logic (DTL) applications, and those impacts associated with long term storage depending on the usage rates in remote locations; and 4) impacts on emissions/fuel economy and opportunities/challenges switching between fuels, if necessary. Alternative fuels, blends, additives, or an after-treatment device must work in the rail environment and offer minimal impacts to operations. The use of biodiesel (B5) and renewable diesel (B30) is being studied in a variety of applications for rail.

2.14.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Determine opportunities and requirements for utilizing biodiesel content up to B20 and renewable diesel up to R50 through testing and demonstration programs.	Address original equipment manufacturers (OEMs) and roads to attempt to benefit from work already completed.	This research will hopefully determine the performance characteristics and suitable climates for higher blend biodiesels and renewable diesels.	Alternative fuels are very valuable in the short to medium term for emissions reductions. This project will help give locomotive manufacturers and railways confidence that these fuels are safe and effective.

Determine infrastructure changes, if any, needed to allow the use of B20/R100 due to issues of environmental conditions and alternative fuel characteristics (Pour Point, etc.).	Study usage and storage pattern to determine issues. Use information from other modes of transport at extreme conditions.	Determine issues with storage and usage of higher blends.	Determine applicability and/or limitations of low-carbon fuel options in North American rail operations.
Consider implications of localized or industry-wide usage of alternative fuel (remote location and DTL fueling infrastructure) and applicability to local motive power engine design.	LNG powered locomotive, hydrogen fuel cell, hydrogen light rail vehicle (LRV), battery-electric locomotive (BEL) demonstrations.	Identify system wide applicability of alternative fuels/power sources based on variations in operations across a rail network.	Determine limitation of full system implementation based on variations to fueling infrastructure. Consider implications to emissions if alternative fuels are not available in all areas
Determine opportunities and requirements for using biodiesel content up to B90 and renewable diesel up to R100 through testing and demonstration programs.	Study usage and storage pattern to determine issues. Use information from other modes of transport at extreme conditions.	Build on information gathered as blends, etc., increase.	Determine opportunities for improvements in emissions outputs as blend values go higher.
Consider opportunities for using alternatives such as nano-particle fuel additives on railroad size diesel engines vs. the emissions benefits.	Research listed in references done on small-size engines.	Positive emissions and fuel consumption opportunities identified.	Consider building on work in railroad-size engines for emissions/efficiencies. Focus on opportunities for consistent fuel in rail applications.
Identify and test various engine modifications (heat rejection) and post-treatment technologies that can enhance fuel efficiency and emissions output from railroad-size diesel engines.	Build on small scale engine studies of various alternatives. Determine opportunities and challenges for testing on locomotive-scale engines.	This research will determine what, if any, engine modifications and fuel treatment measures are needed to use high blend biodiesel and renewable diesel across the Canadian railway network, with an emphasis on colder climates.	Currently, there are issues with the cold weather performance of biodiesels, with many railways avoiding its use due to fear of damaged equipment. Engine or fuel modifications to offset these issues could help with widespread adoption.

2.15 Zero-Emission Rail Propulsion Technologies

2.15.1 Current Landscape

Zero-emission rail propulsion technology research is focused primarily on shock and vibration and the crashworthiness of these systems. Techno-economic analysis studies exist, but many have been done internationally on rail industries with needs and layouts far different than those in North America. The charging/refueling infrastructure remains a key concern for industry stakeholders, but lack of research leaves the path for implementing these systems unclear. The keys to the implementation of alternative technologies/systems for zero-emission technologies are understanding and mitigating the operational efficiency risks that may come with each of the following: 1) changes required to existing engine designs or replacement; 2) on-board energy storage requirements/capacities; 3) additional equipment needs (e.g., tender vehicles) to meet operational requirements, modifications/replacement of existing fueling infrastructure(s), or the rate of fueling and/or recharging; 4) training needs for staff for operations and maintenance; and 5) safety system requirements. Additional shortcomings exist in the understanding of the effects of ambient conditions on the operations of many potential technologies (biodiesel/renewable diesel), battery life in cold temperature, and the ability to gasify cryogenics (natural gas/hydrogen/other) adequately.

2.15.2 Opportunities for Future Research

Going forward, the North American rail industry can use the experience of current demonstrations and operations that can assist with earlier implementation of technologies while avoiding common challenges and focus its research on two main areas. The two primary areas of focus are 1) the safety of and 2) the reliability of zero-emission propulsion systems.

Research opportunity	Previous research	Research outcomes	Value proposition for Canadian stakeholders
Vibration testing must be performed for rail fuel cell systems, and mitigation methods for vibration damage in both battery and fuel cell systems should be compared to AAR *Manual of Standards and Recommended Practices (MSRP)*, Section K-V, Standard S-9401.V1.0.	Vibration testing has been done on other modes of fuel cell transport, like buses, but has yet to been explored on trains.	Data on how vibration from regular freight train operation effects fuel cell systems.	This data will inform designs, codes and standards, and regulations for battery and fuel cell locomotives. With a better understanding of shock and vibration effects, mitigation methods and standards adoption .
A streamlined method for simulating and assessing the fire risk of battery electric locomotives should be developed, accounting for changes in battery size, design, and proximity to infrastructure, including bridges and tunnels. This work will inform fire mitigation methods, reducing fire risk to	Site specific fire simulation has been performed, but no general method has been developed to assess various points of interest.	A model both Class I railroads and short lines railroads can use to quickly assess fire risk at areas of interest.	This work will inform fire mitigation methods, reducing fire risk to manageable levels on new and retrofitted battery electric locomotives, benefiting rail lines and surrounding communities.

manageable levels on new and retrofitted battery electric locomotives.			
Crashworthiness of these systems should be assessed to address their size and design changes. This could be done with both physical testing, adhering to currently available standards, and crash simulations, for extensive, repeatable testing.	Crashworthiness of zero emission systems has been performed using buses, but not freight rail. Crashworthiness reference for fuel tank in AAR *MSRP* Section M, Standard S-5506.	Information on crashworthiness of zero emission locomotive systems and how they perform compared to current diesel locomotives.	This research would inform design changes and help make decisions on codes and standards and regulations.
Better define storage requirements and materials for battery electric and fuel cell systems to inform life-cycle analyses, actual greenhouse gas (GHG) reductions, and lifetime costs.	LNG, hydrogen fuel cell, BEL on-highway, and other programs demonstrating the usage of a variety of fuels.	Identify operating efficiencies and decreases in GHG offered by each alternative.	This research would help inform life cycle analysis of zero-propulsion systems, making GHG reductions and lifetime costs more accurate.
A comparison of island-charging, smart grid, micro-grid, and fast charging systems based on the North American rail landscape, considering both decentralized and centralized energy production. Results from this comparison will help inform implementation strategies and long-term economic modeling.	Various charging systems have been attempted in rail lines internationally, but very little research has been done on Canadian rail lines, leaving the path for infrastructure unclear.	A comparison study in Canada would highlight the best path forward for charging systems along North American rail lines and kick start the development of related infrastructure.	With a clear answer on the best charging system for North America's rail landscape, railways and government can begin the lengthy process of deploying the needed infrastructure.
A feasibility study of on-board supplemental energy storage systems like supercapacitors, flywheels, and hydraulics to determine the extent of their use when retrofitting locomotives with zero-emission systems.	These systems have been tested in several configurations, most in the context of electrified light rail and public transit systems.	Performance data for different supplemental energy systems and design considerations for retrofitting them alongside zero-emission systems.	Knowing which supplemental energy systems perform best in the North American freight context will make retrofitting decisions easier as railways look to reduce the emissions of their fleet.
Advancement of more battery-electric and hydrogen fuel cell pilot projects that will help inform techno-economic assessments and policy development.	Full scale freight, hybrid and hydrogen locomotives are being developed and demonstrated domestically and abroad.	Findings toward benefits and challenges of each technology opportunity.	Current programs will demonstrate capabilities of initial full-scale efforts and help focus future research
Determine associated needs for maintenance and training for railroad staff based on new technologies.	Follow full scale programs and gather impactful data.	Determine areas where technologies require new maintenance and	With information regarding the impact on maintenance, training, and

		training to utilize technologies fully.	operation, railways will be able to make a smoother transition to these technologies and make operational decisions ahead of time to avoid issues and delays. To limit impact on operations, specifics will be needed as technologies are matured
Impact on battery storage/life/depletion capability/charge times are very important to considerations of battery technologies. The ability to gasify liquid fuels should they be used in gaseous form is a consideration.	Current BEL and alternative fuel locomotive demonstration programs in ambient environments. Consider alternative modal demonstrations in extreme environmental conditions	Understand impacts to current rail operations in fuel capacities, fueling times, and impacts of alternatives fuels in various operational environments.	Determine preliminary mitigation strategies should limitations be identified. Assist in developing cost/benefit of full-scale implementation.
The impact on range of operations and mitigation strategies in case line of road failures occur must be recognized and prepared for to make the utilization of alternative fuel technologies look as seamless as it does today with current fuel.	Current BEL and alternative fuel locomotive demonstration programs in ambient environments. Alternative modal demonstrations in extreme environmental conditions.	Understand operational and safety related issues identified through these efforts. Determine if alternative operational or safety responses are required based on the energy sources present.	Determine preliminary alternative response protocols, if necessary.

2.16 Carbon Life Cycle of Track Materials and Rolling Stock

2.16.1 Current Landscape

Numerous carbon life cycle analyses have been conducted, but these analyses tend to be performed new construction of specific lines (e.g., California High Speed Rail) and have either a very general (single carbon value for every asset) or a very specific focus (detailed analysis of single asset). The specificity of previous analyses seems to leave little guidance for North American freight/passenger use, especially considering the range of supplies, component types, and longevity. For example, available literature references may provide a single emission value for "wood ties" or "concrete ties" and not consider how these lifespans may vary drastically based on geographic area or operational environment. With policies that incentivize data collection, such as the "Inflation Reduction Act," significantly more carbon emission data should be available in the next few years. This data collection was prioritized because industry and regulatory agencies see data collection as a necessary first step to inform future decision making.

This topic is generally not considered an immediate priority for existing railroads since railroads do not emit directly from material manufacturing, and emissions from track infrastructure are significantly lower than locomotive emissions. Due to the smaller emission footprint, there should also be caution in promoting reduced carbon track components without considering longevity, installation ability, and other practical considerations. If those other considerations are not properly accounted for, the "theoretical" reduction in emissions may be much less than the "actual" reduction. For example, a railroad tie developed from a material that requires less emissions may theoretically reduce emissions compared to wood or concrete, but if many of these ties break upon installation, have shorter lifespans than marketed, and/or require removal and replacement with a more reliable tie material, the actual emissions would be significantly greater than projected.

2.16.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Once data is readily available, a scan of all relevant component emissions should be performed. This analysis should incorporate 1) different commonly used component types (e.g., wood vs. concrete ties), 2) longevity range estimates based on multiple factors, such as geographic and operational environment, existing maintenance, etc., and	An article in Railway Age discussed the environmental contributions of different crosstie materials, including wood, concrete, plastic composite, and steel. The article highlighted the sustainability aspects of wood crossties, such as carbon sequestration during tree growth and the use of creosote as a naturally biodegradable wood	Quantify and compare the carbon emissions associated with different rail components, such as wood vs. concrete ties under various operational and environmental conditions.	As environmental regulations become more stringent, this research can help Canadian rail operators comply with national and international standards for greenhouse gas emissions, avoiding potential penalties and enhancing their reputation.

3) listing components that could reduce emissions while minimizing the risk of disrupting operations. The purpose of this scan would be to compare emissions of existing components and identify potential opportunities for emission reduction.	preservative. It also mentioned that concrete ties are viewed as environmentally friendly due to their longer life cycle and lack of chemical treatments that could leach into groundwater.		
A scan of all commonly used track/rolling stock components to develop a database of industry accepted greenhouse gas emissions. The purpose of the study would provide all railroad agencies more specific emission values that could also consider different component types, manufacturers, and lifespan considerations.	Researchers at the National Renewable Energy Laboratory (NREL) are collaborating with industry partners to develop a new modeling framework, Advance Locomotive Technology and Rail Infrastructure Optimization System (ALTRIOS), for analyzing and planning net-zero-emission and hybrid freight train systems. This software focuses on optimizing the deployment of locomotive technologies and railway energy supply infrastructure for deep decarbonization.	Provide detailed greenhouse gas emission values for a wide range of track and rolling stock components, including different types of rail ties, locomotives, and wagons.	Canadian rail operators can use the database to make informed decisions about selecting low-emission components, thereby reducing the environmental impact of their operations.
Field test technologically innovative track/rolling stock components that have the potential to reduce greenhouse gas emissions and ensure components would also be acceptable in terms of longevity, ease of installation/transport, and other practical considerations.	Studies comparing the emissions of different types of locomotives, such as diesel-electric, battery-electric, and hydrogen fuel cell locomotives, under real-world operating conditions.	Development and implementation of low-emission locomotives, such as battery-electric or hydrogen fuel cell models.	Promoting the adoption of low-emission technologies to align with Canada’s environmental goals and reducing fuel consumption and operational costs through innovative components and practices.

2.17 Decarbonization of Rail Maintenance Activities

2.17.1 Current Landscape

The decarbonization of rail maintenance activities has not received significant attention since carbon emissions from rail maintenance are significantly lower than locomotive emissions (~80 percent of railroad emissions). However, since there are multiple overlaps with locomotive power, multiple maintenance equipment suppliers are moving toward biodiesel and electric energy sources when necessary. The decarbonization of rail maintenance vehicles can also provide other less tangible benefits (e.g., less vibration/noise for workers).

This topic generally involves the adoption of technology being developed in other economic sectors, so adoption is highly dependent on external factors (e.g., technological advancement) and the specific application of the technology. One successful pilot study implemented battery electric hostler (all-electric terminal yard trucks) at an intermodal facility. Hostler yard trucks are well suited to their operating application due to their regenerative movements and movement within a controlled location. It should also be recognized that diesel-alternative technologies are not direct replacements, so the corresponding infrastructure, reliability, operations, and use-cases for diesel-alternative technologies will be different than those for diesel. A non-comprehensive list of examples includes differences in storage (diesel is more energy dense than most alternatives), refueling/charging, upfront costs, electrical demand, and surge prices at different times of day, regenerative capabilities, travel distance, number of consecutive shifts and available re-charge times, and employee buy-in. A successful fuel source change often requires scaling up from small pilot programs to identify implementation issues. Previous studies show that the amount of CO2 emissions from materials is higher than the emissions from maintenance/replacement, indicating the longevity of existing components is important for CO2 emission reduction.

2.17.2 Opportunities for Future Research

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Scan and support collection of emissions from different rail maintenance vehicles along with the decarbonized alternatives. Data collection is an important first step to prioritize future research and help decision making.	Research that evaluates the emissions, performance and the feasibility of alternative, low-emission options for rail maintenance vehicles, such as electric or hybrid models.	Identification of research and development priorities for creating more sustainable rail maintenance technologies.	Providing data to support the transition to low-emission maintenance vehicles, aligning with environmental goals and regulations, and potentially reducing operational costs through more efficient technologies.
Support pilot studies of decarbonized rail maintenance equipment.	Evaluations of the operational efficiency and environmental impact of these alternatives.	Detailed assessments of the operational efficiency, environmental impacts, and cost-effectiveness	Advancing the adoption of environmentally friendly maintenance equipment and aiding

		of the decarbonized equipment.	in alignment with sustainability goals
Field test technological innovation of rail maintenance vehicles that have potential to reduce greenhouse gas emissions and ensure equipment continues working not only in ideal environments, but non-ideal environments, such as cold weather.	The development of cold-resistant technologies for electric or hybrid vehicles, and the evaluation of alternative fuels or energy sources that are effective in extreme temperatures.	Development of cold-resistant rail maintenance vehicles with reduced greenhouse gas emissions.	Ensuring that rail maintenance vehicles can operate efficiently in cold weather, reducing greenhouse gas emissions, and improving the overall sustainability and reliability of rail operations in Canada.

2.18 Alternative Fuel and Battery Tender Cars

2.18.1 Current Landscape

With existing technological advancements, there are research opportunities to develop tender cars for various alternative fuel types, including batteries to power future zero-emission rail propulsion technologies. Currently, AAR *MSRP* Section T, M-1004 covers the Interoperable Fuel Tenders for Locomotives and is populated with information on LNG tender. These initial guidelines are a clear starting point for the development of additional sections (currently shown as placeholders in AAR M-1004).

Performance specifications for tank cars carrying hazardous materials can be found in 49 CFR 179 – Hazardous Materials Regulations. The various gases, e.g., LNG/CNG, LP/ammonia, and methanol, are transported in approved tank car designs (e.g., DOT 113, DOT 112, and DOT 117 designs). Most tank cars have not been modified/standardized to act as fuel tenders. Rule 49 CFR 173 covers transport of Lithium Cells and Batteries, and ANSI 1973 covers batteries used for light rail. U.S. Navy testing of batteries included in S9310-AQ-010-SAF Rev 3 from "High-Energy Storage System Safety Manual." These references, in addition to multiple current developments/demonstrations, can be used as a pathway for battery tender and standards development.

Tender specifications and tender development for other liquified fuels, gaseous fuels, and batteries represent gaps in the standard and are shown currently as placeholders in M-1004. Other gaps include the definition of tender volumetric energy storage requirements to support various types of rail service(s) that will depend on 1) the mix and efficiencies of locomotive power technologies used to pull trains and 2) the refueling infrastructure/logistics requirements to support those services. Environmental operating conditions will be a major contributor in the development of this component. Consideration of inclusion for multiple tenders/inter-connections to meet operational needs may also be required.

2.18.2 Opportunities for Future Research

Research opportunities to enhance future tender and standards development beyond current M-1004 guidelines should be focused mainly on ensuring the overall safety of the equipment during operations by testing and evaluating emergency scenarios. The design of the testing regimes and information developed and pursued are essential to allowing alternative technologies to be safely and practically implemented.

Research Opportunity	Previous research in the area	Outcomes of proposed research opportunity	Value proposition of stated research opportunity for Canadian stakeholders
Develop crashworthiness modeling for new tender designs, identify laboratory and full-scale testing opportunities of tender designs for alternative	The FRA had performed a study on the crashworthiness of LNG tenders, though none have been performed on alternative or battery tenders.	Similar to those in the recent LNG crashworthiness study. Data on leak rates and collision response mechanisms. Data from physical testing could be used to inform	This testing is crucial to the development of standards for fuel tenders and will ensure the standards can be confidently deployed and

fuels based on the test with cryogenic vehicles for LNG tenders and include on-board battery considerations. Test Results will assist in validation of models.			operated by railways in the future.
Develop connection requirements between railcar/locomotive and railcar/fixed refueling facilities for various fuels and for battery electric tenders.	M-1004 LNG Tender Car Development	Industry standard LNG with placeholders for additional technologies.	Use as a starting point for additional alternatives
Develop safety requirements for operations, maintenance, fueling, fire detection, and fire mitigation for various energy types.	Hydrogen fuel cell locomotive, hydrogen power LRVs. BELs, etc. Impacts tests of cryogenic rail cars. On-highway/other modal experience.	Build on findings from alternative fuel programs to consider impactful lessons on fueling/fire detection, etc.	Develop enhanced safety protocols for new tender vehicle fuel types that provide appropriate safety for maintenance, fire detection, fire mitigation, etc.
Consider modification to operation and maintenance practices based on fuel type and identify training needs for operations and maintenance personnel.	Demonstration programs of hydrogen fuel cell, alternative fuel, and BELs. On-highway/other modal experience.	Identification of areas of mechanical/electrical/control system/fueling system limitations based on the rail environment for alternative fuel tenders/technologies.	Develop enhanced training protocols incorporating new tender vehicles and equipment that allow for decreased down time due to failures.
Modeling to better define energy storage requirements leading to economic analysis for various fuel type/storage technologies.	LNG powered locomotive, hydrogen fuel cell, hydrogen LRV, BEL demonstrations	Determine efficiency of various fuel types in rail demonstration programs to fully understand the capabilities of fuel types in actual use cases.	Build on available data to fully identify needs of tender vehicles for various alternative fuel types.

Appendix A: Research Themes

1. **Track and infrastructure inspection technologies:** Continuous improvement and evaluation of autonomous track geometry measurements systems; fiber optic acoustic sensing; emerging complementary track inspection technologies, such as instrumented wheelsets, camera-based AI defect detection, drone-based telemetry detection, and digital twins for predictive analytics of climate change impacts, effects of mitigation measures, etc.
2. **Equipment and rolling stock inspection technologies:** Train inspection portals, development of AI use cases, remote safety inspections, detection of air leakages (affecting fuel efficiency), research on new wayside inspection systems, wayside detectors and algorithms for inspections and trending analyses, wayside detectors for brake testing, the use of seeking cameras for reviewing crossings over a long period of time in specific areas, etc.
3. **Fire risk monitoring and mitigation technologies:** Fire fuel load detection algorithms and their data capture systems; bridge fire protection technologies, such as retardant wrappings and vegetation controls; fire detection inspection systems from onboard sensors; various track thermal imaging and sensor technology; equipment and component safety improvements, such as modified braking systems to reduce sparking or tank car flammability improvements, fuel additives to decrease excess fuel in exhaust, development of integrated networks that incorporate weather, wind, and other fire detection and modeling software into a comprehensive tool, etc.
4. **Flooding/washout risk monitoring and mitigation technologies:** Drone-based water level monitoring, satellite-based InSAR water-level monitoring, development of guidance for culvert and drainage system designs accounting for climate change impacts, fiber-optic acoustic sensing for monitoring beaver dam activity, etc.
5. **Geohazard monitoring/mitigation technologies:** GNSS-RTK monitoring and monitoring systems (geocube, sparkFun), drone-based monitoring, fiber-optic acoustic sensing, LiDAR sensing, ground penetrating radar, borehole inclinometers and Piezometers, satellite-based InSAR monitoring, development of algorithms for prediction/early detection, etc.
6. **Technologies for managing cold weather operational challenges:** Cold weather air brake leak detection and testing, automatic parking brakes, considerations for higher speed (e.g., 200 km/h) rail systems in colder climates with snow accumulation, frost penetration in railway embankments, monitoring of continuous welded rail curves, considerations for maintaining reliability of electrified rail systems for intercity travel during cold weather operations (e.g., countering ice buildup on catenary systems in Canadian climates), etc.
7. **Technologies for subgrade stabilization:** Technologies for stabilizing thawing permafrost, geotextiles for managing drainage and erosion issues, etc.
8. **Enhanced train control:** Connectivity (e.g., satellite, cellular, hardwired, Train-to-X), satellite coverage, use cases, security, coverage of/connectivity in grey zones, etc.
9. **Technologies for increasing grade-crossing safety:** V2X safety warning systems and situational awareness, detection of near misses with camera systems, radar, use of AI for

reporting and preventative measures, crowd sourced data collection of near misses via smart phone apps, etc.

10. **Technologies for monitoring trespassing:** Hot spot analysis using demographic data, fiber-optic acoustic sensing, detection of hot spots with drone/satellite imaging, crowd sourced data collection of near misses via smart phone apps, etc.
11. **Development of tools and analytics for risk assessment:** QRA tools for transportation of dangerous good movements, assessing risks of emerging technologies, assessing performance of emerging technologies versus conventional methods, etc.
12. **Cybersecurity:** Challenges and vulnerabilities in the Canadian rail context; guidance for improving cybersecurity resilience in the rail operating context; exploration of areas of concerns, including legacy systems, Industry 4.0 technology (big data, automation, AI, IoT), cyber-awareness/training, rail wireless spectrum, and lack of understanding modern cyber-attack methods; development of a uniform cyber-resilience framework, threat classification model, and cyber-security assessment tool, etc.
13. **Human factors:** Impacts of emerging in-cab warning systems, wearable technologies for improving worker safety in yards and work zones, task analysis of remote inspections to improve defect detection, technology to help yard workers avoid uncontrolled movements, etc.
14. **Low carbon fuels:** Low temperature performance of various biodiesel blends and mitigation options, performance/maintenance impacts of low-carbon fuels derived from various feedstocks, feasibility of hydrogen-diesel combustion for locomotives, assessing the impact of higher blend rates of biodiesel (B90, B100) and renewable diesel on locomotive engines, etc.
15. **Zero-emission rail propulsion technologies:** Risks and hazards to battery and hydrogen fuel cells systems, including cold weather; shock and vibration; human factors and crashworthiness considerations; feasibility of island-charging systems (intermittent catenary charging for batteries), in line-haul operations; increasing battery capacity, energy density, and charging speeds; optimizing recharging, and refueling options, etc.
16. **Carbon life cycle of track materials and rolling stock:** Carbon lifecycle analysis of existing/emerging track materials, and rolling stock manufacturing, etc.
17. **Decarbonization of rail maintenance activities:** Development of alternative propulsion rail maintenance vehicles (i.e., what has been developed and what has its adoption been like, etc.
18. **Alternative fuels and battery tender cars:** Explore the use of hydrogen, ammonia, methanol, and battery tender cars; how might designs for LNG tender cars be translated to alternative fuel and battery tender cars for locomotives? Determine the difference in risk profile from alternative fuel and battery tender cars compared to LNG tender cars, etc.

Appendix B: Industry Stakeholder Interviews

To give a more well-rounded view of the emerging technology landscape, industry stakeholders from Canadian Class I railroads (3), short line railroads (5), and academic research institutions (2) were interviewed as part of the technology scan. Appendix B provides a high-level overview of the stakeholder interviews. Two general topics from the interviews are summarized: 1) collaboration with government and industry stakeholders and 2) technology advancement opportunities.

B1. Class I Railroads (Canadian National, Canadian Pacific Kansas City and Via Rail)

Collaboration with government and industry stakeholders:

- Collaboration with government on regulatory safety standards for advancements in decarbonization technologies (e.g., AAR *MSRP* M-1004 Interoperable Fuel Tenders for Locomotives).
- Collaboration with government and various other stakeholders on the development of energy infrastructure for alternative fuels and locomotive engine designs (e.g., safety).
- Collaboration with government and various stakeholders on the development of maintenance infrastructure to support alternative locomotive engine designs (e.g., safety, new plant development, supply chain).

Technology advancement opportunities:

- New locomotive propulsion technology
- Line-haul hydrogen-powered locomotives
- Battery-electric freight locomotives
- Testing and exploring greater use of sustainable renewable fuel blends
- AI application to locomotive train handing to reduce fuel consumption and GHGs

The following section includes excerpts from Canadian Class I railroad websites related to climate change, sustainability, and technologies that align with the research theme interviews.

Canadian National (CN): www.cn.ca, March 2024
Locomotives: CN is working with locomotive OEMs and fuel suppliers on testing and exploring greater use of sustainable renewable fuel blends. With the acknowledgement that new locomotive propulsion technology will be necessary to achieve net-zero emissions by their target date of 2050, CN has announced the purchase of a Wabtec battery-electric freight locomotive, and the company is actively engaging with other rail companies, locomotive OEMs, fuel suppliers and customers.

Cleaner Fuels: In the medium term, the Canadian Clean Fuel Standard, and other renewable and clean fuel standards in jurisdictions where CN operates, will continue to present an important opportunity for us to further reduce our emissions. We are also actively working with our fuel suppliers and locomotive manufacturers and are focused on testing and exploring the greater use of sustainable renewable fuel blends, beyond regulated amounts, in our locomotives, to achieve our target. In 2021 we announced a partnership with Progress Rail and Chevron REG to test high-level renewable fuel blends including both biodiesel and renewable diesel in support of our sustainability goals. Trials and qualifications of up to 100% bio-based diesel fuel, important steps in reducing GHG emissions from CN's existing locomotive fleet, have continued to progress in 2022. The program will allow CN and Progress Rail to better understand the long-term durability and operational impacts of renewable fuels on locomotives, especially in cold weather, and plan needed modifications to leverage their usage over the next decade.

Achieving our target is dependent in part on the continuing successful development and availability of innovative technologies and the availability of sufficient volumes of cost competitive sustainable renewable fuels in the years to come. The extent of our ability to fully deploy and implement new technologies, as well as to obtain and use sufficient volumes of sustainable renewable fuels, will require collaboration between locomotive manufacturers and fuel producers. This ecosystem of collaboration is a key area of focus and potential risk.

CN is also a rail industry leader in the employment of radio-control (R/C) for switching locomotives in yards, resulting in reductions to the number of yard workers required. CN has frequently been touted in recent years within North American rail industry circles as being the most-improved railroad in terms of productivity and the lowering of its operating ratio, acknowledging the fact the company is becoming increasingly profitable. Due to the rising popularity of ethanol, shuttle trains, and mineral commodities, CN Rail Service is increasing in popularity.

Canadian Pacific Kansas City Railway (CPKC): www.cpkcr.com
Climate: CPKC recognizes the work that lies ahead of developing a target aligned with a 1.5°C future. The company has a strong foundation of existing low carbon and fuel efficiency initiatives to build on, including:

- Industry-leading Hydrogen Locomotive Program to develop North America's first line-haul freight locomotives using hydrogen fuel cells and batteries to power the locomotive's electric traction motors.
- Development of hydrogen generation capacity at CPKC facilities, including via renewably generated electrolysis at the corporate headquarters in Calgary.
- Technology trials on a range of fuel sources, including plant-based diesel (biodiesel), battery technology, and hydrogen fuel cells.

- Deployment of advanced fuel efficiency technologies including automatic engine start and stop (AESS) technology, Trip Optimizer (TO) technology, horsepower per trailing ton guidelines, and locomotive fleet modernization programs.
- Fuel Switching: Considering electrification as a proxy for alternative locomotive fuels, fuel switching has the potential to provide medium- and long-term fuel and carbon cost savings.
- Alternative propulsion for locomotives and network modifications

Hydrogen fuel cell/battery hybrid propulsion technology is being tested worldwide as a viable alternative fuel for the transportation sector with particular promise for long-haul heavy freight transportation systems including rail. This technology may be capable of eliminating GHG emissions for railway locomotives. In addition to zero-GHG emissions, hydrogen power may offer other benefits, such as reducing operational noise and vibration generated by diesel-electric engines. CP has initiated a program to convert three different types of diesel-electric locomotives into zero-emissions hydrogen-powered locomotives using fuel cells and batteries to power electric traction motors. Supported by a $15 million grant from Emissions Reduction Alberta, the project will include installing hydrogen production and fueling facilities at two CP rail yards in Alberta. This program will demonstrate and evaluate the technical performance of hydrogen-powered locomotives and fueling infrastructure in real-world rail operations and is, thus, expected to generate critical industry knowledge and experience to inform potential commercialization and future development.

VIA Rail: www.viarail.ca
Fleet replacement: The Fleet Replacement Program is a building block of our modernization plan which will help VIA Rail contribute to building a more connected Canada. In 2022, VIA Rail began deploying a new generation of trains on the Quebec City-Windsor corridor, transforming the travel experience for Canadians. A more comfortable, sustainable, and accessible service that improves the environmental footprint through advanced energy-efficient technology.

Cleaner fleet:

- A cleaner fleet equipped with advanced diesel engines that meet Environmental Protection Agency (EPA) Tier 4 emission standards that will reduce particulate matter (PM) and nitrogen oxide (NOx) emissions by 85–95%.
- Ability to convert the fleet to dual-mode (diesel-electric) if the infrastructure is electrified.

Energy efficient fleet:

- New bi-directional configuration allowing trains to operate in both directions, avoiding delays for turnarounds and other time losses with engines running.

- Locomotives equipped with an electrodynamic braking system designed to recover braking energy to power the on-board electrical system and reduce total fuel consumption.
- Energy-efficient LED lighting on trains.

More modern, greener, and LEED certified maintenance centers:

- We are aiming for LEED certification of the Montreal and Toronto Maintenance Centers by applying LEED principles with, among other things, improved and more efficient mechanical and electrical systems.

Artificial intelligence (AI): We (VIA Rail) created a pilot project that brings together our long-established mode of transportation with a new cutting-edge technology that is AI to reduce our fuel consumption and GHGs, all without impacting travel time.

Back in 2021, VIA Rail started working with a promising start-up company, RailVision Analytics, to test an AI-enabled software called EcoRail. Based on the analysis of several factors such as speed, slope of the tracks, equipment used, season, or schedule, EcoRail provides simple and applicable driving recommendations to our locomotive engineers to help them further enhance their fuel-effective train handling behaviors. The initial six months of tests completed in our state-of-the-art simulators on the Ottawa-Toronto route confirmed a potential reduction of up to 15% in fuel consumption and resulting GHGs.

With these promising and inspiring results, we (VIA Rail) continue moving forward on our sustainability journey and have decided to extend this AI pilot project in order to test the practical application of the AI-generated recommendations during live train operations.

This pilot project is a key endeavor that will contribute to one of VIA Rail's goals of reducing its environmental footprint.

B2. Short line Railroads - Quebec North Shore & Labrador (QNSL), Ontario Northland Transportation Commission (ONTC), Hudson Bay Railway (HBR), Southern Railway of British Columbia (SRY) and Western Short line Association (WCSLRA)

Collaboration with government and industry stakeholders:

- Government funding is critical to operational safety (e.g., grade crossings, acquisition of track inspection capabilities).
- Collaboration with government for fire mitigation and monitoring (e.g., real-time satellite data on ground conditions, real-time fire risk index) to improve safety planning capabilities.
- Possible collaboration with Class I Railroads to utilize (share) network detector (e.g., acoustic bearing detector) car performance data for short line owned cars operating over the rail system.

- Possible collaboration with other stakeholders to share technology (e.g., drones, inspection equipment) that have the capacity to serve more than one railroad.
- Government webcasts (e.g., safety, regulatory, training) to support virtual learning. Short lines typically do not have resources and funding for attendance at organized events that disseminate critical information.

Technology advancement opportunities:

- Low-cost fit for purpose track geometry inspections systems (e.g., Railpod) to increase right-of-way safety.
- Acquisition of UAVs for improved track inspection capabilities.
- Upgrading the Initial Operational Capacity (IOC) Geohazard Management System
  - Used to assess risk based on a variety of geohazard types with climate-driven triggering factors, such as freeze thaw cycles, antecedent precipitation, and intense precipitation events.
- Development of instrumented car: Wheel/rail force using instrumented wheelsets (collaboration with NRCC).
  - In-train forces
  - Carbody vertical displacement
  - Carbody vertical, lateral, and longitudinal acceleration
  - Side frame vertical acceleration
  - GPS (precise track location of anomaly)

B3. Academic research institutions: (University of British Columbia and University of Alberta-CaRRL)

Collaboration with government and industry stakeholders:

- Collaborative pilot projects and data sharing with Canadian Class I Railroads to advance technology.
- Pilot project for tram-train service fashioned after the current Karlsruhe-model (tram/light rail trains and commuter/regional rail operating on the same tracks), powered by zero-emissions Fuel Cell/Battery Hybrid Rail (Hydrail) technology, along 342-kilometre route between Osoyoos, B.C., at the US Border, and Kamloops, B.C., the Canadian VIA rail hub.
- Collaboration with government on regulatory safety standards for advancements in decarbonization technologies (e.g., infrastructure and equipment).

Technology advancement opportunities:

- Mapping imaging technologies using satellite and UAVs as they relate to data management and data integration, cloud computation services, and machine learning (AI).
  - **Data management and data integration.** Data acquired through these technologies is significant, posing a challenge for processing, interpreting, and adopting into day-to-day operations. Opportunities arise through leveraging machine learning, AI, and

cloud computing to automate data acquisition and pre-processing towards smooth integration with operations.

- **Cloud computational services.** Large databases and complex analyses that are currently computationally expensive have become too slow for practicable use in day-to-day operations. Cloud computing can allow complex tasks to be performed in a significantly shorter amount of time so results are less resource expensive, thereby facilitating integration. Research could identify areas where this could be leveraged as well as optimal integration approaches.
- **Machine learning (AI).** Large datasets and complex interrelations that could provide enhanced understanding of factors towards traffic optimization and safer operations can lead to complex models. Machine learning and AI have been known to provide a means to automate such analyses or provide pre-processed data that can be evaluated in simpler terms by users for implementation in day-to-day operations. Research could identify these opportunities from a current state of practice in machine learning and AI as it can be integrated into operational needs.

Appendix C: Reference Materials

C1. Track and Infrastructure Inspection Technologies

Report Title: Innovative Diagnostics of the Railway Track Superstructure

Technical Journal/Source: Transportation Research Procedia

Researchers/Research Organization: Lviv Polytechnic National University, Kaunas University of Technology, Ukrainian State University of Science and Technologies

Publication Date: 2024

Technologies examined: Rail Grate Inspection tools/methods/categories.

Key findings:

The rail grate is a vital structural component of railway tracks, comprising rails, sleepers, and a rail fastening system. Rails transmit forces from railway vehicles, guiding their direction and height. Railway ties, along with the rail fastening system, transfer loads to the subsoil, maintaining track gauge and overall stability of the rail grate. Rail grate diagnostics involve inspecting spatial position, structural and geometric arrangement, and structural elements. The authors categorized methods of rail grate diagnostics into followings:

- **Visual:** The method relies on subjective visual detection and assessment of diagnosed parameters, necessitating the expertise and experience of the inspecting party in railway track monitoring.
- **Geometric:** Geometric methods in railway diagnostics include both direct and indirect approaches. Direct methods involve measuring the actual value of a structural element and comparing it with the specified value in technical documentation. Indirect methods measure the deviation between actual and prescribed values, employing specialized instruments such as polygonal, long-chord, or leveling techniques within this category. These methods serve for both operational and initial diagnostic assessments in railway infrastructure.
- **Graphic-computational and computational:** In diagnosing the structural and geometrical arrangement of curved tracks, the arc coordinates method can be applied. This technique involves recording, processing, and assessing circumferential coordinates of geometric curves.
- **Physical non-destructive:** In railway operations, physical non-destructive methods play a crucial role in diagnosing and detecting concealed errors and deficiencies in the rail grate and its structural elements. The prevalent physical methods encompass.
    - **Ultrasonic techniques:** Ultrasonic testing for railway diagnostics relies on detecting errors through mechanical oscillations of particles with frequencies higher than 20 kHz.
    - **Radiographic techniques:** Radiographic methods in railway diagnostics operate on the principle of ionizing X-ray or gamma radiation interacting with the mass of the rail material. This method allows for the visualization of areas with inhomogeneities, such as bubbles in weld metal, where radiation intensity changes less than in healthy material.

  - **Capillary techniques:** This method operates based on the capillarity and wettability of suitable liquids, including their coloring or fluorescence. Capillary inspection is employed to identify defects, such as cracks and pores, in common crossings or switch blades, detecting both open surface and through imperfections.
- **Optometric Methods:** In the context of automated inspection, optical methods, involving lasers and distance meters, are explored for defect identification in railway infrastructure.
- **Photometric and Related Photogrammetric Methods:** In the context of automated inspection, the predominant method in this group involves using linear cameras with a high image capture frequency, mounted on a measuring wagon moving at speeds up to 120 km/h in railway operation. The endless photo generated by these cameras is then analyzed using algorithms for identifying potential defects, vectorizing objects at potential defect sites, and classifying defects based on error catalogues. Deep learning, Markov recognition processes, feedback learning, neural networks with elements of artificial intelligence, and modern IT solutions utilizing machine vision and neural network libraries are applied in this method.
- **Optical Methods:** In the context of automated inspection, optical methods, involving lasers and distance meters, are explored for defect identification in railway infrastructure.

The authors also discussed the sensing equipment in this article. The main takeaway is that the dynamic development of Information and Communication Technology (ICT), especially within the context of industry 4.0, has significantly improved the efficiency of diagnostics and defectoscopy in railway infrastructure. The authors point out that the introduction of innovative solutions, such as visual inspection using an inspection camera, allows for automated video inspection of the rail grate, even when the rail vehicle is in motion at maximum speed.

Opportunities for future research:

Authors suggest future works can focus on combination of one or more of the following methods:

- Utilize laser detectors and meters for measurement.
- Apply point cloud, vectorization, and linearization techniques to models.
- Measure distances between points and construct 3D models.
- Compare 3D models with reference models using 3D cameras.
- Test video inspection equipment and develop new mathematical algorithms.
- Optimize data-related processes for collection, archiving, evaluation, interpretation, distribution, and redistribution.
- Develop an experimental electronic tool for an intelligent diagnostic system focused on video inspection of metal parts and rail grates.

Report Title: An autonomous rail-road amphibious robotic system for railway maintenance using sensor fusion and mobile manipulator

Technical Journal/Source: Journal of Computers and Electrical Engineering

Researchers/Research Organization: Network Rail Ltd

Publication Date: 2023

Technologies examined: Push trolley, Rail-road Vehicle (RRV), Train-borne system, specialist trains, AI based inspection tools, Control and Command systems, autonomous rail-road amphibious robotic system.

Key findings:

The authors first reviewed the current autonomous inspection tools including Push trolley, Rail-road Vehicle (RRV), Train-borne system, and specialist trains. Push-on-track trolleys traditionally used in railway maintenance for track inspection and equipment transport have limitations due to their slow pace, significant human involvement, and suitability only for short-range and low-intensity workloads, despite being capable of detailed damage inspection and track surveying. Rail-road Vehicles (RRV), equipped with both pneumatic and retractable rail wheels for travel on railways and roads, offer flexible access and quick mobility for overhead electrical line maintenance and track surveying; however, human operators are still required for activities like driving and detailed maintenance. Train-borne systems, exemplified by Balfour Beatty's Omnivision and Omnicapture3D, and Machines with Vision's track condition monitoring system, could be deployed to conduct convenient inspection and monitoring of railway infrastructure, providing automated inspection and modeling functionalities but lacking the adaptability for modifications or repair capabilities due to predetermined structures and sensors. Specialist trains, exemplified by the New Measurement Train (NMT) and Mobile Maintenance Train (MMT) in the United Kingdom, provide a comprehensive solution with numerous sensors and repair tools for large-scale track inspection and maintenance, including automated filling and tamping systems for track correction; however, the acquisition and maintenance of these specialized trains entail significant expenses, making certain repair jobs less cost-effective and relying heavily on on-site laborers for tasks like track cutting and grinding.

The authors next focus on AI based inspection tools. Track-based systems like the Felix and JDT track inspection robots provide efficient rail-compatible solutions for autonomous inspection, generating real-time evaluation reports and predictive analyses. However, most track robots lack repair intervention capabilities, and their current Command and Control (C&C) systems have limitations.

Eventually authors propose an autonomous rail-road amphibious robotic system for railway inspection and maintenance, addressing current challenges associated with human involvement in maintenance tasks. The system, equipped with both road and rail-autonomous mobility, aims to minimize track possession during maintenance operations. It integrates a payload mobile manipulator and sensor fusion for versatile inspection and repair activities. The design incorporates a rule-based expert system strategy for remote operation, demonstrating a high level of technological readiness for autonomous railway maintenance and intelligent asset management. The sensors and payloads include 3D lidar, environmental camera, robot arm, RTK-GNSS, Wrist camera, IMU, and Depth camera.

Opportunities for future research:

- Inspection performance compatibility with inspection non-destructive testing methods like ultrasonic testing or alternative current field measurement
- Practical in-situ repair tools like rail cutters and grinders.

Report Title: Track Inspection Products & Services

Technical Journal/Source: ENSCO booklet

Researchers/Research Organization: ENSCO

Publication Date: 2022

Technologies examined: Track inspection technologies.

Key findings:

ENSCO provided a long list of products including the followings:

- **Track Inspection Vehicles:** ENSCO has developed a range of self-propelled rail vehicles, including converted work crew carriers weighing 20 tons and custom high-speed rail cars of up to 100 tons, designed specifically for track inspection purposes. ENSCO also leverages Hi-rail vehicles that can be used for light, medium, and heavy inspection. ENSCO offers Towed coaches as a cost-effective solution for high-speed rail track inspection, enhancing network capacity amid increasing traffic density.
- **Track Geometry Measurement System:** ENSCO's Track Geometry Measurement System covers fundamental track measurements, offering variations like car body mounting for easier maintenance and zero-speed measurement. The integrated system correlates track geometry data with other measurements for comprehensive analysis.
- **Ultrasonic Rail Flaw System (URFS):** URFS is a solution for preventing broken rails, the primary cause of track-related derailments. URFS could integrate with ENSCO automated track inspection technologies, including Zero-Speed Track Geometry, Rail Profile Measurement, and machine vision. ENSCO claims that such approach results in enabling accurate defect location, cross-correlation of data, standardized operator controls for minimal training, and an enhanced assessment of overall rail integrity when combined with ENSCO's complementary machine vision inspection technologies, such as the Rail Surface Imaging System and Joint Bar Imaging System.
- **Rail Profile Measurement System (RPMS):** It is a laser profiling component integrated into the Track Geometry Measurement System, designed for crucial wear measurements. With its ability to measure vertical and horizontal rail wear, and automatic identification of rail size, RPMS supports predictions of rail wear trends, aiding in the identification of optimal timing and locations for necessary rail maintenance. ENSCO enables car body mounting for TGMS & RPMS, suitable for autonomous operation.
- **Rail Corrugation Measurement System (RCMS):** is crucial for identifying and addressing rail corrugation issues that can lead to safety concerns. The system includes laser-based measurement, offering high accuracy and the ability to measure at zero speed, as well as an acceleration-based option.
- **Vehicle/Track Interaction (V/TI) Monitor:** This tool inspects tracks by measuring ride quality, wheel/rail impacts, and track surface conditions. Installed on revenue vehicles, it provides real-time alerts, facilitating proactive maintenance to reduce track-related derailments. The system, based on FRA-sponsored research, offers a constant safety net for identifying and addressing deteriorating track conditions swiftly.
- **Ride Quality Measurement System (RQMS):** This tool synchronizes car body, suspension, and wheel acceleration data with track geometry and machine vision, enabling

identification of rough ride locations, track conditions, and potential derailment risks. RQMS also measures passenger ride comfort and correlates with the Track Geometry Measurement System (TGMS) for corrective actions, contributing to derailment prevention and providing synchronized defect images with the Rail Surface Imaging System (RSIS).

- **Clearance Measurement System (CMS):** Offers real-time, high-resolution assessment of railway line clearances, including Structure Gauge, Tunnel Clearance, Object Encroachment, Track Centerline Offset, Rolling Stock Kinematic Analysis, and Platform Track Interface Analysis. The system utilizes a LiDAR distance laser mounted on the front of the vehicle to generate a high-resolution virtual model of the railway corridor, enabling measurements at track speed.
- **Instrumented Wheel Sets (IWS):** IWS is equipped with calibrated strain gauges for real-time measurements of vertical, lateral, and longitudinal wheel/rail forces, as well as wheel/rail contact location. The IWS offers continuous monitoring at all speeds, flagging exceptions when parameters exceed set thresholds, and has been successfully used for qualifying passenger and freight cars in various locations, including the Transportation Technology Center
- **Joint Bar Imaging System (JBIS):** JBIS uses patented vision inspection technology with high-speed cameras to detect cracks, missing bolts, and measure rail gap in joint bars and rails, enhancing inspection efficiency and reducing labor costs. The system, developed in collaboration with the Federal Railroad Administration, provides real-time exception reports, continuous line scan images, and inventories all joint bars and cracks, offering a comprehensive visual and internal assessment of rail flaws to prevent derailments.
- **Imaging System:** ENSCO developed several imaging systems to captures high-resolution images of tracks, tunnels, driver views, overhead wire, water leaking, etc.
- **Thermal Imaging System (THIS):** The system identifies temperature variations in power infrastructure, rail bases, and tunnels to prevent operational disruptions, fire risks, and corrosion. The system synchronizes with other inspection tools, like the Joint Bar Imaging System, to detect rail base corrosion and deteriorating infrastructure conditions enabling detection of hot spots and cold locations.

Opportunities for future research:

- Leveraging combinations of above tools and additional new sensors to provide higher accuracy diagnosis of rail and infrastructure failures.

Report Title: Railroad Bridge Inspection Utilizing Drone-Based Digital Image Correlation

Technical Journal/Source: FRA publication

Researchers/Research Organization: FRA, University of South Carolina (UofSC), CSX

Publication Date: Feb 2023

Technologies examined: StereoDIC, autonomous drone platform, precise flight control.

Key findings:

Visual inspections are time-consuming and can lead to inconsistent results. In this research project conducted between April 2021 and June 2022, the University of South Carolina (UofSC) developed and tested a new uncrewed aircraft system (UAS) for structural inspections. A stereo digital image correlation system (StereoDIC) on this drone made noncontact measurements of deformation and stress on infrastructure. With support from CSX Transportation (CSX), UofSC tested the system on a railroad bridge in Columbia, SC. Project results show that this type of system may be useful for inspecting railroad bridges and other structures. The use of Unmanned Aerial Systems (UAS) for infrastructure inspection is an emerging application, with current focus on visual inspection and qualitative assessment. However, integrating non-destructive evaluation (NDE) techniques, such as StereoDIC, which measures precise 2D and 3D coordinates, allows for more extensive inspections, including dynamic response measurements and identification of microscopic defects. The University of South Carolina (UofSC) has developed an improved drone for field deployment, enhancing capabilities for structural assessments beyond what was possible with a previous laboratory prototype. The project aimed to assess the effectiveness of a StereoDIC-equipped drone for inspecting railway infrastructure, considering challenges related to functionality, safety, and access difficulties at remote bridges and monitoring points. The UofSC project, despite some limitations in measurement resolution, marked a notable advancement in utilizing StereoDIC-enabled drones for railroad infrastructure inspection. The success included the development of an effective speckle application method for StereoDIC measurement, the creation of an autonomous drone platform for precise flight control, and the identification of camera vibration from drone rotor dynamics as a crucial factor in the measurement system.

Opportunities for future research:

- Designing a StereoDIC camera mount to shield cameras from vibrations caused by the drone or its motion.
- Conducting additional laboratory experiments to validate improved camera isolation and its impact on measurement precision.
- Assessing whether enhanced precision allows the system to achieve the required accuracy for recording low strain levels in railroad bridge structures.
- If successful, proceeding with additional field testing.

Report Title: Report to Congress: Automated Track Inspection Technologies

Technical Journal/Source: US department of transportation, FRA

Researchers/Research Organization: FRA

Publication Date: August 2023

Technologies examined: TGMS, ATGMS, GPR, Lidar, 3D imaging, Machine Vision

Key findings:

FRA mandates visual inspections for railroad track safety, and automation like Track Geometry Measurement Systems (TGMS) has reduced derailments. Class I railroads, including BNSF, explore automated technology's potential to enhance safety and possibly reduce the frequency of visual inspections, with six conducting FRA-approved track inspection test programs by January 20, 2023. TGMS assesses track geometry conditions, identifies defects, and can be operated traditionally by dedicated crews or autonomously (ATGMS) mounted on trains during revenue service, allowing broader track coverage. FRA regulations don't prohibit ATGMS use. Railroads use novel instrumentation systems alongside TGMS or ATGMS for supplemental inspections and resource allocation. Technologies like ground-penetrating radar, Lidar/3-D imaging, machine vision, and vertical deflection measurement assist in identifying issues with ballast, mapping grade crossings, imaging track structures, and evaluating track stiffness, respectively. The accuracy and reliability of these systems vary, and their use is not restricted by FRA regulations. In addition, many rail technologies utilize machine learning or artificial intelligence to identify track components, diagnose safety or maintenance issues, and interpret results. Although no existing technologies can detect all FRA-regulated defects, the Track Inspection Test Programs focus on ATGMS for its potential to reduce derailments caused by track geometry.

Opportunities for future research:

- Additional research on new sensors and technologies and their combinations
- Further technology holistic research on ATGMS and its potential to prevent derailment.

Report Title: CN: Investing for Growth and Safe, Efficient Supply Chains

Technical Journal/Source: RAC – Canada Moves by Rail SEPTEMBER 5, 2019

Researchers/Research Organization: CN

Publication Date: September 2019

Technologies examined: Automated Track Inspection Tools, Automated Inspection Platform,

Key findings:

CN Autonomous Track Inspection Program utilizes specially equipped railcars in regular train service, employing advanced sensor and AI technology to fully automate track inspections. This approach eliminates the need for slow-speed hi-rail vehicles on the tracks, resulting in increased inspection frequency, improved quality, and more accurate preventative maintenance. The program aims to enhance safety, unlock capacity, and improve service reliability by minimizing track disruptions.

CN Automated Inspection Portals, employing high-resolution imaging hardware and advanced machine learning, yield immediate advantages by reducing manual roll-by inspections at train departure, leading to improved yard capacity and decreased start delays. The CN technology promises future benefits by potentially eliminating time-consuming Certified Car Inspections (CCI), contributing to border fluidity for intermodal trains, ensuring manifest accuracy before border crossing, and enhancing inspection frequency and quality, particularly in challenging areas like the undercarriage, aligning with safety objectives.

In another document published in 2018, CN listed the details of technologies they use for inspection. These technologies are Ultrasonic Rail Flaw Detector (RFD), Track Evaluation Systems (TEST) Cars, Vehicle Track Interaction Units (V/TI), High Rail Units for Track Geometry Testing (TG) and Joint Bar Inspection, New Autonomous Track Geometry Test Box Car, Tie Rating Technology, Optical Track Inspection System, Rail Grinding, Bridge Testing System (BTS), Slide Detection/Roadbed Stability Detection, Hot Bearing Detector (HBD), Dragging Equipment Detector (DED), Hot and Cold Wheel Detectors (HWD & CWD), Wheel Impact Load Detector (WILD), Truck Hunting Detector, Wheel Dimension and Profile Detector (WDPD), Image Detection System, Locomotive Digital Video Recorders and Telemetry, Trip Optimizer (TO), Distributed Power (DP).

The description of each system, their regulatory requirement, and their novelties are explained in the same document.

Opportunities for future research:

- Combination of above mentioned to provide more precise inspection procedure.

Report Title: Remote Condition Monitoring of Rail tracks using Distributed Acoustic Sensing (DAS): A Deep CNN-LSTM-SW based Model.

Technical Journal/Source: Green Energy and Intelligent Transportation, Available online 19 January 2024, 100178

Researchers/Research Organization: The Laboratory for Advanced Non-Destructive Testing, In-situ Monitoring, and Evaluation (LANDTIE), Department of Manufacturing Engineering, Georgia Southern University, Statesboro, GA

Publication Date: Jan 2024

Technologies examined: Distributed Acoustic Sensing (DAS), Convolutional Neural Network - Long Short-Term Memory - Sliding Window (CNN-LSTM-SW)

Key findings:

Railroad condition monitoring is crucial for preventing accidents, and the use of Distributed Acoustic Sensing (DAS) - fiber optic cables along railroads offers a viable solution. This paper introduces a novel Convolutional Neural Network - Long Short-Term Memory - Sliding Window (CNN-LSTM-SW) model that leverages deep learning to analyze DAS data efficiently, enhancing the monitoring system. The proposed model demonstrated effective detection of train positions and various railroad conditions, showing promising potential for accurate identification and exploration of anomalies along rail track networks.

The developed CNN-LSTM-SW model exhibits high accuracy (97%) on the training dataset, demonstrating robustness and potential for practical use in fiber optic sensing along railroads. Combining CNN and LSTM layers with a sliding window approach, the model efficiently captures intricate patterns, achieving nearly 100% accuracy on the testing dataset. The automatic label prediction capability streamlines evaluation processes, ensuring quick assessment of the model's performance, and the proposed structure enhances railroad anomaly detection systems, providing a robust, automated, and adaptive solution for safeguarding rail networks.

Opportunities for future research:

- Optimizing and fine-tuning the CNN-LSTM-SW model for broader applications in railroad condition monitoring, considering different types of infrastructure and environmental conditions.
- Integrating real-time data from DAS and fiber optic sensing technologies to enhance the model's responsiveness and adaptability.
- Exploring additional features or sensor inputs that could complement the CNN-LSTM-SW model.

Report Title: A review of infrared thermography applications for ice detection and mitigation

Technical Journal/Source: Cold Regions Science and Technology 218 (2024)

Researchers/Research Organization: UiT-The Arctic University of Norway, Norway

Publication Date: 2024

Technologies examined: Infrared Thermography (IRT), ice detection methods.

Key findings:

Ice accretion on both onshore and offshore structures poses severe risks, prompting the need for effective detection and mitigation methods. While certain ice mitigation techniques are established in aviation and railway sectors, their adaptability to these and other systems is yet under research. This study assesses various methodologies and identifies Infrared Thermography (IRT) as a promising, non-destructive technique, particularly for its capacity for wide area monitoring in contrast to point-based monitoring. In railways, precipitation icing may cause flashovers and derailment and hence disruption to rolling stock. The authors first review the current ice detection tools. The list includes ultrasonic damping, microwave ice detection, pressure sensing, vibration probe method, impedance sensor measuring change in inductance, temperature change using thermistors, resistance temperature detectors, thermocouples, hot-wire method, dual wet-dry heated elements, ice load measurement through load-cell, and optical measurement like infrared thermography, reflected light method, total internal reflection, and LiDAR measurements. Authors then list expand on indirect methods which involve dewpoint, relative humidity (RH), droplets mean volume diameter (MVD) measurement, visibility of cloud base height, double anemometer technique based on wind velocity measurement, and noise detection, particularly effective for moving blades. Next authors expand on Infrared Thermography (IRT) and several research in rail applications addressing issues around ice formation in bridges, and on the tracks. Eventually, the article highlights the importance of integrating ice detection methodology into autonomous systems, citing infrared thermography (IRT) as a promising solution due to its wide area coverage, ability to provide 2D thermal images, and applicability in various applications, including risk assessment and device malfunction detection. The study's laboratory experiments support the deployment of an Ice Detection System utilizing infrared thermography, suggesting its potential in creating an automated, reliable, and economically feasible ice protection system for remote locations facing winterization challenges.

Opportunities for future research:

- Integration of Infrared Thermography (IRT) system in autonomous rail inspection platforms

Report Title: Autonomous Localization and Motion Control of Under-Vehicle Inspection Robot

Technical Journal/Source: IFAC-PapersOnLine, Volume 56, Issue 2, 2023, Pages 3060-3065

Researchers/Research Organization: School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China

Publication Date: 2023

Technologies examined: 3D Lidar, laser distance sensors, 3D Simultaneous Localization and Mapping (SLAM) framework.

Key findings:

The manual inspection of train under-vehicles remains a crucial method for ensuring railway safety, with workers inspecting key components by walking along inspection pits. However, this manual process is labor-intensive and poses risks to workers who spend prolonged periods in the hazardous inspection pit environment. This paper discusses a robot designed for inspecting the undersides of trains, equipped with 3D LiDAR and laser distance sensors. It introduces a specialized 3D Simultaneous Localization and Mapping (SLAM) framework and motion control algorithm to address challenges in navigating the confined and repetitive spaces of an inspection pit. The proposed SLAM framework incorporates laser odometry, loop closure detection, and utilizes features from the 3D LiDAR for optimal localization. The autonomous robot navigates within the inspection pit alongside the train and employs its robotic manipulator to position the 3D camera accurately, capturing point cloud features and images of various components. The gathered data is then transmitted to an algorithm server cluster, which provides maintenance recommendations for the train. Additionally, a motion control algorithm leverages side features of the inspection pit for precise closed-loop control of angular velocity. Experimental results, both in simulation and real-world scenarios, demonstrate the robot's accurate navigation along a straight path within the inspection pit, showcasing the effectiveness of the proposed algorithms with a minimal localization and navigation error.

Opportunities for future research:

- Integration and coupling of inertial measurement unit (IMU) data.
- optimization of feature map management to improve the performance of the SLAM localization framework.

Report Title: Vision based rail track extraction and monitoring through drone imagery

Technical Journal/Source: IFAC-PapersOnLine, Volume 56, Issue 2, 2023, Pages 3060-3065

Researchers/Research Organization: Institute of Technology Roorkee, Roorkee, Uttarakand, 247667, India

Publication Date: 2019

Technologies examined: computer-vision using drone imagery.

Key findings:

The importance of track detection and gauge measurement in railway inspection has shifted from traditional human monitoring to computer vision-based systems, often utilizing cameras mounted on carts or trains. This paper investigates the feasibility of employing drones for such monitoring, emphasizing their cost-effectiveness and accuracy. The experimental results confirm that the proposed computer vision-based method using drone imagery ensures high reliability and accuracy in railway inspection. Current systems employ diverse methods like electromagnetic inspection, eddy current testing, ultrasonic techniques, and optical approaches such as lasers and cameras mounted on mobile carts for track inspections. Researchers have increasingly turned to computer vision for analyzing railroad components, aiming to enhance efficiency, objectivity, and accuracy in inspection systems. he DJI Phantom 3 Professional, equipped with a 4k camera featuring Sony sensors capable of producing 4000 × 3000-pixel images and recording videos in UHD, FHD, and HD with various frame rates, along with a downward vision system, is employed for this purpose. The processing of drone data involves addressing challenges like rectification, ground sample distance calculation, and frame extraction from videos. Following the acquisition of still images, MATLAB scripts are used for resizing and cropping, with subsequent processing, including Gaussian smoothing to reduce noise. Variations in weather conditions and illumination are considered, with the use of HSV color extraction as a technique to handle these challenges effectively. Edge detection and Track detection were conducted after pre-processing and to ensure the algorithm works fine, the authors tested it on more than thousand samples of aerial images captured in different weather conditions. Computer vision and image analysis ensure dependable and precise evaluations across diverse domains during aerial image inspections.

Opportunities for future research:

- Applying drone monitoring to detect various components of railway track.

Report Title: Rail Flaw Imaging Prototype Based on Improved Ultrasonic Synthetic Aperture Focus Method

Technical Journal/Source: Materials Evaluation, Vol. 82(1). https://doi.org/10.32548/2024.me-04371

Researchers/Research Organization: Chengyang Huang, Francesco Lanza di Scalea, University of California San Diego

Publication Date: 2024

Technologies examined: Ultrasonic Phased Array, Synthetic aperture focus (SAF) imaging technique.

Key findings:

The existing manual hand verification process of detected internal anomalies in rails is usually done using a hand-held ultrasonic transducer with a wedge that is manually moved around the anomaly to estimate the flaw size using a -6 dB threshold. This process yields rail flaw sizing results that are highly subjective to the operator's judgment. An improved flaw verification would allow the generation of 3D ultrasound images of the internal flaw to determine flaw size and orientation objectively. Knowledge of the correct flaw size can inform the most appropriate remedial actions, which can vastly reduce the cost of rail maintenance and improve safety.

A prototype device that uses phased array ultrasonic technology for manually imaging defects in rails was developed. It uses a scheme widely used in medicine, the synthetic aperture focus (SAF) imaging technique, that fires subsets of the array elements rather than each one individually, and this gives quicker results than in the full matrix capture method with little degradation of image quality. The SAF detection matches the ground truth with some exceptions, specifically when the defect is under the head corner or when the head is severely worn.

Opportunities for future research:

- Further development, verification, evaluation, and implementation of such approach in dynamic rail flaw inspection or during the hand verification.

Report Title: **<u>Research on New High-speed Detection Technology of Rail Flaw Detection for Heavy Haul Railway</u>**

Technical Journal/Source: Proc. 12th IHHA Conference, Paper 63, pg. 767-774 / IHHA.net

Researchers/Research Organization: China Energy Investment Group Co., Ltd.; Southwest Jiaotong University, China; Beijing LEAD Time Science & Technology Co., Ltd., China

Publication Date: 2023

Technologies examined: Phased-Array Ultrasonic, Machine Learning Algorithms.

Key findings:

Efficient rail flaw detection is critical for maintaining the integrity of tracks and poses huge safety implications if internal defects are not detected in a timely manner. This paper discusses the use of Fast Automated Angle Scan Technique (FAAST) phased array technology, which was used to develop a GTC-80II rail flaw detection vehicle for heavy haul railway in China that achieved high-speed (80km/h) rail flaw detection capability.

The GTC-80II vehicle consists of a tractor carriage and a detection carriage, and the length of each coach is approx. 21m. The coach adopts a hydraulic transmission mechanism, which enables a maximum running speed of 120km/h, and the maximized flaw detection speed is 80km/h. The power system is a dual power submerged centralized arrangement that uses an EFI water-cooled diesel engine with a rated power of 2 × 353kW.

The phased array architecture implemented simulated 42 ultrasonic channels simultaneously with a movement speed of 80km/h. The phased array ultrasonic probe holder adopts a sled design. Each side includes two phased array probes (eight channels per probe), two 37 ° probes, one 0° probe, and two 70° probes. Also, a machine learning (Yolov5s architecture) algorithm was utilized to train ultrasonic B-scans (80×80 grid, 50000 B -B-scans, 48h training) to achieve an accuracy rate and recall rate of 0.91 and 0.99, respectively.

It is reported that the repeatability of the detection performance of the developed system is high and good. The system continuously tracks 30 typical defects (such as welds) on the main line, and 16 defects are located on the curve with R800 or smaller, and the missing rate is less than 1.3%, indicating that the flaw detection system is based on FAAST phased array technology is stable.

Further work needs to focus on the performance of FAAST phased array technology in small radius curves, height differences, and other types of trail tracks.

Opportunities for future research:

- Further verification and validation of such a system at 80kph is needed.

Report Title: Artificial Intelligence based Systems for Detection of Rail Operating Hazards and Safety Enforcement

Technical Journal/Source: Proc. 12th IHHA Conference, Paper 26, pg. 1017-1027 / IHHA.net

Researchers/Research Organization: Derel Wust, 4AI Systems Inc, Australia

Publication Date: 2023

Technologies examined: Machine Vision Cameras, Machine Learning Algorithms.

Key findings:

This paper highlights the importance of automated authorization of train movements, monitoring them continuously, and managing hazards to protect trains. Artificial intelligence and machine learning technologies present opportunities by integrating sensor data (on-board vision cameras) to compare the current track environment with the previous record of any given track section to detect any hazards or differences. This would enable the early recognition and management of potential hazards, ultimately enhancing the safety of train operations.

Key Benefits

- Reduced infrastructure
- Improved risk management
- Continuous route learning
- Shared route knowledge
- Shared hazard knowledge
- Improved above-rail open access

AI System includes:

- A locomotive sensor element 'front-end' with all sensors (machine vision cameras) mounted at the front and high on the vehicle,
- An onboard processing element based on industrial computers for AI inferencing and other processing onboard a rail vehicle, and
- A radio and data communications element for data networking and alarming.

While autonomous rail vehicles will evolve in many applications, the technology may not be ready for widespread implementation yet because more operational experience and data will be needed to train AI/ML systems. Also, operational data will be needed that needs to be collected and processed to establish the technology's maturity for more advanced automated roles.

Opportunities for future research:

- Develop railway personal skills in artificial intelligence and machine learning technology.
- Conduct more proof-of-concept trials of artificial intelligence technology so that informed decisions can be made on the technology's applicability to onboard systems before continuing major investment in trackside legacy systems.

Report Title: **Onboard Broken Rail Detection Concept and Evaluation**

Technical Journal/Source: Proc. 12th IHHA Conference, Paper 11, pg. 927-932 / IHHA.net

Researchers/Research Organization: Mohamad Khater, MxV Rail

Publication Date: 2023

Technologies examined: Electromagnetics.

Key findings:

Enhanced train control methods, such as a moving block communications-based train control (CBTC), have the potential to improve safety, capacity, and average velocity on the nation's rail network. New supporting systems for broken rail and occupancy detection will become necessary as moving block CBTC is realized. In North America, the terms "CBTC" and "positive train control" (PTC) are generally used to mean the same thing.

The Onboard Broken Rail Detection (OBRD) concept presented uses electromagnetic transmission and receiving coils, mounted on opposite rail sides in front of the train's first axle, and passive tuned shunts along the track. The transmission coil induces an alternating current (AC) signal that propagates down the rail through the track and tuned shunts and is then detected by the receiving coil. The tuned shunts in the track allow signal propagation to the other rail to help determine the states of occupancy, broken rail, or clear track, based on the received signal.

The concept was tested in both laboratory and field environments. The test results proved the OBRD viability with the transmission coil successfully inducing detectable signal in the rail. Additionally, data analysis of AC track impedance was conducted to provide insight on trends for impedance variables with varying frequencies and under different environmental and ballast conditions.

Opportunities for future research:

Future work should focus on improving the detection and range capabilities of the overall system placing an emphasis

- Eliminating crosstalk between Tx and Rx coils
- Adding frequency selectivity to the shunts in the test setups
- Carrying out track impedance characterization over a longer section of track
- Developing a breadboard and prototype of the system for testing.

Report Title: **Computer Vision Based Track Conditions Detection**

Technical Journal/Source: Proc. 12th IHHA Conference, Paper 24, pg. 511-515 / IHHA.net

Researchers/Research Organization: Shanyue Guan, Purdue University

Publication Date: 2023

Technologies examined: Machine learning algorithms

Key findings:

Three neural network-based machine learning algorithms to detect the railroad track fastener conditions of railroad track images collected from the site.

- MobileNet
- VGG-16
- Residual Network (ResNet)

Dataset Source used

- Kaggle
- 1300 images used for training and 100 images used for testing

Both MobileNet and VGG-16 achieved an accuracy of more than 0.96 and will be used for further research.

Opportunities for future research:

- Testing, validation, and optimization of AI/ML models for real-world applications.

Report Title: **Leveraging 3D Laser Scanning Data for Track Condition Change Detection**

Technical Journal/Source: Proc. 12th IHHA Conference, Paper 15, pg. 454-462 / IHHA.net

Researchers/Research Organization: J. Riley Edwards, University of Illinois at Urbana-Champaign

Publication Date: 2023

Technologies examined: Laser and vision-based techniques; Machine Learning/ Artificial Intelligence

Key findings:

The railroad industry uses hi-rail vehicles for visual inspections, but these inspections are subjective and challenging due to the logistics of performing detailed inspections at hi-rail speeds. Machine Learning-based inspection tools that leverage digital imaging, image processing, and artificial intelligence (AI) to augment human inspections present several opportunities for efficient and effective track inspections.

The system used was developed by Railmetrics, Inc. (a subsidiary of Pavemetrics, Inc.) and is known as the Laser Rail Inspection System (LRAIL). The LRAIL system is unique in that it has very high 3D scan resolution (i.e., more than 100 million points per second), with simultaneous capture of 2D images and broad AI-based inspection capability which can identify ballast level and surface fouling, crossties, tie plates, fasteners, insulators, anchors, joint bars, and rail wear. Data were collected on the high tonnage loop (HTL) at the Transportation Technology Center (TTC) in Pueblo, CO, USA. Three-dimensional (3D) scans were captured via two 3D laser sensor heads mounted on a hi-rail test trailer that was pulled by a hi-rail pick-up truck.

The study demonstrated that machine vision-based track inspections can be a valuable resource for infrastructure owners as they generate linear track health and condition data that can be used to detect and track condition changes as a function of time and tonnage. Visualizing this data can aid decision-makers in prioritizing and optimizing maintenance strategies to mitigate the risk of track-caused derailments. With this data's recurring gathering, storage, and dissemination, additional analytics may be developed for predictive maintenance and capital planning forecasting.

Opportunities for future research:

- Further testing and Implementation.

Report Title: **<u>Enhanced Ultrasonic Monitoring Technologies for Real-Time and Full-Field Rail Track Inspection</u>**

Technical Journal/Source: Proc. ASNT Research Symposium, 2023, Columbus, OH, DOI: https://doi.org/10.32548/RS.2023.023

Researchers/Research Organization: Ali Zare Hosseinzadeh, Francesco Lanza di Scalea, University of California San Diego

Publication Date: 2023

Technologies examined: Non-contact sonar-based ultrasonic testing technique; Vision Camera; Machine Learning Algorithms.

Key findings:

This paper presents two non-contact ultrasonic testing-based concepts to support condition assessment of ties and internal defect detection in rails.

The first technique uses ultrasonic ranging (sonar) technology to reconstruct the deflection profile of ties to identify any potential deterioration in ballast level. A camera was also added to the sensing system to grab and save the images of the probed objects, which were further analyzed to extract the spatial location of the tie tracking system by tracking robust features in each pair of the successive images. Using artificial intelligence (AI) algorithms, the proposed technique was automated such that the tie boundaries were demarcated by machine vision, and subsequently the ranging technique was implemented at the tie locations. The proposed tie scanning technology was prototyped and used in a series of test runs at a BNSF yard in San Diego, CA, to reconstruct tie deflection profiles. The deflection profiles reveal a normal deflection, without any central excessive negative bending as a sign of bad ballast support.

Similarly, the second technique used control acoustic source together with natural excitation from rolling wheels as an excitation source (transmitter) and an array of non-contact air-coupled ultrasonic transducers (receivers) to detect rail defects. The proposed testing system was prototyped and attached to a test car at TTCI, Pueblo, CO to perform flaw detection on HTL loop (with known internal defects) at different train speeds (e.g., 25, 33, and 40 mph).

If proven successful, it is envisioned that these proposed techniques can potentially be operated at revenue speeds, with real-time data acquisition and processing capabilities, highlighting the concept of a ‘smart train.’

Opportunities for future research:

- Further development, research, and testing
- Smart train detection system prototype development - Tie condition assessment as well as flaw detection in rails.

Report Title: Rail Base Defect Detection via Line Scan Thermography

Technical Journal/Source: Proc. ASNT Research Symposium, 2022, St. Louis, MO, DOI: https://doi.org/10.32548/RS.2022.020

Researchers/Research Organization: Guilherme Gandia, Jackson Winn, Connor Seavers, Anish Poudel, James Mathias, Tsuchin Chu, Southern Illinois University

Publication Date: 2022

Technologies examined: Line Scan Thermography NDT method.

Key findings:

Rail base defects present challenges within the railroad industry as they are difficult to detect until failure. While various in-motion nondestructive evaluation (NDE) methods exist for inspecting rail, none of the current methods can inspect the rail base area reliably and efficiently. This paper provides results from finite element and experimental testing of line scanning thermography (LST) approach for dynamic inspection of the rail base area. Previous findings of LST applications for inspecting metallic subjects have primarily been limited to thin-wall structures; however, recent investigations using static infrared thermography (IRT) methods have shown potential for detecting rail base defects.

Opportunities for future research:

- Further development, research, and testing.

Report Title: **<u>New Sensors and Digital Data Processing Algorithms for Monitoring Railway Bridges</u>**

Technical Journal/Source: Digital Railway Infrastructure. Digital Innovations in Architecture, Engineering and Construction. Springer.

Researchers/Research Organization: Piotr Olaszek

Publication Date: 2024

Technologies examined:

- uniaxial gravity inclinometer with measuring range of ±1°
- triaxial piezoelectric accelerometer with measuring range of ±5g

Inclinometers are installed in one line on a bridge girder and accelerometer at the point of displacement examination.

Key findings:

The deflection of railroad bridges under in-service loads is an essential indicator of the structure's health. Structural health monitoring (SHM) of railway bridges using vision-based approaches for displacement tracking has started using more innovative sensing technologies and machine learning algorithms.

Tests of the system with inertial sensors carried out so far proved its usefulness for monitoring bridges in railways with intensive traffic of passenger and freight trains (with speeds up to 50 km/h) and in a high-speed railway (up to 200 km/h), as well as their ability to achieve high accuracy while determining dynamic displacements using an indirect method. It should be noted that this accuracy is close to or better than those of other measurement methods designed for continuous monitoring and not requiring reference points.

Opportunities for future research:

- Carry out future works to further validate and evaluate systems accuracy and repeatability

Report Title: **Remote Inspection of Railway Bridges Using UAVs and Computer Vision**

Technical Journal/Source: Digital Railway Infrastructure. Digital Innovations in Architecture, Engineering and Construction. Springer.

Researchers/Research Organization: Ali Mirzazade and and Cosmin Popescu, Luleå University of Technology, Luleå, Sweden

Publication Date: 2024

Technologies examined: unmanned aerial vehicles (UAVs), Photogrammetry, Machine Vision, AI/ML.

Key findings:

Ensuring the safety of railway infrastructure is crucial, and regular inspections are necessary to monitor and detect defects that may lead to further damage. Typically, human inspectors conduct these inspections and document any defects found through field measurements and visual observations. Data is usually recorded in paper-based forms that must be well-organized to support future inspections. However, this process may be limited by the experience and knowledge of the inspector and may need to be performed correctly in hard-to-access areas, especially for larger structures like railway bridges.

Kedkejokk bridge was used as a case study to test the capabilities of deep learning algorithms for autonomous crack detection and measurement in hard to access areas with poor lighting. A 3D model of Kedkejokk bridge was generated and detected cracks were then segmented using the trained CNNs, and an orthophoto was generated to measure the width of the cracks. high level of accuracy was achieved, although it should be noted that the accuracy of results relies heavily on the GSD of the images captured.

Opportunities for future research:

- Further testing and evaluation of the developed approach.

Report Title: **Digital Twins for Condition Assessment of Railway Infrastructures**

Technical Journal/Source: Digital Railway Infrastructure. Digital Innovations in Architecture, Engineering and Construction. Springer.

Researchers/Research Organization: M. M. Futai, L. B. Machado, R. R. Santos, B. L. Poncetti, T. N. Bittencourt, and A. L. Gamino; University of São Paulo, Brazil.

Publication Date: 2024

Technologies examined: Digital Twin (DT) Concept

Key findings:

A digital twin (DT) is a virtual copy of a real-world object or system that can be used in different applications, such as railway infrastructure management and condition assessment. The digital model incorporates various tools and technologies, including sensors, IoT, machine learning techniques, data analytics, and 3D geometric strategies, to represent its real-world counterpart accurately. Inspection and monitoring technologies are crucial data sources for creating a digital twin ecosystem.

The successful implementation of digital twin technology in railway infrastructure depends on the industry's technological advancements. This chapter highlights some of the challenges and innovations that can be expected, such as complete management of railway infrastructure through the digital twin, cloud computing analysis for real-time data acquisition, the use of computer vision algorithms for damage detection and monitoring, and the incorporation of machine learning algorithms for automatic alerts. In addition, the structural design of the asset can be continuously monitored and diagnosed over its life cycle by incorporating sensors and inspection information in the digital twin.

Opportunities for future research:

- Further development, testing and evaluation of the suggested approach.

Report Title: **Geometric Criterion for Flange Climb Derailment and IWS-Based Implementation**

Technical Journal/Source: Advances in Dynamics of Vehicles on Roads and Tracks II

Researchers/Research Organization: Yuqing Zeng, Nicholas Wilson, William Lundberg, Russell Walker, Xinggao Shu, MaryClara Jones

Publication Date: August 2022

Technologies examined: Instrumented wheelsets, Flange climb assessment, Derailment risk management.

Key findings:

This paper presents how to prevent and manage flange climb derailment using the data collected by instrumented wheelsets. The limitations of using L/V ratio are discussed in the paper, so the current lateral/vertical load (L/V) ratio-based criteria may not be adequate to assess the risk of derailment. Authors propose an innovative geometric criterion to derailment risk assessment and modify the instrumented wheelset (IWS) processor to use the wheel profile to determine the wheel/rail (W/R) vertical contact position and contact angle. This new criterion aims to evaluate whether flange climb is imminent, providing a more accurate assessment of derailment risk compared to L/V ratio-based criteria. Analysis conducted by MxV Rail indicates that the uncertainty of friction coefficients and the non-monotonic behavior of contact angles during flange climb can lead to misjudgments of derailment risk when relying solely on L/V ratio-based criteria. In contrast, the newly developed geometric criterion, along with the recommendation to use W/R contact position as an index for derailment risk assessment, provides more accurate insights into the potential for flange climb derailments.

Opportunities for future research:

- Implementing in revenue service for testing

Report Title: Real-time railroad track components inspection based on the improved YOLOv4 framework

Technical Journal/Source: Automation in Construction, https://doi.org/10.1016/j.autcon.2021.103596

Researchers/Research Organization: Feng Guo, Yu Qian, Yuefeng Shi, University of South Carolina

Publication Date: February 2021

Technologies examined: Computer vision, Convolutional neural network, Track component inspection.

Key findings:

Track component failure is one of the major causes of train accidents. Despite the development of computer-aided track inspection methods, manual inspections still dominate, especially for missing or broken track components. Leveraging convolutional neural networks (CNNs), authors develop a fast, accurate, easy-operation and low-computation track inspection method using imaging technology. The proposed framework based on YOLOv4 offers improvements in detection accuracy and processing speed, addressing the need for efficient track inspection tools. Unlike most automatic inspection methods that often require expensive equipment and skilled operators, the proposed method just requires a camera, an edge computing unit (NVidia Jetson Orin), and a pushcart. The inspection tool can detect missing or broken track components, such as spikes and ties. The customized YOLOv4-hybrid model achieves high accuracy (94.4 mean average precision) and processing speed (78.7 frames per second), outperforming many other models. This framework aims to reduce track inspection costs and enhance track safety.

Opportunities for future research:

- More detection features can be included in the framework
- Need to install on board for further testing

Report Title: **Digital Twins for Condition Assessment of Railway Infrastructures**

Technical Journal/Source: Part of the Digital Innovations in Architecture, Engineering and Construction book series (DIAEC)

Researchers/Research Organization: Marcos Massao Futai, Lucas Bellini Machado, Ruan Richelly Santos, Bernardo Poncetti, Túlio Bittencourt, A.L. Gamino, University of São Paulo

Publication Date: January 2024

Technologies examined: Digital twins.

Key findings:

This passage provides a comprehensive overview of Digital Twins (DTs) and their application in the context of railway infrastructure integrity management and condition assessment. The paper uses two examples (bridges and tunnels) to show how DTs have been used in real applications and what challenges have faced, emphasizing the importance of integration, inspections, monitoring, and maintenance for ensuring safe operation. It mentions emerging technologies used for inspecting and monitoring railways, such as UAVs, laser scanners, and IoT (Internet of things).

- **Integration with Computational Analysis:** Integrating digital twins with computational simulations allows for evaluating assets' structural behavior under different conditions, predicting potential failures, and determining maintenance needs. Commercial software (Abaqus and SAP2000) and more sophisticated computational solutions are employed for this purpose.
- **Risk-Based Inspection and Maintenance Planning:** Risk-based inspection methodologies integrated with digital twins enable quantifying the impact of inspections on the risk level of rail infrastructure, optimizing inspection strategies, and enhancing decision-making throughout the asset life cycle.
- **Monitoring and Condition Assessment:** Integrating monitoring activities with digital twin frameworks enhances asset integrity management by providing accurate and timely information on structural conditions.

Finally, it highlights the benefits of using DTs in railway infrastructure management, including improved safety, optimization of investments, and enhanced decision-making processes.

Opportunities for future research:

- Investigating challenges and exploring implementation of using DTs for condition assessment of railway infrastructure

C2. Equipment and rolling stock inspection technologies

Report Title: An Implementation Guide for Wayside Detector Systems

Technical Journal/Source: FRA report, 2019

Researchers/Research Organization: FRA

Publication Date: 2019

Technologies examined: Acoustic Bearing Detector (ABD), Trackside Acoustic Detection System (TADS®), Railway Bearing Acoustic Monitor (RailBAM®), Automated Cracked Wheel Detector (ACWD), Dragging Equipment Detector (DED), Hot Box Detector (HBD), Hot Wheel Detector (HWD), Truck Bogie Optical Geometry Inspection (TBOGI), Truck Hunting Detector (THD), Truck Performance Detector (TPD), Weigh-In Motion Detector (WIM), Wheel Impact Load Detector (WILD), Wheel Profile Measurement System (WPMS) or Wheel Profile Detector (WPD), Wheel Temperature Detector (WTD).

Key findings:

The article discusses the Federal Railroad Administration's (FRA) objective of enhancing safety in railroad operations through the implementation of wayside detector systems. These systems are designed to monitor the performance of rolling stock equipment, allowing for proactive identification of maintenance needs. In collaboration with Metro-North Railroad (MNR) and Long Island Rail Road (LIRR), the FRA Future Team focuses on researching and developing technologies that support their safety mission. The article details the creation of an implementation guide aimed at assisting railroads in adopting wayside detector systems. This guide covers various wayside detection technologies available in North America, providing recommendations for implementation, including site selection criteria, data communication, test requirements, system thresholds, action plans for triggered events, and calibration/maintenance requirements. The article also provides brief descriptions and reviews of different wayside detector systems including Acoustic Bearing Detector (ABD), Trackside Acoustic Detection System (TADS®), Railway Bearing Acoustic Monitor (RailBAM®), Automated Cracked Wheel Detector (ACWD), Dragging Equipment Detector (DED), Hot Box Detector (HBD), Hot Wheel Detector (HWD), Truck Bogie Optical Geometry Inspection (TBOGI), Truck Hunting Detector (THD), Truck Performance Detector (TPD), Weigh-In Motion Detector (WIM), Wheel Impact Load Detector (WILD), Wheel Profile Measurement System (WPMS) or Wheel Profile Detector (WPD), Wheel Temperature Detector (WTD). Special attention is given to the Wheel Impact Load Detector (WILD), with a detailed discussion on its functionality, benefits, and practical examples from selected North American railroads.

Opportunities for future research:

The reports do not provide explicit future suggestions. However, followings can be considered as future work:

- Advancements in Data Analytics: Leverage advancements in data analytics, including artificial intelligence and machine learning, to enhance the capabilities of wayside detection systems in predicting and preventing equipment failures.
- Integration with IoT and Edge Computing: Explore the integration of Internet of Things (IoT) and edge computing technologies to enable real-time data processing and decision-

making, reducing latency and improving the overall efficiency of wayside detection systems.

- Enhanced Cybersecurity Measures: Prioritize the development and implementation of robust cybersecurity measures to safeguard wayside detection systems against cyber threats, ensuring the integrity and security of the collected data.

Report Title: Effectiveness of Wayside Detector Technologies on Train Operation Safety

Technical Journal/Source: FRA report, 2022

Researchers/Research Organization: FRA

Publication Date: 2022

Technologies examined: Wheel Impact Load Detector (WILD), Truck Hunting Detector (THD), and Truck Performance Detector (TPD), Data analysis from the Association of American Railroads (AAR)' Equipment Health Monitoring System (EHMS) InteRRIS® database.

Key findings:

The Federal Railroad Administration (FRA) directs its efforts toward enhancing railroad operational safety through innovative technologies. Between 2009 and 2012, the FRA, under the Rail Safety Improvement Act of 2008, supported research on wayside detection systems. The primary goal was to use automated technologies to detect defects in rolling stock, ensuring safety. Sharma & Associates (SA) was commissioned by FRA to analyze data from the Association of American Railroads (AAR)' Equipment Health Monitoring System (EHMS) InteRRIS® database, focusing on wayside detection system impact.

There are several steps taken including data analysis, correlation with derailments, trend analysis, and identification of advancement. As for data analysis, SA analyzed EHMS InteRRIS® data, specifically wheel impact load, truck hunting, and truck gauge spreading force data for a representative sample of 133,000 cars in the North American fleet. In the correlation stage, the authors studied the correlation of wayside detection system installations with derailment causes likely influenced by measured parameters. In trend analysis, the impact of high impact wheel loads, truck hunting, and high lateral truck forces on reducing equipment and vehicle component issues that lead to derailments was assessed. The study also emphasized the need for advancements in addressing issues like broken rim failures.

The implementation of wayside detection systems, notably Wheel Impact Load Detector (WILD), Truck Hunting Detector (THD), and Truck Performance Detector (TPD), had a positive impact by significantly reducing derailments associated with overheated bearings and poorly steering trucks. This positive outcome was further supported by a strong correlation between the growth of detector installations and a noticeable reduction in derailments. However, the analysis also identified areas for improvement, particularly in addressing challenges related to broken rim failures. Despite the overall success, ongoing efforts are directed towards reducing derailments further, with a focus on industry-wide acceptance of a bearing temperature trending criterion. The reduction in derailments underscores the effectiveness of wayside detection systems in enhancing railroad operational safety.

Opportunities for future research:

- Ongoing scrutiny of hot bearing-related derailments and the exploration of new technologies, such as ultrasonic wheel crack detection, showcase a continued focus on reducing derailments and improving safety.

Report Title: State-of-the-art Wayside Condition Monitoring Systems for Railway Wheels: A Comprehensive Review

Technical Journal/Source: 2023 IEEE Access

Researchers/Research Organization: Mehran University of Engineering and Technology, Jamshoro | National Center of Robotics and Automation-Condition Monitoring Systems Laboratory MUET | Polytechnic University of Catalonia, Spain | Universidad de Malaga, Spain

Publication Date: 2023

Technologies examined: Field Measurement (ACFM), radiography, Electro Magnetic Acoustic Transducers (EMATs), Acoustic Emissions (AE), Magnetic Flux Leakage (MFL), Eddy Current (EC), Ultrasonic Testing (UT)

Key findings:

The article discusses the increasing demand for faster, longer, and safer railway networks, posing challenges for condition monitoring systems in modern railway vehicles. It emphasizes the degradation of critical parts like wheels over time due to operational and environmental factors, leading to defects and, ultimately, derailments. The paper highlights existing research and commercial products for condition monitoring, incorporating sensors and data collection methods.

Article first summarizes the main faults that wheels may/could experience as:

- Polygonization Defects: These include periodic/non-periodic non-roundness of wheels.
- Surface Defects: These involve scaled wheels, spalling, wheel flats, and cracks on the wheel surface.
- Sub-Surface Defects: This category includes hardening, cracks, residual stress, shelling, and contamination beneath the surface.
- Profile Defects: These encompass high flange, thin flange, wide flange, small flange angle, hollow wear.

There are several reasons that these faults may occur including:

- Thermoelastic Instability: This occurs between the wheel tread and cast-iron blocks, leading to wheel undulation during braking.
- Congenital Vibration: Natural vibrations in the wheel-rail system contribute to wheel polygonization through mechanisms like sliding vibration, lower bending of the wheelset, P2 resonance, and self-excited frictional vibration.
- Wheels Initial Defects: Factors such as wheel reprofiling, static and dynamic inequities, and inhomogeneous properties of the wheel material influence the origin and development of out-of-round (OOR) wheels. and wheel diameter variation.

Surface defects, potentially causing martensite formation and rolling contact fatigue, may arise during sliding on tracks. Subsurface defects, induced by non-metallic inclusions or blisters, can lead to fatigue failure due to repeated rolling contact with tracks. Profile variations in the wheel are influenced by its motion on straight paths and curves.

As article states, the railway system employs diverse techniques and sensors, including Alternate Current Field Measurement (ACFM), radiography, Electro Magnetic Acoustic

Transducers (EMATs), Acoustic Emissions (AE), Magnetic Flux Leakage (MFL), Eddy Current (EC), Ultrasonic Testing (UT), etc. The article then categorizes the common wayside sensing systems as:

- Ultrasonic sensing
  - Ultrasonic Sensors using methods such as Rayleigh waves based Ultrasonic signal processing can be employed offline to identify wheel flats.
  - Lasers and interferometer device can use technique such as Signal processing with a pulsed IR Nd: YAG laser for offline detection of faults such as surface and subsurface faults of wheel tread.
  - Ultrasonic sensors using wavelet transform and threshold denoising maybe used for online detection of sub-surface defects.
- Strain Gauges: Wheel Impact Load Detector (WILD) system utilizes a series of strain gauges to effectively identify and manage potential wheel defects within railway operations:
  - Strain sensors can use data fusion model for offline detection of "out of round" and "wheel flats."
  - Strain gauges may leverage machine and deep learning methods for online detection of "out of round" and "wheel flats."
  - Strain sensors may leverage multi-sensor fusion techniques for offline detection of "wheel flats."
  - Strain sensors may leverage envelope spectrum approach for offline detection of "wheel flats."
- Fiber Bragg Grating
  - This tool leveraging statistical methods, signal processing and AI methods for online health monitoring of wheel thread, out of roundness, wheel flats, etc.
- Laser & Camera
  - High speed cameras, laser beams, light vision sensors using statistical methods, ML & DL, and data fusion methods, can provide online and offline monitoring of wheel faults.
- Acoustic Emissions (AE)
  - AE technology is suitable for wayside fault diagnosis and condition monitoring of high-speed train wheelset bearings due to its high sensitivity and frequency.

The article then list summary of relevant literature under each theme.

Opportunities for future research:

- It identifies a research gap in advanced onboard monitoring systems and suggests the potential of Machine Learning/Deep Learning methods.
- The need for comprehensive solution for accurate detection of wheel flats around the entire circumference and the focus on sub-surface defect detection

- Explore advancements in optical sensors, particularly FBG sensors, for wheel condition monitoring, addressing the limitations of traditional strain gauges and enabling early fault detection.
- Investigate the potential of vision sensors, coupled with machine vision and image processing, for early detection of wheel tread faults, focusing on the development of advanced algorithmic techniques for ROI segmentation, data quality enhancement, and profile estimation.
- Leverage Deep Learning (DL) techniques to revolutionize pattern recognition in the field, allowing for the extraction of useful features from noisy or cluttered data.
- Fill knowledge gaps by simultaneously considering wheel tread faults and geometric profile parameters, emphasizing a more synergistic approach to enhance precision in wheel condition information.
- Explore the portability and deployment challenges of current wayside systems, seeking innovative solutions for onsite deployment and early detection of faults.
- Investigate the integration of multiple sensor technologies to create a comprehensive and robust wheel condition monitoring system.

Report Title: An investigation into wayside hot-box detector efficacy and optimization

Technical Journal/Source: International Journal of Rail Transportation

Researchers/Research Organization: University Transportation Center for Railway Safety (UTCRS), University of Texas Rio Grande Valley (UTRGV)

Publication Date: 2019

Technologies examined: Wayside hot box detectors.

Key findings:

The paper focuses on Wayside hot-box detectors (HBDs), which are devices employed for monitoring the health of railcar components such as bearings, axles, and brakes by assessing their temperatures. These HBDs use infrared (IR) sensors to measure the temperatures of railroad bearings, and when certain conditions are met, flagged bearings are removed for inspection. The main categories of HBDs discussed in the article are predictive and reactive systems, with wayside HBDs traditionally considered reactive. Efforts have been made to transition these detectors into predictive systems by tracking individual bearing temperatures and implementing integrated monitoring systems. The paper evaluates the efficacy of HBDs, addressing challenges such as the rapid failure modes associated with overheated bearings. It explores various calibration methods, the impact of scanning locations, and alternative scanning technologies. The study aims to improve the accuracy of HBD measurements to enhance safety and reduce operational costs in the railway industry. The study investigates the effectiveness of wayside hot-box detectors (HBDs) used in rail service by employing a laboratory HBD simulator and conducting experiments with healthy and defective bearings at various conditions. The analysis reveals that field HBD readings are influenced by bearing class and that scanning location significantly affects temperature measurements, with the inboard raceway region providing the most accurate readings. Wayside HBDs tend to underestimate temperatures, and the study focuses on calibration procedures to optimize measurements. Linear calibrations, especially a linear fit through all acquired data, prove to be the most effective. Despite improvements, the study highlights a major shortcoming: HBDs cannot distinguish between healthy and defective bearings. To address this, the authors propose a system using temperature, load, and vibration sensors directly on the bearing adapter for continuous monitoring, showing promise in reliably detecting defects and tracking deterioration.

Opportunities for future research:

- Scanning Location Optimization: Investigate and optimize scanning locations for wayside HBDs.
- Calibration Enhancement: Explore advanced calibration procedures for wayside HBDs, propose three linear calibrations, emphasizing the need for an optimized calibration technique.
- Comprehensive Monitoring System: Develop a comprehensive monitoring system combining temperature, load, and vibration sensors directly on the bearing adapter, Acknowledge the limitations of relying on temperature alone and highlight the potential of a multi-sensor approach for continuous monitoring.

Report Title: Automated Train Inspection

Technical Journal/Source: PSI Technics Website

Researchers/Research Organization: PSI Technics

Publication Date:

Technologies examined: Cameras, Image processing, AI methods.

Key findings:

PSI Technics promoted their product as an automated inspection workflow for the roof, side, and underbody structures of trains. As the train passes the inspection system, images are recorded. The software employs templates to learn the characteristics of each train type, and analysis is conducted using pre-defined templates. The diagnostic software analyzes the recorded images, and the results are accessible via a web interface. The features of the interface include displaying analysis results, viewing individual images, adding inspection notes, and generating reports/documentation. The recorded findings serve as a basis for subsequent maintenance optimization. The results, including measurement data and images, are stored in a database. Users can access and examine these results through a graphical user interface, which may be connected to a server or cloud platform. The system is designed for controlled measurements, ensuring comprehensive inspection and facilitating maintenance planning based on historical data. The system is capable of identifying potential damages or defects include wear and tear like indentations, spalling, cracks, and abrasions, as well as contact burns, structural changes, misalignments, missing components, dirt accumulations, leakages, damaged insulation, and issues with cables, among other possibilities.

The product leverages Intelligent analytics software which utilizes large datasets to enhance and streamline train maintenance. This involves compiling statistics, documenting results, conducting time-delayed analyses, identifying safety risks and wear, enabling cloud connectivity, implementing condition-based maintenance, creating inspection templates for diverse train models, and employing artificial intelligence for smart decision-making in image processing. The continuous learning ability of artificial intelligence, coupled with data mining, allows for improved interpretation and correlation identification, contributing to precise maintenance planning and streamlined processes across multiple locations. Early detection of wear ensures optimized maintenance and continuous monitoring of safety-critical components.

Opportunities for future research:

There are no suggestions provided by manufacturer in the pamphlet, but these are the potential suggestions for future work:

- Leveraging more advanced image processing technique to improve the quality of diagnosis.
- Developing time series to predict the emergence of faults.

Report Title: [A review of applications of visual inspection technology based on image processing in the railway industry]

Technical Journal/Source: Transportation Safety and Environment

Researchers/Research Organization: Central South University, UNSW Sydney

Publication Date: 2019

Technologies examined: Broad spectrums of visual inspection technologies.

Key findings:

The advent of computer technology and monitoring allows for the implementation of visual inspection systems. These systems, consisting of hardware and software components, efficiently integrate data acquisition, monitoring, and image processing to detect faults in the railway system. The visual inspection process involves capturing image information of targeted components, processing it through computer programs employing image-processing algorithms, and providing feedback to staff. The paper delves into the crucial role of image-processing technology, tracing its evolution, and categorizes its applications in railway fault detection, encompassing the railway structure, pantograph–catenary network, train body, and infrastructure inspection. Since the track side is covered in the previous, I included the summary of findings for catenary and car body.

- **Pantograph–contact network system**

The visual inspection technologies under this category include an automatic onboard neutral section passing control device utilizing image recognition to optimize break/close markers, fault diagnosis techniques based on image processing for detecting arc faults, machine-vision-based methods for real-time control of pantograph contact points, 3D inspection systems for detecting contact strips, visual anomaly-detection frameworks employing probabilistic Bayesian methods, and high-precision detection approaches using laser ranging and neural networks. These innovations aim to reduce installation and maintenance costs, improve fault detection accuracy, and ensure the integrity and safety of the pantograph–contact network system in diverse railway environments.

- **Train Body components**
    - **Wheel-set defect detection**; Railway systems incorporate diverse technologies to ensure the optimal performance and safety of train wheels. Online non-contact measurement, utilizing machine-vision technology with CCD cameras and linear lasers, facilitates real-time assessment of wheel sets, analyzing internal parameters like rim thickness. Line-structured light vision sensors dynamically measure wheel diameter by collecting contour data, offering a reliable, contactless method. Machine learning plays a crucial role in detecting wheel defects based on vertical forces, employing SVMs and artificial neural networks to enhance classification accuracy. Additionally, an algorithm utilizing 3D modeling detects wheel pairs through rotation centers, providing stable and accurate wheel-pair detection with eight sensors. These technologies collectively contribute to precise, safe, and real-time monitoring of train wheels, categorically falling into non-contact measurement, vision sensors, machine learning for defect detection, and rotation center algorithms with 3D modeling.

- **Small train components inspection:** The technological advancements include computer vision systems for measuring wheel-set parameters, detecting wheel defects, and preventing accidents in specific railway sections. Machine-vision algorithms and image acquisition systems enhance the analysis of railway vehicle chassis images, optimizing inspection resource utilization. Fault identification algorithms, integrated with the train fault detecting system (TFDS), facilitate rapid and reliable detection of issues like center plate bolts faults. Visual inspection methods, employing TFDS, address safety concerns related to angled plug doors and bogie block keys (BBK), achieving impressive fault-detection rates. The automatic fault recognition system based on TFDS, leveraging CNN models, provides accurate positioning and recognition of faults inside frame keys (SFKs) and shaft bolts (SBs).
- Sign and limit detection; Advanced technologies have been developed for railway safety and efficiency. In wheel-set inspection, non-contact machine-vision technology enables online measurement of parameters and dynamic diameter assessment. Machine learning is applied to detect wheel defects based on vertical forces. Computer vision systems measure the displacement between wheels and rails, while other algorithms identify faults in train components. Vision-based systems automatically inspect critical elements, such as bogie block keys and train tail signs, enhancing safety and maintenance. These technologies contribute to automated, efficient inspections, reducing the risk of accidents and improving overall reliability in railway systems.

- **Railway crossing**

Technological advancements in railway level crossing safety include novel methods for near-miss detection using video data. These approaches convert images from cabin to bird's eye view, extract railway centerlines, and employ detectors to calculate vehicle distance, operating seamlessly across varied conditions. Vision-based non-contact image-processing techniques are utilized for switch and horizontal cross-detection, achieving an accuracy of 90.3%. Additionally, a Computer Vision algorithm detects trespassing near-misses using surveillance video footage, leveraging red signals as triggers and robust background models, ensuring operational reliability in diverse lighting conditions. These technologies play a crucial role in real-time monitoring, preventing accidents at railway level crossings.

The main takeaway from the comparison of image-processing technology with traditional detection methods in railway inspection includes the following advantages: high detection efficiency at speeds above 200 km/h, elimination of subjective misjudgment, stable accuracy due to non-contact detection, low costs with reusable equipment, strong scalability allowing for algorithm optimization, convenient data storage for review, no damage to sensors or detection targets, and potential for AI-driven intelligence.

Opportunities for future research:

- **Advanced Computing Optimization:** Focus on further optimizing computing algorithms to address challenges related to processing time, calculation load, and reliability. This includes leveraging the latest advancements in GPU technology for faster image processing.

- **Multi-Sensor Fusion:** Future research should explore integrating data from various sensors such as IMU, laser radar, mechanical sensors, and temperature sensors.
- **AI Integration**: There is a need to delve deeper into integrating artificial intelligence (AI) into visual inspection technology. AI-driven models can enhance self-determination and early warning capabilities, making the inspection systems more intelligent and adaptive to changing conditions.
- **Weather-Resilient Systems:** Enhancements in visual inspection systems should account for weather dependence, especially in adverse conditions such as rain and snow.
- **Accuracy Improvement:** Continued efforts should be made to improve the accuracy of visual inspection systems, ensuring reliable detection results. This involves refining algorithms, exploring innovative approaches, and incorporating feedback mechanisms for continuous improvement.
- **Early Warning Systems**: Building intelligent early warning systems within visual inspection technology will contribute to increased productivity and improved detection efficiency in the railway industry.

Report Title: Rail Industry Pushes Sensors Over Brakes After Ohio Train Crash

Technical Journal/Source: BNN Bloomberg website

Researchers/Research Organization: Politecnico di Torino, Torino

Publication Date: 2019

Technologies examined: Cameras, Image processing, AI methods.

Key findings:

The article discusses the aftermath of a train derailment in East Palestine, Ohio, involving a Norfolk Southern Corp. train that spilled toxic chemicals. The incident has reignited the debate on railroad safety, with a focus on the potential adoption of electronically controlled pneumatic (ECP) brakes. The Biden administration and safety advocates support ECP brakes, but industry players, facing challenges and costs associated with their implementation, are exploring alternative solutions. A coalition called RailPulse proposes placing sensors on railcars to detect faulty equipment promptly and notify the train crew and remote monitors. The article explores the potential benefits of this sensor-based approach and compares it to the debated adoption of ECP brakes. The technology aims to enhance rail safety by identifying issues like overheated wheel bearings early on. The article emphasizes the ongoing political and industry discussions surrounding these safety measures and their implications for the rail freight sector.

Opportunities for future research:

- Failure equipment using sensors; unfortunately, the specific types of sensors are not detailed in the text, but it mentions that the sensors are part of a pilot program testing five different types of sensors. These sensors are intended to detect various issues, such as overheated wheel bearings, and potentially other problems like open doors or signs of equipment failure.

Report Title: Wayside detection technology

Technical Journal/Source:

Researchers/Research Organization:

Publication Date: 2019

Technologies examined:

Key findings:

In CN's safety plan, they prioritize the proactive monitoring of locomotive and railcar mechanical health during active train operation to detect real-time issues and take preventive action. The approach involves implementing multiple layers of technology and defense mechanisms to prevent incidents, along with incorporating new technologies for the early identification of components that are challenging to visually inspect. This strategy aims to enhance the productivity of mechanical employees by providing advanced notifications about components requiring repair before trains reach yards. Additionally, it contributes to improving network fluidity by reducing the frequency of train stoppages caused by component failures.

Multiple detector technologies across CN's Network are used to capture the followings:

- Hot bearing
- Acoustic bearing
- Wheel impact load
- Wheel profile
- Dragging equipment
- High/Wide Load
- High Water
- High Wind
- Landslide

These technologies are Ultrasonic Rail Flaw Detector (RFD), Track Evaluation Systems (TEST) Cars, Vehicle Track Interaction Units (V/TI), High Rail Units – Track Geometry Testing/ TG and Joint Bar Inspection, New Autonomous Track Geometry Test Box Car, Tie Rating Technology, Optical Track Inspection System, Rail Grinding, Bridge Testing System (BTS), Slide Detection/Roadbed Stability Detection, Hot Bearing Detector (HBD), Dragging Equipment Detector (DED), Hot and Cold Wheel Detectors (HWD & CWD), Wheel Impact Load Detector (WILD), Truck Hunting Detector, Wheel Dimension and Profile Detector (WDPD), Image Detection System, Locomotive Digital Video Recorders and Telemetry, Trip Optimizer (TO), Distributed Power (DP).

Opportunities for future research:

No suggestions for the future are provided. However, there is another document from 2018 which explores each of technologies in detail.

Report Title: Wayside Cameras, Integrated Sensors as Logistics Tools

Technical Journal/Source: Railway Age Website

Researchers/Research Organization: Railway Age

Publication Date: 2022

Technologies examined: Digital telematic network monitoring.

Key findings:

The article delves into the utilization of digital telematic network monitoring, specifically through wayside cameras and integrated sensors, to enhance visibility and efficiency in railway operations. It explores Amtrak's initiative to deploy digital cameras along the CSX freight route for gathering independent data to inform regulatory discussions. RailState, a Canadian start-up, is spotlighted for its cutting-edge network visibility technology, offering real-time, impartial rail network data to shippers, regulators, and stakeholders. The piece underscores how RailState's data aids decision-making during disruptions, providing insights into train movements, priorities, and potential network issues. The benefits extend to traders, providing real-time information on commodity movements, and subscribers like Transport Canada, enhancing transparency in monitoring the rail supply chain. The article concludes by stressing the significance of converting collected data into monetized opportunities or losses for a comprehensive financial impact assessment.

Additionally, the article explores the potential widespread adoption of strategic camera coverage at critical bottlenecks on Class I railroads in the U.S. It suggests deploying off-rail property cameras to monitor and assess train fluidity on key routes, with a focus on top grain, coal, and intermodal routes for initial monitoring. RailState, the Canadian start-up, is again highlighted for using private off-site cameras/sensors to provide unbiased, real-time rail network data. The article discusses the technology's application in assessing Amtrak/CSX disputed routes and its potential regulatory implications, emphasizing the value of converting collected data into financial impact assessments. It concludes with insights into the potential applications and challenges of this monitoring technology in the rail industry.

Opportunities for future research:

- **Refinement of Camera Technology:** The refinement and advancements in image capturing, data analysis algorithms, and the integration of additional sensors.
- **Comparative Analysis of Monitoring Technologies**
- **Network Visibility in Different Geographical Contexts:** The article primarily focuses on the Canadian rail network. Future research could extend the analysis to different geographical contexts, exploring the applicability and effectiveness of monitoring technologies in diverse rail networks. This could involve case studies in different regions with varying operational challenges.
- **Integration with Other Data Sources:** The article highlights the benefits of RailState's data in decision-making during disruptions. Future research could explore the integration of rail network monitoring data with other relevant data sources, such as weather data, traffic data, or supply chain data. This could provide a more holistic view for stakeholders in the rail industry.

Report Title: Reliability of a North American Freight Railcar Air Brake Inspection Method Using Wheel Temperature Detectors

Technical Journal/Source: Thesis

Researchers/Research Organization: University of Alberta

Publication Date: 2018

Technologies examined: Automated train break effectiveness, wayside wheel temperature detectors, automated equipment identification.

Key findings:

The thesis revolves around the evaluation of the current legally mandated train air brake test in Canada and a comparative analysis with a technology-driven approach used by Canadian Pacific called Automated Train Brake Effectiveness (ATBE). The traditional No. 1 Air Brake Test, mandated by Transport Canada, is contrasted with the ATBE method, which involves dynamic testing using wayside detectors such as wheel temperature detectors (WTD) and automated equipment identification (AEI).

The ATBE approach, applied to moving trains, triggers alarms for both Hot and Cold Wheels based on designed detection site locations. The study focuses on the effectiveness of both inspection methods in identifying air brake failures and defects not directly related to air brake systems. The assessment includes detection rates, reliability in identifying brake failures, and an examination of maintenance records for repairs associated with brake defects.

The thesis argues that ATBE has significantly higher alarm rates than the manual air brake test. The higher alarm rates, coupled with the ability of both methods to identify various defects, suggest that an inspection method leading to increased railcar repairs could contribute to improved fleet health. The research also discusses the impact of dynamic braking on the ATBE process.

In summary, the thesis aims to provide a comprehensive evaluation of the ATBE approach compared to the traditional air brake test, emphasizing its potential benefits in terms of detection rates, reliability, and overall railcar fleet health.

Opportunities for future research:

- Maintain ATBE test conditions consistency of air brake application prior to detection sites, passing speed over detectors, and limit train stops prior to passing detectors.

Report Title: https://www.mxvrail.com/technology-digest/ Wheel Profile Whear Trending TD23-19

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2023

Technologies examined: Wheel profile detectors.

Key findings:

The report studies trends in wheel profile wear over multiple sites and detectors and identifies indicators for wheel life tracking.

Opportunities for future research:

- Real-time wheel health monitoring and dependencies on operational conditions.

Report Title: https://www.mxvrail.com/technology-digest/ Measuring Wheel Impact Force through the Bearing Adapter TD23-003

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2023

Technologies examined: On-board Sensors.

Key findings:

The report studies measurement methods for quantifying wheel impact loads from on-board the railcar.

Opportunities for future research:

The report finds shortcomings with the use of force sensors on the load path. Future work will include studying alternative measurement requirements for improving accuracy.

Report Title: https://www.mxvrail.com/technology-digest/ Camera Placement and Optimization for Type E/F Y-47 Coupler Securement TD23-003

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2023

Technologies examined: Machine Vision

Key findings:

The report studies camera view angles for imaging the Y-47 pin on type E/F couplers.

Opportunities for future research:

Additional camera view angles to be implemented on machine vision inspection systems. Adding analytics for automated detection.

Report Title: https://www.mxvrail.com/technology-digest/ Camera Placement and Optimization for E-Type Coupler Securement TD22-022

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2022

Technologies examined: Machine Vision

Key findings:

The report studies camera view angles for imaging the retainers on E-type coupler securements.

Opportunities for future research:

Additional camera view angles to be implemented on machine vision inspection systems. Adding analytics for automated detection.

Report Title: https://www.mxvrail.com/technology-digest/ On-Board Thermocouple analysis for Locomotive Traction Motors TD22-009

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2022

Technologies examined: On-board sensors

Key findings:

The report studies temperature trends for locomotive driveline components and their respective ranges during normal operation.

Opportunities for future research:

This work is primarily prescriptive for informing temperature limits for thermal sensing systems. The work can be extrapolated to inform placement of wayside locomotive thermal detectors.

Report Title: https://www.mxvrail.com/technology-digest/ Revenue Service Evaluation of In-Track Locomotive Undercarriage Thermal Inspecitn Systems (LUTIS) TD22-008

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2022

Technologies examined: Wayside Thermal Detectors

Key findings:

The report documents performance of wayside locomotive undercarriage thermal detectors.

Opportunities for future research:

Operational deployment parameters such as placement of detectors, thresholds, and automation algorithms for practical deployment.

Report Title: https://www.mxvrail.com/technology-digest/ Wheel Defect Detection using Electromagnetic Acoustic Transducers TD21-017

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2021

Technologies examined: Cracked Wheel Detection

Key findings:

The report studies the sensitivity of electromagnetic acoustic transducers for detecting known wheel defects in a laboratory environment.

Opportunities for future research:

The report lays the groundwork for future application of EMATs for sensing wheel defects on moving trains. All further future commercialization efforts are suggested to include sensor development, system architecture, and analytic software deployment. This work is being pursued privately.

Report Title: https://www.mxvrail.com/technology-digest/ Machine Learning Approach for Railway Machine Vision Systems TD21-013

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2021

Technologies examined: AI learning algorithms applied to machine vision inspection

Key findings:

The report presents AI results for algorithms applied to a library of machine vision data. It reports capabilities for identifying truck type, detect spring group locations, and measure spring coil compression.

Opportunities for future research:

The report lays the groundwork for future development of AI algorithms.

Report Title: https://www.mxvrail.com/technology-digest/ Tycho ACWDS Service Implementation TD21-002

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2021

Technologies examined: Automated Cracked Wheel Detection

Key findings:

The report studies and documents the performance of an ultrasonic cracked wheel detection system from Tycho that was deployed and evaluated at TTC over the course of 7 years. Cracked wheels detected by the system were verified by manual hand-scans.

Opportunities for future research:

Future work in automated cracked wheel detection would address the shortcomings identified. Alternative sensor types and defect detection technologies should be addressed. Reference TD 18-033 Monitoring of Sub-Surface Fatigue Cracks in Railway Wheels using ACWDS, TD17-003 Tycho ACWDS Detection Performance Summary, TD17-002 Automated Cracked Wheel Detection with Tycho ACWDS.

Report Title: https://www.mxvrail.com/technology-digest/ Imaging the Draft Key Retainer/Cotter Pin TD20-005

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2020

Technologies examined: Machine Vision

Key findings:

The report studies camera view angles for imaging the draft key retainers on multiple car types and draft arrangements.

Opportunities for future research:

Required camera view angles, lighting, resolution, and algorithm development. Reference TD16-049 Facilitating Machine Vision of Draft Gears

Report Title: https://www.mxvrail.com/technology-digest/ Flash Infrared Thermography for In-motion Cracked Axle Detection TD20-003

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2020

Technologies examined: Crack detection using Thermography (machine vision with thermal excitation)

Key findings:

The report studies laboratory results for surface crack detection on an axle using thermal imaging with excitation. In-motion flash IRT testing of a simulated cracked axle demonstrated the fundamental physics of the approach.

Opportunities for future research:

Develop a prototype flash IRT system based on the findings. Develop data collection, storage, display, and axle identification methods. Develop thresholding, filtering, image analysis methods, and crack recognition methods. Reference TD-18-030 Investigating the Use of Flash Infrared Thermography for Cracked Axle Detection.

Report Title: https://www.mxvrail.com/technology-digest/ Automated Cracked Axle Detection Using Resonance Testing TD18-008

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2018

Technologies examined: Resonance testing, impact excitation

Key findings:

The report studies laboratory results for surface crack detection on an axle using resonance response with impact excitation. Accelerometers mounted on the axle recorded responses in the ultrasonic spectrum. Frequency response differences were observed between good and cracked axles, however, the differences were on the same order as differences between different good axles.

Opportunities for future research:

Apply laser vibrometers for non-contact measurement of axle response. Alternative mechanical excitations. Algorithm development.

Report Title: https://www.mxvrail.com/technology-digest/ Review of Railroad Axle Nondestructive Evaluation Inspection Technologies TD18-007

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2018

Technologies examined: MPI, ACFM, ICFPD, Low angle UT scan, Near End/High Angle UT scan, Phased Array Ultrasonic Testing, AC Thermography, Laser UT, Digital Image Correlation, Laser Shearography

Key findings:

The report summarizes overall capabilities and potential application for axle inspection of the technologies studied.

Opportunities for future research:

Research opportunities for static and in-motion axle defect detection based on the technologies presented.

Report Title: https://www.mxvrail.com/technology-digest/ WILD Trending for Broken Wheel Detection TD18-006

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2018

Technologies examined: WILD, Prompt Jump, Dynamic Difference

Key findings:

The report studies two analytic methodologies for their potential to detect and identify broken wheels amidst the population of high impact wheels. Both methods identified some broken wheels, but both had very high false detection rates.

Opportunities for future research:

Study alternative algorithms, including AI. Algorithm development.

Report Title: https://www.mxvrail.com/technology-digest/ Undercarriage and Truck Component Inspection of Railcars using new Vision TFDS TD17-019

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2017

Technologies examined: Machine vision, Laser range finding

Key findings:

TFDS creates true depth 3D images by combining 2D area scan photos and 1D laser range data. Image capture confirmed up to 45 mph on the High Tonnage Loop at the TTC. Comparator algorithms demonstrated for defect detection. High false alarm rates and missed detections were seen. Inspections included undercarriage, truck component, and coupler systems.

Opportunities for future research:

Algorithm development.

Report Title: https://www.mxvrail.com/technology-digest/ Undercarriage Inspection of Railcars Using Duos Technologies VUE™ System TD17-018

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2017

Technologies examined: Machine vision, precision speed sensor, car detection and identification, high speed line scan camera

Key findings:

The VUE™ machine vision inspection system demonstrated capability to provide high resolution images of the FAST test train at speeds up to 45 mph. Occasional image noise is seen during hours when the sun is near the horizon and at high noon. Image templates and threshold filters are used to detect changes from run to run for individual railcars. Environmental conditions (e.g., rain, ice, weeds) can cause staining that leads to high false alarm rates.

Opportunities for future research:

Algorithm development. Addition of additional railcar components to the active inspection list.

Report Title: https://www.mxvrail.com/technology-digest/ Accelerating Machine Vision Inspection Algorithm Development TD17-017

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2017

Technologies examined: Machine vision, image capture, viewing portal, manual reviewer, defect definition, vetted defect images

Key findings:

The report summarizes the development of a manual image reviewer. The viewer was implemented with truck component inspection data captured at FAST® at the TTC. The manual reviewer relies on a human expert to review and confirm images derived from machine vision inspection systems. All aspects of the human review are stored in the database along with the images as a way to populate a database for AI learning.

Opportunities for future research:

Algorithm development. Addition of additional railcar components to the active inspection list.

Report Title: https://www.mxvrail.com/technology-digest/ Investigating the Use of Digital Image Correlation for Cracked Axle Detection TD16-031

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2016

Technologies examined: Digital Image Correlation, Machine Vision, whole field strain measurement

Key findings:

This study was performed under conditions that would approximate the measurement environment for inspecting the visible portion of an axle on a moving train. The optical technique reveals surface strain. Nominal strains on the order of 300 microstrain were observed. Spatial resolution of the digital image correlation was not sufficient to detect stress concentrations near an artificial crack.

Opportunities for future research:

Study alternative whole field NDE techniques such as laser shearography.

Report Title: https://www.mxvrail.com/technology-digest/ EMAT NDE for In-Motion Wheel Defect Detection TD22-021

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2022

Technologies examined: EMAT, automated subsurface wheel defect detection

Key findings:

This study was performed under laboratory conditions to study the feasibility of applying EMAT to wheel inspection. The method showed good signal to noise ratio for indicating both known and artificially created subsurface defects.

Opportunities for future research:

Further testing to commercialize the method.

Report Title: https://www.mxvrail.com/technology-digest/ Laser Broken Rim Detector (BRD) – Part II TD22-019

Technical Journal/Source: Technology Digest

Researchers/Research Organization: MxV Rail

Publication Date: 2022

Technologies examined: Laser imaging, broken rim detection

Key findings:

On-track testing of a prototype showed detection capabilities for artificial broken rim defects. High rates of false detection were reported.

Opportunities for future research:

Alternative inexpensive technologies. This was the second generation of work.

C3. Fire risk monitoring and mitigation technologies

Report Title: Machine learning techniques for fine dead fuel load estimation using multi-source remote sensing data

Technical Journal/Source: Remote Sensing, 13(9)

Researchers/Research Organization: Marina D'Este, Elia, M., Giannico, V., Spano, G., Lafortezza, R., & Sanesi, G.

Publication Date: April 2021

Technologies examined: Estimate fine dead fuel load using Synthetic Aperture Radar (SAR, Sentinel-1), optical (Sentinel-2), and Light Detection and Ranging (LIDAR) data through three different algorithms: Multiple Linear regression (MLR), Random Forest (RF), and Support Vector Machine (SVM).

Key findings:

Fine dead fuel load (fuel with a moisture content of less than 30%) estimation was conducted using multi-source remote sensing data and machine learning techniques. The Random Forest (RF), Support Vector Machine (SVM), and Multiple Linear regression (MLR) models were employed to predict 1-h fuel load and to understand which remote sensing variables are most important to determine it. Model performances were evaluated using Root Mean Squared Error (RMSE), Mean Squared Error (MSE), the coefficient of determination (R2) and Pearson's correlation coefficient (r). The results showed that RF had more predictive power compared to the other models, while SVM and MLR showed similar performances. LIDAR variables (Canopy Height Model and Canopy cover) were more important in fuel estimation than optical and radar variables. In fact, the results highlighted a positive relationship between 1-h fuel load and the presence of the tree component. This is most likely related to the fact that if the degree of coverage and the height of the canopy increase, then the biomass in terms of leaves, twigs, and small branches (e.g., fine and coarse dead fuel loads) increases as well. The geomorphological variables (Slope, Elevation, and Easterness) showed lesser importance in estimating the 1-h fuel load, probably due to their relationship to the landscape topography rather than to vegetation.

Opportunities for future research:

- Future studies are needed to improve the knowledge on which predictors determine and influence the distribution of fine dead fuel. For example, in fuel load estimation models, future research should include new variables. Variables related to climate or landscape heterogeneity such as moisture content, humidity, temperature, and wind speed play a fundamental role in influencing the ignition of fuel loads and, consequently, fire ignition. Therefore, the introduction of new variables could significantly contribute to building fire prediction models.
- Determine the ability to integrate environmental conditions (such as slope, elevation, etc.) and additional variables such as moisture content and humidity into the fire susceptibility assessment tool.

Report Title: Efficient Detection of Forest Fire Smoke in UAV Aerial Imagery Based on an Improved Yolov5 Model and Transfer Learning

Technical Journal/Source: Remote Sensing Vol. 15

Researchers/Research Organization: Yang H., Wang J., Wang J.

Publication Date: November 2023

Technologies examined: A refined UAV-centric forest fire smoke detection approach utilizing the YOLO (You Only Look Once) v5 model.

Key findings:

This study evaluated a novel system for forest fire smoke detection and notification that leverages an enhanced YOLOv5 model and UAV imagery through various experiments. The improved model allows small target smoke in mountains and forests to be identified more accurately and quickly. UAVs were used in this study over satellite remote sensing as remote sensing is constrained in identifying initial small fires due to weather conditions and cloud cover. The proposed backbone network consists of FasterBlock modules, designed based on partial convolution (PConv) that offers rapid memory access capabilities. Additionally, a conditional access (CA) module was integrated at the end of the backbone, effectively focusing the model's attention on the foreground smoke targets and distinguishing them from the background to further enhance feature extraction. The experiments in this study included ablation experiments and three controlled experiments on different attention mechanisms modules, different backbone architectures, and different state-of-the-art models. The results of the controlled experiments on different attention mechanisms modules show that the model with CA performed the best in almost all the evaluation metrics. Additionally, heatmap experiments with various attention mechanisms indicated that the CA module possesses superior foreground-background differentiation capabilities and heightened accuracy in the detection of forest fire smoke. The results of the controlled experiments on different backbone architectures show that, the study's designed backbone elevated the average precision (AP) metrics. While the proposed approach may not surpass YOLOv5s in terms of model parameters and inference speed, it successfully achieved a favorable balance between speed of inference and accuracy of detection. The ablation study results indicate that the inclusion of a backbone design, CA module, and small target detection head module enhanced the accuracy of the original YOLOv5s model. The experimental results demonstrate a significant improvement in the performance of our model compared to YOLOv5s and other commonly used models.

Opportunities for future research:

- Focus on distinguishing between forest fire smoke and similar smoke-like objects, such as clouds and haze. The integration of both infrared and visible cameras on the UAV to capture diverse types of smoke imagery is proposed.
- Test the practical application of the forest fire smoke detection module proposed in this paper.

Report Title: *Forest Monitoring System for Early Fire Detection Based on Convolutional Neural Network and UAV imagery*

Technical Journal/Source: 2020 28th National Conference with International Participation (TELECOM)

Researchers/Research Organization: Georgiev, G., Hristov, G.V., Zahariev, P.Z., & Kinaneva, D.

Publication Date: October 2020

Technologies examined: Early Forest Fire Detection System using an unmanned aerial vehicle (UAV) with onboard thermal camera.

Key findings:

An object detection method, based on a convolutional neural network, using live video feed from an unmanned aerial vehicle (UAV) which patrols over the risky area was developed as an approach for autonomous early fire detection. To make better predictions on the fire probability, the optical camera of the UAV and an on-board thermal camera were used. A fixed-wing UAV with vertical take-off and landing was used in this experiment due to its long-term observation capabilities. The drone flies at a medium altitude. A pre-trained model from TensorFlow object detection zoo called Faster 5-CNN was used to train a neural network to detect fire in the UAV video feed. To train a robust classifier, images from the World Wide Web were used, which either included wildfires or no wildfires. These images were labeled and the areas containing fire and smoke were enclosed to show to the neural network that it should be looking for. With the help of Node-RED, a web-based platform was developed to present the acquired data in real-time and notify the interested parties. Node-RED is a platform for visual programming and was selected for this project as it can take in and unite data from different devices and programming languages. The developed platform did not show any false negatives; however, false positives were common. This was solved using the OpenCV computer vision platform which would check for the presence of certain shades of red on the thermal images taken by the UAV.

Opportunities for future research:

- Research the benefits and feasibility of incorporating the technology into fire risk operations monitoring purposes.

Report Title: Forest Fire Susceptibility Mapping for Uttarakhand State by Using Geospatial Techniques

Technical Journal/Source: Sustainable Community Resilience & Responses

Researchers/Research Organization: Swati Singh, K. V. Suresh Babu

Publication Date: 2021

Technologies examined: Forest fire susceptibility map.

Key findings:

In this study, a forest fire susceptibility map was generated for the State of Uttarakhand in India by using the MODIS TERRA and AQUA land cover-type product (MCD12Q1) and SRTM digital elevation model (DEM) datasets. The input parameters like vegetation cover, moisture condition, slope, aspect, elevation and human disturbance index were taken as to generate the fire susceptibility map. International geosphere-biosphere program (IGBP) landcover type from MCD12Q1 product was used for the vegetation cover, while the topo-graphic features such as slope, elevation and aspect were generated from the SRTMDEM data. The MODIS global disturbance index was used in this study to measure the anthropogenic activities in the forests and downloaded from the Numerical Terra-dynamic Simulation Group (NTSG) website. The susceptibility map was generated by integrating all the parameters, and active fire data of 2018 and 2019 were used for estimating the accuracy. The results were showing an accuracy of more than 80%.

Opportunities for future research:

- Research on integrating input parameters like moisture condition, slope, aspect, elevation and human disturbance index into the Fire Susceptibility Assessment Tool using SRTMDEM data.
- Research on integrating historical fire data from Canada using the CWFIS or other equivalent data source.

Report Title: Novel Ti3C2Tx MXene/epoxy intumescent fire-retardant coatings for ancient wooden architectures

Technical Journal/Source: Journal of Applied Polymer Science

Researchers/Research Organization: Huang S, Wang L, Li Y, Liang C, Zhang J.

Publication Date: February 2021

Technologies examined: Ti3C2Tx MXene/epoxy intumescent fire-retardant coating (TEIFC)

Key findings:

This work provides a novel method for preparing epoxy-based intumescent fire-retardant coating and will greatly expand the industrial applications of MXene-based polymer composites in the field of fire prevention of ancient wooden buildings. This study demonstrated that the Ti3C2Tx transition metal carbide/carbonitride (MXene) was applied as the synergetic agent, waterborne epoxy resin as the film-forming agent, ammonium polyphosphate, dipentaerythritol, and melamine (P-C-N system) as the intumescent fire-retardant system to prepare Ti3C2Tx/epoxy intumescent fire-retardant coating (TEIFC). The results showed that MXene significantly improved the fire-retardant performance of the coating. The combination of Ti3C2Tx and P-C-N system enhanced the Shore hardness of the coating. Furthermore, 3 wt% Ti3C2Tx (TEIFC-3) presented high thermal stability. The prepared fire-retardant coating (TEIFC) demonstrated significantly improved fire-retardant performance.

Opportunities for future research:

- Research to examine and test the practical applications of TEIFC on railway infrastructure such as wooden bridges.

Report Title: Performance optimization of thin fire blankets by varying their radiative properties

Technical Journal/Source: Journal of Fire Sciences, Volume 40

Researchers/Research Organization: Brent KM, T'ien JS.

Publication Date: October 2021

Technologies examined: Thin fire blankets.

Key findings:

An optimization study on the performance of thin fire blankets has been carried out. There were two optimization objectives: maximizing the heat block efficiency and minimizing the blanket backside temperature. The blanket radiative properties to be optimized were the blanket front and backsides emissivity (or reflectivity). Results showed that there are two optimal schemes for blocking incident heat from reaching a structure in quasi-steady-state conditions: reflective and emissive. The optimal front in high heat-blocking efficiency and low back surface temperature when a fire blanket is exposed to a constant set of incident heat conditions consists of a reflective scheme which dominates all, some, or none of a set of emissive tradeoff solutions. The performance of a fire blanket can be improved by allowing the front surface emissivity to change once some value for the front surface temperature has been exceeded. This may create a "smart" fire blanket. The nature of smartness can be either passive such as the case with aluminum coating which melt away at high temperature or be actively controlled in possible future designs. Numerical results obtained in this study were compared against a bench-scale experimental study by Hsu et al., 2011[1]. The numerical computation and its comparison with the bench-scale experiment data have a peak incident heat flux up to 100 kW/m2, however, some real wildfires have been reported with a heat flux that reaches 200–300 kW/m2.

Opportunities for future research:

- Conduct an experiment to test the effectiveness of the thin fire blanket against a heat flux of 200–300 kW/m2. Determine modifications needed to optimize the performance of the fire blanket in this range.
- Determine how fire blankets can be used in the context of rail; for example, what can they do to prevent the spread of fires into rail yards or how they can be used to protect rail infrastructure such as bridges.

1 Hsu S-Y, T'ien JS, Takahashi F, et al. Modeling heat transfer in thin fire blanket materials under high external heat fluxes. Fire Saf Sci 2011; 10: 973–986.

Report Title: Revenue Service Evaluation of In-Track Locomotive Undercarriage Thermal Inspection Systems (LUTIS)

Technical Journal/Source: MxV Rail

Researchers/Research Organization: Anish Poudel, Ryan Alishio, Matthew White

Publication Date: May 2022

Technologies examined: Locomotive undercarriage thermal inspection systems – a wayside technology.

Key findings:

The assessment consisted of two commercial test locomotive undercarriage thermal inspection systems (LUTIS) also known as "In-Track Thermal Detectors" being installed and tested on a BNSF Railway track near Lenwood, California. Three BNSF locomotives were instrumented with onboard thermocouples and data loggers to record real-time temperatures of the driveline components of the locomotives. The thermocouples were installed on the gear case, U-Tube outer bearings, the traction motor outer bearings, under the axle bearings and on the center of the case (underneath). MxV Rail compared the temperature values for measurements made by the onboard thermocouples to each of the two wayside undercarriage thermal scanners on the three locomotives. The results showed a good correlation between the LUTIS and the onboard temperature measurements, suggesting a strong potential for using thermal scanning technology to monitor major driveline components of locomotives.

Opportunities for future research:

- Additional work is needed to measure some failing component temperatures to fully demonstrate the technology.
- Research can be done to determine the ability and use potential for the locomotive undercarriage thermal inspection systems to mitigate the risk of the locomotive components catching on fire or sparking.
- Research can be done to incorporate the technology into an Artificial Intelligence algorithm to identify component type and location along the undercarriage of each locomotive in which data is collected.

Report Title: Increasing the safety operation of railway tanks in emergency situations by improving the design of boiler bottom protective elements

Technical Journal/Source: IOP Conference Series: Material Science and Engineering, Volume 1002

Researchers/Research Organization: Pavol Šťastniak, Juraj Gerlici, Kateryna Kravchenko

Publication Date: 2020

Technologies examined: Design of a protective shield for the ends of railway tanks.

Key findings:

The study evaluated the designs of the boiler bottom protection and the prevention of wagon crawls on top of each other in collisions and analyzed the requirements for the tank protective elements. A technical solution to improve the protective shield of the bottom was developed, taking into account the requirements of the rail tank car manufacturer (Tatravagónka Poprad Zacns 98 m³), as well as the requirements of the Code for the International Carriage of Dangerous Goods by Rail (RID). The proposed shield was made of metal sheets of the material EN S355 due to sufficient yield strength and low cost. Strength analysis was performed in ANSYS 19.2, and the shield geometry was inserted into a numerical program, which was created as an assembly in the Catia V5R20 program. The results revealed that the maximum stress was 342.27 MPa, which does not exceed the yield strength of the EN S355 material used. Additionally, results showed a relatively low overall deformation of the structure with a maximum displacement of 2.15 mm recorded at the upper edge of the structure. The proposed solution will increase rigidity and strength of the protective shield structure, reduce the risk of damage to the railway tank boiler bottom when the protruding elements of the adjacent wagon collide, and can used for different designs of rail tank cars in connection with the use of special holes for placement of rail car elements.

Opportunities for future research:

- Investigate the parameters of the tank car used in the study (Tatravagónka Poprad Zacns 98 m³) and compare features and dimensions to common tank cars in North American rail operations. Use ANSYS perform further strength analysis of the proposed protective shield design on North American tank cars.
- Preform real-world crash tests of the protective shield and compare results to current measures.

Report Title: Adaptive Thin Film Temperature Sensor for Bearing's Rolling Elements Temperature Measurement

Technical Journal/Source: Sensors, Volume 22

Researchers/Research Organization: Cui Y, Gao P, Tang W, Mo G, Yin J.

Publication Date: April 2022

Technologies examined: Thin film thermocouple temperature sensor.

Key findings:

Bearing temperature monitoring of high-speed trains is one of the most important ways to ensure the safe operation of trains. A thin film thermocouple temperature sensor was developed to measure the real-time temperature of the bearing's rolling elements during train operation. Using DC pulse magnetron sputtering technology, Al_2O_3 film, NiCr film, NiSi film, and SiO_2 film were successively deposited on an aluminum alloy substrate. The study examined their microstructure, static characteristics, dynamic characteristics, and repeatability. Finally, an adaptive film temperature sensor was installed on a bearing testing machine to measure the temperature of the rolling elements. The results show that the developed temperature sensor has good linearity in the range of 30~180 °C. The Seebeck coefficient (a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material) is 40.69 μV/°C, the nonlinear fitting error is less than 0.29%, the maximum repeatability error is less than 4.55%, and the dynamic response time is 1.42 μs. The temperature of the measured rolling elements is 6~10 °C higher than that of the outer ring, which can reflect the actual temperature of the bearing operation.

Opportunities for future research:

- Next steps include high-speed railway bearing experiments, actual locomotive experiments, and long-term data monitoring of the sensors.

Report Title: Nanoparticles as fuel additive for improving performance and reducing exhaust emissions of internal combustion engines

Technical Journal/Source: International Journal of Environmental Analytical Chemistry

Researchers/Research Organization: Saddam Khan, Yogesh Dewang, Jitendra Raghuwanshi, Abhisar Shrivastava, Vipin Sharma

Publication Date: January 2022

Technologies examined: Nanoparticles as fuel additives.

Key findings:

The paper provides an overview of the research progress in the use of nanoparticle fuel additives in diesel, biodiesel, and blended fuels. Fuel additives were found to enhance the thermo-physical properties and improve combustion characteristics of the fuel. The roles of the addition of metallic additives, metal oxides, carbon-based particles, organic particles and nanofluids were reviewed. Addition of the fuel additive resulted in early combustion and shortened the ignition delay. The fuel additive enhances fuel properties which enable the blending of biodiesel with diesel. Results found that the nanoparticles - owing to the high surface area - provide better combustion characteristics, high reactivity, shortened ignition delay and fast energy release. The addition of metallic nanoparticles enhances heat transfer rate of the fuel and subsequently shortens the ignition delay. Improvement in combustion characteristics leads to a reduction in emissions and enhancement of the brake thermal efficiency (BTE). Metal oxide nanoparticles in fuel provide extra oxygen during combustion and hence complete combustion can be achieved. The concentration and size of nanoparticle fuel additives have a significant effect on engine performance and exhaust emissions. Improvement in performance and reduction of exhaust emission was found to increase with the increase in nanoparticles' concentration. However, higher concentration of nanoparticles can decrease engine performance. It was pointed out that higher concentration of the nanoadditives increases viscosity and density, and also lowers calorific value of fuel blend.

Opportunities for future research:

- Conduct a full-scale experimental study on the effect of nanoparticle fuel additives and the decrease in excess fuel in locomotive exhausts specifically.
- Determine the ability of nanoparticle fuel additives to decrease fire risk of locomotive exhausts.

Report Title: Water Mist Fire Suppression System Feasibility Study

Technical Journal/Source: Federal Railroad Administration: Office of Research, Development and Technology

Researchers/Research Organization: Bernard, Kennedy

Publication Date: 2022

Report Title: https://www.mxvrail.com/technology-digest/ Fire Risk in Railway Operations for Transport Canada P-23-015

Technical Journal/Source: MxV Rail

Researchers/Research Organization: Clasby, Dustin

Publication Date: 2023

Report Title: Tie treatment options offer sustainability, safety, and fire retardancy

Technical Journal/Source: https://www.progressiverailroading.com/sustainability/article/Tie-treatment-options-offer-sustainability-safety-fire-retardancy--52973

Researchers/Research Organization: Progressive Railroading

Publication Date: 2017

Report Title: WildFireSat: Enhancing Canada's ability to manage wildfires

Technical Journal/Source: https://www.asc-csa.gc.ca/eng/satellites/wildfiresat/

Researchers/Research Organization: Canadian Space Agency, and Natural Resources Canada (NRCan)

Publication Date: 2024

C4. Flooding/washout risk monitoring and mitigation technologies

Report Title: *Emerging Technologies for Monitoring and Managing Water Levels around Railway Tracks, Phase II-Stage II*

Technical Journal/Source: Transport Canada Innovation Centre Published Reports

Researchers/Research Organization: National Research Council Canada and Transport Canada – Innovation Centre

Publication Date: March 2023

Technologies examined: Various water level monitoring technologies

Key findings:

NRC in collaboration with ARSL at McGill University and VIA Rail Canada performed an extensive field investigation by employing satellite images (space), unmanned aerial vehicles (UAV) (airborne), and an instrumented hi-rail truck (track level) at several test sites along a VIA Rail line to explore the potential of these technologies for monitoring surface water "near" railway tracks.

Using high resolution (3 m spatial resolution) imagery from the PlanetScope satellite constellation at four different times, surface water (and its changes) was mapped over a large area near a long extent of VIA Rail track between Ottawa and Brockville. The map was found to be beneficial to extract the overall area that is prone to flooding. The spatial resolution of these images presented some difficulties as very few areas of exposed surface water are large enough to be the main contributor to the pixels.

A UAV (DJI's Matrice 300 RTK) was used to survey four test sections along VIA Rail's track that are prone to flooding. The flights were mainly carried out at 80 m height and covered an area within a 50 m buffer on both sides of the tracks. The use of a high precision RTK-enabled UAV with a photogrammetric camera is fundamentally important for generating the datasets (3D point clouds, orthomosaics, and DSM) used in this type of analysis. The consistent multi-temporal UAV datasets and their associated products were found to be suitable to quantify the spatial and temporal variations in the surface water area as well as the water level. Additionally, the diverse datasets were used to enhance the algorithm developed in Phase-I (Railwater-UNet) and also to develop a new algorithm (Railwater-ConvTrans) that takes advantage of recently developed machine learning techniques.

A hi-rail truck instrumented with a suite of sensors (LiDAR, RGB camera, and longwave infrared camera) was used to further narrow down the water mapping problem to the areas located next to the track (within the visibility range from track level). The LiDAR and the inertial measurement unit (IMU) data was fused together to construct a 3D map of the test sections (same sections surveyed by the UAV). Although water was not represented strongly in these maps, they were found to be useful for a number of railway inspections tasks. The instrumented hi-rail truck was found to be an effective and flexible method to map water bodies that are located next to the track and within the line of sight.

Opportunities for future research:

- Testing imagery from other satellite platforms with higher spatial resolution and comparing the results of imagery from these platforms to identify the level of detail that can be extracted from each platform.
- Using high efficiency UAV LiDAR in addition to RGB cameras to enable data collection over longer sections of track and potentially operating a UAV beyond visual line of sight.
- Developing guidelines for using UAV as a means for scheduled water inspection to assist railways in the systematic recording and organization of UAV data for later reference, comparison, and trend analysis, which can help railways enhance their ability to predict when, where, and to what extent mitigation measures may be required.
- Developing a UAV-based approach that is flexible, scalable, practical, and easy-to-use to enable Canadian railways to use UAV during the inspections that are conducted following extreme events such as heavy rainfall to ensure track safety prior to train passage.
- Using the most recent techniques in machine learning to mitigate some of the water detection challenges including the use of the transfer learning technique and supervised/unsupervised techniques.
- Optimizing the position and quality of the sensors installed on the hi-rail truck to enable the creation of 2D orthomosaics and 3D point clouds from track level. These optimizations can add to the capability of the hi-rail platform and could be used to inspect other track features such as embankment movement.
- The developed algorithm to map water from infrared images collected by the hi-rail truck can be further improved by implementing a multi-spectral data fusion scheme by considering an additional input stream provided by the RGB images.

Report Title: *Railway Investigation Report R18W0168: Main-track train derailment*

Technical Journal/Source: The Transportation Safety Board of Canada (TSB)

Researchers/Research Organization: The Transportation Safety Board of Canada (TSB)

Publication Date: Not listed

Technologies examined: Track washout – culverts, hi-rail inspections, track geometry testing, ultrasonic rail flaw detection.

Key findings:

On 4 July 2018, a VIA Rail Canada Inc. (VIA) operating crew was ordered at 22:30 in Canora, Saskatchewan, for VIA passenger train P69341-04. The train was to operate northward from Canora to Hudson Bay, Saskatchewan, on the Canadian National Railway Company (CN) Yorkton Subdivision. On July 5, 2018, while operating on the Turnberry Subdivision, the VIA crew observed a number of locations with high water adjacent to the track. As a precaution, the crew began to slow the train. While travelling at 33 mph, the train encountered a track washout in a remote location north of Hudson Bay at Mile 23.60 of the Turnberry Subdivision. The 2 locomotives derailed and came to rest on their side. About 800 feet of track was damaged or destroyed. In addition to the washout location at the derailment site, there were 9 other washout locations further north on the Turnberry Subdivision. The most recent track geometry testing and ultrasonic rail flaw detection were conducted on 2 July 2018 and 16 April 2018, respectively. These tests revealed that there were no urgent or near-urgent defects within 1 mile of the derailment location. On the afternoon of 4 July 2018, due to high water in the area, CN Engineering personnel were dispatched to conduct a hi-rail inspection of the subdivision. That evening the track patrol traversed the area near and reported that all culverts were functioning as intended. In addition to this washout location, the nearby highway and culverts were washed out. A bridge was also washed out. Following this occurrence, CN initiated the following safety action:

- CN's SkyGuard warning system was modified to identify weekly accumulation of precipitation and to communicate warnings when water capacity thresholds are reached for a specific area.
- Additional track patrol when rainfall occurs over multiple days or a severe weather advisory is to be issued.

Opportunities for future research:

- Research should be done to enhance advanced flood/washout/track obstruction warning systems.
- Research should be done on optimizing culvert designs for extreme weather events.
- Predictive/risk mapping for extreme weather events.

Report Title: *Rail transportation safety investigation report R18W0237: Main-track train derailment*

Technical Journal/Source: The Transportation Safety Board of Canada (TSB)

Researchers/Research Organization: The Transportation Safety Board of Canada (TSB)

Publication Date: April 2020

Technologies examined: Washout - wood box culverts.

Key findings:

On 15 September 2018, Hudson Bay Railway (HBR) freight train 995 was proceeding northward on the Wekusko Subdivision at 25 mph when train encountered a void in the roadbed surface ahead due to a washout that was about 50 feet long and 15 feet deep. The 3 head-end locomotives and the first 4 cars derailed. The conductor died of his injuries and the locomotive engineer was in critical condition. The locomotive fuel tanks were ruptured and released about 6800 liters of diesel fuel. The washout and subgrade failure occurred as a result of water saturation and pore pressure buildup in the moisture-sensitive sand fill, caused by the elevated water levels that had built up adjacent to the track. Elevated water levels along the right of way had surged above the top of the culverts. Water flowed through the saturated grade, dislodging and destroying the wood box culverts. Additionally, the reduction of Hudson Bay Railway's beaver control program left the track infrastructure vulnerable to a washout event, particularly in situations when a beaver dam is breached. Following the occurrence, HBR inspected all of the culverts on all of its subdivisions, reinstated its beaver control program, and hired a specialist in bridges, structures and culverts for all planned inspections.

Opportunities for future research:

- Research can be done to optimize culvert design for extreme weather leading to flooding.
- Predictive/risk mapping for extreme weather events.
- Research should be done to enhance advanced flood/washout/track obstruction warning systems.
- Research in fiber optic acoustic sensing for monitoring beaver dam activity.

Report Title: *Coupled Brinkman and Kozeny–Carman model for railway ballast washout using the finite element method*

Technical Journal/Source: Journal of the Royal Society of New Zealand

Researchers/Research Organization: Kalyanaraman, B., Meylan, M. H., & Lamichhane, B.

Publication Date: April 2021

Technologies examined: Model for railway ballast washout.

Navier–Stokes equation, Brinkman equation, projection method, method of characteristics, Kozeny–Carman law, particle simulations

Key findings:

This study models the problem of railway ballast washout under flooding conditions. The action of floodwater can degrade the ballast under the effect of mild flows and under more severe flooding can wash the ballast away completely. The medium permeability changes with respect to the fluid amount in the porous medium. In such cases, the permeability is assumed to be a nonlinear function of the porosity. This study proposes a penalization approach based on the Navier–Stokes'/Brinkman equation to model the wash–away of porous media. The problem is formulated using a unified Brinkman equation on the domain with a nonlinear permeability which is given a function of porosity, which in turn is governed by an advection equation. The permeability is assumed to be governed by the Kozeny–Carman equation which relates the permeability with the average grain size and porosity. The model is solved using an adaptive finite element method in space and the method of characteristics in time. Finally, numerical examples are provided to illustrate the model and discuss possible extensions. The results obtained by solving the Brinkman problem can be used to simulate particle–laden flows.

Opportunities for future research:

- The determined model for railway ballast washout should be used to research and design ballast systems that are less susceptible to washout and mitigation methods to prevent washout.

Report Title: *Rail Climate Change Adaptation Program*

Technical Journal/Source: Transport Canada

Researchers/Research Organization: Canadian National Railway Company (CN), Hudson Bay Railway Corporation (HBR) / Arctic Gateway Group, Ontario Northland Transportation Commission (ONTC), Tshiuetin Inc., Great Western Railway (GWR), Red Coat Road and Rail (RCRR), Agawa Canyon Railroad (ACR) /Watco, Southern Railway of British Columbia (SRY)

Publication Date: March 2023

Technologies examined: Washout risk management system, remote sensing technologies such as drones, satellite imagery, hi-rail trucks, digital tool for improvements to culvert design, flood monitors, water level sensors.

Key findings:

- *Washout Hazard Risk Assessment and Monitoring System Deployment:* This project will reduce the impact of flooding on CN's rail network by creating a proactive washout (i.e., flooding) risk management system, including a site inventory process, risk management methodology, and an automated risk monitoring system.
- *Hydrology Incident Prediction and Response System:* This project from HBR and Arctic Gateway Group will use satellite and drone data to better predict and respond to rail incidents caused by water movement issues. These issues include atmospheric rivers, plugged culverts, overland flooding, and thawing snow/permafrost.
- *Integrating satellite and instrumented hi-rail truck data into current, railway water inspection procedures to improve its effectiveness amidst changing climate conditions:* This project involves using remote sensing technologies such as drones, satellite imagery, hi-rail trucks, and data analysis to monitor regional water level changes along ONTC's rail right-of-ways, in order to better assess potential risks to their rail infrastructure.
- *Study of Hydraulics and Hydrology of the Entire Tshiuetin Railway Network:* This project will perform a flood risk evaluation of its infrastructure, and subsequently develop and implement a maintenance and infrastructure replacement plan. This will include conducting a field survey of existing culverts and using a digital tool to identify potential improvements to culvert design and/or maintenance practices to improve drainage/water level management.
- *Culvert Assessment and Replacement on Great Western Railway:* This project seeks to mitigate the risks that torrential rain and flash flooding events pose to culverts along the Great Western Railway's lines in southwest Saskatchewan. The project will assess and replace high-priority culverts with newer and more effective designs.
- *Culvert Assessment and Replacement on Red Coat Rail:* This project will assess and replace high-priority culverts with newer and more effective designs. These culverts will be identified using visual inspections and track maintenance records. A secondary visual inspection will also be conducted after a high-precipitation event to form a proactive maintenance plan of the new culvert designs.
- *Northern Ontario Short Line Flood Monitoring Project:* This project focuses on reducing risks associated with extreme weather conditions on the ACR, by using specialized flood monitoring technologies at 10 different sites along a 392 km stretch of track. The flood

monitors will provide an advance warning system for high-water events that could pose a risk to the integrity of the track bed, enabling proactive intervention.

- *Water Level Sensor Technology for Remote Monitoring of Flood Risk on Rail Bridges in Southern British Columbia and Improving Bridge Resiliency:* This project will install water level sensors along the rail line to enable remote monitoring of river water levels near rail bridges in the southern British Columbia region. Project data will provide real-time information about the status of water levels, and provide notifications when levels threaten the structural safety of bridges.

Opportunities for future research:

- Monitoring and follow-up studies can be done on each of the projects to determine the effectiveness of the different remediation methods. Future research can be developed based on the results of each project.

Report Title: *RISK VIP: Evaluation of Flood Risk on the French Railway Network Using an Innovative GIS Approach*

Technical Journal/Source: 3rd European Conference on Flood Risk Management

Researchers/Research Organization: Mark Cheethama, François Chirouze and Laurent Bredier

Publication Date: October 2016

Technologies examined: Geographic Information System (GIS) model RiskVIP.

Key findings:

Flooding can have significant direct and indirect negative effects on a railway network affecting both infrastructure and rail operations. Identifying sections of railway line at risk from flooding allows appropriate actions to be targeted at specific areas and contributes to an effective asset management plan. This paper details an innovative approach developed at the SNCF using a Geographic Information System (GIS) model to identify zones of the railway network at risk of different types of flooding. The GIS model RiskVIP has been constructed through the assessment of three distinct components of risk: 'Vulnerability' (assessment of the susceptibility of the railway infrastructure to flood conditions using the infrastructure type, geometry and presence of hydraulic structures), 'Intensity' (capacity of a catchment to generate a flood flow characterized by the physical properties of the catchment), 'Probability' (probability of a rainfall event using data relating to important historic rainfall events). The model has been tested in the region of Languedoc-Roussillon in France on a reach of over 380km of railway line. The model RiskVIP allows the evaluation of flood risk to be undertaken at different scales and will aid in targeting precise reaches of railway line to be studied in more detail. It is a tool which can aid in the management of flood risk on the railway network, optimizing for example the maintenance program of drainage structures, ensuring monitoring and inspections are targeted at problem reaches, identifying areas where civil works are necessary and improving the overall resilience of the railway system.

Opportunities for future research:

- Develop a similar model to identify zones of the Canadian railway network that are at risk of different types of flooding.
- Incorporate the evaluation of how climate change could affect the risk of flooding to railway infrastructure into the model.

Report Title: *Idealizations of Dynamic Modelling for Railway Ballast in Flood Conditions*

Technical Journal/Source: Applied Sciences

Researchers/Research Organization: Kaewunruen S, Tang T.

Publication Date: April 2019

Technologies examined: Idealized single-degree-of-freedom system (SDOF) for ballast.

Flooded ballast; dynamic behaviors; SDOF system; idealization model analysis

Key findings:

Numerous studies into train–track interactions focused on ballast modelling and idealization in completely dry environments, but recent studies have found that, in extreme weather such as floods, water can clog natural ballast beds and change the initial state of their properties. The single degree of freedom (SDOF) idealization for ballast enables a non-destructive field-testing technique for monitoring of railway components in practice. In this study, the suitability of the idealization of ballast for dynamic characteristics has been evaluated. Full-scale experiments were conducted, and 6 models of ballast idealization concepts were formulated. The modal identification results reveal that the fundamental model (Model 1: spring dashpot) prevails over other models in terms of accuracy and precision. The more complicated models (such as Model 2 to 6) are not suitable for ballast idealization, especially in a flood condition. The experiments were performed with a variety of ballast conditions in flooding levels from 0 to 40 cm, with a frequency range of 0–500 Hz. The results clearly show that the increase in the flood level will result in increasing dynamic damping of more than 50% of dry natural ballast whilst reducing its stiffness and natural frequency. The novel insights are of great significance for exploring the non-linear dynamic traits of ballast in extreme environments, which can be integrated into the coupled train–track analysis that can better express more realistically the dynamic train–track interaction and load transfer mechanism of flooded railway tracks.

Opportunities for future research:

- This study considered a flash flood case only. In reality, the flood condition can also reduce the load carrying capacity and stiffness of the subgrade layer. In addition, the experiments in this study reveal that a frequency-based condition monitoring technique might have certain limitation in practice. Future work will highlight the development of new SDOF model that is more realistic and more capable of defining state-dependent characteristics of the railway tracks submerged under flood conditions.
- The influence of impulse energy as well as the track mass will also be investigated in the near future.

Report Title: *Blockage of box-shaped and circular culverts under flood event conditions: a laboratory investigation*

Technical Journal/Source: International Journal of River Basin Management

Researchers/Research Organization: Alrdadi R, Meylan MH.

Publication Date: October 2023

Technologies examined: Culvert drainage and design.

Urban drainage; flood; culvert; blockage; debris

Key findings:

Culverts are used to allow runoff to pass through roads, railways, and embankments. Accumulation of debris during flood events reduces the culvert flow capacity and hence flow overtopping results in culvert failure both hydraulically and structurally. This paper presents the results of an experimental study of temporal variations of blockage upstream of culverts due to woody debris under unsteady flow conditions. To simulate flood conditions, a synthetic flow hydrograph was produced in the laboratory. Cylindrical wooden dowels with two different diameters were used to simulate the woody debris carrying during flood events. Two culvert shapes including box and circular pipe culverts are examined here. The results showed that the maximum percentage of blockage occurs during the falling limb of the hydrograph. Although the feeding rate of smaller diameter woody debris into the flow is of considerable importance in the culvert blockage, the blockage percentage is not influenced by the feeding rate of large woody debris. It was also found that the pipe culvert is more susceptible to blockage than the box-shaped culvert. For the experimental conditions used in this study, it was found that a circular pipe culvert produces 9% more blockage than a box culvert. This is due to the fact that woody debris accumulates at the interior top inlet of the pipe. It is due to that pipe has minimum top width when it is close to fully full flow. Therefore, it is practically recommended to select a box shape culvert as an alternative rather than a circular shape culvert. Some empirical equations have been presented based on regression analysis for the calculation of blockage percentage and its height which can be used by hydraulic designers to increase the reliability of their designing against blockage. The results may be interesting for the stakeholders in the operational phase to increase the reliability of the culvert performance.

Opportunities for future research:

- The debris feed into the flume represented selected sizes from a range of potential debris sizes and different effects would be expected if the debris had a wider range of sizes. Therefore, more study is required to generalize the results for practical application.

Report Title: *Cross-drainage culvert design under global climate and land use changes*

Technical Journal/Source: ARPN Journal of Engineering and Applied Sciences

Researchers/Research Organization: Wirat Nuannukul, Anujit Phumiphan, Anongrit Kangrang

Publication Date: May 2021

Technologies examined: Fluid flow through pipes, R.C. box culvert and bridges under changing climate conditions.

Key findings:

In order to minimize the impact of water crossing the environment, culverts require the proper size, design and installation, to ensure that they do not cause downstream erosion, upstream flooding, alter stream habitat or block the passage of organisms. A drainage culvert should be designed according to design standards that can safely drain the design peak flow. The Rational Method relates the runoff-producing potential of a watershed, design rainfall intensity, and the watershed drainage area. However, the calculated flow from the Rational Method has to be adjusted for different catchments in various geographical locations throughout Thailand by the percentage of lake area and a correction factor for climate change. The objective of this research is to assess the effects of climate and land use changes on the amount of runoff that flows through 3 types of hydraulic structures: pipes, R.C. box culvert and bridges in Roi -Et Province, Thailand. This study used the Soil and Water Assessment Tool (SWAT) model which evaluated runoff using the simulation of climate scenarios with the data from the PRECIS model (a regional climate model) under the emission conditions of the IPCC SRES scenario B2 and considering the current land use data. The IPCC SRES scenario B2 models the sustainable social, economic, and environmental problem solving. The results showed that runoff volume estimated from the SWAT model was more than calculated with the Rational Method, which used the graph of the rainfall intensity-duration-frequency curve (IDF Curve). Therefore, the resulting the cross-sectional area size of the hydraulic structures evaluated from the SWAT model have more hydraulic cross-sectional area size than the estimated cross-section by the Rational Method and cross-sectional area size from the survey data.

Opportunities for future research:

- A similar study should be conducted using environmental and geographical data from Canada to determine the hydraulic cross-sectional area size needed in culverts, pipes, and bridges to account for climate change.

Report Title: *Automated machine learning recognition to diagnose flood resilience of railway switches and crossings*

Technical Journal/Source: Scientific Reports

Researchers/Research Organization: Jessada Sresakoolchai, Mehmet Hamarat, Sakdirat Kaewunruen

Publication Date: February 2023

Technologies examined: Automated machine learning recognition model to detect and predict the deterioration of railway turnouts exposed to flooding conditions.

Key findings:

This study develops new intelligent automation based on a machine learning pattern recognition model to detect and predict the railway turnout support deterioration which can be used in different situations especially flooding situations. Nonlinear finite element models which are validated by actual field measurements[2] are used to imitate the flooding and train the machine learning models. The key parameter used as a representative of the deterioration is stiffness. The machine learning technique that is used to develop the predictive model is convolutional neural network (CNN). Data used to train the model is numerical data obtained from LS-DYNA as finite element method (FEM) model simulations. The numerical models are verified with field measurements to make sure that the outputs from simulations are reliable. Outputs from FEM models that are used to train the machine learning model are axle box accelerations (ABAs) and crossing nose displacement. Outputs from FEM models are used in three forms to investigate the performance of the machine learning model. It is found that the use of both ABAs and crossing nose displacement provides the best performance when the accuracy of the prediction is higher than 0.98 followed by the use of ABAs when the accuracy is higher than 0.97. The use of crossing nose displacement provides a lower accuracy which is 0.93. It can be seen that adding one more sensor does not provide a significant improvement in prediction. However, the accuracy of every approach is high. It is to be noted that the features of the machine learning model are in time-series data form. CNN model seems to do well dealing with this format of data because it can detect the pattern hidden in the time-series data. For the deterioration prediction or regression problem, the developed machine learning model provides the highest accuracy of 0.98 when the error is less than 0.21 MN/m which is very accurate and good enough in practice. The study exhibits that the novel recognition model yields the potential capability to recognize and classify turnout support deteriorations facing extreme weather conditions which will be beneficial for responsible parties to schedule and plan maintenance activities.

Opportunities for future research:

- Field trials should be conducted by installing accelerometers at axle boxes of rolling stocks to measure the ABAs or cameras to measure the displacement of the crossing nose or both. The raw data collected by sensors can be fed into the machine learning model which will detect and predict the deterioration of turnout support deterioration.

2 Wan, C., Markine, V. L. & Shevtsov, I. Y. Analysis of train/turnout vertical interaction using a fast numerical model and validation of that model. *Proc. Inst. Mech. Eng. F J. Rail Rapid Transit.* **228**(7), 730–743 (2014).

Report Title: *Climatic Impacts on Railroad Infrastructure*

Technical Journal/Source: Technical Digest (AAR)

Researchers/Research Organization: Steve Wilk, Silvia Galvan-Nunez (MxV Rail)

Publication Date: July 2023

Technologies examined: Climate Change Projections, Satellite

Key findings:

- Increased extreme precipitation events are anticipated to occur in North America in coming decades, with the potential to increase flooding, washouts, embankment erosion, and substructure issues.
- The risk of these events is anticipated to vary significantly by geographic region, depending on increases in extreme precipitation, seasonality of precipitation, compounding factors, and human impact.
- Accurate risk assessments likely required detailed localized analyses.
- Multiple publicly available resources are being developed, improved and made more accessible. These resources, including but not limited to public databases and satellite imagery, can be adopted by railroads to reduce the risk from extreme precipitation and other climatic events.

Opportunities for future research:

- Broad but detailed regional climatic analysis for Canada that looks at precipitation, heat, and cold
- Continue exploring use cases of satellite data

Report Title: *Riverline Erosion Hazard Assessment*

Technical Journal/Source: Presentation at AREMA Sustainability and Resiliency 2024 Conference

Researchers/Research Organization: Aaron Moore (TranSystem), Curtis Heinsen (BNSF), and Scott Mackiewicz (Bruan Intertec)

Publication Date: February 2024

Technologies examined: Satellite, Riprap embankment

Key findings:

- Developed riverline erosion risk assessment for a pilot study in Clovis Sub (New Mexico). The assessment combined a desk study (satellite data) with field visits. An aggregate risk value was calculated by combining the two factors. Modeling was used to predict future erosion and determine the amount of time before track became at risk. Remediation was selected to fix immediate risk and work down the list
- Immediate risk locations were remediated with riprap embankments. Modeling was performed to determine how the fix would affect the riverflow and ensure issues were not created downstream
- Immediate risk locations required heavy remediation but it was discussed that once the immediate risk locations were resolved, the intermediate risk locations (5 year timeframe) could be addressed by other means such as vegetation.

Opportunities for future research:

- Technique could be expanded and adopted for other risks

Report Title: *Analysis of the effect of shoulder cleaning on particle migration within ballast based on a coupled CFD-DEM approach*

Technical Journal/Source: Transportation Geotechnics

Researchers/Research Organization: Jung Shu, Yi Wong, Yi Wian, Jamil Khan (University of South Carolina)

Publication Date: November 2022

Technologies examined: CFD/DEM Simulations, fine migration in ballast

Key findings:

- Developed a the computational fluid dynamics and discrete element method (CFD-DEM) to capture the interactions between fine particles/particles and fine particles/flow
- Flow through ballast requires a computationally intensive analysis that combines flow and discrete particles. For particle flow through a system involve factors governing particle-laden gravity-driven flow within the ballast with and without shoulder cleaning are considered, including the fouling index, fouling profile, and cohesive energy density (interparticle bonding forces that depend on the contact area between two particles)
- Particle migration and flow will be highly dependent on the permeability and flow structure of the ballast itself.

Opportunities for future research:

- The analysis was conducted for a different focus but this type of coupled CFD-DEM simulation approach will likely be needed for washout simulation
- There may be significant work in other sectors such as coastal but the unique track properties will need to be defined before those models can be adopted and used
- Fundamental parameters to define different embankment and ballast conditions are needed
- Continued improvement of the models are needed.

C5. Geohazard monitoring/mitigation technologies

Report Title: Analysis and Evaluation of Land Subsidence along Linear Engineering Based on InSAR Data

Technical Journal/ Source: KSCE Journal of Civil Engineering / 25(9)

Researchers/Research Organization:

Institute of Marine Science and Technology, Shandong University, Qingdao 266237, China

Publication Date: 2021

Technologies Examined: Synthetic Aperture Radar (SAR), Interferometric Synthetic Aperture Radar (InSAR), Small Baseline Subset (SBAS) InSAR, Global Positioning System (GPS), Precision Leveling, and Geographic Information System (GIS)

Key Findings:

This article focuses on monitoring and analyzing land subsidence along the Lunan high-speed railway using Synthetic Aperture Radar (SAR) images, high precision leveling results, and groundwater level monitoring data. The authors employ Small Baseline Subset (SBAS) Interferometric Synthetic Aperture Radar (InSAR) technology, spatial analysis technology of the geographic information system, and the contribution rate method to study the spatial and temporal evolution characteristics, influencing factors, and the contribution rate of each factor to land subsidence from 2016 to 2018.

The study demonstrates the effectiveness of SBAS-InSAR technology in monitoring land subsidence from 2016 to 2018 along the Lunan high-speed railway, showcasing the potential of SAR and InSAR technologies for comprehensive subsidence risk assessments to railway infrastructure. By analyzing SAR images, leveling results, and groundwater level data, it identifies key factors contributing to land subsidence, such as coal mining activities, the thickness of compressible layers, and groundwater level changes, emphasizing the importance of understanding these factors for the development of targeted mitigation strategies in the rail industry. The research quantifies the impact of subsidence, with maximum accumulated subsidence reaching 499 mm and rates exceeding -55 mm/yr in certain areas, providing crucial data for evaluating the implications on railway safety and operational efficiency. Furthermore, the accuracy of the InSAR monitoring results is verified through comparison with high precision leveling data, validating the reliability of InSAR technology for geohazard monitoring and supporting its use for continuous surveillance and risk assessment in the railway sector.

Opportunities for future research:

- Conducting longitudinal studies over an extended period could provide deeper insights into the long-term trends and effects of land subsidence on railway infrastructure. This would aid in understanding the cumulative impact of subsidence and the effectiveness of mitigation strategies over time.
- Developing advanced predictive models that incorporate machine learning or artificial intelligence to analyze InSAR data could enhance the accuracy of subsidence predictions. Such models could use historical data to forecast future subsidence events and their potential impact on railway safety and operations.

- Investigating the effectiveness of different land subsidence mitigation techniques, such as water injection, changes in land use, and infrastructure reinforcement, could provide valuable information for railway companies on the most cost-effective and sustainable strategies to combat subsidence.
- Exploring the relationship between climate change, groundwater level fluctuations, and land subsidence could offer insights into how changing environmental conditions affect subsidence rates. This research could contribute to developing adaptive strategies for railway infrastructure resilience in the face of climate change.
- Combining InSAR data with other geohazard monitoring technologies, such as GPS and LiDAR, could provide a more comprehensive understanding of the geohazard risks to railway infrastructure. Research could explore how these integrated technologies can be used for real-time monitoring and early warning systems.
- Conducting case studies on railways situated in diverse geological settings and soil types could help in understanding how different environmental conditions influence subsidence patterns and impacts. This could lead to the development of location-specific management and mitigation plans.

Report Title [Surface Deformation from Sentinel-1A InSAR: Relation to Seasonal Groundwater Extraction and Rainfall in Central Taiwan]

Technical Journal/ Source: Remote Sensing Vol 11

Researchers/Research Organization:

Department of Civil Engineering, National Chiao Tung University, 1001 Ta Hsueh Rd., Hsinchu City 30010, Taiwan

Publication Date: 2019

Technologies Examined: Sentinel-1A Synthetic Aperture Radar (SAR), Small Baseline Subset (SBAS) method, Global Positioning System (GPS), Leveling, and Interferometric Synthetic Aperture Radar (InSAR)

Key Findings:

The research utilized Sentinel-1A SAR data alongside GPS and leveling data to assess land subsidence, which is notably influenced by groundwater extraction for agriculture, aquaculture, and industrial purposes. The study's findings are validated through calibration with GPS measurements, reducing the velocity difference between the two sensors from 15.0 mm/a to 8.5 mm/a. It was observed that the dry-season subsidence significantly contributes to the annual subsidence, accounting for 60%-74% of it. The research also identified previously unknown subsidence spots over an industrial zone and a steel factory, demonstrating the high spatial resolution capability of InSAR data.

The study highlights the significant contribution of dry-season subsidence (October to April) to annual subsidence rates, emphasizing the impact of seasonal groundwater extraction. It demonstrates the effectiveness of calibrating InSAR-derived displacement rates using GPS measurements to improve the accuracy of subsidence monitoring, showcasing the benefits of integrating InSAR with GPS data. InSAR data's ability to identify subsidence spots in areas with limited leveling measurements underscores its utility in detecting subsidence in under-monitored regions. The research also points out the relationship between subsidence areas and dry-season rainfall, noting that significant subsidence areas expand with declining dry-season rainfalls, and a severe drought in 2015 markedly increased the subsidence area, highlighting the effect of climatic variations. Furthermore, the study suggests that the Hushan Reservoir's capacity to supply surface water during dry seasons could help reduce land subsidence caused by groundwater extraction, stressing the importance of water management strategies in subsidence mitigation. The reliability of InSAR as a monitoring tool is affirmed through its comparison with leveling data, proving its capability in detecting significant subsidence areas and supporting the assessment of subsidence mitigation measures.

Opportunities for future research:

- Conducting studies over a longer time period to better understand the long-term trends of land subsidence and its correlation with climatic patterns, especially considering the impact of climate change on rainfall variability and groundwater levels.

- Integrating InSAR data with advanced climate models to predict future subsidence patterns based on projected changes in rainfall patterns and groundwater extraction practices. This could help in developing proactive water management and land use planning strategies.
- Expanding the research to different geographic areas with similar subsidence issues to compare the effectiveness of various subsidence mitigation measures, such as the introduction of new water reservoirs or changes in agricultural practices.
- Exploring the use of higher-resolution InSAR technologies and new SAR satellites to detect even finer subsidence movements and understand their impacts on specific infrastructure components, such as railway tracks and foundations.
- Investigating the socio-economic impacts of land subsidence and mitigation measures on local communities, including the cost-benefit analysis of infrastructure adaptations versus long-term water management solutions.
- Combining geotechnical engineering, hydrology, and remote sensing to develop comprehensive models that can predict subsidence due to a combination of factors, including groundwater extraction, soil compaction, and natural sedimentation processes.
- Applying machine learning and artificial intelligence techniques to InSAR and other geospatial data to predict subsidence hotspots and their potential impact on infrastructure, allowing for dynamic risk assessment and management.

Report Title: **InSAR technique applied to the monitoring of the Qinghai–Tibet Railway**

Technical Journal/Source: NHESS Vol 19

Researchers/Research Organization:

The first Monitoring and Application Center, China Earthquake Administration, Tianjin, China

Publication Date: 2019

Technologies Examined: Interferometric Synthetic Aperture Radar (InSAR), Differential InSAR (D-InSAR), Permanent Scatterer Interferometry SAR (PS-InSAR), Small Baseline Subset InSAR (SBAS-InSAR), Stacking method, and Full Rank Matrix Small Baseline Subset InSAR (FRAM-SBAS)

Key Findings:

This article focuses on using Interferometric Synthetic Aperture Radar (InSAR) technology to monitor ground deformation along the Qinghai-Tibet Railway, particularly between Lhasa and Naqu. This railway, the highest in the world, traverses complex geological conditions, including permafrost regions, making it susceptible to deformation due to human activities and geological disasters. The study employs Advanced Synthetic Aperture Radar (ASAR) and TerraSAR-X data spanning from 2003 to 2012, covering periods before and after the railway's opening. Utilizing the Full Rank Matrix Small Baseline Subset InSAR (FRAM-SBAS) time-series analysis, the research provides insights into the subsidence patterns and their correlation with geological hazards along the railway.

Before the inauguration of the railway from 2003 to 2005, surface deformation was minimal, with a maximum rate of approximately 5 mm per year observed. However, post-opening, significant subsidence occurred in certain segments, particularly in the Damxung district, where subsidence rates reached up to 20 mm per year, attributed to the impacts of the railway's construction and operation. The railway's roadbed exhibited considerable instability in the initial 2-3 years following its opening, with various subsidence and uplift zones emerging along its length. Over time, the road surface gradually stabilized, and deformation rates decreased. The distribution of subsidence areas was found to correspond with geological hazards, especially in the Damxung area, suggesting that subsidence was influenced by the surrounding geological conditions and faults. This underlines the importance of continuous monitoring to ensure the railway's safety, highlighting InSAR technology's significance in geohazard assessment for railway monitoring. Despite the Qinghai-Tibet Railway's overall stability, the presence of permafrost and geological hazards necessitates ongoing monitoring. The study advocates for comprehensive deformation monitoring through geodetic surveys, such as GPS and InSAR, a detailed analysis of geological hazards along the railway, and the application of advanced data processing techniques for long-term regional monitoring.

Opportunities for future research:

- Exploring the integration of newer, more advanced InSAR technologies and other remote sensing methods to improve the accuracy and resolution of deformation monitoring. This could involve the use of high-resolution satellite data and the development of algorithms for better atmospheric correction and noise reduction.

- Conducting long-term monitoring studies to assess the evolving nature of ground deformation and its impacts on railway infrastructure over time. This would provide insights into the effectiveness of various mitigation strategies and the long-term stability of railway foundations in permafrost and other challenging environments.
- Combining InSAR data with ground-based monitoring techniques, such as GPS, seismic surveys, and soil analysis, to create comprehensive models of subsurface processes affecting railway stability. This multidisciplinary approach would enhance the understanding of complex interactions between geological hazards and railway infrastructure.
- Utilizing InSAR and other remote sensing data to develop detailed maps of geological hazards along railway routes. This would involve identifying potential risk zones for landslides, sinkholes, and permafrost thawing, and assessing their impact on railway safety and operation.
- Investigating the relationship between fault movement, seismic activity, and railway deformation. Future studies could focus on the impact of major seismic events on railway alignment and stability, providing critical data for earthquake preparedness and infrastructure resilience.
- Examining the impacts of climate change on permafrost degradation and its implications for railway infrastructure in cold regions. Research could focus on modeling future scenarios of permafrost thaw and developing engineering solutions to mitigate its effects on railway stability.
- Based on the findings of subsidence patterns and their correlation with geological hazards, research could explore innovative engineering solutions and mitigation strategies to enhance railway resilience. This might include the design of adaptive railway foundations, cooling techniques for permafrost, and early warning systems for geohazards.

Report Title: [Rainfall Scouring Mechanism of the High-Speed Railway Subgrade Slope with Coarse-Grained Soil]

Technical Journal/ Source: NHESS Vol 19

Researchers/Research Organization:

Railway Engineering Research Institute, China Academy of Railway Sciences Corporation Limited, Beijing 100081, China

Publication Date: 2023

Technologies Examined: Rainfall simulation experiments, Soil erosion modeling, Universal Soil Loss Equation (USLE), Hydraulic erosion process analysis, Erosion calculation models, Artificial rainfall experiments for slope instability studies, and Numerical modeling and simulation techniques.

Key Findings:

This study highlights the vulnerability of HRSS to erosion and landslides caused by rainfall, which poses significant stability risks. The authors developed an incipient flow velocity formula that integrates soil properties and slope characteristics, offering a more accurate and direct method for assessing erosion risks on subgrade slopes. This formula considers factors such as soil particle size, slope gradient, internal friction angle, and cohesion, demonstrating that erosion resistance on the slope decreases with increasing slope gradient and improves with higher cohesion (C) or internal friction angle (φ).

The study introduces a formula for determining the critical incipient flow velocity necessary for scouring, which comprehensively incorporates soil characteristics and slope features, offering a valuable tool for assessing erosion risks on HRSS slopes. It demonstrates that incipient flow velocity inversely correlates with slope gradient, highlighting the influence of slope gradient on erosion susceptibility. Furthermore, the study emphasizes the significant role of soil shear strength parameters, particularly cohesion (C) and internal friction angle (φ), in affecting erosion resistance. It notes that the internal friction angle (φ) exerts a more pronounced impact on erosion resistance for particle sizes ranging from 0.1 mm to 20 mm. Through comparison with field tests and existing empirical equations, the proposed formula is validated, showcasing its reliability and broad applicability for assessing erosion risks on both horizontal and subgrade slopes. Based on these insights, the research recommends enhancing the shear strength of slope soil as a strategy to improve erosion resistance. This contributes to the design of effective slope protection measures by offering a quantitative analysis tool that can guide the development of targeted erosion mitigation strategies.

Opportunities for future research:

- While the current study focuses on coarse-grained soils, future research could examine a wider range of soil types, including fine-grained and mixed soils, to understand how different soil compositions affect erosion mechanisms under rainfall.
- Investigating the impact of varying rainfall intensities and durations on subgrade slope erosion could provide deeper insights into erosion dynamics. This includes

studying extreme weather conditions and their potential to cause catastrophic slope failures.

- Developing and testing new erosion protection measures tailored to the characteristics of high-speed railway subgrade slopes. This could include innovative materials, bioengineering methods, or combinations of ecological and engineering protections that are both effective and environmentally friendly.
- Utilizing advanced numerical modeling and simulation techniques to predict erosion under various scenarios. This could help in designing more resilient infrastructure by considering the complex interactions between soil, water flow, and protective measures.
- Exploring the role of vegetation in mitigating erosion on railway subgrade slopes. Research could focus on the effectiveness of different plant species, root systems, and vegetation cover densities in protecting against erosion while also considering ecological benefits.
- Assessing how climate change, with its implications for increased frequency and intensity of extreme weather events, might affect the erosion risk of railway subgrades. This area of research is critical for developing long-term, climate-resilient infrastructure planning and management strategies.
- Implementing long-term field monitoring programs to collect data on erosion processes in real-world settings. This could validate and refine theoretical models and simulations, ensuring they accurately reflect practical conditions.
- Combining the findings with geospatial technologies, such as GIS and remote sensing, to map erosion vulnerability across extensive railway networks. This could facilitate targeted maintenance and proactive protection measures.
- Adopting interdisciplinary approaches that integrate insights from soil science, hydrology, environmental science, and civil engineering to address the multifaceted nature of erosion processes and slope stability.

Report Title: [Geohazards Analysis of the Litang–Batang Section of Sichuan–Tibet Railway Using SAR Interferometry]

Technical Journal/Source: IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 14, 2021

Researchers/Research Organization:

Second Tibetan Plateau Scientific Expedition and Research

Publication Date: 2021

Technologies Examined: Interferometric Synthetic Aperture Radar (InSAR), Sentinel-1 SAR images, Small Baseline Subset (SBAS) analysis method, and ALOS World 3D 30 m (AW3D30) digital surface model.

Key Findings:

This article presents a comprehensive study on the identification and analysis of geohazards along the Litang–Batang section of the Sichuan–Tibet Railway (STR) using interferometric synthetic aperture radar (InSAR) technology. The STR is a crucial infrastructure project connecting the Tibet Autonomous Region with the rest of China, traversing through challenging terrains marked by significant undulations, complex geological conditions, and active tectonic movements. This makes the identification of potential geohazards like landslides, sand-sliding slopes, collapses, ice avalanches, and debris flows critical for the construction and operation of the railway.

The study utilized the small baseline subset (SBAS) analysis method with C-band Sentinel-1 SAR images to successfully identify various geohazards, including landslides, sand-sliding slopes, and seasonally frozen soils along the railway section. Notably, high-risk geohazard areas, particularly in the Maoyaba-Batang section, were highlighted through hotspot and cluster analysis methods. It identified the head area of the ancient earthquake-triggered Luanshibao landslide as active, with a displacement rate of -15 mm/yr, posing a potential threat to the Sichuan–Tibet highway and possibly the railway. Additionally, the study detected seasonal displacements related to freeze-thaw cycles of seasonally frozen soils in the alluvial area of the Litang River, with a maximum amplitude of 20 mm. These displacements exhibited seasonal accelerations correlated with concentrated rainfall, indicating the influence of environmental factors on slope stability. The research also emphasized the presence of sand-sliding slopes with significant displacement rates, underscoring the importance of considering these areas during railway construction and operation. Overall, the study demonstrated the effectiveness of InSAR technology in detecting and monitoring mountainous unstable slopes, providing valuable insights for route selection, geohazard prevention, and ensuring the safety of railway construction and future operation, while highlighting the impact of seasonal environmental and climatic factors, especially rainfall, on slope stability.

Opportunities for future research:

- Developing more sophisticated models that integrate InSAR data with other remote sensing technologies and ground-based observations. These models could improve the prediction accuracy of geohazard occurrences and their potential impacts on infrastructure.

- Establishing long-term monitoring programs that utilize InSAR and other remote sensing methods to track the evolution of identified geohazards over time. This would help in understanding the dynamics of geohazards and their response to climatic and environmental changes.
- Investigating the impacts of climate change on the frequency, intensity, and distribution of geohazards. Research could focus on how changing patterns of precipitation, temperature fluctuations, and extreme weather events influence the stability of slopes and the occurrence of landslides and other geohazards.
- Developing integrated risk assessment frameworks that consider the complex interplay between geological, hydrological, climatic, and human factors in geohazard risk evaluation. This would aid in making informed decisions for railway construction, maintenance, and operation.
- Exploring innovative engineering solutions and mitigation strategies to address identified geohazards. Research could focus on the design and effectiveness of various slope stabilization, drainage improvement, and erosion control measures in mountainous terrain.
- Conducting studies on the socio-economic impacts of geohazards on infrastructure projects like the Sichuan–Tibet Railway. This includes assessing the costs of geohazard prevention, mitigation, and response strategies, as well as their implications for local communities and economies.

Report Title: **Risk assessment of geohazards along Cheng-Kun railway using fuzzy AHP incorporated into GIS**

Technical Journal/ Source: GEOMATICS, NATURAL HAZARDS AND RISK2021, VOL. 12

Researchers/Research Organization: MOE Key Laboratory of Intelligent Manufacturing Technology, Department of Civil and Environmental Engineering, College of Engineering, Shantou University, Shantou, Guangdong, China

Publication Date: 2021

Technologies Examined: Analytic Hierarchy Process (AHP), Triangular Fuzzy Number-Analytic Hierarchy Process (TFN-AHP), Geographic Information Systems (GIS), and Raster calculator (within GIS)

Key Findings:

This study employs TFN-AHP and GIS to predict geohazard risks along the Cheng-Kun Railway, emphasizing areas with high potential for geological hazards such as Ya'an, Leshan, Liangshan, and Kunming. The assessment considers environmental factors, the existing warning system, and workers' perceptions of risk to enhance the railway's safety and operation. The methodology effectively identifies high-risk regions, validating its consistency with recorded geological events over the past decade.

The study effectively predicted geohazard risks through the integration of TFN-AHP with GIS, closely aligning with the actual occurrence of geological disasters along the railway. High-risk regions were primarily identified in Ya'an, Leshan, Liangshan, and Kunming, with a particular emphasis on the vicinity of the railway. Notably, the TFN-AHP method demonstrated higher efficiency in identifying high-risk areas compared to the traditional AHP method, showing a greater percentage of high-risk sections and indicating a more sensitive detection of potential hazards. The assessment's validity was further confirmed by the fact that approximately 86.66% of the recorded geological hazards along the railway occurred in areas identified as high-risk, reflecting real-world conditions accurately. The study underscores the importance of collecting and organizing operational data to enhance the geological disaster warning system and suggests the establishment of a management flowchart that integrates disaster feedback into safety risk management processes to update hazard databases and provide background analysis for future events. Additionally, it recommends involving local communities and enhancing safety awareness among railroad workers and residents in high-risk areas as part of new management strategies.

Opportunities for future research:

- Future research could explore integrating real-time environmental and geological data, such as rainfall intensity and seismic activity, into the TFN-AHP model to provide dynamic risk assessments that can adapt to changing conditions.
- Incorporating machine learning and artificial intelligence techniques to analyze and predict geohazard risks could improve the accuracy and efficiency of risk assessments. These models can learn from past events to predict future geohazards more precisely.

- Comparing and cross-validating the TFN-AHP method with other risk assessment models could provide insights into the strengths and limitations of various approaches and lead to the development of hybrid models that leverage the best features of each.
- Researching the impact of climate change on geohazard frequency and intensity along the railway could provide valuable information for long-term planning and mitigation strategies.
- Examining how communities along the railway perceive geohazard risks and their willingness to participate in mitigation efforts could inform more effective community-based risk management strategies.
- Studying the economic impact of geohazards on railway operations, including the cost of disruptions, repairs, and preventive measures, could help prioritize investments in risk mitigation based on cost-benefit analyses.
- Research into developing and implementing advanced early warning systems for geohazards that use the TFN-AHP method's findings to alert railway operators and communities could enhance safety and reduce damages.
- Conducting detailed case studies of successful geohazard management practices in other railway systems around the world could provide valuable lessons and best practices that can be adapted to the Cheng-Kun Railway.

Report Title: [Deformation of the Zhangjiazhuang high-speed railway tunnel: an analysis of causal mechanisms using geomorphological surveys and D-InSAR monitoring]

Technical Journal/ Source: Journal of Mountain Science

Researchers/Research Organization: School of Earth Sciences, Lanzhou University, Lanzhou 730000, China

Publication Date: 2021

Technologies Examined: InSAR (Interferometric Synthetic Aperture Radar), GPS/GNSS (Global Positioning System/Global Navigation Satellite System), UAV (Unmanned Aerial Vehicle) imagery, 3D numerical simulation, Electrical resistivity technology, and Ground penetrating radar.

Key Findings:

This article provides an in-depth analysis of geohazard monitoring in the rail industry, focusing on the specific case of the Zhangjiazhuang tunnel deformation incident along the East-West High-speed railway in China. This case study highlights the complexities and challenges associated with tunnel construction in geologically sensitive areas, particularly those prone to landslides and other geohazards.

The relationship between landslides and tunnels is complex and directly influences tunnel deformation, with varying positions leading to different stress characteristics and deformations. Advanced modeling and theories, such as the 'slip line' theory, contribute to understanding and mitigating these effects. Technological advances in geohazard monitoring, including InSAR technology and 3D numerical simulations, provide high-precision monitoring of surface movements and the ability to analyze landslide impacts on tunnels. However, traditional investigations remain essential for a detailed understanding of geohazard characteristics. Geological structures like joint sets and faults, as well as geomorphological processes such as erosion and loose landslides, significantly affect tunnel stability, necessitating detailed investigations for safe tunnel construction and operation. The case study of the Zhangjiazhuang tunnel deformation illustrates the importance of comprehensive geohazard assessments, attributing the incident to a combination of geological conditions, previous landslide activity, and potentially active faults. These findings underscore the need for detailed geohazard assessments, encompassing geological, geomorphological, and hydrological investigations, to effectively identify and mitigate risks to tunnel safety.

Opportunities for future research:

- While InSAR and GPS/GNSS technologies provide critical data on surface deformation, future research could explore the integration of these methods with emerging technologies such as machine learning and artificial intelligence. These approaches could improve the prediction of geohazards by analyzing patterns of deformation over time and predicting future movements with greater accuracy.
- Further development of 3D numerical models to simulate the complex interactions between geological processes and tunnel structures. This includes the effects of groundwater dynamics, seismic activity, and anthropogenic factors on tunnel stability.

Enhancing these models could lead to better understanding and mitigation of potential risks.

- Investigating new materials and construction techniques that could enhance the resilience of tunnels to geohazards. This includes the development of flexible, durable, and repairable tunnel lining materials that can withstand deformation without significant damage.
- Deepening the understanding of the mechanisms behind deep-seated landslides and their impact on underground structures. This involves detailed subsurface investigations, long-term monitoring of groundwater levels, and the study of pre-existing geological faults.
- Since water plays a significant role in triggering landslides and other geohazards, future research could focus on the hydrogeological impacts on tunnel stability. This includes studies on the effects of irrigation, changes in land use, and climate change on groundwater levels and flow patterns.
- Given the potential impact of active faults on tunnel integrity, as suggested by the tunnel deformation case study, further research is needed to understand the relationship between fault activity, seismic events, and tunnel deformation. This includes developing methods for early fault detection and assessing the long-term stability of tunnels in fault-prone areas.
- Developing comprehensive risk assessment and management frameworks that incorporate the latest research findings and technological advances. These frameworks should aim to improve decision-making processes related to tunnel design, construction, and maintenance in geohazard-prone areas.
- Encouraging cross-disciplinary research that combines geology, engineering, material science, and environmental science to address the multifaceted challenges of tunnel construction in geohazard-sensitive areas.

Report Title: **IPL Project 202: Landslide Monitoring Best Practices for Climate-Resilient Railway Transportation Corridors in Southwestern British Columbia, Canada**

Technical Journal/ Source: Progress in Landslide Research and Technology, Volume 1

Researchers/Research Organization: Geological Survey of Canada, 1500-605 Robson Street

Publication Date: 2022

Technologies Examined: Satellite Interferometric Synthetic Aperture Radar (InSAR) analysis, Unmanned Aerial Vehicle (UAV) photogrammetry, Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) surveys, Electrical Resistivity Tomography (ERT) surveys, Piezometers, Geophysical surveys, and Bathymetric surveys.

Key Findings:

This article discusses the implementation and findings of ICL-IPL Project 202 in southwestern British Columbia, Canada, focusing on landslide mapping and change-detection monitoring in relation to the national railway infrastructure. The region's unique geophysical and biogeoclimatic characteristics contribute to various landslide types that pose risks to transportation corridors. The project employs a comprehensive approach combining remote sensing, GIS, and in-situ monitoring technologies to understand landslide dynamics and inform mitigation strategies for railway safety.

The study area exhibits diverse landslide types, ranging from rapid landslides like rock and debris avalanches in high-relief areas to slower movements like rockslides and slumps in moderate to low relief areas. Remote sensing datasets, including satellite InSAR analysis and UAV photogrammetry, are integrated into a GIS to capture spatial relationships between landslide distribution, terrain features, and environmental conditions correlated with landslide activity. The research emphasizes the effective use of various monitoring solutions such as satellite InSAR analysis, UAV photogrammetry, and RTK-GNSS surveys to detect and analyze landslide movements, providing crucial data for managing railway infrastructure risks. In-situ monitoring technologies like ERT surveys and piezometer installations offer detailed insights into the internal structure of landslides and hydrological factors influencing their behavior. The study also recognizes the impact of geological conditions, extreme weather events, and climate change on landslide activity, highlighting the need for robust monitoring and mitigation strategies. Collaboration among government agencies, the rail industry, and academia is deemed essential for developing effective landslide risk management practices, underscoring the importance of shared knowledge and resources. The article proposes a best-practice solution involving three levels of investigation—fundamental geoscience, geospatial benchmarks, and time-series monitoring—to comprehensively understand and manage the wide range of landslide phenomena.

Opportunities for future research:

- Investigating the integration of newer, more advanced remote sensing technologies, such as higher resolution satellite imagery, LiDAR (Light Detection and Ranging), and UAVs equipped with advanced sensors, to improve the accuracy and efficiency of landslide detection and monitoring.

- Conducting detailed studies on the impact of climate change on the frequency, magnitude, and distribution of landslides, especially in relation to extreme weather events, to better predict and manage these geohazards in the future.
- Exploring the use of machine learning and artificial intelligence in processing and analyzing large datasets from remote sensing and in-situ monitoring for predictive modeling of landslide occurrences and behavior.
- Fostering interdisciplinary research that integrates geoscience, civil engineering, climatology, and information technology to develop comprehensive strategies for landslide risk assessment, mitigation, and adaptation.
- Developing and testing new in-situ monitoring technologies, such as wireless sensor networks and automated monitoring stations, that can provide real-time data under extreme environmental conditions.
- Researching engineering solutions and design practices that enhance the resilience of railway infrastructure to landslides, including the development of new materials and construction techniques that can withstand geohazard forces.
- Assessing the socioeconomic impacts of landslides on railway operations, including cost-benefit analyses of mitigation strategies, to inform policy and investment decisions.

Report Title: **Technogenic Hazards of Russian North Railway**

Technical Journal/ Source: Transportation Soil Engineering in Cold Regions, Volume 1

Researchers/Research Organization: Lomonosov Moscow State University, Moscow, Russia

Publication Date: 2020

Technologies Examined: Drilling, Landscape zoning, Near-field transient electromagnetic sounding (NTES), and Electrical resistivity tomography (ERT)

Key Findings:

This article investigates the impacts of permafrost degradation on railway infrastructure, focusing on a segment of the Russian North Railway between Pesets and Hanovey stations where thaw subsidence has been particularly problematic. The study, conducted in summer 2018, identified zones of subsidence as high as 0.5 meters. A combination of drilling, landscape zoning, near-field transient electromagnetic sounding, and electrical resistivity tomography was employed to assess the stratigraphy and permafrost conditions underlying the railway embankment.

The degradation of permafrost is identified as a significant challenge for railway infrastructure in cold climates, with thaw subsidence directly impacting the stability and performance of railway tracks. The study reveals that the soils beneath the railway embankment exist in both thawed and frozen states, exhibiting a discontinuous spatial arrangement that complicates engineering and geological conditions. Thaw settlement is attributed to snow accumulation along the railway embankment, insulating the ground in winter and preventing further ground freezing, thereby exacerbating thaw subsidence. Various geophysical methods, such as near-field transient electromagnetic sounding and electrical resistivity tomography, are employed to assess permafrost conditions, providing valuable insights into the thickness of permafrost and the distribution of thawed and frozen zones. Borehole data and geological analysis indicate that the area consists of loam and silt with varying ice content, overlaying Permian bedrock. Construction and maintenance of railways in permafrost regions face challenges due to the thermal sensitivity of frozen ground, where minor changes in heat transfer at the ground surface can trigger thaw and result in significant embankment settlements. The study suggests that allowing for natural thaw settlement and periodic reloading of the embankment may be the most economically viable mitigation strategy, with continuous monitoring of subsidence rates recommended for effective management and maintenance of railway infrastructure.

Opportunities for future research:

- Exploring the development and application of more advanced remote sensing and geophysical technologies for real-time monitoring of permafrost conditions. This includes satellite-based radar interferometry, drones equipped with thermal cameras, and ground-penetrating radar with higher resolution to detect early signs of permafrost thaw and subsidence.
- Developing and refining numerical models to simulate the thermal regime and mechanical behavior of permafrost under various climate scenarios. This research

would aim to predict future thaw settlement patterns and assess the long-term stability of railway infrastructure on permafrost.

- Investigating the impacts of climate change on permafrost degradation patterns, particularly focusing on the increased frequency of extreme weather events and their effects on the thermal balance of permafrost areas. This includes studying the role of snow insulation and vegetation changes on permafrost thaw.
- Researching innovative engineering solutions and construction materials that are adaptable to changing permafrost conditions. This could include the design of adaptable foundations, the use of geosynthetics for soil reinforcement, and the development of embankment structures that minimize heat transfer to the underlying permafrost.
- Developing sustainable management practices for railway operations in permafrost regions, focusing on minimizing the anthropogenic impact on permafrost and enhancing the resilience of railway infrastructure through adaptive design and maintenance strategies.
- Conducting comparative studies of railways operating in permafrost regions across the globe to share knowledge, best practices, and lessons learned in managing permafrost-related geohazards.
- Assessing the economic impacts of permafrost degradation on railway operations, including the costs associated with maintenance, repair, and potential rerouting, to inform investment decisions and prioritize mitigation efforts.

Report Title: **Freeze-Thaw Deformation Cycles and Temporal-Spatial Distribution of Permafrost along the Qinghai-Tibet Railway Using Multitrack InSAR Processing**

Technical Journal/Source: Remote Sensing Vol 13

Researchers/Research Organization: Key Laboratory of Digital Earth Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing

Publication Date: 2021

Technologies Examined: Sentinel-1A Synthetic Aperture Radar (SAR), Multitrack Time-Series Interferometry Synthetic Aperture Radar (MTS-InSAR) Method, Sentinel-1 Dataset, ISODATA Classification Method, Savitzky–Golay (SG) Filter Algorithm, and Range-Doppler (RD) Geolocation Algorithm

Key Findings:

This article presents a comprehensive study on geohazard monitoring along the Qinghai-Tibet Railway (QTR) through large-scale seasonal deformation and annual average deformation rate maps obtained using the Multitrack Time-Series Interferometry Synthetic Aperture Radar (MTS-InSAR) method. This approach enabled the analysis of freeze-thaw cycles and the identification of sections along the QTR with potential geohazards.

The study conducted a comprehensive analysis of surface deformation in the area, finding that the seasonal amplitude ranged from -70 to 20 mm, with most areas exhibiting values smaller than 30 mm between March 2017 and March 2020. The Line of Sight (LOS) deformation rate varied from -40 to 20 mm/year, indicating a generally small secular subsidence trend. Notably, higher values of seasonal deformation were primarily observed in specific regions, including glacier outwash plains, the vicinity of Salt Lake, Beiluhe areas, braided stream plains of Tuotuohe, downstream of the Chumar River, the Yangbajing area, and the southern region of Lhasa. Within the 10 km buffer zone along the Qinghai-Tibet Railway (QTR), seasonal deformation ranged from -50 to 10 mm, with the LOS deformation rate spanning from -30 to 15 mm/year. The study validated these findings against leveling data, demonstrating low absolute errors and high correlations, confirming the reliability of InSAR measurements. Sections along the QTR with significant subsidence were identified, encompassing areas from Golmud to Xidatan, Budongquan to Hoh Xili, Wudaoliang to Beiluhe, Fenghuo Mountain to Wuli, Tuotuohe to Yanshiping, Tanggula Mountain to Amdo, Naqu to Damxung, and Yangbajing to Lhasa, which were noted for potential geohazards due to their high deformation rates. Additionally, the study proposed a novel approach for mapping permafrost distribution based on InSAR time series deformation results, classifying permafrost into permafrost, seasonally frozen ground, and degraded permafrost. These classification results were mostly consistent with Zou's method, providing new insights into permafrost distribution mapping. Future work aims to utilize multisource SAR data for a comprehensive surface deformation survey and active layer thickness retrieval on the Qinghai-Tibet Plateau (QTP), combining InSAR data with other measurement and remote sensing data to advance permafrost distribution studies.

Opportunities for future research:

- Integrating multi source SAR data, including high-resolution and different frequencies (e.g., L-band, C-band, and X-band), could provide detailed insights into permafrost dynamics and geohazard mechanisms along Canadian railways traversing permafrost regions.
- Developing methodologies for active layer thickness retrieval using InSAR data could enhance understanding of permafrost changes over time and their implications for railway infrastructure stability in Canada.
- Conducting longitudinal studies to track the progression of identified geohazards over time along Canadian railways would be valuable for assessing the effectiveness of mitigation measures and understanding the long-term impacts of climate change on permafrost regions.
- Integrating InSAR-derived permafrost deformation data with climate models could improve predictions of permafrost thawing rates and the potential for geohazard development under various climate change scenarios, particularly relevant for Canadian northern regions.
- Exploring the influence of vegetation cover and soil moisture variations on permafrost stability and seasonal deformation patterns along Canadian railways could offer insights into the complex interactions between surface conditions and permafrost dynamics.
- Utilizing InSAR data to develop comprehensive risk assessment models for infrastructure along Canadian railways could lead to the formulation of targeted mitigation strategies to protect against geohazards.

Report Title: [IPL Project 202: Landslide Monitoring Best Practices for Climate-Resilient Railway Transportation Corridors in Southwestern British Columbia, Canada]

Technical Journal/Source: Progress in Landslide Research and Technology, Volume 1, Issue 1, 2022

Researchers/Research Organization: David Huntley et al. (Geologic Survey of Canada)

Publication Date: 2022

Technologies Examined: Boreholes, Satellite InSAR, UAV, RTK-GNSS Surveys, Piezometers, Inclinometers, Acoustic Waves, Weather Stations

Key Findings:

The paper outlines landslide mapping and change-detection monitoring protocols based on the successes of ICL-IPL Project 202 in southwestern British Columbia, Canada. In this region, ice sheets, glaciers, permafrost, rivers and oceans, high relief, and biogeoclimatic characteristics contribute to produce distinctive landslide assemblages. Bedrock and drift-covered slopes along the transportation corridors are prone to mass-wasting when favourable conditions exist. In high-relief mountainous areas, rapidly moving landslides include rock and debris avalanches, rock and debris falls, debris flows and torrents, and lahars. In areas with moderate to low relief, rapid to slow mass movements include rockslides and slumps, debris or earth slides and slumps, and earth flows. Slow-moving landslides include rock glaciers, rock and soil creep, solifluction, and lateral spreads in bedrock and surficial deposits. Research in the Thompson River Valley aims to gain a better understanding of how geological conditions, extreme weather events and climate change influence landslide activity along the national railway corridor. Remote sensing datasets, consolidated in a geographic information system, capture the spatial relationships between landslide distribution and specific terrain features, at-risk infrastructure, and the environmental conditions expected to correlate with landslide incidence and magnitude. Reliable real-time monitoring solutions for critical railway infrastructure (e.g., ballast, tracks, retaining walls, tunnels and bridges) able to withstand the harsh environmental conditions of Canada are highlighted. The provision of fundamental geoscience and baseline geospatial monitoring allows stakeholders to develop robust risk tolerance, remediation, and mitigation strategies to maintain the resilience and accessibility of critical transportation infrastructure, while also protecting the natural environment, community stakeholders, and the Canadian economy. We conclude by proposing a best-practice solution involving three levels of investigation to describe the form and function of the wide range of rapid and slow-moving landslides occurring across Canada, which is also applicable elsewhere.

Opportunities for future research:

- Continue advancing real-time monitoring of landslides in Canada to further refine best-practices
- Start developing a scalable framework to assess risk across a large section of track/network

Report Title: Landslide Monitoring with RADARSAT Constellation Mission InSAR, RPAS-Derived Point-Clouds and RTK-GNSS Time-Series in the Thompson River Valley, British Columbia, Canada

Technical Journal/Source: Progress in Landslide Research and Technology, Volume 2, Issue 1, 2023

Researchers/Research Organization: David Huntley et al. (Geologic Survey of Canada)

Publication Date: 2023

Technologies Examined: Satellite InSAR, UAV, RTK-GNSS Surveys, M3C2**Key Findings:**

The four landslide change-detection methods evaluated in this study have their individual strengths and limitations when applied to mapping slow-moving rotational-translational landslides. RTK-GNSS surveying is well accepted as being both accurate and precise. However, collecting data is laborious, and achieving wide area measurement coverage similar to InSAR or RPAS surveying, even at small sites, is impractical.

M3C2 is a simple and accessible algorithm to run. It is free and open source. By operating directly on point-clouds, the complexity of intermediate processing steps is greatly reduced. The displacement magnitude of the M3C2 output may appear simple to interpret, but the variability in measurement direction, and the insensitivity to surface parallel movement are major limitations for rotational and translational landslides. Since variation in movement direction is only measured on surface normals, M3C2 is the only measurement technique that cannot be directly compared with other methods.

InSAR is the only method not requiring physical site visits. RCM data acquisitions allowed for a set of measurements that were not only broad in spatial coverage, but also dense in temporal measurements. These data provided a level of insight into the seasonal dynamics of landslide movement not possible with other methods. The LoS limitation of InSAR added complexity to interpretation and satellite tasking.

Generally, we found good agreement between our InSAR and 3D RPAS methodologies for stationary and lower deformation rates. However, in parts of the landslide where the deformation rate approached approximately 20 cm yr.−1, InSAR measurements typically reported lower rates than the 3D RPAS method. This may have been a result of an imperfect comparison of datasets with different measurement periods.

Combining RPAS digital image correlation with the DSM of difference was the only method able to provide a full 3D movement vector for each point with broad coverage across the landslide. Compared to M3C2, the processing requires more complexity and familiarity with a number of open source tools. However, the outputs are more directly interpretable, and capable of providing better insights into the landslide dynamics.

Opportunities for future research:

- Continue advancing monitoring capabilities and develop scalable framework that can assess a large section of track/network.

C6. Technologies for managing cold weather operational

Report Title: *Long-term diagnostic technology for the monitoring of continuous welded rail on curves in a cold area*

Technical Journal/Source: AIP Advances, Volume 11

Researchers/Research Organization: Rixin Cui, Liang Gao, Jun Ye, Xiangmin Zhang

Publication Date: July 2021

Technologies examined: A long-term and remote diagnostic system for the monitoring of CWRs on curves which includes a sensor subsystem, a data acquisition and transmission subsystem, and a data analysis and management subsystem.

Key findings:

In cold areas where the annual rail temperature difference can exceed 90°C, continuous welded rails (CWRs) on small-radius curves are more likely to buckle or distort owing to the large radial temperature force and large lateral deformation of the rails. To facilitate safe operation of trains in cold areas, a magnetostrictive displacement measurement technique was used to measure the lateral displacement of CWRs in this study. Then, a long-term monitoring system, including a sensor subsystem, a data acquisition and transmission subsystem, and a data analysis and management subsystem, was established for the monitoring of CWRs on small-radius curves and applied in a field test. The sensor subsystem monitors the ambient temperature, rail temperature, and lateral deformation of the curve. The data acquisition and transmission subsystem are responsible for collecting the data captured by the sensors and sending these data to a remote server using the general packet radio service (GPRS) network. The data analysis and management subsystem receives and analyzes the signal transmitted by the GPRS data transmission module. Each monitoring terminal can obtain data from the server through the internet. The field test site was chosen as a set of CWRs on a small-radius curve of a passenger and freight mixed transportation line with a ballasted track in Northeast China. This test line was built with CWRs whose neutral temperature was set as 19 °C. At the beginning of the test, the track had been in operation for about 2 years.

One year of continuous observation results showed that this monitoring system could effectively realize the functions of real-time acquisition, wireless transmission, and data storage in a cold climate. Particularly, the magnetostrictive displacement sensor was successfully able to resist low temperatures and oil and collect displacement data with no signal drift or calibration during its operation. The monitoring system has good application prospects for state monitoring tests on railways in severe environments. The preliminary analysis of the monitoring data shows that the lateral deformation of CWRs on the small-radius curve has close association with the rail temperature, and it is also affected by the local conditions of the railway line, such as the curve superelevation and the train operation speed.

Opportunities for future research:

- Determine the limit value of rail temperature and lateral deformation of CWR stability under the combined action of temperature load and wheel-rail force.
- Combined with the proposed limit value, the collection and analysis of these observation data, including the air temperature, rail temperature, and lateral displacement of the rail, can be further applied for the stability prediction of CWRs on small-radius curves.

Report Title: *A method for long-term on-line monitoring of temperature stress of continuously welded rail*

Technical Journal/Source: Advances in Mechanical Engineering, Volume 13

Researchers/Research Organization: Sun L-J, Li Z-W, Zhu W-F, et al.

Publication Date: August 2021

Technologies examined: A mathematical model of ultrasonic stress detection and an online monitoring system for the temperature stress of critically refracted longitudinal wave steel rails.

Key findings:

In this paper, the stress detection model of ultrasonic rail is established, and the corresponding relationship between stress and ultrasonic acoustic velocity is studied. The 3D finite element model of rail temperature stress detection is established. The effects of key factors such as incident angle and frequency of the longitudinal wave and transducer distance on the detection accuracy are analyzed. The corresponding relationship between temperature stress and critical refracted longitudinal wave signal sound velocity is obtained. Finally, an online monitoring system of rail thermal stress is set up in the training base of the Changzhou section of the Shanghai-Nanjing high-speed railway in China for long-term real-time monitoring. The specific conclusions are as follows:

- Theoretical analysis shows that ultrasonic longitudinal wave is sensitive to the thermal stress in its propagation direction. The acoustic propagation varies with thermal stress, proving that it is feasible to detect rail thermal stress by critical refraction longitudinal wave.
- The numerical simulation analysis shows that the temperature stress of the rail is measured. The transducer with a 4 mm radius is used. The incident frequency of the longitudinal wave is 5 MHz, the incident angle is 28°, and the distance between transducers avoids the integer times of echo distance. The receiving transducer can receive the clearest critical refraction longitudinal wave signal, and the highest detection accuracy can be achieved.
- Through the online monitoring system of rail temperature stress, temperature stress monitoring data of the line in 2019 has been accumulated. The accumulation of long-term monitoring data forms the design specification of seamless lines, providing technical support for the construction and maintenance management of public works.

Opportunities for future research:

- The method for rail temperature stress detection using the critically refracted longitudinal wave can realize the long-term monitoring of the rail temperature stress and is superior to other ultrasonic detection temperature stress methods. However, the mining of accumulated data has not yet been carried out. Therefore, future research should focus on the early intelligent warning of rail temperature force monitoring.

Report Title: *Effect of Culverts on the Thermal Regime of a Railway Embankment*

Technical Journal/Source: Journal of Cold Regions Engineering, Volume 37

Researchers/Research Organization: Mahya Roustaei, Michael Thomson Hendry, Alireza Roghani/NRC

Publication Date: December 2022

Technologies examined: Culvert configuration to minimize frost penetration.

Key findings:

A common issue for Canadian railway operators is the development of localized frost heave near railway culverts, which leads to nonuniform deformation of the track surface and degradation of the track geometry, damages the track component, and affects the quality of rides in railway operations. This paper investigates the effects of culverts and insulation layers on changing the temperature regime of the ground during the winter–spring period through numerical modeling in TEMP/W (version 2019) two-dimensional (2D) and three-dimensional (3D) software, a finite-element software product for modeling thermal changes in the ground due to environmental changes or the construction of facilities such as buildings or pipelines. The model was calibrated using actual field measurements collected from an instrumented section of the track that has suffered from frost heaves at the proximity of a culvert. The study site is located on a section of the VIA Rail track in eastern Ontario that is extensively monitored with structural and geotechnical instrumentation. Using the results from 2D simulation, the effect of culverts on extending the frost zone, in both horizontal and vertical directions, was quantified. In addition, the effects of shape, installation depth, and the number of culverts on the frost penetration depth were discussed. Using TEMP/W 3D results, the most appropriate configuration to install the culverts was studied to minimize frost penetration.

The results demonstrate that the culvert had a warming effect on the ground during summer and a cooling effect during winter, with this effect strengthening in winter when minimum temperatures are imposed at the culvert locations. Additionally, results clearly show that the cooling and warming effect of culverts in freezing and thawing periods becomes stronger at locations deeper in the embankment and closer to the culvert, with the embankment temperature more affected by fluctuations in ambient temperature. The parametric study showed that increasing the diameter and burial depth of the culvert will result in deeper frost depth while increasing the amount of water in the culvert limits the area of the thermal exchange surface and markedly reduces the frost depth. Changing the geometry of the culvert did not markedly change the maximum frost penetration depth; however, the area of the frozen zone was affected. The simulation results of 3D numerical modeling showed that adding a geofoam layer as a thermal insulation technique reduces the effect of culverts on soil temperature profiles. The location of the geofoam layer was relevant, with this study showing that the most effective arrangement was a 75-mm insulation layer attached to the culvert walls combined with a 50-mm U-shaped layer wrapped around it (Scenario A1 + A3).

Opportunities for future research:

- Conduct further research on the use of thermal insulation for reducing the longitudinal distance of influence of culverts and the duration of the freezing phase of subgrade soil.

- Conduct a field study using the findings of this study and compare real-world results to the modeled results.

Report Title: *The study of frost heave mechanism of high-speed railway foundation by field-monitored data and indoor verification experiment*

Technical Journal/Source: Acta Geotechnica

Researchers/Research Organization: Niu, F., Zheng, H., & Li, A.

Publication Date: October 2018

Technologies examined: Frost heave mitigation methods.

Key findings:

Due to the rigid deformation limit of high-speed railways, the anti-frost heave design has become a critical concern in seasonally frozen regions. In this study, the authors explained the frost heave mitigation techniques adopted for the high-speed railway between Harbin and Dalian in northeast China and then presented the thermal, deformation, and water content data monitored on the Gongzhuling test site. Data was collected using a series of automatic monitoring equipment. According to these data, the authors proposed the possible frost heave mechanisms of the high-speed railway foundation. The foundation is composed of well-graded gravel with cement and A/B group fill, which are treated as non-frost-susceptible materials in general. Based on the monitored data, the authors found that the surface layer (0–0.5 m) contributed most to the total frost heave and this might be caused by local water accumulation inside the foundation (0.6–1.2 m). In order to demonstrate the frost heave ability of these "non-frost-susceptible" materials, the authors conducted an indoor frost heave test with a mixture of gravel and 3% Kaolinite clay. Through this experiment, it was demonstrated that, with sufficient water supply, gravel with a limited amount of fine material can produce significant frost heave. Accordingly, we can conclude that the accumulated water inside high-speed railway foundation causes the frost heave deformation. For the engineering mitigation methods of frost heave, the authors have two suggestions: first, prevent the outside water from entering the high-speed railway foundation by closing the surface and side boundary of the foundation; second, disrupt local water accumulation and cut the water migration path by inserting waterproof sheets into the middle layer.

Opportunities for future research:

- This study was conducted for the high-speed railway between Harbin and Dalian in northeast China. There is potential for a similar study to be conducted on a railway in Canada facing frost heave to determine if similar mitigation techniques can be used.

Report Title: *Lessons learned from long-term frost heave monitoring under a railway embankment*

Technical Journal/Source: NRC Publications Archive

Researchers/Research Organization: Roghani, A.; Caldwell, Robert; Hiedra-Cobo, Juan; Charbachi, Paul, National Research Council Canada

Publication Date: November 2021

Technologies examined: The mechanism of frost development.

Key findings:

National Research Council Canada in collaboration with VIA Rail Canada has conducted a 3-year field investigation to study the mechanism of frost development and its impact on safety and performance of train operations. In this project, a 50 m section of VIA Rail track was instrumented with various geotechnical and structural monitoring systems, including thermistors, borehole extensometers, ShapeArrays, and piezometers. These instruments measured track response under static (every 10 minutes) and dynamic modes (100 Hz, triggered by each train passage) during the monitoring period which consisted of two freeze-thaw seasons. In addition, measurements from ground penetrating radar (GPR) and a track geometry car were collected over 90 km of track to map frost-susceptible sections of track and quantify its effect on track geometry degradation. The GPR assessment was proven to be useful and cost effective when the assessment is needed over long distances. It also helps to identify the source of frost heave, whether it is highly fouled ballast, frost-susceptible sub ballast, or a problem within the subgrade. The integration of GPR data with other measurements such as track geometry proved useful to not only detect the source of the problem but also identify its impact on track performance. The difference in winter conditions during the monitoring period in terms of temperature and snow on ground, induced different temperature regimes within the track substructure and led to different track responses. The limited field observations in this project suggested that even though the warmer and drier winter may result in a shorter freezing period and shallower frost depth, the higher number of intermittent freeze-thaw cycles (FTC) lead to larger differential frost heave in winter and higher track roughness in spring. This may lead to a condition that is more detrimental to track geometry and safe operations than a cold winter.

Opportunities for future research:

- The research conducted in this project was limited in scope and was performed over a well-maintained class 5 track in Ontario. Further research is required for the performance of a lower-class track in a colder region of Canada.

Report Title: *Study on the splashing behavior of high-speed railway ballast in ice and snow environment: Analysis of the influence of the train speed, ice mass and striking position*

Technical Journal/Source: Construction and Building Materials, Volume 411

Researchers/Research Organization: Hong Xiao, Yihao Chi, Zhihai Zhang, Mahantesh M. Nadakatti, Shaolei Wei

Publication Date: January 2024

Technologies examined: Simulation model of snow flight on high-speed train-ballasted track.

Key findings:

In severe cold areas, ice and snow blocks often adhere to the bogie position of a high-speed train body. With the high-speed running of the train, the ice and snow blocks are easy to fall off and hit the ballast on the surface of the ballast bed, causing the ballast flight and impacting the train body structure simultaneously. This is referred to as the problem of snow flight. The snow flight in severe cold regions has occurred on many high-speed railway lines in China, directly impacting the safety of high-speed railway operations. In this paper, a coupling simulation model integrating the Discrete Element Method (DEM), Multi-Body Dynamics (MBD), and Computational Fluid Dynamics (CFD) is used to build a refined simulation model of snow flight on high-speed train-ballasted track. The DEM-MBD-CFD coupling analysis method uses the DEM module of the ballast bed as an intermediate medium to carry out data exchange with the CFD module of track flow field and the MBD module of track power. This model reveals the main types of snow flight hitting the train body and identifies the flow field distribution characteristics on a ballasted track under high-speed train operation conditions. The accuracy of the model is validated through on-site measurements. The results show that the wind pressure amplitude at the center of the ballast bed is the largest, the bottom of the rail is the second largest, and the shoulder of the ballast is the smallest. After the ballast particles fly away from the ballast bed, the main power source is the negative pressure generated by the train's airflow field. The number of flying ballast particles and the impact force on the train floor grow with the increase of train speed. With the increase of ice mass, the impact stress first increases rapidly and then slowly. When the ice mass is 7 kg, the impact stress has exceeded the yield strength of the train body, seriously affecting the safety of the operation. Prevention measures can be taken to reduce the damage of snow flight, such as:

1. Reducing the operation speed. It is recommended to reduce the speed to below 250 km/h on high-speed railway lines under severe ice and snow conditions.
2. Implementing ice and snow removal. It is recommended to prepare ice and snow removal tools, equipment, and personnel in advance.
3. Installing anti-splash coating and grille. It is recommended to apply anti-splashing coatings on the surface between the ballast and the sleeper to solidify loose ballast particles or install an anti-splashing grille on the surface of the ballast.
4. Optimizing the structure design. It is suggested to reduce the ballast height at the center of the ballast bed, raise the height of the rail bearing platform, optimize the ballast gradation on the surface of the ballast bed, adopt aerodynamic optimization sleepers, and add deflectors at crucial parts of snow cover to improve the airflow performance in these areas. At the same time, it is suggested to adopt a streamlined, smooth train body and front snow baffle to optimize the train body structure.

Opportunities for future research:

- Similar research should be conducted in Canada as higher speed passenger trains are anticipated with the development of High Frequency Rail.

Report Title: *Study on the braking distance of composite brake blocks covered with ice for freight trains in winter*

Technical Journal/Source: Journal of Rail and Rapid Transit

Researchers/Research Organization: Zhang Y, Liu Z, Stichel S.

Publication Date: January 2023

Technologies examined: A numerical model to study the influence of ice on braking distance.

Key findings:

This work studies the influence of composite brake blocks covered with ice on the braking performance of freight wagons in winter. With this model, the relationship between braking distance and the influencing factors, e.g., ice thickness, ambient temperature, initial speed, and brake pressure/axle load, can be studied. The experimental validation of the model is difficult because it is hard to measure some parameters like ice thickness and COF. The results, however, are compared with general findings from test results reported in the literature as much as possible. The following conclusions can be drawn from the presented study:

1. Ice on the brake block's friction surface significantly influences the braking distance of freight trains. Thick ice, low ambient temperature, low initial speed, empty wagons, or low brake pressure increase the braking distance because more time is needed to remove ice in all these cases.
2. Reducing the clearance between the wheel and brake block helps to enhance the braking performance because the ice thickness is limited by clearance. Conditioning brake also helps to keep good braking performance because ice cannot grow continuously. High brake pressure helps to remove ice fast because it generates high friction heat flux during braking.
3. Cast iron has better braking performance than composite brake blocks in winter because composite materials have higher wettability than cast iron. Ice grows easier on composite brake blocks than on cast iron, which makes a significant difference in ice thickness.

Opportunities for future research:

- Investigate the importance of how ice is built up on the surface of brake blocks.
- Using a dynamometric test rig and modelling more brake pad properties are necessary to further validate and develop the model.

Report Title: *Experimental investigations on the performance of anti-snow designs for urban rail train bogies*

Technical Journal/Source: Journal of Wind Engineering & Industrial Aerodynamics

Researchers/Research Organization: Tiantian Wang, Yu Wang, Guangjun Gao, Changlong Zhao, Chen Jiang

Publication Date: February 2022

Technologies examined: Anti-snow structures - deflectors and wheelset snow shields.

Key findings:

In this study, the engineering issue about snow and ice accumulation on the bogies of urban rail trains was investigated. To analyze the snow and ice accumulation process, experiments for real urban rail train non-powered bogie were conducted for the first time in the Central South University Icing and Snowing Wind Tunnel (CSU-ISWT). Two anti-snow structures of urban rail train bogies were proposed and tested. Based on the experimental results, the following conclusions can be drawn.

1. The snow and ice accumulation were serious on the original bogie, with numerous icicles and ice blocks appearing at the bottom of the bogie. When the deflectors or wheelset snow shields were installed on the bogie, snow accumulated in a finite area of the bogie surface. The icing rate decelerated, and the final ice volume evidently decreased.
2. The snow particles carried in the incoming airflow and the meltwater from the heating components both contributed greatly to the snow and ice on the bogie. The distribution on the bogie under the three cases was similar. The amount of snow and ice on the lower part of the bogie was greater than that on the upper part, and the amount on the windward side of frame was greater than that on the leeward side.
3. From the quantitative data, the brake device was the severest icing component on original bogie. The mass reduction rates of the two optimization schemes were more than 50%, indicating that the anti-snow structures can effectively reduce the mass of snow and ice on the bogie. Moreover, they made outstanding contributions to the snow prevention performance in some crucial components or regions, such as brake devices and the bottom of the train body.

Opportunities for future research:

- Conduct experimental tests in Canada on operational locomotives to test the efficacy of deflectors and wheelset snow shields as anti-snow structures.

Report Title: *Numerical and experimental investigation on snow accumulation on bogies of high-speed trains*

Technical Journal/Source: Journal of Central South University

Researchers/Research Organization: Gao, G., Zhang, Y., & Wang, J.

Publication Date: May 2020

Technologies examined: Semi-empirical snow saltation model.

Key findings:

Snow accumulation on the undercarriage of a train is an important issue that significantly degrades the safety and performance of the vehicle. This phenomenon is primarily attributed to snow saltation induced by train-generated wind gusts. This study numerically investigated the snow accumulation on a train by modelling the snow saltation for the initial movement of drifting snow from the ground. A semi-empirical snow saltation model was applied to the boundary condition for a snow-covered ground, and Eulerian governing equations were solved for snow phase flow. Using the present method, a high-speed train model comprising multiple cars and a single-car model were simulated. The results presented the novel trend of snow accumulation, which gradually increased towards the rear of the train but remained relatively constant after a third car.

Opportunities for future research:

- In the future, a low-temperature wind-snow experimental platform will be built for the investigation of the snow issue of bogie. The movement characteristics around a rear bogie cavity will be recorded using high-speed camera, and the accumulating mass and distribution on the bogies will be accurately measured. Moreover, the heat radiated by motors, gear covers brake calipers and rotating wheels will be reproduced during the experiment, and the complex phase-changing process among snow, water and ice will be considered simultaneously.

Report Title: *A Trolley Wire Deicing System*

Technical Journal/Source: Energies 2022, Volume 15

Researchers/Research Organization: Grzegorz Radomski, Sławomir Karyś, Paweł Stawczyk

Publication Date: September 2022

Technologies examined: Trolley wire deicing system.

Key findings:

This paper presents a dedicated system for deicing trolley wires. The proposed issue is appropriately under the protection of intellectual property for solving as described in patent no. B1 230665 PL in the Patent Office of the Republic of Poland. In the solution presented herein, deicing is achieved mainly by electrodynamic force excitation and secondarily as a result of heating. Because ice is removed primarily through vibrations, it avoids a large consumption of electricity associated with the high specific heat of water. More importantly, operation is nearly simultaneously applied to the total distance of the trolley power grid between two substations. For this reason, it requires less electricity consumption and less time to apply than in heating, mechanical, or chemical methods.

Spectrums of the vibration of components of a trolley power grid were derived from the experiments. Based on this data, one can conclude that there are a number of resonant frequencies of different parts of a trolley power grid that could be useful for deicing. Because resonant frequencies change, in the case of variable meteorological conditions it is necessary to apply an algorithm with online optimization of vibrations. Due to the differences in built of spans, the control method should scan a frequency band for voltages that are able to excite enough vibrations to deice each span of the traction line.

Opportunities for future research:

- In Poland and other countries with DC traction supplied by a voltage of approximately 3 kV, most of the main electric traction lines have double trolley wires, consisting of two component wires spaced 0.1 m from each other. Research should be done on the type of trolley wires used in Canada and how the findings of this experiment can be transferred.
- Further experimental verification should be carried out on a real traction line. The proposed method allows for the deicing process to be applied over the entire distance of the traction line in a relatively short time.

Report Title: *Modelling anti-icing of railway overhead catenary wires by resistive heating*

Technical Journal/Source: International Journal of Heat and Mass Transfer, Volume 143

Researchers/Research Organization: Fritjof Nilsson, Ali Moyassari, Ángela Bautista, et. al.

Publication Date: November 2019

Technologies examined: Prevention of ice formation on metallic, non-insulated electrical cables using resistive heating.

Key findings:

Aggregation of ice on electrical cables and apparatus can cause severe equipment malfunction and is thus considered as a serious problem, especially in arctic climate zones. This study examines how resistive heating can be used for preventing formation of ice on metallic, non-insulated electrical cables. A resistive heating strategy for overcoming ice-aggregation on outdoor railway cables has been examined with 3D FEM multi-physics simulations and corresponding climate chamber measurements and the results have been compared with existing semi-empirical equations. The heat equation was solved together with Navier-Stokes equations for predicting the cable temperature as function of external temperature, wind speed, cable radius, applied electric energy and wind direction. In order to validate the FEM results and confirm the possibility to use the anti-icing strategy in realistic conditions, a model railway cable system was built and tested in a climate chamber. When the resistive heating efficiency, i.e., the ratio between applied electrical energy and resulting thermal energy, was set to 68%, the transient FEM simulation curves coincided nearly perfect with the experimental data but note that this value is a wire-specific variable rather than a universal constant. It is thus very important to take the heating efficiency into account when designing anti-icing systems based on model predictions. An analytical equation for the heat transfer coefficient h was derived from the multi-physics FEM simulations, an equation that can potentially be used in anti-icing prediction expert systems.

Opportunities for future research:

- The experimental portion of this study was conducted in a climate chamber with a special chamber for creating icing conditions. Field studies should be conducted on using resistive heating as a method for deicing.

Report Title: *Rail transportation safety investigation report R19C0015: Uncontrolled movement of rolling stock and main-track train derailment*

Technical Journal/Source: The Transportation Safety Board of Canada (TSB)

Researchers/Research Organization: The Transportation Safety Board of Canada (TSB)

Publication Date: March 2022

Technologies examined: Automatic parking brakes and maintenance of brake cylinders on freight cars in cold weather.

Key findings:

On 4 February 2019, the Canadian Pacific Railway Company (CP) freight train 301-349 being operated by a relief crew derailed on Field Hill near Field, British Columbia, on a 13.5-mile section of track with a steep descending grade (average 2.2%) and several sharp curves. The 3 crew members—a locomotive engineer, a conductor, and a conductor trainee—were fatally injured in the derailment. The incident occurred on the steepest part of a mountain in extreme cold temperatures (below −25 °C). The emergency brakes were required and were maintained for around 2.5 hours. During this time, the ambient temperature had dropped to −28 °C, and the train's air brake system had been leaking compressed air, reducing the brakes' capacity to hold the train on the steep grade and causing the derailment. TSB outlined the safety deficiencies contributing to the accident which include the degradation of air brake systems in extreme cold temperatures and the limitations of current train brake test methodologies to accurately evaluate air brake performance in these temperatures.

Many technological advancements are available to North American railways to enhance train brake performance, including automatic parking brakes, high-capacity fade-resistant brake shoes, control valves with a brake cylinder maintaining feature, and retention of dynamic brake force on remote locomotives. There is AAR-approved technology available for securing trains, which takes most of these variables out of the equation: automatic parking brakes for rail vehicles (APBs), such as Wabtec's Automatic Park Brake and New York Air Brake's ParkLoc. APB technology has been tested and approved for use on North American railways, but it has not been widely adopted.

Opportunities for future research:

To address the systemic safety issues that posed a significant risk in this occurrence, the Board made 3 recommendations, namely:

- that the Department of Transport establish enhanced test standards and requirements for time-based maintenance of brake cylinders on freight cars operating on steep descending grades in cold ambient temperatures (TSB Recommendation R22-01).
- that the Department of Transport require Canadian freight railways to develop and implement a schedule for the installation of automatic parking brakes on freight cars, prioritizing the retrofit of cars used in bulk commodity unit trains in mountain grade territory (TSB Recommendation R22-02)

Report Title: Test Report Cold Weather Air Brake Research: Phase 2

Technical Journal/Source: N/A

Researchers/Research Organization: National Research Council Canada and Transport Canada - Innovation Centre

Publication Date: N/A

Technologies examined: Cold weather air brake research and testing.

Key findings:

The objective of this research is to understand the performance and operations of freight train air brakes under controlled and repeatable cold weather conditions; to develop recommendations on design, operational practices, and procedures for mitigating risks of the loss of air brake performance; and to develop recommendations to improve current train brake test methodologies to accurately evaluate air brake performance in colder conditions. Two rounds of testing were completed on 12 separate air brake systems (8 service worn supplied by railways, 4 new/refurbished) in 2022-2023. Results show that the service worn brake systems at all conditions tested consistently produced lower brake force as temperature was reduced. In the range from 0°C to -20°C the reduction was not severe, but from -30°C to -40°C a considerable loss of brake force was observed for the service worn systems. For emergency brake applications, results were compared for 10 minutes and 90 minutes after application. As with the service braking, the service worn systems overall produced lower emergency brake force. The retainer valve tests showed that the service worn systems retained brake force poorly at colder temperatures and even new retainer valves on new systems did not hold the force well below -30°C. A variety of failure modes were observed in the colder temperature conditions that were not present at warmer conditions: premature release, failure to pressurize, slow loss of pressure, loss of emergency pressure reservoir, loss of response to pressure commands, over pressurization. Preliminary automatic parking brake (APB) test results were shared with government-industry working group on APB technology.

Opportunities for future research:

- Future research will focus on understanding sources of leakage in the air brake system how these sources may or may not be detected as temperatures fall, as well as testing the effectiveness of typical locomotive operating procedures for cold weather and effectiveness of ‘recover and release’ procedure.
- Automatic parking brake testing should be done on an operational locomotive to further validate the technology.

Report Title: *Autonomous detection of compressed air leaks on trains*

Technical Journal/Source: Rail Safety IDEA Program

Researchers/Research Organization: Christopher Stoos, Southwest Research Institute (SwRI)

Publication Date: September 2022

Technologies examined: Autonomous detection of compressed air leaks on trains.

Key findings:

Southwest Research Institute developed a proof-of-concept system to autonomously detect compressed air leaks on moving trains. The system uses audio detection technology, cameras and machine learning to autonomously detect, identify and report air leaks. The system uses a small, commercially available Fluke SV600 fixed acoustic imager that uses a 64-microphone array and camera tuned to detect frequencies of 30-45kHz, the frequencies at which compressed air leaks best stand out from most background noise. This instrument works together with a secondary visual spectrum camera. To automate the detection process, machine learning algorithms were trained and implemented to identify air leaks from the sensor outputs while ignoring non-leak related outputs. The YoloV5 model was used for air leak detection along with tracking logic which looked for leak persistence through time as it progresses through the field of view for the sensor. A basic notification system was developed to notify mechanical department personnel of the number of leaks, the leak locations, and the system confidence in each leak detected. During testing, the prototype system successfully detected a range of air leaks at various locations on locomotives with a false positive rate of only 0.03%. The system detected, on average, 11 out of every 13 leaks on a moving train. Once an air leak was identified, an alert with an accompanying image was shared electronically with appropriate personnel showing the area in need of inspection and repairs.

Opportunities for future research:

- This proof-of-concept system was trained with a relatively small amount of data and the data contained only locomotives on a ~1/4 mile stretch of track. To improve the equipment range, performance and reliability of the model, more data is needed of longer trains with varied rail cars and equipment at various operation speeds. This cannot be achieved in a lab or shop setting and will require field testing on an active rail line.
- The inputs to the model were constrained by available access to the SV600 camera feeds. A notable improvement could be achieved with access to the SV600's raw camera stream and Audio mask. Additionally, separating the audio mask and video streams could eliminate the need for the visual spectrum camera as a separate sensor.
- Initial testing was limited in track speed of less than 10 mph. Additional testing at a suitable location will be required to determine the upper limits of track speed at which accurate detection could occur. Detection is limited by sensor frame rate, distance from the track, and train speed. If it is possible to increase the frame rate of the SV600 (30fps) detection could occur at significantly higher track speeds.
- Research must be done one how to detect leaks without direct line of sight, and how to address those leaks.

Report Title: *Ultrasonic Rail Flaw Testing Parameters in Extreme Cold Temperature*

Technical Journal/Source: Transport Canada Innovation Centre Published Reports

Researchers/Research Organization: MxV Rail, Transport Canada - Innovation Centre

Publication Date: May 2023

Technologies examined: Ultrasonic rail flaw testing parameters in extreme cold temperatures.

Key findings:

This research investigated the ultrasonic testing (UT) parameters associated with the ultrasonic rail flaw testing as related to extreme cold conditions. The specific objective of this research was to assess the effect of extreme cold temperatures on the velocity of ultrasound in couplants and rail steel. The research measurements were intended to provide data on densities and ultrasonic wave velocities at temperatures ranging from -40° C to 0° C. The effect of extreme cold temperatures on the refraction angle of ultrasonic waves was also examined. Some of the key findings of this research include:

Contact UT Tests: Data scatter was observed during most of the velocity measurements. These velocity measurements were result of amplitude shifts (erratic readings) of the recorded A-scans. The amplitude shifts in A-scans may be due to the changes in the piezoelectric crystal properties due to prolonged exposure to the lower temperature.

- Average L-wave velocity, average S-wave (45°) velocity, and average S-wave (70°) velocity were determined at both room temperature and at -38°C with changes of 0.22%, 2.61%, and 1.65% respectively.

Non-Contact UT Tests: Ultrasonic velocity increased with decreasing temperature for all fluids tested. All velocity measurements followed the same linear trend (increasing) with the decrease in temperature.

- L-wave velocities for rail steel were measured from 23°C to only -30°C. Temperatures below -30°C were not achievable in the chiller batch. Measurements at temperatures of -20°C, -25°C, and -30°C were not consistent with the overall trend velocity increasing as temperature decrease.
- The procedure used for a 45° S-wave was effective but again proved problematic for 70° S-waves due to ultrasonic signal losses in the immersion liquid (80/20 glycol/water) as temperatures decreased.
- A 45° refraction angle change as a function of temperature was found to be 0.0782°C, and the relationship was found to be linear.

UT Beam Modeling and Simulation: Ultrasonic beam modeling and simulation was conducted to assess ultrasonic beam field responses for the range of ultrasonic velocities and densities determined for different cold temperatures.

- The refraction angle shows a decreasing linear trend with a linear regression value of 0.98 for both cases. This shift in the angle of refraction can cause the beam to shift away from the targeted inspection zone, a shift that can cause the beam to possibly miss defects in that zone during the inspection process.

- Except for the water/steel simulation at room temperature, all other simulations conducted for extreme low temperatures failed to detect transverse type defects as a result of the change in the refraction angle.

Opportunities for future research:

- Contact UT Tests: Future research will need to be performed to better understand how the cold temperature affects the UT A-scan amplitudes.
- Non-Contact UT Tests: The experimental results reported were developed from the data on ultrasonic velocities; additional detailed testing is needed to characterize attenuation changes as a function of temperature. Additionally, the phenomena of increased attenuation in both the rail steel and the liquid couplant may be worthy of further study. Very little data is available in the literature to document this effect.
- UT Beam Modeling and Simulation: Based on the possibility of a shift in the angle of refraction, it is highly recommended that hi-rail ultrasonic system calibration is conducted at cold temperatures when performing testing at cold temperatures.

Report Title: *Investigation of Tie Plate Icing/Ice Jacking*

Technical Journal/Source: Transport Canada Innovation Centre Published Reports

Researchers/Research Organization: MxV Rail and Transport Canada Innovation Centre

Publication Date: May 2023

Technologies examined: Tie plate icing/Ice jacking.

Key findings:

Investigated and documented the tie plate icing/ice jacking during three field inspection trips to three railroads in cold weather conditions. The overall goal of this research is to understand 1) the root causes and effects of tie plate icing on track performance and train operation safety, 2) potential methods for identification and monitoring of tie plate icing, and 3) potential remedial methods and actions for tie plate icing. Case studies (field inspections) were conducted at the railroad sites where tie plate icing problems occurred in the past to gain an understanding of the issue and acquire the experience from the railroads. The key findings from this study include the following:

- Tie plate icing is difficult to identify in track with covered snow. Typical indications of the occurrence of tie plate icing include "black marbling" or "cauliflowering" of snow by rail movement, changes in track gage, and rail cant.
- Tie plate icing is believed to be caused by a combined effect of track conditions and weather conditions. The areas of concern, including curves, joints, turnouts, road crossings, bridge approaches, etc., are typically associated with wood ties with cut spikes and significant rail movements. Poor tie condition and fouled ballast are often found to be in the areas of tie plate icing.
- Two conditions that could cause tie plate icing are: rail jacked by snow and rail jacked by ice. The first condition happens when that snow gets blown against the bottom of the rail and then becomes packed layer by layer to jack up the rail. The second condition occurs when weather conditions create freeze-thaw cycles where snow/ice melts and becomes trapped in the gap between the bottom of the rail and tie plate and freezes again.
- Based on the experience of the three railroads, the remediation actions included manual removal of ice or melting with snake rope, replacement of degraded ties and fasteners, improved ballast drainage, and maintenance to tighten up geometry.
- A preliminary finite element (FE) model was developed for the next phase of this study. This model consisted of a detailed rail-tie-fastening system capable of simulating the effect of tie plate icing on track performance.

Opportunities for future research:

- Future work will focus on comprehensive modeling efforts, laboratory testing, and the development of remediation methods for in-track testing. A brief conceptual laboratory test plan was prepared for the next phase. The main purpose of the laboratory test is to validate the computer model. However, this plan will need to be expanded and detailed with the steering committee and railroads.

Report Title: *Review of the current state of knowledge regarding the design, construction and maintenance of railway lines over permafrost*

Technical Journal/Source: Transport Canada Innovation Centre Published Reports

Researchers/Research Organization: National Research Council Canada and Transport Canada – Innovation Centre

Publication Date: March 2023

Technologies examined: The design, construction and maintenance of transportation infrastructure on permafrost regions.

Key findings:

This literature review was conducted to document the current state of knowledge regarding the design, construction and maintenance of transportation infrastructure, in particular railway tracks, on permafrost regions around the world. Methods to prevent permafrost include sheds, shading boards, coarse (crushed) rock embankment, air (ventilation) ducts, insulation layers (typically composed of polystyrene or polyurethane), a heat drain, which is an innovative system developed by Groupe de recherche en ingénierie des chaussées de l'Université Laval, and the thermosyphon cooling method. Measures to protect the permafrost under a cutting slope include construction of a retaining wall, turf and insulation covering, coarse-grain soil replacement and insulation, and drainage systems. During railway construction in permafrost regions, to preserve permafrost and minimize the environmental impacts, highway embankments are often constructed during the winter.

Opportunities for future research:

- Studying the implications of climate change on permafrost degradation at different regions across northern Canada using the most recent climate models and evaluating its impact on the cost of developing new railway lines and maintaining existing ones.
- Investigating the proper embankment height and width and the optimized size of rock aggregates, ballast, and sub ballast particles to preserve permafrost below the embankment. There have been a lot of simulations and in-field studies in this area, however testing various configurations under controlled laboratory conditions would provide a basis for a route-optimized design. The NRC's large climatic chamber enables testing of large-scale models under various climatic conditions.
- Investigating the most suitable types of track components for railway construction in northern Canada including rail, ties, fastening systems, etc. The types currently used in Canada's rail network may not necessarily be sufficient for the extremely cold temperatures of the north. The research may involve testing components under controlled laboratory conditions.
- Investigating proper rail neutral temperature for constructing continuously welded rail in the north to minimize the risk of rail breaking.
- Testing train braking systems under extreme cold temperature.

MxV Rail Tech Scan References

Report Title: *Investigating the impact of frost heave and thaw softening on hanging the vertical force at wheel/rail interface*

Technical Journal/Source: 2021 Canadian & Cold Regions Rail Research Conference

Researchers/Research Organization: Alireza Roghani, Yan Liu, & Paul Burgess

Publication Date: November 2021

Technologies examined: The effect of frost heave and thaw softening on vehicle track interaction and train safety.

Key findings:

Frost heave and thaw softening results in non-uniform deformation of the track substructure and causes track geometry irregularities. The resulting rapid deterioration of track structure, adverse vehicle track interaction and poor ride quality can jeopardize train safety. NUCARS® simulations were conducted to evaluate the changing track condition because of freeze-thaw cycles. Surveyed track geometry data from a section of track that was monitored throughout 2019 and 2020 were used in the simulations and the results were evaluated against the vehicle track worthiness criteria in AAR M-1001. A maximum of 28% in wheel unloading was observed in the results occurred at a culvert location, and the operating conditions deteriorated over time. It was noted that the thawing stage in the freeze-thaw cycle created worse combinations of wheel-rail force.

Opportunities for future research:

- The study only considered track geometry deviations as a result of the freeze-thaw cycles. The model can be enhanced by taking geological survey data and characterizing the subgrade stiffness during the winter season and adding a track layer into the multibody dynamics model.
- The study modelled one type of passenger car. Further studies can be conducted to expand the scope of car types modelled and address any potential safety issues for both passenger and freight trains.
- Detection and mitigation measures against unsafe operating conditions caused by frost heave and thaw softening can also be investigated.

Report Title: *Assessment of the applicability of a thawing-guided drainage system for old railway tunnel icicle prevention in cold weather*

Technical Journal/Source: Applied Sciences, 2022, Vol.12 (22), p.11645, Article 11645

Researchers/Research Organization: Sangjoon Kang, Taehoon Koh, Hanju Yoo

Publication Date: November 2022

Technologies examined: Icicle prevention in railway tunnels.

Key findings:

As train failures from icicles annually recur in old railway tunnels in cold weather, fundamental measures to prevent the formation of icicles within the tunnels are necessary for the safe operation of trains and efficient maintenance of old tunnels. This study develops and tests a thawing-guided drainage system for old railway tunnels. The proposed system consists of heating panels, supporting stands, and drainageways for discharging leaked water. A heating panel is composed of a film heater, thermal insulator, and a steel plate. The heater installed on a steel plate supplies the heat source to prevent icicle formation. This system uses a low-power module lining structure, which fundamentally prevents the formation of icicles from cracks in old railway tunnels and induces the drainage of thermally melted icicles to the outside of the track. A prototype system was installed in the Seungbu tunnel (a railway tunnel) and monitored over 3 weeks in winter from 22 December 2021 to 12 January 2022. The icicle prevention and guided drainage performances were verified at an ambient temperature of about -10 °C, with an internal temperature for maintaining the system above 0 °C throughout the test period. The proposed system was showed to be effectiveness through icicle prevention performance, and operational safety which does not interfere with train operations.

Opportunities for future research:

- Although this is a practical problem threatening train safety in the winter, a survey is required to understanding its applicability in Canada. Railways traditionally used icicle breaker cars to break the icicles as trains travelled through tunnels, the potential negative effects of icicle breaker cars are not widely understood. Icicle breaker cars may not be effective if they are placed behind cars equipped with a pantograph.
- Canadian winters can be much colder than -10 °C and the viability of a powered heating system needs to be assessed.

Report Title: *Investigating the mechanism of frost penetration under railway embankment and projecting frost depth for future expected climate: A case study*

Technical Journal/Source: Cold regions science and technology, 2022, Vol.197, p.103523, Article 103523

Researchers/Research Organization: M. Roustaei a, M.T. Hendry, A. Roghani

Publication Date: February 2022

Technologies examined: Using a calibrated numeric model to predict frost penetration.

Key findings:

A common issue for railways constructed in cold regions is the development of localized frost heave on the surface of railway tracks during winter and track softening during the spring thaw. Both frost heave and thaw softening cause track geometry degradation and often require frequent maintenance and the reduction of train speeds to ensure safe operating conditions. This study investigated the mechanism of frost development within a railway embankment through field observations and numerical simulations. This paper uses the temperature measurements from an instrumented section of railway track in Ontario, Canada to calibrate a numerical model and then uses this model to quantify the effect of ambient temperature and the amount of snowfall on the frost penetration within railway foundations. Key highlights:

- Thicker snow cover maintains higher mean annual ground temperatures and shallower frost penetration depths.
- The effect of snow cover is reduced due to thermal conductivity and microstructural changes after being compacted.
- A widespread frost zone develops in the embankment in winter, lasts until May and results in less proper support of the tracks. Ambient temperature has a stronger effect on frost penetration than snow on the ground.
- More rainfall could result in higher volumetric water content, more required energy for phase change and a shallower frost depth.
- The maximum frost depth of the next 75 years at this site were anticipated using a regression model and a climate model.

Opportunities for future research:

- Continued monitoring and validation of the model using the current site data.
- Quantifying the effect of local environmental variables, i.e., can this model or method be used universally across geographic regions with varying environmental conditions.

Report Title: *Characteristics of snow cover distribution along railway subgrade and the protective effect of snow fences*

Technical Journal/Source: Journal of arid land, 2023, Vol.15 (8), p.901-919

Researchers/Research Organization: LEI Jia, CHENG Jianjun, GAO Li, MA Benteng, AN Yuanfeng, DONG Hongguang

Publication Date: April 2023

Technologies examined: Optimizing snow fence configuration to reduce wind and snow disasters along railway lines.

Key findings:

The study focuses on the impact of wind and snow disasters on railways built in cold, snowy, and sparsely populated regions, specifically investigating a section of the Altay-Zhundong Railway in China's Xinjiang Uygur Autonomous Region. Using various tests and analyses, including the use of numerical modelling of snow deposition, the researchers studied the variations in deposited snowfall characteristics on different sides and areas of the railway, considering factors like porosity, fence heights, and arrangement distances of snow fences. Without protective measures, significant differences in snow cover distribution and thickness were observed between the embankment and cutting areas. The collaborative use of snow fences and embankments was analyzed, ranking factors by their sensitivity to deposited snowfall. The study suggests that, for adequate protection against wind and snow, a specific combination of snow fence characteristics: porosity of 75%, fence height of 4.8 m, and arrangement distance of 60 m proved to be the most effective for the Altay–Zhundong Railway.

Opportunities for future research:

- This study is specific to one region, replications can be done in Canada to assess the optimal embankment and snow fence combinations for Canadian winter operations.

Report Title: *Railway operations in icing conditions: a review of issues and mitigation methods*

Technical Journal/Source: Public transport, 2023, Vol.15 (3), p.747-765

Researchers/Research Organization: Arefeh Lotfi, Muhammad S. Virk

Publication Date: August 2023

Technologies examined: Literature review identifying icing effects on railway infrastructure, rolling stock, and operations and summarizing existing solutions to address these issues.

Key findings:

This article focuses on studying the current literature about railway operations in icing conditions, identifying icing effects on railway infrastructure, rolling stock, and operations, and summarizing the existing solutions for addressing these issues. The authors examined research from various cold regions of the world in both passenger and freight rail applications. The authors summarized various problems caused by ice and snow, their financial impacts, and current mitigation methods. A gap has been identified in the understanding of ice accretion on railway infrastructure, while there are currently mitigations being researched and implemented for rolling stock and operations.

Opportunities for future research:

- There is a broad spectrum of problems and solutions examined by this literature review. The individual studies should be examined more closely to understand their scope and applicability to the Canadian winter environment.
- As the authors mentioned, further research could be conducted to better understand the accretion of ice on railway infrastructure and their effective mitigation.

Report Title: *Experimental and numerical investigation on thermal-moisture-mechanical behaviors on a new anti-frost cutting bed of high-speed railway in deep seasonally frozen ground regions under extreme climate*

Technical Journal/Source: Computers and geotechnics, 2021, Vol.136, p.104251, Article 104251

Researchers/Research Organization: Bowen Tai, Zurun Yue, Shouchen Qi, Pengcheng Wang

Publication Date: May 2021

Technologies examined: Monitoring and modelling of temperature, unfrozen water, and deformation behaviours of anti-frost cutting bed for a high-speed railway.

Key findings:

Using field measurements and numerical simulation data, this paper focused on the study of the thermal-moisture-mechanical behavior of anti-frost cutting beds in deep seasonally frozen ground regions. The main conclusions are as follows:

- In deep seasonally frozen ground regions, the external air temperature has a significant effect on the ground temperature of near-surface ground, but the effect on the ground temperature of deep soil layer lags behind. More specifically, the greater the snow depth, the higher the ground surface temperature, and the smaller the frost depth.
- The responses of the unfrozen water in different soil layers to changes in ground temperature are delayed. The closer the soil layer is to the ground surface, the earlier the unfrozen water in its corresponding soil layer begins to decrease or increase. The sunny-shady slope effect on cutting is mainly reflected in different thermal-moisture conditions on the cutting slopes.
- Frost heave increases with decreases of MAGT and increases in the soil's water content. Frost heave mainly occurs in the initial freezing and freeze–thaw alternating periods. Snow cover will play a role in the insulation action on the ground surface. To ensure the safe operation of HSR, the insulation materials or anti-seepage asphalt layer should be used on the subgrade bed layer.
- A slope's freeze-thaw interface is prone to instability and collapse in cold regions with respect to the following conditions: 1) Slope soil type; 2) Slope shape characteristics; 3) Climate environment; 4) Slope vegetation. Finally, when dealing with frozen soil slope disasters in cold regions, a combination of preventative engineering and ecological measures should be adopted.

Opportunities for future research:

- Similar research can be carried out to validate the findings and calibrate results with the Canadian environment.

Report Title: *System dynamics modeling and experimental study of railway track with thermoelectric heater/generator in extreme weather conditions*

Technical Journal/Source: Journal of cleaner production, 2020, Vol.249, p.119367, Article 119367

Researchers/Research Organization: Fan Yang, Mingyuan Gao, Jianli Cong, Ping Wang

Publication Date: January 2020

Technologies examined: Thermoelectric heater to heat up rail pads using energy harvest from ambient thermal radiation.

Key findings:

This paper presented a novel intelligent railway fastener system with thermoelectric heater/generator, established a fractional derivative Zener model for the vehicle-track coupled system considering the temperature and frequency dependency properties of rail pads, and conducted theoretical and experimental studies. The clean ambient thermal energy can be harnessed by the thermoelectric generator integrated in the railway track system and converted into electric energy without production of pollution, which can supply sufficient power to heat the rail pads and maintain a proper working temperature of the fastener system. The feasibility of the novel intelligent fastener system was verified by theoretical and experimental research. The heat flow simulation and the dynamics of the coupled vehicle-track system were simulated by the finite volume method of FloTHERM and fractional derivative Zener model in extreme cold climate conditions. The experimental results showed that the thermoelectric harvester can generate an electric power of 5.8 mW across a resistance load with a low temperature gradient of 8 °C, and the working temperature of the rail pads can be improved by an average of 9.5 °C with 4 heaters of 2.5 W in the case of four different ambient temperatures. According to the results calculated by the FDZ model, the vibration of the coupled vehicle-track system can be reduced by 41.5% for the proposed fastener system in extreme cold weather conditions. Both the laboratory and field experimental studies were conducted, and the results agree well with the theoretical calculation. Therefore, the vibration characteristics of the coupled vehicle-track system can be significantly improved by the novel railway fastener system in extreme cold weather conditions, which ensures a sustainable and safe operation of the railway system.

Opportunities for future research:

- Validations should be conducted to assess the performance of the technology and its viability in Canada.
- An economic analysis could be conducted to assess the financial viability of such a product. Can they be mass-produced and achieve the reliability that is required for the winter operating environment, especially in heavy haul applications?

Report Title: *Simulation and experimental study on abrasive wear of brake discs*

Technical Journal/Source: Tribology transactions, 2022, Vol.65 (4), p.610-620

Researchers/Research Organization: Jianyong Zuo, Xueping Wang, Sufen Zhou, and Fan Yang

Publication Date: May 2022

Technologies examined: Thermoelectric heater to heat up rail pads using energy harvest from ambient thermal radiation.

Key findings:

In snow and low-temperature weather, the friction pairs on the high-speed trains in the study were always surrounded by ice and snow, which prevents them from releasing automatically. Some rigid particles were mixed in the ice and snow, forming a mixture of ice impurity. Due to the small gap between the friction blocks of the brake pad, the ice impurity was sandwiched in the gap of the friction pair and the brake disc surfaces were scratched repeatedly. The maximum scratch depth of brake discs can reach about 7 mm, which exceeds the application limit. Abnormal scratches on brake discs can shorten the service life and seriously affect the safe operation of trains.

The characteristics and main influence factors of brake disc abrasive wear were studied by the bench tests and FE simulation. Based on simulation results, a validated staged braking strategy was proposed to effectively mitigate the brake disc wear. Key findings include:

- The mechanism of significant scratches on the brake disc was analyzed by brake disc wear tests under low-temperature and snow conditions. The test results show that the roughness of the contact surface increases with quartz sand particles within the gap of the friction pair, and the average friction coefficient increases by about 1.2. In addition, the effect of the hard particles on the friction coefficient was related to the initial braking speed and braking pressure.
- The FE model of single abrasive particle and brake disc was established based on the Lagrangian method. It was found that the train running speed, vertical pressure, and abrasive particle shape have obvious influence on the brake disc wear depth. When the contact state changed from point-to-face contact to face-to-face contact, the damage area of the brake disc gradually transitioned from the internal area to the surface area. The most serious wear state of brake discs is low speed accompanied by high pressure.
- Based on FE simulation results, a staged braking strategy was proposed to mitigate the brake disc wear by optimizing the train running speed and braking pressure under the premise of meeting the maximum stopping distance requirements of the train. It was found that appropriate braking pressure reduction at lower speeds can effectively improve brake disc wear, and the maximum wear depth reduction can reach about 40%, which indicates the significance and validity of the proposed staged braking strategy.

Opportunities for future research:

- Canadian rolling stock equipped with disc brakes could be inspected during winter operations to understand the extend of abnormal brake disc wear.
- If identified as a problem, similar study can be conducted in Canada, and the staged braking strategy can be tested to determine the effectiveness of the method and its long-term effects.

C7. Technologies for subgrade stabilization

Technical Journal/Source: Construction and Building Materials

Researchers/Research Organization: Rostov State Transport University, Russian Federation

Publication Date: 2019

Technologies examined: Modern methods and structures of reinforcing the track formation soils.

Key findings:

The author first conducted a review study of typical failure of track foundations and listed the finding as Intensive plastic deformation with formation of ballast pocket, progressive shear failure, swelling/shrinkage, frost action, mud pumping, massive shear failure, consolidation settlement, liquefaction, slope erosion, and sinkhole failure.

Three main group of methods are considered for improving of stability of railway track foundation under heavy haul trains including:

- Protective Layer: Reinforcement layer (uniform distribution of the train load), waterproofing layers (protection of the subgrade from atmospheric water), separating layer (preventing mixing the particles of the ballast material and the subgrade soils), frost protection layers (protection against freezing of the underlying frost-susceptible soils of the subgrade), vibration protection layers (providing effective mitigation of impact and vibration damping from trains).
- Soil improvement: Vibro-compaction, mixing of soils, soils modified with cements/limes, soils modified with polymer.
- Structural polymers: Horizontal reinforcement, pile reinforcement, prefabricated vertical drains.

Example of using protecting layers are as follows:

- Epoxy asphalt-based concrete, Asphalt mixture, Asphalt concrete, shock matts, Rubber tire, Geotextiles (all for sub-ballast conditions)
- Asphalt concrete and grogrid (subgrade application)
- Geogrid, geocomposite, and Polyurethane - mixed ballast (Ballast)

Example of soil improvement are cement, deep mixed columns, lightweight foam, cement soil piles, short soil–binder columns, and Jet-grouting.

Example of structural solutions are Tied back-to-back system, mechanically stabilized earth (MSE) walls, Micropiles, Prefabricated vertical drains, Screw piles, and Lime-soil compaction piles.

Opportunities for future research:

- Exploring the use of impurities to existing soils to improve the mechanical properties of the subgrade soils, and to ensure quality control of soil compaction to achieve its maximum and uniform density.
- Use of geosynthetics, asphalt mixtures, concrete and piles are currently the most common ways of stabilizing the railway track foundation when organizing heavy train traffic. Development a methodological roadmap/guide for choosing the optimum method(s)

based on integrated assessment of soil, hydrological, climatic conditions, and the type of construction.

Report Title: [Construction of a new and stabilization of the exploited subgrade on the conditions of the permafrost soils of the northern latitudinal railway]

Technical Journal/Source: Transportation Research Procedia

Researchers/Research Organization: Russian University of Transport

Publication Date: 2022

Technologies examined: Berm, Cooling loops, polystyrene covers.

Key findings:

The Northern Latitudinal Railway is a Russian railway line that was initially envisioned to be completed by 2030. A significant portion of the railway is situated in the permafrost zone of Russia. Consequently, permafrost in railway embankments is deteriorating due to increasing temperatures in this region. The authors explain that deformations in the foundation constructed on permafrost can be attributed to three main mechanisms. Firstly, initial deformations arise from the degradation of permafrost at the foundation's base, triggered by disruptions in natural heat exchange conditions. Secondly, in Arctic regions with a tundra landscape, changes in snow deposits due to embankment construction and blizzard-induced transport led to uneven distribution of snow cover, causing permafrost degradation under specific embankment areas. Thirdly, deteriorating surface water runoff conditions near the embankment result in stagnation and thermo-karst formation, contributing to the lowering of the upper boundary of permafrost and subsequent instability in the subgrade. To stabilize the roadbed on permafrost, various strategies are implemented. For permafrost degradation, berms are suggested for embankments over 3 meters high, while cooling loops are recommended for lower embankments. Additionally, low embankments benefit from a cut-in apron and a cover made of expanded polystyrene plates to counteract subsidence, frost swelling, and plastic lateral uplifts. In hazy landscapes, constructing side ditches without equipment movement on hazy surfaces is proposed to regulate surface runoff. The regulation of surface runoff is further supported by the construction of additional transverse culverts using foundation-less metal corrugated pipes. These measures aim to mitigate deformations caused by permafrost-related issues and enhance roadbed stability. The design of new subgrades focuses on addressing deformations in weak soils beneath embankments, especially lateral uplift in long-term exploited areas. Effective measures include dumping berms from draining soils and creating a cooling circuit with thermosyphons. The authors conducted numerical simulations that suggest installing structures along embankments for those up to 6 meters high and using 10 cm thick extruded polystyrene foam plates for higher embankments. These measures prevent subsidence of the upper permafrost boundary, ensuring stability over a 30-year period. Additionally, it is crucial to restore drainage systems, eliminate thermokarst, and prevent seasonal thawing on low embankments using thermal insulation under the ballast with a polystyrene foam coating.

Opportunities for future research:

- Evaluate the long-term effectiveness of strategies such as berms, cooling circuits, and thermal insulation to refine and optimize their application.

- Use remote sensing data to explore how rising temperatures and altered precipitation patterns may affect permafrost stability and devise strategies to mitigate these impacts.
- Evaluate the ecological impact of stabilization measures, such as the restoration of drainage systems and the use of thermal insulation.

Report Title: Rail Trackbed stabilization using micro-piling

Technical Journal/Source: The PWI Journal, April 2023

Researchers/Research Organization: Van Elle railway, Arcadis consultant firm

Publication Date: July 2023

Technologies examined: Micro-piling.

Key findings:

Railway tracks built on soft subgrades often suffer from low stiffness, leading to performance issues in rail networks. This results in excessive track deformations during train passages, increasing the risk of rapid deterioration and derailment, necessitating costly speed restrictions. To address this, Trackbed Stabilization (TBS) methods aim to enhance trackbed stiffness, especially in areas with poor load-bearing capacity due to soft subgrades. This study focuses on a novel TBS technique using screw piles (micro-piling). Field measurements from case studies in the UK and Ireland show improved track performance after micro-piling, indicating its effectiveness in increasing track foundation stiffness over soft subgrades and improving slope stability. The authors conducted four case studies using various configuration of TBS methods and used numerical simulations and confirmed that the use of TBS techniques, the life of specific sites with soft subgrades suffering from high rates of deterioration and critical speed effects can be extended, their maintenance needs can be reduced, and the railway performance and capacity will be improved. However, the choice of TBS technique depends on project circumstances and limitations.

Opportunities for future research:

- Research on hybrid methods such as exploring micro-piling with Geocells, and micro-piling with grouting.
- Leveraging non-contact measurement techniques such as vision-based monitoring systems for accurate measurement of rail or sleeper deflection.
- Using Track geometry measurement system to continuously track quality.
- Leverage Finite Element Analysis to find optimal micro-piling configuration.

Report Title: Track Performance in Tunnels and Rail Transition Areas with Under Tie Pads and Under Ballast Mats

Technical Journal/Source: FRA research draft

Researchers/Research Organization: FRA, University of Florida, Kansas State University, Rural Railroad Safety Centre, Penn State Altoona, California State University

Publication Date: June 2022

Technologies examined: Under Tie Pads and Under Ballast Mats

Key findings:

The use of under tie pads (UTP) and under ballast mats (UBM) in rail track construction has become a common practice to enhance load distribution, reduce track modulus, and increase tie-to-ballast contact area. This report discusses the implementation of UTP and UBM in the Virginia Avenue Tunnel, Washington, DC, and their impact on track performance. The study, conducted by the University of Florida under a contract with the Federal Railroad Administration (FRA), involved instrumenting a section of the tunnel to collect data on track load distribution, tie movement, and tunnel floor pressure and vibration over the first 20 months of service. The results indicated that the use of pads and mats reduced track modulus, decreased overall track stress, and lowered the force on ties, leading to a more than 10 percent reduction in average force under train axles compared to areas without mats. The report highlights the importance of using mats and pads in locations with stiff support conditions, such as approaches to railway structures, to mitigate issues like ballast breakdown, excessive vibration, and track settlement. The Virginia Avenue Tunnel, with its transition from subgrade to a concrete-supported ballast track, serves as an example where mats and pads were incorporated into the entire tunnel track design. The elastomeric properties of these materials allow designers to adjust track stiffness for optimal performance, creating a more gradual change in stiffness at critical locations. The study outlines the specific details of the track design, including the thickness and composition of the ballast mat and pads used. The project provides valuable insights into the positive effects of using these components for improved track performance.

The analysis of 20 months of initial service data from the tunnel revealed that the use of mats aided in distributing axle forces across more ties, thereby reducing overall track stiffness. The track experienced a settlement of 0.157 inches (4mm) in the first 6 months but subsequently stabilized. The combination of pads and mats contributed to the creation of a stable track structure, potentially leading to a decrease in track tamping frequency and minimizing ballast breakdown.

Opportunities for future research:

- Detailed investigation and further study to assess the influence of both mats and pads on track load distribution, aiming to determine which of the two components has a more significant impact in enhancing overall track performance.
- Conducting Final Element Analysis (FEA) and structural simulations of track with and without pads and mats to better understand the differences in performance of the track.
- Investigate the effect of environmental conditions such as temperature, humidity, etc. on the performance of track with and without pads and mats.

Report Title: Railway Improvement System

Technical Journal/Source: Tensar Corporation webpage

Researchers/Research Organization: Tensar Corporation

Publication Date: 2022

Technologies examined: Geogrid.

Key findings:

A geogrid is a geosynthetic material composed of polymers, such as polypropylene or polyester, arranged in a grid-like structure. This material reinforces soil, rock, or granular substances by adding tensile strength and stabilizing the structure. The American Railway Engineering and Maintenance of Way Association (AREMA) has recognized the significance of geogrid technology in trackbed stabilization, incorporating a chapter on geogrids in its 2010 Manual for Railway Engineering. Tensar is a company that claims that their triangular Geogrid advertised as TriAx, presents enhanced performance compared to conventional bi-directional Geogrids, leveraging triangular structure for increased stiffness and aggregate confinement. As per Tensar's claim the transition to a triangular grid aperture, coupled with improved rib thickness and junction efficiency, minimize ballast settlement and lateral creep, maintain effective drainage of the trackbed, extend the life of mechanical rail line components. Tensar claims that TriAx Geogrids provide effective stabilization for trackbed structures in two keyways. First, when placed at the bottom of the sub-ballast, they efficiently distribute imposed loads over the subgrade, reducing the required sub-ballast layer thickness. Second, when positioned between the ballast and sub-ballast layers, the geogrids limit lateral particle migration, minimizing track settlement. This contributes to a significant extension in the time between maintenance cycles, offering improved stability and reduced maintenance frequency.

The company offers two other products. The first one is Geopier GeoSpikeSM system which claims to offer a cost-effective solution for strengthening weak railroad track subgrades. Installed without removing tracks, ties, or ballast, GeoSpike elements are driven to design depths, with aggregate backfilled within the premanufactured shell. The system claims to effectively stabilizes subgrades, decreasing track deflections. Based on the company release, CN used this system in National St. Clair sub-division

The second system, Geopier SRT® system addresses embankment slope repair by stabilizing slopes on existing railway embankments prone to shallow slides. Plate Pile™ elements, closely spaced, create horizontal barriers, forming a continuous line of resistance against downslope movement. This is type of mechanical enhancement for the subgrade. The SRT system claims to offer a fast and permanent solution for shallow slides on rail embankments, enhancing global stability for steeper constructed slopes.

Opportunities for future research:

- Investigating different shape and geogrid materials and evaluate their impact on the sub-grade.
- Conducting further experimental tests to assess the effect of using different geogrids on inspection intervals.

Report Title: Application of self-sensing cement-stabilized sand for damage detection

Technical Journal/Source: Journal of Construction and Building Materials

Researchers/Research Organization: University of Minho, Portugal

Publication Date: 2023

Technologies examined: Carbon nanotubes and graphene nano-plates.

Key findings:

The sensing ability of carbon nanomaterials has garnered attention in the scientific community for applications in cement and concrete. However, their use in stabilized soils has been limited. Cement is commonly employed to stabilize subgrade soils in transportation infrastructures, including sand. Motivated by this, the authors developed an advanced cement-stabilized sand by incorporating Carbon Nanomaterials (CNMs) to detect degradation and cracks. The selected cement and sand match the desired requirements of the railway tracks subgrade. This work explores the incorporation of multiwalled carbon nanotubes (MWCNTs) and graphene nanoplates (GNPs) in cement-stabilized sand. These materials not only enhance the mechanical properties of cement-stabilized sand but also transform it into a self-sensing material, crucial for structural health monitoring (SHM). The composite was subjected to varying stresses to detect strain, cracks, and damage under cyclic loading. The study showed there is an optimum balance between the mechanical strength and sensing ability when CNM and MWCNTs are incorporated into the cement. They also found the material senses strain better under heavy pressure, not so much under light pressure which makes it appealing for rail applications. The authors also found that fractional chance in resistance (FCR) can identify the trends of elastic behavior to failure in cementitious composites. They found that FCR stayed steady until the first crack appeared, then increased as cracks grew and decreased when cracks shrank. Such parameter along with Piezoresistivity and stress measurement can produce a guideline for enhancing the cement stability and autonomous inspection.

Opportunities for future research:

- Studying the effect of environmental factors (i.e., moisture and temperature) on piezoresistivity and self-sensing ability of Carbon nanotubes and graphene nano-plates incorporated cements.

Report Title: Performance evaluation of rail trackbed stiffness: pre and post stabilization

Technical Journal/Source: Construction and building materials.

Researchers/Research Organization: Nottingham Trent University, University of Twente

Publication Date: Sept 28, 2023

Technologies examined: Micro-piling, computer vision-based monitoring.

Key findings:

Rail deflection is often linked to poor track bed stiffness, stemming from soft subgrade or contaminated ballast. Various track bed stabilization (TBS) methods exist to address these problems and enhance track safety. Traditional TBS methods are costly and disruptive, involving track removal. A less intrusive approach is micro-piling, where screw piles are installed between sleepers. This study examines the impact of screw pile TBS on a UK rail line with a soft subgrade and contaminated ballast. Using a computer vision system, rail vertical deflections during train passages were measured before and after remediation. The data were analyzed to assess track bed stiffness. Additionally, 3D finite element models were developed and validated using on-site measurements. These models were employed to simulate different scenarios, exploring the effects of changes to the TBS piling layout and additional measures like ballast improvement. Site measurements indicated that TBS reduced rail deflection by 20–30%, demonstrating the effectiveness of micro-piling for soft subgrades. The finite element analysis showed that the efficiency of micro-piling depends on ballast conditions, ground strength at the pile toe, and pile arrangement. Optimal conditions could reduce rail deflection to approximately 50% of the pre-TBS state. Authors concluded that the effectiveness of the micro-piling system is influenced by ballast and sub-layer conditions, with higher stiffness in these elements corresponding to greater track quality improvement. Consideration of ballast condition and pile length is crucial, and sometimes a hybrid stabilization approach is necessary to achieve the desired track bed performance. Also, their final element analysis suggests that adjusting the pile arrangement can balance track quality enhancements with cost considerations. The study identifies a triangular pile arrangement as the optimal solution for improving track quality.

Opportunities for future research:

- **Extended Monitoring for Long-Term Performance:** Conduct a follow-up study with extended and continuous monitoring over several years to assess the long-term effects of micro-piling on trackbed stability and degradation rates.
- **Hybrid Stabilization Approaches:** Explore the potential benefits of hybrid stabilization approaches that combine micro-piling with other methods. For instance, assess the performance of a combined strategy involving both micro-piling and ballast improvement to achieve enhanced track quality.
- **Optimizing Pile Arrangement for Cost-Efficiency:** Further investigate and refine the optimal arrangement of piles in terms of cost-effectiveness. Evaluate different pile layouts and configurations to strike a balance between improving track quality and minimizing costs.
- **Expanded Geographical Scope**: Expand the geographical scope of the study to include diverse regions and track conditions. This would enhance the generalizability of the

findings and provide insights into the adaptability and performance of micro-piling in different environmental and operational contexts.

- **Incorporating Advanced Monitoring Technologies:** sensor technologies, data analytics, and artificial intelligence for real-time monitoring can offer more comprehensive and dynamic insights into trackbed performance.

Report Title: Effectiveness of a Geocomposite-PVD system in preventing subgrade instability and fluidization under cyclic loading

Technical Journal/Source: Geotextiles and Geomembranes Journal

Researchers/Research Organization: University of Sydney

Publication Date: May 2022

Technologies examined: Integrated effects of Prefabricated Vertical Drains (PVDs) and geocomposites

Key findings:

The instability of subgrade soil, often linked to soil fluidization, can result in uncontrolled deformation and failure after a critical number of loading cycles, given a specific cyclic deviator stress and frequency. While previous projects confirmed the performance of Prefabricated Vertical Drains (PVDs) and geocomposites, the effectiveness of this combination in mitigating subgrade fluidization under repeated cyclic loading remains inadequately understood. Laboratory experiments demonstrate that the continuous dissipation of excess pore water pressure (EPWP) and the significant reduction in drainage path lengths facilitated by PVDs can effectively prevent subgrade fluidization at shallow depths. Simultaneously, geocomposites contribute to adequate surficial drainage and efficient confinement at the ballast/subgrade interface. The test results, which measured Excess Pore Pressure Gradients (EPPGs) during cyclic loading, strongly suggest that the PVD-geocomposite combination performs well under different loading conditions. The main goal is to assess how geosynthetics perform under repeated loading, aiming to reduce excess pore water pressure (EPWP) and manage particle movement in a soft subgrade soil. The laboratory tests indicated that this approach is an effective way to stabilize soft subgrade soil under adverse hydro-dynamic conditions, while controlling critical factors such as the excess pore water is very important for optimized performance of the subgrade.

Opportunities for future research:

- **Long-Term Performance Monitoring:** Conduct a study with extended, continuous monitoring to assess the long-term performance and durability of integrated Prefabricated Vertical Drains (PVDs) and geocomposites
- **Comparative Analysis of Ground Improvement Techniques:** Comparing various ground improvement techniques, such as mechanical methods, chemical additives, geosynthetics, prefabricated vertical drains, and deep mixing columns. Assess the effectiveness, cost, and environmental impact of each method under different soil conditions.
- **In-Depth Investigation of Deep Mixing Methods:** Exploring the effectiveness of both deep dry and deep wet mixing. Compare their performance in different regions and soil types, taking into account factors such as unconfined compressive strength limitations.
- **Stone Column and Pile-Supported Embankment Studies:** Investigate the use of stone columns either solely or in combination with geosynthetics to fortify soft soils or loose sand. Explore the consolidation rate, settlement reduction, and increased load-bearing capacity achieved through stone column applications. Additionally, study the impact of pile-supported embankments on reducing ground vibrations caused by passing trains.

Report Title: Embankment Stabilization Techniques for Railroads on Permafrost

Technical Journal/Source: 2016 Joint Rail Conference

Researchers/Research Organization: Michigan Technological University

Publication Date: April 2016

Technologies examined: Stabilization techniques.

Key findings:

The worldwide degradation of permafrost conditions poses stability challenges for structures built upon them, particularly impacting railway lines in permafrost regions where differential settlements can be problematic. To address these issues, various passive and active engineered solutions, such as awnings, shading boards, crushed rock embankments, ventiduct embankments, and thermosyphons, have been developed. Local site conditions, including soil type, temperature, ice content, and precipitation, influence the selection of stabilization methods. Often, a combination of multiple alternatives proves to be the most This paper discusses solutions, focusing on the Hudson Bay Railway (HBR) in northern Manitoba, Canada. Given the prolonged thaw settlements experienced by HBR, the paper discussed the applicability, advantages, disadvantages, and potential benefits of different stabilization methods, emphasizing the effectiveness of combining multiple approaches.

Permafrost stabilization techniques available can fall under these three broad principles:

- Controlling solar radiation
  - Adjusting Color of Embankment Surface
  - Awnings and shading boards
- Controlling heat convection
  - Crushed Rock Embankments: Crushed rock embankments act as thermal semiconductors, inducing Raleigh-Bernard convection in winter by transferring warm embankment air upward, while in summer, minimal convection occurs as the colder and denser embankment air remains within
  - Ventiducts Embankments: a ventiduct embankment, derived from "ventilation duct," is a conventional embankment with perforated hollow pipes functioning as air culverts to facilitate the transfer of air from the embankment core to the atmosphere.
  - Thermosyphons; Thermosyphons, utilizing convective heat exchange, protect permafrost by evaporating and condensing a low boiling point liquid within sealed tubes inserted into the embankment, maintaining thermal stability in both winter and summer.
- Controlling heat conduction
  - Leveraging material with the properties of a thermal semi-conductor that will lower the ground temperature by increasing the heat loss in winter and decreasing the heat gain in summer.

- Other stabilization techniques
    - Expanded Polystyrene Insulation
    - Dry Bridges

Authors found that use of heat pipes can help resisting the permafrost along HBR.

Opportunities for future research:

- Conduct further research to find the best combination of above methods for HBR and other railways.

Report Title: Use of Geosynthetics in Diverse Railroad Applications

Technical Journal/Source: GAP 2019Conference

Researchers/Research Organization: TTCI (currently MxV Rail)

Publication Date: November 2019

Technologies examined: Geosynthetics

Key findings:

Multiple geosynthetics were shown to successfully mitigate two different subgrade issues for a North American Class 1 railroad. The first example used ballast drains and geogrid to stabilize a 7-ft ballast pocket in an embankment. Prior to remediation, the location required weekly surfacing and this was reduced to once a quarter after remediation. The second study looked using geosynthetics as a barrier layer between the ballast and shale subgrade in a track region that experiences frequent flooding. After flooding events, the ballast frequently fouls and this is attributed to subgrade particles pumping up from the subgrade. All three geosynthetics (Tracktex, geoweb with filter barrier, and geogrid with filter barrier) reduced the fouling levels after two years of insulation compared with a control that just had ballast replacement. This study emphasized that geosynthetics have many uses in freight railroad environments but care mut be taken to use the geosynthetic in a manner that addresses the root cause and supplement with other non-geosynthetic remedial work (e.g., ballast drains) when appropriate.

Opportunities for future research:

- Additional test applications
- Develop improved guidance on appropriate use of various geosynthetics that address the root cause of the subgrade issue

Report Title: Track Substructure Management System

Technical Journal/Source: Proprietary Association of American Railroads (AAR) Document

Researchers/Research Organization: TTCI (currently MxV Rail)

Publication Date: 2017

Technologies examined: Design, Inspection**,** Geosynthetics

Key findings:

The Track Substructure Management System (TSMS) is a proprietary AAR document that was developed to compile basic substructure knowledge in a single document. The TSMS includes definitions, general issues, inspection, and remediation. The purpose of the TSMS was to provide railroads with a document that could be referenced for substructure training and fixes that could be performed internally by the railroad and does not require outside consultation. The TSMS was considered a "work-in-progress" and could be significantly expanded upon.

While the TSMS is proprietary to AAR members, an open-sourced single-source document that compiled substructure knowledge for railroad practitioners could be useful.

This would include importance of substructure components, warning signs to help identify the substructure issue, and available remediation (both simple solutions such as trench drains and more complex solutions such as geosynthetics or subgrade stabilization).

Opportunities for future research:

- Compilation of knowledge of general substructure knowledge. While there is a strong emphasis on solutions and high-end products, many railroad subgrade issues can be solved by proper drainage maintenance.
- General guidance when particular solutions are needed. For example, when would a trend drain solve an issue and when is subgrade stabilization needed?

C8. Enhanced train control

Report title: Cybersecurity Considerations for Communication Based Train Control

Journal/Source: IEEE

Researchers/Research organization:

Italy CINI Cybersecurity Laboratory: Simone Soderi, Daniele Masti

University of Oulu: Matti Hämäläinen, Jari Iinatti

Publication date: August 2023

Keywords: Railway security, Jamming, TS 50701, Railway communications, Telecommunications security, Railway signaling

Technologies examined: Wifi communications, CBTC, Eurobalise

Key findings:

CENELEC TS 50701 is the first European government standard that aims to encompass process for cybersecurity risk management within the railway industry. It was stated that among practitioners CENELEC TS 50701 is an active field of discussion, especially when dealing with communication-heavy subsystems. This paper describes two cyber-attack scenarios against wireless Communication-based train control (CBTC) systems that can have potential safety concerns with respect to the framework described by CENELEC TS 50701. The paper specifically investigated the safety concerns of Jamming attacks and the common weak points regarding Vehicle to Infrastructure (V2I) communication based eurobalises. Jamming attacks can cause trains to have delays and stops to be missed, which could potentially lead to collisions. Jamming attacks can also be done relatively easily with just public knowledge of the system, because of this, it is suggested that interference detectors are used to effectively identify disturbances and classify disturbances as faults or external actors.

There was an identified trend in applying general purpose wireless technology in intra-vehicular, Vehicle-to-vehicle (V2V), and Vehicle-to-Infrastructure (V2I). Nowadays, wi-fi communications technologies that are based on IEEE 802.11 (along with other standards) are often selected in CBTC for safety related applications such as V2V and V2I, however these general-purpose communications technologies typically lack industrial safety and security considerations during their design.

It was identified that there are issues and vulnerabilities around the conduits (a component that is part of the framework described in CENELEC TS 50701). The investigation concluded that the standards do not fully describe what is considered a conduit.

Opportunities for future research:

- The research team plans to continue research on novel high-fidelity hardware-in-the-loop simulation environments as a means to test and validate the proposal outlined in the report.
- The proposed mitigation measures require extensive experimental validation while considering new regulatory constraints and practical implications.

Report title: Deep Hybrid Learning Based Fault Diagnosis for Data Communication Systems in Communication-Based Train Control Systems

Journal/Source: IEEE

Researchers/Research organization: State Key Laboratory of Rail Traffic Control and Safety: Sen Lin, Li Zhu, Qingheng Zhuang

Publication date: November 2022

Keywords: Fault diagnosis, Radio frequency, Bit error rate, Feature extraction, Control systems, Data models, Hybrid learning

Technologies examined:

Key findings:

This paper proposed a Deep Hybrid Learning (DHL) method to identify faults within a Data Communication System (DCS). When fault information is extracted manually it is labor intensive and information can be lost. This project aims to mitigate information loss when extracting valuable information from faults. This paper highlights the advantages of utilizing the DHL model for fault diagnosis and shows how the simulation results for the proposed DHL model achieves substantial accuracy compared to traditional machine learning algorithms such as Decision tree and Bayesian network.

The proposed model uses a pre-trained Chinese Bidirectional encoder representation from transformers (BERT) deep learning model and the Random Forest model (combined is the DHL model) to automatically extract fault features from raw text logs and then classify the faults by the extracted features.

Opportunities for future research:

- Further investigation into other possible deep learning algorithms should be done to explore new methods for more effective DCS fault prediction tasks.

Report title: Advances in Computational Modeling of EMC/EMI Effects in Communication-Based Train Control (CBTC) Systems

Journal/Source: IEEE

Researchers/Research organization: Xingqi Zhang, Weibin Hou, Costas D. Sarris

Publication date: November 2021

Keywords: Geometry, Computational modeling, Control systems, Computational electromagnetics, Mathematical models, Communication networks, Time-domain analysis

Technologies examined: Communication Based Train Control Systems, Electromagnetic Interference

Key findings:

Communication-based train control systems need to operate in a variety of communications situation, including tunneled and open-air sections, within busy stations, and in areas that have wi-fi and cellular communication networks.

There is no model that can efficiently represent the electromagnetic compatibility and interference (EMC/EMI) issues, so this project investigates hybridizing several computational electromagnetic techniques to improve their overall efficiency.

This paper presents an overview of applicable standards, EMI scenarios for CBTC systems, and recent advances in hybridizing the Vector parabolic equation (VPE) method, Raytracing (RT), and the Finite-difference time-domain (FDTD) technique.

At the time of this paper, it was noted that advanced propagation methods based on FDTD, VPE, and RT methods were being developed to characterize radio wave propagation within the railway environment. The example of hybrid models demonstrated in this paper shows potential for using RT for complex station geometries, VPE for rail sections containing long tunnels, and full wave methods (FDTC in this paper) for the exterior and interior geometry of trains.

Opportunities for future research:

- Future extensions to this project could aim to include 5/6G systems, as well as millimeter-wave and THz frequencies.

Report title: Parameter Adaptive Research of Automatic Train Control Algorithm Based on Sliding Mode PID

Journal/Source: Sage Journals

Researchers/Research organization:

Shanghai Key Laboratory of Rail Infrastructure Durability and System Safety, School of Transportation Engineering: Ziwei Wang, Dongxiu Ou

Publication date: July 2023

Technologies examined:

Key findings:

This paper highlights a sliding mode proportional-integral-derivative (PID) control model that is optimized with back propagation (BP) neural networks. In the first part of the study the train operation model that considers response delay was constructed. In the second part, an analysis of existing research methods concluded that neural networks and sliding mode control techniques will be utilized for train speed control. Specifically, dynamic sliding techniques were used to optimize PID control.

During each control cycle for the PID error amount is checked to see if it exceeds the target optimization error. The difference between the actual train speed and the target train speed is used as the optimization target to iteratively adjust the PID control parameters. If the error requirement is satisfied the optimized parameters are output to the train control process.

This study utilized real operation data from urban rail transit to validate and simulate different control methods for the model. The results demonstrated how the sliding mode PID control model that utilized a BP neural network performed better with error distribution, average error value, and control variance under different simulation scenarios. It was also able to achieve better tracking and operation at the target speed. Overall, the described model has better adaptability and accuracy than within train operation tracking control.

Opportunities for future research:

- Further research into how the application can reduce resource and time cost needed to select sliding PID control parameters for actual operation should be conducted.
- Future technologies will likely require higher control requirements for train control algorithms so more research into the expansion of the proposed system may be needed.
- The algorithms proposed also have potential applications in optimizing vehicle control systems.

Report title: GNSS Jamming Detection and Exclusion for Trustworthy Virtual Balise Capture in Satellite-Based Train Control

Journal/Source: IEEE

Researchers/Research organization:

Frontiers Science Center for Smart High-speed Railway System: Jiang Liu, Bai-Gen Cai

School of Electronic and Information Engineering and the Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation: Jian Wang, De-Biao Lu

Publication date: September 2022

Technologies examined: Global Navigation Satellite Systems, Virtual Balise

Key findings:

For safety critical train control systems that utilize Global Navigation Satellite Systems (GNSS), jamming attacks are a major threat since they can disrupt the operations of the system. The concept of Virtual Balise (VB) enables a viable means to use GNSS and reduce the amount of physical balises needed.

To ensure the safety of VBs, jamming attacks need not pose a threat to their operation. As such, this paper presents a novel GNSS jamming detection and exclusion solution. The proposed method is an advanced architecture for a VB reader that incorporates an interference qualifier module (IQM), alongside a conventional GNSS-enabled VB framework.

The IQM detects and identifies any signal interference by examining the real and predicted GNSS pseudo-ranges. So long as the receiver is not completely disabled by an attack, the solution is able to identify the quality of available GNSS measurements and determine if it is viable.

The results from testing two typical GPS jamming attacks validate the tolerance of the proposed system and shows that the solution has the potential to protect against GNSS attacks within a satellite-based train control system that utilized VBs.

Opportunities for future research:

- This study will continue and focus on:
  - improving coverage to the additional satellite measurements over the pseudo-range
  - conducting more studies with different jamming signals beyond AM and coherent CW
  - Testing other GNSSs, such as Galileo and BeiDou
  - Conducting more tests with GNSS jammers and specific test instruments in real railway operations to optimize key parameters in the proposed solution.
  - Expanding the scope of research beyond just jamming attacks to include complicated interface modes and sophisticated GNSS spoofing attacks.
  - Developing a field demonstration for the train control system.

Report title: Beyond Full Implementation: Next Steps in Positive Train Control

Journal/Source: National Transportation Safety Board

Researchers/Research organization: National Transportation Safety Board

Publication date: September 2023

Technologies examined: Positive Train Control

Key findings:

This report highlights the findings from an investigation, conducted by the National Transportation Safety Boards (NTSB), of the current Positive train control (PTC) and current PTC-related technologies and regulations. The investigation looked into the capabilities, limitations, safety goals, and safety performance of PTC.

The findings from this report include:

- Current PTC systems are able to enforce a fixed speed limit, however insufficient information regarding train location prevents PTC from effectively detecting and responding to potential train-to-train collisions while the train is operating under restricted speeds.
- While operating under restricted speeds in a permissive block, PTC must be able to ensure safe train separation. To achieve safe separation technologies that can reliably identify and locate the end of the train must be deployed so this information can be communicated to other trains.
- Technologies should be deployed for precision improvements in PTC and PTC-related technologies to help prevent or mitigate the severity of end of track collisions within terminals.
- For the interoperable electronic train management system, the switching mode software components require human intervention to activate PTC protection on the main tracks. This could result in the engineer leaving the PTC signal enforcement unnecessarily disables within 5 miles of the switching operation.
- Miscommunication between dispatcher and roadway workers can cause the working limits for PTC to be mistakenly removed. Removing working limits prematurely creates an unprotected work zone for personnel.
- Implementing technology that supplements verbal communication along with engineering controls can help improve the safety of work zones by improving work zone enforcement. These technologies will help mitigate the risks involved with potential miscommunication that could result in unauthorized or unsafe incursions within the set working limits.

Opportunities for future research:

- As a result of this investigation, the TSB makes the following recommendations:
  - Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.

- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Work with railroads to remove terminal exceptions currently granted under Title 49 *Code of Federal Regulations 236.1019* using available improved PTC-related technologies.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.
- Require railroads to implement technologies that eliminate the risk of miscommunication between dispatchers and roadway workers in charge regarding establishing working limits and PTC protection.

Report title: Formal Verification of the European Train Control System (ETCS) for Better Energy Efficiency Using a Timed and Asynchronous Model

Journal/Source: MDPI

Researchers/Research organization:
Faculty of Transport, Warsaw University of Technology: Andrzej Kochan, Juliusz Karolak
Institute of Computer Science, Warsaw University of Technology: Wiktor B. Daszczuk, Waldemar Grabski

Publication date: February 2023

Technologies examined: European Train Control System

Key findings:

The European rail traffic management system (ERTMS) and European train control system (ETCS) is the newest automatic train protection system and is being implemented all through the European Union with the goal of increasing energy efficiency and operational safety.

Currently verification techniques that use dynamic testing with actual rolling stick fail to verify all cases. As such, this paper presents a methodology and environment for the time-based verification of ETCSs.

In order to achieve errorless configuration of ETCS the proposed methodology will utilize the Integrated Model of Distributed Systems formalism and the temporal tool Dedan. These tools will allow the verification of specified conditions by analyzing all system runs at once. The formal model proposed is specifically designed for distributed systems and automated verification of real-time dependent systems.

The main contribution of the proposed model is the asynchronous and timed verification, since it:

- appropriately models the distributed nature of ETCS.
- allows the analyzation of time dependencies.
- allows the user to set the range of train velocities in which the operational scenario is valid.

In ETCS, a device's operation is dependent on its current state and external signals acquired. This property alongside real-time analysis enables the actual behavior of interconnected devices to be observed.

Opportunities for future research:

- Future plans for this project include:
  - building a library of common ETCS system components to allow for the verification of large cases.
  - Incorporate timed verification into the Dedan tool for better presentation of counterexamples.
- The tool could be expanded to consider several consecutive trains for improved energy efficiency of the entire transportation system.

Report title: Train-Centric Communication Based Autonomous Train Control System

Journal/Source: IEEE

Researchers/Research organization: Haifeng Song, Shigen Gao, Yidong Li, Ling Liu, Hairong Dong

Publication date: July 2022

Technologies examined: Autonomous Train Control System

Key findings:

The development and integration of driverless train control systems are becoming more popular as a means to improve operational efficiency. The automatic train operation systems that are currently utilized operate under a framework where a ground control center generated network elements and movement authorities, making the systems automated but not autonomous.

This paper highlights the research done for an Autonomous Train Control System (ATCS) that aims to improve train movement coordination and efficiency. The paper discusses the systems structure, general operating scenarios, the data isolation breakdown, how data prediction and edge-based information fusion are applied to process real dynamic data (to estimate train speed and position), and how data fusion, modeling, and data-based control methodologies are used.

The goals of the ATCS includes:

- Running trains closer
- Dispatching trains faster
- Optimizing energy use
- Providing low-cost railway solutions
- Increasing safety

The ATCS enables ground resources to be used more efficiently since the train will be able to provide the following train the necessary information from the preceding train. To achieve this train-to-train and train-to-ground communication channels, a resource management unit, and an infrastructure controller will be used. Through the benefits of the mentioned on-board equipment and data systems, the train will be able to record more accurate real-time dynamic data and will have precise control when compared to current automated train control.

Opportunities for future research:

- The proposed system needs practical experimental data to validate its efficiency. The addition of real-world experimental data would enhance the research argument. As such, the future plans for this project include:
    - building a physical or digital twin platform that would obtain actual data through channel simulators and sensors.
    - Further discussion on the data-based model-free control algorithm.
- The above future plans should be investigated to see what has been done since the development of this report.

Report title: Methods for Applying Public Communication Lines to Communication-based Train Control Systems

Journal/Source: J-Stage

Researchers/Research organization: Train Control Systems Laboratory: Takayasu KITANO, Akihiro GION

Publication date: November 2023

Technologies examined: Communication-Based Train Control

Key findings:

This paper highlights a method for applying public communication lines to communication-based train control (CBTC). The goal of the proposed system is to reduce the amount of maintenance needed by reducing the amount of equipment, while still meeting the safety requirements.

The proposed system utilizes radio to transmit information between ground and on-board equipment. The trains position will be detected on-board, and the on-board equipment controls the train, which will reduce the amount of ground equipment needed to maintain operational safety. The system will be able to:

- Correct recognition of the train position by the on-board equipment
- Correct transmission of the train position, recognized by on-board equipment, to the ground equipment.
- Configuration of the route and setting of the movement authority, according to each train position, by the ground equipment
- Transmission of the set move authority to the set ground on-board equipment
- Creation of brake profiles according to the transmitted information

The system will need to apply countermeasures for third-party cyber-attacks to ensure the safety and security of the system. The main attacks identified included spoofing, tampering, and denial of service attacks. To mitigate many of the attacks, implementing a message authentication system is recommended.

Opportunities for future research:

- Future work will focus on the drafting of specifications and construction of a prototype for the described system.
- Further investigation on cyber-attack mitigation strategies needs to be conducted to ensure operational safety requirements are met.

Report title: Wireless Train Detection Based on Null-Filled UHF RFID Reader Antenna for Communications-Based Train Control

Journal/Source: IEEE

Researchers/Research organization:

University of Macau**:** Zi-Yu Pang, Kan-Weng Tam, Wai Son Kuan

Foshan University: Guan-Long Huang

Publication date: October 2023

Technologies examined: Axle counting system, ultra-high frequency technologies, Radio frequency identification systems.

Key findings:

This paper presents a novel Ultra high frequency (UHF) Radio frequency identification (RFID)-assisted axle counting system for wireless train detection. In the proposed system the train compartments will have RFID tag antennas attached to them. When a train travels across a signal indicator, the reader will detect the RFID tag and the acle counter will count the number of axles that have passed by. Traditional reader antennas have a blind reading zone that could potentially cause safety issues. To mitigate the blind reading zone this project proposes a new null-filled monopole UHF RFID reader antenna that eliminates the radiation blind reading zone at the antenna zenith. Traditional reader antennas are also directional and would not be compatible with the proposed system.

The new antenna described in this paper was developed using 3D printing out of polylactic acid which makes the antenna low-cost, lightweight, and easy to process. The antenna was demonstrated to have good performance, which shows its feasibility in an industry setting. The proposed RFID-assisted acle counting system also was shown to be low cost and have simple maintenance requirements.

It should be noted this report also offers a more technical overview of the proposed system, describing the structure of the proposed system, bandwidth, zenith gain, horizontal radiation gain, and other technical specifications.

Opportunities for future research:

- This research offers an additional axle counting system for railways, the best areas of application for this system should be conducted.
- Research into the cybersecurity aspects of the new system should be conducted.

Report title: ITC PTC interface control documents (ICDs)

- Positive Train Control Office-Locomotive Segment—Interface Control Document (ICD)

Standard S-9361

- Interoperable Train Control (ITC) Wayside-Locomotive Interface Control Document (ICD)

Standard S-9362

- Additional ITC PTC-related ICDs have been published by AAR, but those cited here are particularly relevant.

Journal/Source: AAR

Researchers/Research organization: ITC Committee

Publication date: 30 Dec 2021 for S-9361; 19 Jul 2023 for S-9361;

Technologies examined: Inter-segment messaging

Key findings:

These documents present highly relevant examples, potential templates, and reusable content that will be required to achieve interoperability among different railroads' or suppliers' ETC equipment and also to achieve interoperability with ITC PTC.

Opportunities for future research:

- Determine what can be reused and what needs to be different between ETC ICDs and ITC PTC ICDs.
- Possibly perform similar analyses with respect to other train control systems, such as ETCS. However, for interoperability reasons, ITC PTC may take precedence in this analysis.

Report title: ITC PTC communications protocol specifications

- Edge Message Protocol, Standard S-9354
- Class C Messaging, Standard S-9355
- Class D Messaging, Standard S-9356

Journal/Source: AAR

Researchers/Research organization: ITC Committee

Publication date: 30 Oct 2018 for S-9354; 26 Aug 2022 for S-9355; 30 Oct 2018 for S-9356;

Technologies examined: Inter-segment communications protocols

Key findings:

These documents present highly relevant examples, potential templates, and reusable content that will be required to achieve interoperability among different railroads' or suppliers' ETC equipment and also to achieve interoperability with ITC PTC.

Opportunities for future research:

- Determine what can be reused and what needs to be different between ETC ICDs and ITC PTC ICDs.
- Determine the frequency bands, waveforms and protocols to be used for ETC RF communications, which may be different than for ITC PTC.
- Possibly perform similar analyses with respect to other train control systems, such as ETCS. However, for interoperability reasons, ITC PTC may take precedence in this analysis.

Report title:

- Interoperable Train Control Wayside Interface Unit Requirements Standard S-9202
- Additional ITC PTC-related requirements specifications have been published by AAR, but the one cited here is particularly relevant.

Journal/Source: AAR

Researchers/Research organization: ITC PTC Committee

Publication date: 1 Aug 2014

Technologies examined: Functionality required for the wayside train control segment

Key findings:

This specification defines the wayside interface unit (WIU), which is a device that provides an interface to the wayside signal system to forward signal information to locomotive PTC segment in a vital manner. The WIU connects to, and monitors the states of, existing signal equipment, including signal lamps, switches, and hazard detectors.

A non-proprietary AAR specification for the ITC PTC locomotive segment is currently under development. PTC office segments are railroad or supplier-specific so there is no AAR standard for the office segment.

Opportunities for future research:

- Determine what can be reused and what needs to be specified differently for ETC vs. ITC PTC.
- Possibly perform similar analyses with respect to other train control systems, such as ETCS. However, for interoperability reasons, ITC PTC may take precedence in this analysis.

Report title: Higher Reliability and Capacity Train Control - DOT/FRA/ORD-22/30

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: 27 Dec 2019

Technologies examined: Safety and operational enhancements to PTC that could be applicable to ETC as well

Key findings:

This report describes the evolution envisioned for ITC PTC from its current state to Enhanced Overlay PTC (EO-PTC), Quasi-Moving Block (QMB) and Full Moving Block (FMB). Each of these advanced stages of PTC provides increases in safety and/or operational performance (e.g., headways and capacity).

Opportunities for future research:

- This report provides background for the specification documents cited herein for EO-PTC, QMB and FMB. Opportunities for future research are cited with the associated references.

Report title: Full Moving Block Concept and Requirements Specifications for Railroad Operations - DOT/FRA/ORD-24/03

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: 31 Aug 2022

Technologies examined: Safety and operational enhancements to PTC that could be applicable to ETC as well

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.
- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.

Two potential solutions to all of the safety issues cited immediately above, referred to as Quasi-Moving Block (QMB) PTC and Full Moving Block (FMB) PTC, are described and specified in this report. In addition, QMB and FMB can provide a reduction in headways and increase in rail line capacity.

Opportunities for future research:

- The specifications contained in the appendices to this report for the QMB and FMB enhanced modes of train control should be validated.
- Then these systems should be implemented and tested.

Report title: Advanced QMB/FMB Requirements and Algorithms

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: Pending

Technologies examined: Safety and operational enhancements to PTC that could be applicable to ETC as well

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.
- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.

Two potential solutions to all of the safety issues cited immediately above, referred to as Quasi-Moving Block (QMB) PTC and Full Moving Block (FMB) PTC, are described and specified in another report cited herein report. This report defines advanced requirements and algorithms that supplement the other report.

Opportunities for future research:

- The advanced requirements and algorithms for the QMB and FMB systems should be validated.
- Then they should be implemented and tested.

Report title: Office Safety Checker for Moving Block Train Control Systems - DOT/FRA/ORD-23/28

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: 11 May 2022

Technologies examined: Safety enhancements to PTC that could be applicable to ETC as well

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.
- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.

Two potential solutions to all of the safety issues cited immediately above, referred to as Quasi-Moving Block (QMB) PTC and Full Moving Block (FMB) PTC, are found in another report referenced herein. QMB and FMB require "safety checker" functionality as specified in this referenced document.

Opportunities for future research:

- If ETC is to include QMB or FMB functionality, the specifications in the referenced report for the Safety Checker should be validated.
- Then the Safety Checker should be implemented and tested as part of a QMB or FMB implementation.

Report title: Development of Enhanced Overlay Positive Train Control (EO-PTC) - DOT/FRA/ORD-19/44

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date:

Technologies examined: An enhancement to PTC that improves operational performance

Key findings:

This report describes a simple proven modification to ITC PTC track data and operating rules that reduces train headways and increases line capacity.

Opportunities for future research:

- This alternative to baseline train control data configuration should be considered when evaluating potential performance for an ETC deployment.

Report title: Interoperable Employee-In-Charge Portable Remote Terminal (EIC-PRT)

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: January 2022

Keywords: Positive Train Control, PTC, Employee-in-Charge, EIC, Employee-in-Charge Portable Remote Terminal, EIC-PRT, work zone, electronic instructions

Technologies examined:

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Require railroads to implement technologies that eliminate the risk of miscommunication between dispatchers and roadway workers in charge regarding establishing working limits and PTC protection.

A solution to address the above NTSB recommendation, referred to as Employee in Charge Portable Remote Terminal (EIC-PRT), is found in this report.

Collaborating with the North American railroad industry, MxV Rail developed systems engineering documents defining the EIC-PRT system, including interoperable requirements for the EIC-PRT, EIC server, and onboard segments. Additionally, MxV Rail and its subcontractors developed a prototype roadway worker terminal application per the interoperable requirements and tested the application to demonstrate compliance with the requirements.

Opportunities for future research:

- The EIC-PRT specifications should be evaluated for potential inclusion in the ETC specifications.

Report title: Positive Train Location: Final Report

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: June 2018

Technologies examined: Onboard train location determination

Key findings:

This report along with similar reports from prior phases of the Positive Train Location (PTL) project describe a system and test results thereof that increases the accuracy and dependability of train positioning for use as part of systems such as PTC and ETC. It eliminates the potential for human error in determining which track a train occupies in multiple track scenarios that cannot be resolved by standard positioning systems. PTL can be used at both the front and rear of a train. In the case of rear-of-train implementation, PTL can determine where is the end of a train relative to a turnout or other track point of interest. PTL can also be integrated with QMB and FMB systems to provide safe train separation in following moves, e.g., when operating at or below restricted speed.

Opportunities for future research:

- A cost vs. benefits analysis should be performed for the potential use of PTL with ETC.

Report title: ITC PTC security requirements specifications

- S-9008 – PSA-2 Design Specification
- S-9009 – Certificate Requirements
- S-9010 – Data Protection
- S-9415 – Automated Certificate Update Process
- S-9416 – ITCSM Agent Requirements to Support PSA-2
- S-9418 – PSA-2 Gateway Requirements
- S-9419 – PSA-2 Back Office Application Requirements
- S-9420 – ITC Key Management Service
- S-9421 – WIU ITCSM Agent Requirements to Support PSA-2
- S-9504 – PSA-2 W-OPK File Service Requirements

Journal/Source: AAR

Researchers/Research organization: ITC Security Team

Publication date: S-9009 was published on 24 Oct 23. S-9010 was published on 24 Jul 19. The other security documents cited are out for comment in draft form and therefore are not yet published.

Technologies examined: Security requirements, certificates, key management, gateways

Key findings:

These documents address one of the greatest challenges for ETC security, namely, key management (for authentication and encryption). They also address other security-critical issues from an interoperability perspective.

Opportunities for future research:

- Security requirements should be developed for ETC that leverage similarities and address differences between ETC and ITC PTC and that address issues encountered during ongoing the implementation of these standards in ITC PTC deployments.

Report title: IEEE 802.15 WSN, Task Group 16t, Licensed Narrowband

Journal/Source: IEEE

Researchers/Research organization: IEEE Task Group 16t

Publication date: 20 July 2022

Technologies examined: Wireless data communications

Key findings:

This IEEE task group has developed a non-proprietary specification known as 802.16t for a versatile, RF band agnostic, data radio protocol that could possibly be used for ETC communications among base stations, locomotives, and wayside devices. A non-proprietary radio protocol that is implemented by multiple vendors has the potential to result in lower cost products than a proprietary product developed specifically for ETC. On the other hand, a confidential proprietary radio protocol may present somewhat of a barrier to potential spoofers.

Opportunities for future research:

- This radio waveform and protocol (along with others, such as ITCnet) should be evaluated with respect to the needs of ETC to determine if it would suffice and satisfy security requirements.

Report title: DOP Geographical Distribution for the Galileo and GPS Constellations

Journal/Source: https://destevez.net/2020/01/dop-geographical-distribution-for-the-galileo-and-gps-constellations/

Researchers/Research organization: Daniel Estévez

Publication date: Unknown

Technologies examined: GPS and Galileo-based satellite positioning systems

Key findings:

Communications-based train control systems such as PTC and ETC depend upon an onboard location determination system (LDS). Satellite-based positioning is preferred over balise-based systems in many cases when many miles of track must be covered and cost is a significant consideration. The accuracy of a satellite-derived position estimate depends upon both the measurement geometry as represented by dilution of precision (DOP) values, and range errors caused by signal strength, ionospheric effects, multipath etc. This paper illustrates that satellite positioning accuracy can vary with latitude of the track, which is the only point of its being referenced here. Any further use of the results in this paper would first require validation or cross-verification with other reports.

Opportunities for future research:

- Investigation is needed into the effects of DOP upon satellite-based train positioning for the range of latitudes over which ETC will operate for each of the satellite systems under consideration. Balise-based positioning may be considered as an alternative.
- While DOP does not apply to satellite communications, geography does nonetheless play a role in the suitability (or lack thereof) of using satellite communications in train control. If satellite communication is considered for ETC, particularly in areas lacking supporting infrastructure (towers, electrical power, backbone or internet connectivity, etc.), geographic implications related to view angle from the ground will need to be analyzed in consideration of the high latitudes of Canadian railroads.

Report title: GPS Problem Report Status

Journal/Source: Navigation Center, United States Coast Guard, U.S. Department of Homeland Security
https://www.navcen.uscg.gov/gps-problem-report-status

Researchers/Research organization: Anyone in the world reporting a suspected incident of GPS service disruption, due to jamming, spoofing, or other cause.

Publication date: Ongoing

Technologies examined: Satellite-based positioning.

Key findings:

Various sources show that jamming and spoofing events do occur that can disrupt satellite-based positioning.

Opportunities for future research:

- Determine to what extent jamming and spoofing detection, reporting, and mitigation functions need to be designed in to ETC, for GPS as well as communication of other messages.

Report title: PTC Communications: Cybersecurity Technology Review and Concept of Operations - DOT/FRA/ORD-23/39

Journal/Source: FRA

Researchers/Research organization: Meteorcomm, L.L.C.

Publication date: December 2023

Technologies examined:

Key findings:

Researchers sought to determine how to improve the confidentiality of information passing through the PTC network without significantly affecting network performance. Phase 1 of the project reviewed requirements and assessed existing technologies. Phase 2 focused on implementation, migration, and deployment challenges. A recommendation to consider widely available algorithms covered by recognized open standards resulted in a project decision to focus on the National Institute of Standards and Technology Lightweight Encryption Algorithms and the ELLI algorithm covered by ISO/IEC 29192-4. Phase 3 identified technology gaps and areas for further research outside the scope of the project. Phase 4, the focus of this report, pulls together the work from Phases 1-3 to propose solutions to improve confidentiality, including a concept of operations for each solution.

Opportunities for future research:

- The findings and recommendations in this report should be considered to determine and achieve a satisfactory level of confidentiality for ETC communications.

Report title: Railway applications – Cybersecurity – CLC/TS 50701:2023

Journal/Source: European Standards s.r.o.

Researchers/Research organization: Commonwealth Standards Network (CSN)

Publication date: 2023

Technologies examined: Cybersecurity for railroad applications

Key findings:

The CLC/TS 50701:2023 standard deals with railway applications and their cyber security, providing guidance and specifications on how cybersecurity will be managed and the security assurance of systems and components/equipment. The objective of this standard is to provide guidelines and recommendations for the protection of information technology in railway systems against possible cyber threats. The standard contains several key aspects related to cyber security in railway applications:

- identification of threats and risks,
- protection of critical functions,
- incident management,
- safe development processes.

CLC/TS 50701 RAILWAY APPLICATIONS - CYBERSECURITY

Opportunities for future research:

- The guidelines in this standard should be considered to determine and achieve a satisfactory level of cybersecurity for ETC.

Report title: Automatic Train Control System and Method

Journal/Source: US Patent Office

Researchers/Research organization: Harris Corporation

Publication date: 27 Oct 1998

Technologies examined:

Key findings:

This patent describes a method for controlling the movement of multiple trains through a multiple-route railway with improved energy efficiency and reduced rail network congestion. Train movements are precisely monitored and orchestrated in accordance with a dynamic schedule that is determined through an evaluation of delivery requirements, coordination among all trains, speed restrictions, changes in conditions, and the effects of track topography and train consist on train response to brake and power application.

The basic concept is that a movement planner in the dispatch office plans the movements of all trains on the railway for at least 8 hours into the future, and continuously updates the schedule based on frequent reports (feedback) of actual train movements. The office system automatically sends time of arrival (TOA) targets via data radio to each train for critical milestones it is to meet along its route. Each train's onboard energy management system (EMS) cues the driver (whether human or automated) to follow a trajectory of train speeds to achieve its TOA targets in the most energy efficient manner feasible. As trains progress and some may deviate from the plan, revised or additional TOA targets are sent from the office to the affected trains.

Opportunities for future research:

- It is recommended that ETC system design incorporate the train scheduling, control and feedback method described in this patent (or something similar) or at least include the hooks to support this messaging and functionality in the future.

C9. Technologies for increasing grade-crossing safety

Report title: An observational study on pedestrian and bicyclist violations at railroad grade crossings: Exploring the impact of geometrical and operational attributes

Journal/Source: ScienceDirect

Researchers/Research organization: (Academics) Adheesh Kumar Vivek, Smruti Sourava Mohapatra

Publication date: December 2023

Technologies examined: Grade crossing safety of bicyclists.

Key findings:

This observational study of grade crossings is aimed to enhance the existing body of research regarding the prevalence of grade crossing violations by bicyclists and pedestrians in India.

It was observed during the investigation that more studies have been conducted on pedestrian use of grade crossings than bicyclists.

The objectives of this study are to:

- Evaluate the influence of various factors associated with pedestrian and bicyclist violations at grade crossings.
- Investigate the impact of geometrical features on factors influencing non-motorists' risky behavior at grade crossings.
- Determine whether the train vehicle unit at grade crossings has an impact on violation and its associated factors.

Out of the 7332 pedestrians and 1684 bicyclists that were observed through the video recordings of grade crossings, this study found:

- 671 pedestrians and 205 bicyclists committed a violation after the gate arms began their descent until the gate arms were in a complete horizontal position.
- 4007 pedestrians and 880 bicyclists committed a violation during gate blockage time (after the gate descended completely but before the train arrived).
- 2037 pedestrians and 436 bicyclists committed a violation during gate blockage time (after the train departed but before the gates were completely raised).
- 617 pedestrians and 163 bicyclists committed a violation after the gate began to ascend until the gate was completely lifted up.

The probability of pedestrian and bicyclist violations were found to be significantly influenced by the trains speed, train occupancy time, gate warning time, gate blockage duration, personal specific characteristics, number of railway tracks, distance between gates, distance between gate and track, and road width.

Opportunities for future research:

- It was found to be difficult to gather significant numbers of non-motorist observations (especially bicyclists). To expand the sample size more observations should be taken at grade crossings that cover a large range of geometrical features to produce sounder statistics.

- Further research should also be done into personal features and environmental parameters that impact the likeliness of a grade crossing violation.
- Practical suggestions outlined in the report include:
    - Arranging regular educational awareness campaigns
    - Investigate creative methods to catch users' attention including auditory or visual warning signs.
    - Implement an automated system to determine gate times, to limit the time after the train leaves but before the gate is open.
    - Implementing foot-over bridges, road-over bridges or underpasses to avoid the need for non-motorists to cross the grade crossing at all.
    - Keep the distance between gates less than 27m.

Report title: 3D-LIDAR Based Object Detection and Tracking on the Edge of IoT for Railway Level Crossing

Journal/Source: IEEE

Researchers/Research organization:

Technical University of Madrid: Cristian Wisultschew, Gabriel Mujica, Jorge Portilla

University of Alcalá de Henares: Jose Manuel Lanza-Gutierrez

Publication date: March 2021

Technologies examined: LIDAR. *Keywords: Edge computing, embedded software, energy efficiency, Internet of Things, LIDAR, object detection, object tracking, railway level crossing, sensor systems and applications*

Key findings:

This research paper presents a real-time object detection and tracking system that utilizes the raw 3D point cloud data generated by a low-resolution LIDAR sensor. By using LIDAR, high accuracy in detecting an object's location was achieved. LIDAR is able to outperform Red, Green, and Blue (RGB) cameras (cameras that record in color) when it comes to functioning in the absence of light and in adverse weather conditions.

The proposed implementation of a LIDAR sensor uses a lightweight object detection and tracking algorithm that is implemented in a low computing-resource and low-power environment as a part of the rail internet-of-things and operates in real-time. The proposed implementation was able to achieve a sensitivity (in the context of this paper, sensitivity is the true positive rate, and it measures the proportion of positive cases correctly identified) value of 99.16%, meaning it is robust against false negatives.

Overall, the results discussed in this research paper show that the large amount of data that the complex LIDAR sensor is able to provide can increase the security of grade crossings, reduce the number of accidents, and decrease the potential severity of accidents.

Opportunities for future research:

- Future lines of work for this project include:
    - Performing 3D object detection and using the information gathered to feed an object classification algorithm, while still maintaining low power consumption and meeting real-time requirements
    - Improving the accuracy of both object detection and classification tasks by using information gathered by various sensors of different types.
- It was noted that there is a trend in combining LIDAR, RADAR, and RGB cameras since the weakness of one is covered by the others.

Report title: Foreign Objects Intrusion Detection Using Millimeter Wave Radar on Railway Crossings

Journal/Source: IEEE

Researchers/Research organization:

Central South University: Huiling Cai, Fei Li, Dianzhu Gao, Yingze Yang, Aina Qin, Chao Hu, Zhiwu Huang

Changsha University of Science and Technology: Shuo Li, Kai Gao

Publication date: December 2020

Technologies examined: Frequency Modulated Continuous Wave (FMCW) RADAR. *Keywords: millimeter wave radar, foreign objects intrusion detection, railway crossings, object detection, processing algorithms.*

Key findings:

The goal of this project is to improve the overall safety of railroad crossings by developing a foreign object detection system. Typical video surveillance systems performance suffers during adverse weather and poor illumination conditions. The foreign object detection system is based on millimeter wave RADAR, due to its higher accuracy without being limited by weather and lighting conditions.

The proposed system will utilize a Frequency Modulated Continuous Wave (FMCW) RADAR, whose frequency increases linearly, and is capable of estimating the distance and velocity of targets. Measuring the distance and velocity of objects may provide critical information to better understand the risk profile of crossings.

The specific RADAR used was the Texas Instruments IWR1643BOOST millimeter wave radar.

The results of the tests conducted demonstrates the system's ability to simultaneously detect multiple targets on the railway crossing. Although the accuracy of the radar does decrease as the number of targets increases, this is still a useful system in the context of railways, since so long as a target is detected an alarm can be triggered so appropriate action can be taken.

Opportunities for future research:

- Future work for this project aims to consider tracking and classification of targets, not just identification.

Report title: Object Detection at Level Crossing Using Deep Learning

Journal/Source: MDPI

Researchers/Research organization: (Academics) Muhammad Asad Bilal Fayyaz, Christopher Johnson

Publication date: November 2020

Technologies examined: CCTV Cameras, RADAR. *Keywords: railway level crossing, sensing system, algorithms, deep learning.*

Key findings:

Throughout Great Britain and Europe, multiple projects in the rail industry have been initiated to address the issues with urban growth and increasing demand for rail services. These projects result in an increase in the number of intersections, junctions, and level crossings throughout the rail network.

This project aims to investigate the work done on automation within railway crossings and determine the most effective technologies.

The proposed methods for object detection within railways are to utilize RADAR and CCTV cameras as the primary and secondary sensing systems and operate as a "2oo2" logic channel interlocking system, and then use deep learning technology for the post processing of data collected by the sensors. The deep learning technology would classify and localize the precise location of detected objects.

It was stated that some of the sensors installed at grade crossings disrupt railway operations during installation and maintenance, which makes it a costly and inefficient technology for railway crossings. The proposed technology is low cost and have a high product lifecycle, making them well suited for rail crossings.

Being able to detect and locate objects without the interference of a manual operator will allow for an efficient automation process of rail crossings and reduce the associated risks.

Opportunities for future research:

- To improve the efficiency and accuracy of the model, the dataset should be investigated for potential biases.
- The same model could be applied to the census of passengers, tracking suspicious behavior, or alarming passenger across the red alert zone at a platform.
- The deep learning model can be integrated with radar to classify obstacles which is difficult with traditional post processing techniques. The deep learning model can train on micro-doppler signals from radar and learn the unique micro-doppler signals for each object at a level crossing.

Report title: NTT: "Aiming to prevent accidents at level crossings" Demonstration experiment started with "AI retention detection system at level crossings" utilizing 5G network, MEC technology, AI

Journal/Source: ProQuest

Researchers/Research organization: Contify Telecom News

Publication date: August 2023

Keywords: Accident prevention, railroad accidents and safety, railroad crossings, Artificial Intelligence (AI), real-time

Technologies examined: 5G networks, Artificial Intelligence (AI)

Key findings:

Railroad crossings account for 40% of railway accidents. To prevent crossing accidents a common approach is to use a system that detects any object that obstructs the crossing. Systems that detect objects on rail crossings are typically able to detect automobiles with a high level of accuracy, however detecting smaller objects, such as bicycles, strollers, handcarts, and people yields worse results.

This article highlights an Artificial intelligence (AI) stagnation detection system being developed by Kanto Railway Co., Ltd. (located in Japan) that uses AI to detect any object that moves onto the tracks, regardless of the objects size. The goal of this project is to develop a system that will help prevent accidents from occurring at railway crossings. The goal will be reached by utilizing 5G networks and AI to improve the systems detection of small objects.

Validation for this project started on September 1st, 2023, and will be completed March 31st, 2024.

Opportunities for future research:

- Over the course of the systems validation, the systems effectiveness will be confirmed, and improvements will be made as necessary.
- The system will expand its features, such as alerting the approaching train's driver when an object is detected on the track.
- Once everything is complete, proposals for introducing the system will be made to railway companies.
- This system is capable of detecting birds, animals, and various small objects. A continued investigation of the applications of this system within railways should be conducted.
- Validation of this project is projected to end March 31st, 2024. The results should be investigated upon its completion.

Report title: 5G Automotive Association Virtual Showcase Highlights Momentum behind C-V2X Technology Deployment for Connected Vehicles and Smart Cities in the U.S.

Journal/Source: ProQuest

Researchers/Research organization: Canada NewsWire

Publication date: October 2020

Keywords: Infrastructure, Railroad crossing, vehicles, transportation planning

Technologies examined: 5G networks, Cellular Vehicle to Everything (C-V2X) communication.

Key findings:

This article discusses the various implementations of Cellular Vehicle to Everything (C-V2X) communications currently being deployed throughout the United States. C-V2X was stated to be an enabler for safer and more efficient transportation systems.

The wide development of C-V2X is a direct evolution path towards 5G-V2X, which will support the mass-deployment of the basic and advanced driving use-cases that are outlined in 5GAA's Visionary 2030 Roadmap.

In the article, specific implementations of C-V2X include:

- The deployment of C-V2X on the Virginia Smart Road Corridor allows a new generation of vehicles capable of communicating not just through cellular towers, but also directly with roadside infrastructure.
- The deployment in Alpharetta, Georgia entails a variety of applications including Emergency Vehicle Preemption, Get-Ready-For Green, and Red-Light Warning, while Traffic Light Priority for Cyclists is being developed for deployment.
- The deployment of C-V2X communications in Arlington will allow drivers to receive Railroad crossing alerts through an app known as TravelSafety.

Opportunities for future research:

- Current technology being deployed and referenced in this article mostly for roadways. Further research should be conducted on the mentioned V2X applications specifically with grade crossing equipment.

Report title: Quantifying the Extent to Which Connected and Autonomous Vehicles Reduce Accidents at Railroad Grade Crossings: A Machine Learning Approach

Journal/Source: SAGE Journals, National Academies

Researchers/Research organization: University of Illinois at Urbana-Champaign: Jacob Mathew, Dr Rahim F. Benekohal

Publication date: June 2022

Technologies examined: C-V2X communication, Machine learning.

Key findings:

This research paper identifies the potential benefits of connected-vehicle safety technologies that have applications at grade crossings for improving safety. Vehicle based technologies, such as railroad crossing violation warnings, drowsiness/distraction driver alert, and automated/semi-automated braking systems, were also identified. Technologies that would require cooperation from the railroad industry include advanced warnings systems for trains that would alert oncoming locomotives of an occupied grade crossing.

Based on the technologies identified, the report also highlights the characteristics of crashes that would allow for the classification of a crash as preventable or non-preventable with the utilization of a connected vehicle environment. A machine learning model was developed with the purpose of classifying crashes into these categories. The specific model used was the 'Random Forest' model, alongside the ZINEBS model. C-V2X combines low-latency direct communications in the 5.9 GHz spectrum band (not requiring network coverage) and mobile network communications with the goal of effectively utilizing connected-vehicle technologies for improved safety.

The results discussed in this report can be used to identify which grade crossings have high safety risks and the specific crossings that would not benefit from a connected-vehicle environment.

Opportunities for future research:

- The model developed a motorist's action is calculated using probabilities from historical data. Field studies should be conducted to determine whether the distributions used are faithful to the real-life scenarios.
- To account for the limitations in this model it is recommended that several crossings with similar characteristics are used to determine the proportion of crashes that could be prevented within a connected vehicle environment.
- Field data should be collected to get the distribution of the behavior of connected and autonomous vehicle drivers in response to the train's presence.
- As more data becomes available the model developed will need to be rerun. Specifically connected autonomous vehicle data and near-miss information can greatly enhance the data set to help identify risky locations.

Report title: Crossing collision, VIA Rail Canada Inc., passenger train no.53, mile 11.75, Smiths Falls subdivision, Richmond, Ontario, 30 June 2021.

Journal/Source: Aurora

Researchers/Research organization: Transportation Safety Board of Canada

Publication date: 2022

Technologies examined: Grade crossing collision incident report.

Key findings:

This collision occurrence report highlights the collision of a motor vehicle and a train at a grade crossing. This particular grade crossing had flashing lights, that activated at the appropriate time, and gates that were fully lowered, at the appropriate time. The locomotive also sounded the horn and bell in accordance with CROR rule 13.

At the time of this occurrence, the temperature was 29°C, skies were clear, visibility was good, and the road was dry. There was also a rail crossing sign well in advance of the grade crossing.

The vehicle that was hit by the locomotive, drove around the lowered gates, resulting in the collision. The locomotive applied its brakes as soon as it could but was too close and going too fast to be able to stop in time.

The grade crossing investigation found that the grade crossing met all regulatory requirements.

Opportunities for future research:

- Research into potential barriers that prevent cars from being able to access the grade crossing at all when a train is approaching could prevent such accidents from occurring.
- Improving citizen education and awareness around grade crossings could also prove beneficial in preventing such accidents from occurring.
- Further considerations that were identified during the grade crossing investigation include that may need further investigation include the visibility of the lowered gates, as depending on the lighting conditions can be difficult to see.

Report title: [Artificial Intelligence-Aided Grade Crossing Safety Violation Detection Methodology and a Case Study in New Jersey]

Journal/Source: Sage Journals, National Academies

Researchers/Research organization: The State University of New Jersey: Asim Zaman, Zhe Huang, Weitian Li, Huixiong Qin, Di Kang, Xiang Liu

Publication date: May 2023

Technologies examined: Computer vision algorithms (including Deep Convolutional Neural Networks (DCNN), Regional Convolutional Neural Networks (RCNN), Fast RCNN, Faster RCNN, You Only Look Once (YOLO)v1-5, Simple Online Realtime Tracking (SORT), and Deep Association matrix to SORT (DeepSORT).

Key findings:

There is a constant concern around fatalities at grade crossings in the United States. To combat these concerns a combination of engineering, education, and enforcement campaigns have been conducted. A specific effort is the deployment of security cameras throughout the rail network. The implementation of these cameras has allowed for the collection of big data that enables research to gain a better understanding of grade crossing violation behaviors. Although the information gained from analyzing footage is valuable, the process for extracting useful information is manual labor intensive.

This project analyzes state-of-the-art vision based Artificial Intelligence (AI) techniques to recognize and understand railway video data in real-time. AI is used to help reach the project's overarching goal of developing better engineering enforcement and education strategies for the mitigation of active grade crossing violations.

This project focuses on the development and utilization of an AI system that will automate data collection involving grade crossing violations. The proposed system is capable of classifying types of violation, weather information, and train events. The investigation of technologies resulted in the YOLOv5 and DeepSORT algorithm to be used for this project, as they were deemed to have superior accuracy and performance compared to other algorithms available at the time of development. YOLOv5 was used for object detection and DeepSORT was used for multiple object tracking.

The proposed system analyzed 1 year of live footage (24 hours a day) from a New Jersey grade crossing and detected 20,054 violation events during this period of time.

Opportunities for future research:

- Further research could increase the amount and variety of data analyzed by the AI system to better understand grade crossing violation behavior and to develop more informed mitigation strategies.
- False positives were omitted in the results. Further investigation into why false positives were present and how to mitigate them for more accurate results should be conducted.

Report title: Machine Learning Approach to Enhance Highway Railroad Grade Crossing Safety by Analyzing Crash Data and Identifying Hotspot Crash Locations

Journal/Source: SAGE

Researchers/Research organization: University of Alberta: Parth Rana, Fereshteh Sattari, Lianne Lefsrud, and Michael Hendry

Publication date: 2023

Technologies examined: Machine Learning models. *Keywords: Artificial intelligence and advanced computing applications, data analytics, machine learning, passenger rail transportation, safety performance and analysis, crash analysis.*

Key findings:

Highway railroad grade crossings (HRGCs) are considered high risk areas within the rail network due to the severity of consequences that result from a collision.

This research proposes a classification model that fits several machine learning models to various samples of the same data and averages the resulting predictions. The Ensemble-supervised machine learning classification models included in this project are Random Forest (RF), Adaptive Boosting (AdaBoost), and Extreme Gradient Boosting (XGBoost). By using ensemble machine learning models for classification, the proposed solution has been able to provide better predictions of high-risk crash-prone areas since it is able to handle complex relationships among the variables.

The results of this report indicate that high train traffic, high vehicle traffic, high highway speeds, and high track speeds are the major factors that contribute to crashes. The results can be used to benefit authorities and policy makers to better direct resource allocation for implementing countermeasures that will reduce the number of HRGC crashes and the associated severity.

Opportunities for future research:

- It should be noted there were gaps in this study. The source datasets had empty features because of poor reporting and were excluded from the analyzed datasets. As such the analysis may not have identified all casual factors for crashes and the associated severity. Also, the classification model did not consider human factor considerations such as driver experience and physical/mental state. Thus, future research should investigate the role of human factors.
- Based on the results from this study possible strategies to reduce HRGC crashes and casualties include:
    - Installing gates and automatic railway-controlled crossings. Installing flashing lights, bells, and gates
    - Developing grade crossing separations for crossings that handle high daily vehicle and train traffic.
    - Implementing advanced warning systems
    - Reducing train and vehicle speeds around grade crossings
    - Installing light sources and clearing obstructions to ensure clear view of the oncoming train.
    - Installing Pavement/rumble strips to help drivers recognize an upcoming grade crossing.
    - Increasing education about traffic discipline and potential consequences

The above recommendations will require their individual study to assess the various available options and determine the most effective approach to reducing risks and improving safety at HRGCs.

C10. Technologies for monitoring trespassing

Report title: Combination of Fiber Optic Acoustic Sensing, IoT & Smart CCTV Data and Its Uses For The Rail Industry

Journal/Source: Science Direct

Researchers/Research organization: Guilherme Beirao, William Harper, Carmina Coronel, Ed Austin

Publication date: 2023

Keywords: Digitalization in Mobility; transport services and sustainable cities; Internet of Things (IoT); Smart Infrastructure; sensing and real time information

Technologies examined: Fiber Optic Acoustic Sensing, Internet of Things (IoT), Closed-circuit television (CCTV)

Key findings:

The purpose of this report and research is to refine and fully automate a system that will use data from multiple sources, including the internet of things (IoT) and closed-circuit television (CCTV), alongside fiber optic acoustic sensing (FOAS) to analyze railways in near real-time.

Utilizing FOAS for object location identification has many potential use-cases within the rail industry. Despite the potential of FOAS, railways have been reluctant to adopt the technology due to insufficient evidence of secure and accurate output.

When using FOAS to detect, locate, and track trains it is a relatively simple task to determine what is a train, whereas other moving objects can be difficult to distinguish due to their subtle differences. The report demonstrated FOAS ability to continuously track multiple trains at once, however these results are not overly useful without the effective detection of other entities.

FOAS for train detection is a relatively developed application, however there is not a lot of development with FOAS for human traffic detection. Past research has demonstrated FOAS have the capability of detecting individual footsteps up to 20 meters from the fiber optic cables. There has also been some research showing promise for FOAS to detect humans and vehicles around rail crossings, although there was no specific mention in the report about alternative forms of transportation, such as cycling. FOAS have their own set of limitations when used by itself, but combining ground truth data, IoT, and CCTV data, areas where FOAS are inefficient or less accurate can be supplemented with more data. The lack of ground truth data and analysis of combined data sources has further dissuaded railways from adopting the technology.

Opportunities for future research:

- Data will continue to be collected from FOAS, IoT, and CCTV sources described in the report.
- To demonstrate the feasibility of the use-cases explained in this report, a variety of techniques will be used to assess:
  - FOAS analysis algorithms with respect to ground truth data
  - Reliability and accuracy of safety/security related railway incidents

- Finally, the last objective is to deploy the technology with potential for a variety of applications within railways.

Report title: Artificial Intelligence-Aided Automated Detection of Railroad Trespassing

Journal/Source: National Academy of Sciences: Transportation Research Board

Researchers/Research organization: Asim Zaman, Baozhang Ren, Xiang Liu

Publication date: May 2019

Technologies examined: Artificial Intelligence, CCTV, Mask R-CNN

Key findings:

This research paper presents an AI framework, capable of analyzing live CCTV video feed in real time, and the initial results of the framework. The AI-aided trespassing detection framework considers ethics, economics, accuracy, demand, support, adaptability, and availability. The goal of this research is to identify trespassing events and send an alert when one occurs.

To reach the goal

- a methodology for AI-trespassing detection and alert was developed.
- a practice-ready tool that implements the algorithm was developed.
- trespassing data was collected and analyzed to better understand trespassing characteristics.

In the case of a trespassing event, the AI algorithm is capable of sending live alerts to personnel in the form of a SMS text or email and a clip from the CCTV camera. The trespassing event is then stored in a database, along with event metadata, to gain insight on the behavioral characteristics of trespassers.

During the testing of this AI framework the AI was capable of detecting all of the trespassing events that occurred. Implementation of this framework would allow for reduced manpower needed for trespasser detection, better development of trespassing prevention/detection methods, and the utilization of the existing CCTV camera infrastructure.

This report also highlights how big video data and this AI have potential applications within other relevant domains.

Opportunities for future research:

Future work planned to continue this research includes:

- Increasing reviewed data to further validate framework, to incorporate more weather events and potentially different trespassing events.
- Apply transfer learning techniques to enable the AI to differentiate between authorized personnel and trespassers through PPE and distinct clothing.
- Conducting a performance analysis and trespasser behavior analysis (for potential suicide prevention measures)

This research can be adapted to a front facing camera on front of the locomotive for suicide prevention. Also, the AI can be adapted to detect anything, not just trespassers, so there are many possible applications.

Report title: A Novel Method of Near-Miss Event Detection with Software Defined RADAR in Improving Railyard Safety

Journal/Source: MDPI

Researchers/Research organization: Subharthi Banerjee, Jose Santos, Michael Hempel, Pejman Ghasemzadeh, and Hamid Sharif

Funded by: University Transportation Center for Railway Safety

Publication date: August 2019

Keywords: safety; radar; software-defined; image processing; railroad; yard safety; rolling stock; accident; near-miss; close-call

Technologies examined: Software-define Radar, RADAR

Key findings:

This research was conducted as an effort to investigate potential technology that has potential to

- Prevent fatal events.
- Monitor large-scale dynamic events.
- Record near-miss events.
- Operate unobtrusively and not cause additional distractions to the workers.
- Address challenges for both employees-on-duty and trespasser protection
- Aid in implementing and adhering to safe practices.

Software defined RADAR (SDRADAR) was deemed a viable detection method because of the advantages it provides with respect to flexibility, range, low-visibility operation, and multiple object detection and tracking. SDRADAR has a tradeoff between detection range and accuracy of small object detection. With a typical RADAR system, the settings are preset and are difficult to change for optimal range vs. resolution, however with SDRADAR different modulation schemes, coding, bandwidth, and sampling rate can be set in real-time to provide the most accurate results based on object size and distance from other objects (RADAR will clump groups of small objects into one, whereas SDRADAR can identify each individually). Due to SDRADAR's versatility, it is capable of blindly detecting objects and its size in low visibility conditions caused by environmental factors or poor lighting.

SDRADAR can be applied to near-miss detection, as it is capable of detecting multiple objects close to one another with varying sizes.

No one technology is currently capable of providing reliable information under every circumstance. Due to potential limitations of SDRADAR by itself it was incorporated alongside a wide-angle camera as a part of a multi-sensor system for object detection.

Opportunities for future research:

- An investigation on where this technology has been applied within a real railway setting and the feasibility of implementing this technology there have not been cases of its application.

Report title: A Deep Learning Approach to Trespassing Detection Using Video Surveillance Data

Journal/Source: IEEE

Researchers/Research organization:

Publication date: December 2019

Technologies examined: Convolutional neural network (CNN), machine learning, deep learning, automated trespassing system.

Key findings:

Trespassing is the leading cause of railroad incidents leading to fatalities yet is an under researched area. The goal of this research is to develop and validate an effective trespassing detection system that produces results in a time and resource efficient manner and allows for the addition of an analytic system to identify trespassing trends.

Video surveillance data on trespassing events is sparce and any video data that can be gathered is majority not a trespassing event, making gathering more video data difficult. The proposed method takes advantage of the large amount of downtime between trespassing events to minimize the need to process video with nothing happening. Needing to process less video data will improve the overall performance of the framework.

The presented framework is known as ARTS (automated railroad trespassing detection system) and uses a two-step approach. First, it filters out video frames that show little to no activity, to increase processing speed during the computer processing intensive phase. Secondly, it utilizes the state-of-the-art machine learning model, CNN, to differentiate trespassing from other movement events.

After the investigation, it was found that the framework is best applied to video surveillance domains where there is sparsity in activity. This is due to the frameworks ability to decide between improved processing time or accuracy.

Opportunities for future research:

- Utilizing the output from the ARTS, a trespassing prediction system can be made to monitor trends and predict when trespassing events may occur.
- The ARTS currently considers every frame individually, doesn't consider time or the previous frame. Using temporal information can improve the accuracy of the ARTS output, especially when the camera's vision is obscured or when the foreground is difficult to distinguish from the background.

Report title: Moving Human Detection and Tracking form thermal video through intelligent surveillance system for smart applications

Journal/Source: Springer

Researchers/Research organization: Manoj Kumar, Susmita Ray, Dileep Kumar Yadav

Publication date: July 2022

Technologies examined: Thermal cameras, background segmentation.

Key findings:

This paper proposes a method for a real-time smart video surveillance system. A large focus was put on the system's execution and ability to distribute accurate results in real-time. The aim of the proposed method will reduce trespassers with ill intentions, minimizes theft, monitor situations as they happen, and record occurrence data for future investigations. Any video surveillance system needs to be fast, robust, and reliable if it includes moving object detections. As such, thermal cameras were used due to their ability to handle complex lighting situations, cluttered backgrounds, noise, and environmental effects. Thermal cameras were also found to be efficient in terms of maintenance. This research proved that the proposed method yields more accurate results than similar detection systems and generates less false positives and false negatives than other systems that utilize the same or similar technology.

To ensure the thermal cameras were able to maintain accuracy and reliability during the complex situations described above, a background subtraction method was developed that would adapt various thresholds to deal with the problems caused by outliers, noise, or background complexity within the recorded images.

Opportunities for future research:

- Conduct research into online visual surveillance applications to accompany the video surveillance system.
- The authors plan to develop a cloud-based GUI framework for object detection and tracking.

Report title: Trespass Prevention Research Study – Worcester, MA

Journal/Source: Federal Railroad Administration

Researchers/Research organization: Federal Railroad Administration

Publication date: April 2021

Technologies examined: Trespassing prevention strategies.

Key findings:

This report aims to present lessons learned and recommendations for implementing and evaluating trespassing prevention strategies. The model used to evaluate trespassing mitigation strategies is the Community, Analysis, Response, and Evaluation (CARE) model (developed by FRA and TC).

The CARE model:

- Community: Identify problems and stakeholders
- Analysis: Collect data, analyze, and identify root causes
- Response: Implement best practices
- Evaluation, Evaluate impact and process. If the evaluation stage doesn't yield the desired results, then return to the analysis step.

To determine how effective the CARE model is, non-technological mitigation strategies for trespassing were implemented at 5 specific sites and analyzed. A basic camera that records video was implemented to gather information on trespassing events, frequency, demographics, and trespassing intent to determine the non-technology-based solutions efficacy and validity of the CARE model.

The non-technology-based solutions include strategies on engineering treatments, education outreach activities, and law enforcement actions. Specifically, adding "No Trespassing" signage, homeless population outreach, and increasing law enforcement patrols.

Although this study does not include new technologies, it aimed to act as a preliminary test for the CARE model and discerns if it is an effective strategy for developing new trespassing mitigation techniques. The CARE model itself also acts as a uniform method to address the trespassing issue. Unfortunately, the final evaluation was not able to be conducted within the timeframe.

Opportunities for future research:

- Since the CARE model was found to have key weaknesses, further research should be done into a uniform model that can investigate and test trespassing prevention methods. The CARE model was found to be resource and time consuming, and also requires a large amount of stakeholder involvement.
- Trespassing prevention methods that don't utilize technology (such as physical barriers) should also be researched to determine their effectiveness in areas that are more remote or have lots of tree cover, since technology is harder to implement and maintain.

Report title: Railroad Near-Miss Occurrence Detection and Risk Estimation System with Data from Camera Using Deep Learning

Journal/Source: IEEE

Researchers/Research organization: Amartuvshin Dagvasumberel, Bilguunmaa Myagmardulam, Byambasuren Myagmar, Byambasuren Luvsankhuu, Tadachika Nakayama

Publication date: July 2021

Technologies examined: Computer Vision, deep learning, CNN.

Key findings:

This paper identifies related work on rail track segmentation and obstacle detection to determine the most effective methods for near-miss detection. This project aims to develop a near-miss occurrence detection and risk analysis solution, by incorporating deep learning techniques and a risk estimation model.

Computer vision and deep learning are the main methods used for object detection. The machine vision methods/algorithms identified in related work includes, speeded up robust features (SURF), oriented fast and oriented brief (ORB), and random sample consensus (RANSAC). For deep learning, CNN's have proven to be an effective and reliable way to classify and segment within medical image applications.

During this project the YOLOv3 model was used for object detection, and was trained using the COCO dataset, which is a free large-scale image recognition dataset. For the segmentation portion of this project, three different segmentation models were used, the LinkNet34, D-LinkNet, and Unet. Out of the trained segmentation models, D-LinkNet was stated to have achieved excellent results with track identification and improved the overall accuracy of the risk estimation.

The application of this project demonstrated that automating obstacle detection during a trains operation and utilizing a model for risk estimation is effective and will benefit the development of safer railways.

Opportunities for future research:

- This technology has the potential to be adapted to specifically focus on trespassing identification or used as a method for gathering information on near miss events.

Report title: Trespasser Detection on Railroad Property Using Unmanned Aerial Vehicles

Journal/Source: Federal Railroad Administration

Researchers/Research organization: Federal Railroad Administration

Publication date: August 2020

Technologies examined: UAV.

Key findings:

In 2018, there were 518 non-suicide trespassing related fatalities and another 272 fatalities determined to be suicides. Trespassing fatalities are an issue within railways, and after identifying limitations with utilizing fixed cameras for trespassing detection, research into the feasibility and efficacy of unmanned aerial vehicles (UAV) to actively look for trespassers was conducted.

This research aims to determine the best UAV technology for trespasser detection and investigate the training required to effectively operate a UAV for trespasser detection. Having a method to record and analyze flight logs is also important for trespassing analysis.

The drone selected for this project was the DJI Matrice 200, for its compatibility with various different camera types.

During this project, over 12 months, there were 32 separate flights in which no trespassers were found. Trespassers within the area were found to traverse the tracks and are only in a specific area for a few minutes at a time. Because of the small timeframe to catch trespassers the drone detection method is best used when people in the area tend to loiter on or near the tracks rather than traverse, or the area is very open, with little to no tree cover.

Some limitations of the drone were also identified, including needing to keep a visual line of sight with the drone, battery life was limited to 30 minutes, and no flying near crowds of people.

Opportunities for future research:

- Conducting hotspot analyses of trespassing in railways can improve trespassing detection regardless of method used.
- Determine if research was continued by Tri-Rail and SEPTA in testing drones for trespasser detection.
- Research into possible beyond visual line of sight operations of drones to increase chance of detecting active trespassers.

Report title: A Systematic Review of Railway Trespassing: Problems and Prevention Measures

Journal/Source: MDPI

Researchers/Research organization: Silvestar Grabusic, Danijela Baric

Publication date: September 2023

Technologies examined:

Key findings:

This report is a literature review of railway trespassing. Although no new technologies are presented, there is coverage of issues with current trespassing prevention measures and ample information on the knowledge gaps within railway trespassing research.

In the past five years, there has been a lack of research on educational measures and a large increase in research relating to trespassing detection systems. The report also states that there is a focus on suicides on the railways, however it is difficult to distinguish a suicide attempt from a typical trespasser.

Trespassing prevention strategies were classified into educational, signalization, technological, and infrastructure measures.

Past studies and research papers covering the effectiveness of trespassing mitigation measures are often tested in controlled environments, which brings the actual effectiveness of such a strategy within a real world setting into question. Alternatively, long-term pilot studies were deemed the most effective at evaluating mitigation strategies.

Opportunities for future research:

- Gaps in research were identified specifically in suicide prevention methods.
- Many trespassing factors are tied to specific locations, therefore trespassing solutions and needs are identified through investigating railway trespassing hotspots alongside identifying why the hotspot exists.
- Some known gaps within the literature review conducted includes:
    - Only English papers were used.
    - The word "trespassing" was always paired with another word, possibly causing reports to be missed.
    - The categories for Factors and Trespassing preventative measures were selected by the authors, possibly creating a bias.
- More research is needed into the factors behind trespassing accidents, trespassing factors in general, such as human behavior, and hotspot analysis to develop preventative measures for high-risk behavior and high-risk railway sections.

Report title: Railroad Crossing Surveillance and Foreground Extraction Network: Weakly Supervised Artificial-Intelligence Approach

Journal/Source: National Academy of Sciences: Transportation Research Board

Researchers/Research organization: Youzhi Tang, Yi Wang, Yu Qian

Publication date: March 2023

Technologies examined: foreground segmentation and background generation methods, CNN.

Key findings:

Trespassing on railways has been recorded as the leading cause of railroad related deaths. This project explores the idea of using a "weakly" supervised learning method for effective foreground segmentation networks and demonstrates the effectiveness of a designed CNN network, called RC-SAFE. This idea is split into three components. The first is a background generation model called SubSENCE, the second is a foreground segmentation model based on the UNet architecture, and the last section is the "weakly" supervised learning technique.

RC-SAFE will minimize the amount of manual labor and time needed to train the system, since images won't need as accurate labeling to be added, compared to other state-of-the-art algorithms. RC-SAFE has the ability to identify both moving and stationary objects. When compared to other state-of-the-art algorithms, RC-SAFE proved to outperform overall, ~~with~~ although it did underperform in some specific situations. The algorithms RC-SAFE was compared against includes, SimpleBSC, DEEPBS, AuBSENSE, PAWCS, and PBAS, and was proven to outperform many of them in most video quality categories (categories include low framerate, night videos, shadows, and overall performance).

Opportunities for future research:

- This research has many applications within the realm of trespassing detection and can easily be adopted for such purposes. Further research would need to be done into the specific algorithms used, but less time needed for the training phase would allow for faster implementation across railways.
- Although this project outperformed many of the state-of-the-art algorithms overall, there were specific image conditions, such as general bad weather, where it underperformed.

C11. Development of tools and analytics for risk assessment

Report Title: A machine learning and data analytics approach for predicting evacuation and identifying contributing factors during hazardous materials incidents on railways

Technical Journal/Source: Safety Science, Volume 164

Researchers/Research Organization: Hadiseh Ebrahimi, Fereshteh Sattari, Lianne Lefsrud, Renato Macciotta, University of Alberta

Publication Date: May 2023

Technologies examined: Emergency evacuation order framework using machine learning techniques.

Machine learning; Railway incidents; Evacuation; Risk assessment; Natural language processing; Co-occurrence network analysis

Key findings:

Machine learning models could improve experts' approaches to decision-making problems. In the first part of this study, the Dangerous Goods Accident Information System (DGAIS) database was used to predict the need for evacuation using various supervised machine learning models (logistic regression model, Naïve Bayes, decision trees, support vector machine, k-nearest neighbor, random forest, and multi-layer perceptron). Based on the various performance metrics used (e.g., precision, recall, F1-score, AUC-ROC curve), random forest was selected as the superior model for evacuation prediction. Based on the random forest analysis, the type of incident, hazmat released (yes/no), type of hazmat, and transport phase were determined to have the greatest effect on the decision to evacuate. The decision tree algorithm was applied to extract incident assessment rules that lead to an evacuation. Text data on incident narratives have been collected over the years and, if properly utilized, can be a valuable source of learning information. In the second part of this study, the descriptions of the incidents that led to evacuations were analyzed using natural language processing (NLP) and co-occurrence network analysis to identify patterns in unstructured text data. The main contributors to evacuations were identified based on the frequency and connection of the nodes in the co-occurrence network. The contributing factors included leak and spill (categorized as different types of incidents), overturning and derailment (categorized as different types of actions on Means of Containment (MOC)), railyard operation and loading operation (categorized as different types of transport phase), and petroleum crude oil, diesel fuel, sulphuric acid, nitrate ammonium, sodium hydroxide solution, and ammonia anhydrous (categorized as different types of hazmat).

Despite the significant insights provided by this study, there are some limitations as follows:

- Railway incidents may occur under different circumstances and propagate differently, and the co-occurrence network can remove the significant information and latent causes.
- Other sources of information, such as the vulnerability of adjacent populations and their ability to respond to hazards, may be considered to develop evacuation plans.
- The input factors used have uncertainty, as they have been collected by risk managers and experts (i.e., type of incidents, action on MOC) and measuring equipment (mileage traversed by trains), and the uncertainties of these values are not reported in the dataset used in this study.

Opportunities for future research:

- The contributing factors identified in this study can be used to extract only the reports that contain these contributing factors. This would enable a deeper probe into the latent causes of the incidents.
- A comprehensive dataset containing various information, including population vulnerability to predict evacuation, could be included in the analysis.
- The uncertainty of the input factors could be reported and used to improve the accuracy of the results.

Report Title: Enhancing strategies for the safe transportation of dangerous goods by rail - Phase 1: Evaluation of leading and lagging performance indicators

Technical Journal/Source: Transport Canada Innovation Centre Published Reports

Researchers/Research Organization: University of Alberta, Transport Canada - Innovation Centre

Publication Date: April 2021

Technologies examined: Safety management systems (SMS) for railways.

Key findings:

This research focuses on safety management systems (SMS) for railways as a possible option to improve safety and reduce risk. The research suggested that performance against lagging indicators (including derailments, collisions, serious injuries, fatalities, dangerous goods (DG) leaks, and DG releases) being reported currently is adequate. Detailed root cause analysis (RCA), bow tie analysis (BTA), and incident databases are used to identify the main causes and consequences of main-track derailments involving DG from the year 2007 to 2017. The results of the study found that the main causes of DG main-track derailments stemmed from rail defects and failures, weaknesses in audits, and inadequacies in guidelines. At the same time, the SMS elements that should be prioritized for enhancement are process and equipment integrity; incident investigation; and company standards, codes, and regulations. By enhancing railway SMS, it will be possible to improve transportation of DGs, and in turn, reduce the potential for negative impact on health/safety, environment, and economy. This study also utilized human factor analysis and classification system (HFACS) as an analytical framework to investigate the contribution of human factors in railway incidents. It was found that most deficiencies as a result of human factors are in the fields of organizational oversight, supervision, and organizational culture. The results reinforced the importance of decision-making at higher managerial levels and the effect of these decisions on the actions of front-line operators that can lead to railway loss incidents.

In addition, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was used to map causal relationships between the subcategories of HFACS to determine the importance of each subcategory. Subsequently, the DEMATEL method was combined with the Analytic Network Process (ANP) method to calculate the weight of each subcategory of HFACS and categorize the leading indicators of railway loss incidents. It was found that organizational climate, organizational process, and resource management have the greatest effect on other subcategories. Improvements in these areas could lead to the prevention of future railway loss incidents. Also, another potential group of leading indicators in railway loss incidents include crew resource management, skill-based errors, and violations.

Opportunities for future research:

Using the application of an innovative approach, knowledge discovery (KD) to allow researchers to analyze large datasets in a more comprehensive manner recommendations for future research are:

- Utilize artificial intelligence (AI) and machine learning (ML) for the datamining of large databases (e.g., RODS) to identify and better understand the important leading indicators identified from Phase 1. The recommendations pertaining to these indicators can then be improved.

- Further develop process models for other important occurrences with the potential for DG release. The results can be used to enhance the existing bow-tie analyses and potentially identify new critical safety controls.
- Use process models and statistical analysis to create a quantitative risk assessment tool that can be used to evaluate risk in major rail occurrences with the potential for DG release. The purpose of this study will be to reduce loss in the railway industry by helping decision-makers efficiently plan on-time emergency evacuations in the case of DG release.

Report Title: Human vulnerability modeling and risk analysis of railway transportation of hazardous materials

Technical Journal/Source: Journal of Loss Prevention in the Process Industries, Volume 80

Researchers/Research Organization: Hadiseh Ebrahimi, Fereshteh Sattari, Lianne Lefsrud, Renato Macciotta, University of Alberta

Publication Date: December 2022

Technologies examined: Procedure to analyze the risk of railway transportation of hazardous materials (Hazmat)

Hazardous materials rail transportation; Population vulnerability; Hazard footprint; Risk assessment; ALOHA; ArcGIS

Key findings:

Hazardous materials transportation (hazmat) railway incidents can pose threats to the people living in the areas close to railway tracks. Risk assessments are necessary to reduce the severe consequences of hazmat release on people. In this study, a procedure was developed to analyze the risk of hazmat railway incidents, and then this procedure was applied to a small city in Canada. The meteorological variables (e.g., stability class, cloud cover, wind speed, solar radiation, etc.) were processed to create hazard maps for the most probable and the most dangerous meteorological conditions. The sociodemographic characteristics of people were identified and ranked to simulate the vulnerability map in the ArcGIS software. Risk maps were generated by superimposing the hazard and vulnerability maps in the ArcGIS software, which indicate a risk range from low to high, using a double-entry risk matrix. Risk maps reflect both hazard and vulnerability maps, which reveal that the areas with high hazards shown on the hazard maps are not necessarily the areas with high risks shown on the risk maps. The risk maps can be used to prioritize emergency response decisions and to improve land-use planning based on population vulnerability. They can also be used to improve the quality of life of the people living in higher-risk areas by boosting education, quality of housing, wellness, etc. This risk assessment method along with other quantitative methods (i.e., decision tree and Bayesian network analysis) can be a great help to evaluate and reduce the risk of hazmat railway incidents. It is worth mentioning that this risk assessment method can also be applied to different types of railway incidents in various locations or the incidents, occurring in other industries if the required data are available.

Opportunities for future research:

- Future research can be done on different types of dangerous goods such as toxic inhalants, and how they interact with meteorological variables (e.g., stability class, cloud cover, wind speed, solar radiation, etc.).
- The risk assessment method is static in this study. However, the population of people and meteorological conditions are changing with time. To consider the change of risk over time, the current risk assessment model could be combined with dynamic models. Deciding to implement a dynamic risk estimate approach, however, would need to balance comprehensiveness and applicability for emergency response purposes.
- The ALOHA software has some limitations, such as estimation of hazard threat zones for a maximum of 10 km or 1 h, and the inability to simulate threat zones for very stable atmospheric conditions or during wind speeds less than 1 m/s. Research should be done

on using the PHAST software which provides a suitable alternative. The procedure presented allows for the use of this or other software packages.

Report Title: Evaluation of Risk Acceptance Criteria for Transporting Hazardous Materials

Technical Journal/Source: U.S. Department of Transportation

Researchers/Research Organization: Federal Railroad Administration

Publication Date: February 2020

Technologies examined: Quantitative risk assessment (QRA) methodology for the transport of hazardous materials on rail.

Liquefied natural gas, LNG, safety assessments, dual fuel, compressed natural gas, CNG, risk criteria, quantitative risk assessment, QRA, locomotive, hazardous materials, rolling stock.

Key findings:

This report provides a recommendation and justification for FRA to adopt a quantitative risk assessment (QRA) methodology for the transport of CNG/LNG on rail. The recommendation is general and can be applied to other hazardous materials if those materials present similar hazards and the time scale over which harm would be caused by a potential accident is comparable. The Dutch Purple Book was used as an example methodology because it is widely accepted across many industries and has been implemented extensively in countries that have risk-based regulations, such as the UK and Netherlands.

The QRA for transportation risk is fundamentally the same as a fixed facility. However, there are differences in calculations of both the probabilities of occurrence and the location of hazards. Involuntary individual fatality risk is recommended to be acceptable for annual probabilities of less than 3 x 10-7 for any population, including vulnerable populations, and may be considered acceptable at the regulators discretion for non-sensitive/non-vulnerable populations if less than 5 x 10-5 and demonstrated to be as low as reasonably practicable (ALARP). Societal risk is recommended to be acceptable if the annual frequency of events that would result in N or more fatalities is less than 10-5/N events per year and may be considered acceptable at the regulators discretion if less than 10-3/N events per year and demonstrated to be ALARP. These criteria should be applied to the societal risk over the entire transportation route, not normalized per-distance. These values are adapted from the National Fire Protection Association (NFPA) 59A, a U.S. and international standard for liquefied natural gas (LNG) facility siting.

Opportunities for future research:

- Future efforts should include determining how to better estimate various aspects of the risk calculations, including mitigation measures to lower risk. The mitigation measures could include decreasing speed in more densely populated areas, decreasing the quantity of natural gas being transported, modifying the natural gas storage tanks, etc.

Report Title: Railway Dangerous Goods Transportation System Risk Assessment: An Approach Combining FMEA With Pessimistic–Optimistic Fuzzy Information Axiom Considering Acceptable Risk Coefficient

Technical Journal/Source: IEEE Transactions on Reliability, Volume 70

Researchers/Research Organization: Wencheng Huang; Yue Zhang

Publication Date: February 2020

Technologies examined: A systemic risk assessment approach combining failure mode and effect analysis (FMEA) and pessimistic-optimistic fuzzy information axiom (POFIA) considering acceptable risk coefficient (ARC)

Risk management; Rail transportation; Uncertainty; Accidents; Hazards

Key findings:

In this article, a new systemic risk assessment approach, which combines failure mode and effect analysis (FMEA) and pessimistic-optimistic fuzzy information axiom (POFIA) considering acceptable risk coefficient (ARC), is proposed to evaluate the risk of railway dangerous goods transportation system (RDNGTS). This approach transforms the system risk assessment problem into the rank problem of severity of risk factors affecting system security. The triangular fuzzy numbers (TFNs) are applied to score the severity of failures (S), portability of occurrence (O), and possibility of detection (D) for each RDNGTS risk sub indicator. The information contents of S, O, and D are calculated for each risk sub indicator, two models are applied to calculate the information contents: POFIA, and POFIA considering ARC (POFIA-ARC). The product of information contents of S, O, and D is used to replace the risk priority number of FMEA. entropy weight method is used to calculate the weight of each risk sub indicator. The comparison among the FMEA-POFIA-ARC, FMEA-POFIA, FMEA, FMEA with TFNs is conducted based on the historical data of Chinese RDNGTS accidents from 1986 to 2017. Results show that the potential human risk should be paid more attention. Compared with the analysis results of statistical accident number, the results of the approaches proposed in this article (especially the FMEA-POFIA-ARC) are more reliable than the results of FMEA and FMEA TFNs combined approach.

Opportunities for future research:

- Weights of the sub indicators are important in this approach, when the initial data of the sub indicator has small fluctuation amplitude, or the data remain unchanged during the operation periods, the weights of these sub indicators are 0. In order to overcome the limitation, the translation-corrected distance entropy, improved group-G1 method, improved group-G2 method, etc., may be applied.
- The TFNs are applied in this article, the intuitionistic fuzzy numbers, e.g., trapezoidal intuitionistic fuzzy numbers, triangular intuitionistic fuzzy numbers, can also be used to improve the FMEA approach.
- Interpretive structural modeling (ISM), which is a powerful qualitative tool and is a suitable modeling technique for analyzing the influence of one element and developing insights into a collective understanding of these relationships and their levels, so the ISM and ISM-based approaches can be used as a systemic method, to solve the risk assessment problem of RDNGTS.

Report Title: [Historical data-driven risk assessment of railway dangerous goods transportation system: Comparisons between Entropy Weight Method and Scatter Degree Method]

Technical Journal/Source: Reliability Engineering & System Safety, Volume 205

Researchers/Research Organization: Wencheng Huang, Yue Zhang, Southwest Jiaotong University

Publication Date: September 2020

Technologies examined: Entropy Weight Method (EWM) and Scatter Degree Method (SDM) for risk assessment.

Railway dangerous goods transportation system; Risk assessment; Entropy Weight Method; Scatter Degree Method; Stability analysis

Key findings:

In this paper, two historical data-driven weight calculation approaches including Entropy Weight Method (EWM) and Scatter Degree Method (SDM), are applied and compared to solve the risk assessment of railway dangerous goods transportation system (RDGTS). The risk is defined as product of occurrence probabilities and their corresponding weights, the occurrence probability and weight of each risk sub-indicator is obtained by using the historical statistical data as the inputs. EWM aims at reflecting relative intensities among the evaluation indicators, however, SDM reflects the projection factor that maximizes the overall difference among the evaluated objects. In order to compare the performance of EWM and SDM, the stability analysis is carried out, which focuses on studying and analyzing the reverse degree order of the weight value when the initial matrix changed. In addition, correlation coefficient between occurrence probability and final assessment results based on the two approaches are conducted. The results of the case study which used the historical RDGTS accidents that happened in China from 1985 to 2017 show: the SDM is more stable than EWM; sub-risk indicators with highest ranks belong to risk factors of Human category, which means the Human unsafe actions and behaviors are the most dangerous factors that influence the normal and safe operations of RDGTS.

Opportunities for future research:

- Due to the impacts of premature regulations or less favorable equipment, the final risk assessment results of the earlier years in the case study (e.g., 1985–2000) might have different values or causes than that of more recent data (e.g., 2001–2016). Hence, the rail accidents per year involving dangerous goods and the dangerous goods volumes transported by rail should be obtained to compare the risk assessment results and safety performance in several different but equal time periods. This will show whether there are differences or similarities and how they influence the overall outcome.

Report Title: Fault Tree and Fuzzy D-S Evidential Reasoning combined approach: An application in railway dangerous goods transportation system accident analysis

Technical Journal/Source: Information Sciences, Volume 520

Researchers/Research Organization: Wencheng Huang, Yuankai Liu, Southwest Jiaotong University

Publication Date: February 2020

Technologies examined: RDNGTS analysis using a Fault Tree and Fuzzy D-S Evidential Reasoning combined approach.

Railway dangerous goods transportation system; Accident analysis; Fault Tree; Fuzzy D-S Evidential Reasoning; Fuzzy Belief Structure

Key findings:

In order to manage the railway dangerous goods transportation system (RDNGTS) successfully, an explicit and effective previous accident analysis and accident control approach is essential and necessary. In this study a Fault Tree and Fuzzy D-S Evidential Reasoning combined approach is proposed to analyze the RDNGTS accident, which can solve the uncertainty modeling and information fusion problems existing in RDNGTS accident analysis. The approach has six steps: (i) identify causes of accident and calculate their weights based on Fault Tree, (ii) establish the Fuzzy Belief Structure model of causes of accident, (iii) handle initial qualitative and quantitative data, (iv) fuse the pre-processing data based on Fuzzy D-S Evidential Reasoning algorithm, (v) allocate Confidence Level of fuzzy intersection and, (vi) rank the final Fuzzy Belief Structure of each component based on trapezoidal fuzzy numbers and triangular fuzzy numbers. A historical lithium battery railway transportation accident happened in 2016 in China is applied as the background to examine the approach mentioned in this paper. The results show that professional skills and attitudes of transportation staffs are the weakest component in this lithium battery railway transportation accident. Some measures such as improve the awareness of safety and protection, train and examine the professional skills of transportation staffs, may be helpful in curbing the negligent working attitude of transportation staffs. Furthermore, the results also show that D-S Evidential Reasoning could provide a unified modeling framework for uncertain, incomplete, inaccurate and even ignorant information. It could solve the limitations in probability reasoning processes effectively.

Opportunities for future research:

- Other weight calculation approaches, such as entropy weight method, improved group-G1 method, improved group-G2 method, picture fuzzy sets related approaches etc. can be applied to obtain the weight of each cause of accident.

Report Title: Quantitative Risk Analysis on Rail Transportation of Hazardous Materials

Technical Journal/Source: Mathematical Problems in Engineering

Researchers/Research Organization: Centre for Risk, Integrity and Safety Engineering (C-RISE), Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X5, Canada

Publication Date: March 2022

Technologies examined: Risk assessment models, Fuzzy-Bayesian, Monte Carlo Simulation, Couple-based Bayesian Network (BN) Technique, Fuzzy-based Approaches,

Key findings:

The management of rail accidents involves the categorization of incidents based on key factors like track, equipment, human, signals, and others. Various techniques are employed to identify major causative factors, encompassing conventional risk assessment, human error analysis, optimal routing, economic impact assessment, environmental impacts, and accident statistical analysis. Quantitative Risk Analysis (QRA) is emphasized as a reliable method for determining safety zones along transportation routes and hazardous material storages, providing a high-precision assessment of the quantitative risks associated with material transportation. In their literature review, authors first listed the following techniques used as part of risk assessment process by various studies:

- **Fuzzy-Bayesian Network Approach:** This approach is used for risk assessment in the process industries, enhancing the integrity and support for various aspects of risk assessment.
- **Monte Carlo Simulation:** The Monte Carlo simulation method is used to assess the quantitative risk of human error in the process industries.
- **Copula-based Bayesian Network (BN) Technique:** This technique is employed to investigate the fault tree analysis (FT) uncertainty for the examination of quantitative risk in process systems.
- **Fuzzy-Based Approaches**
- **Quantitative Risk Assessment of Railway Routes:** Various studies have utilized quantitative risk assessment approaches to model the potential safety risks and consequences of transporting specific materials, such as LPG, hydrogen, and dangerous goods through railway routes.
- **Bayesian Network (BN)**: The Bayesian network is known for its ability to interrelate nonlinear relationships between parameters and enhance computational accuracy.

The paper focuses on the hazardous nature of chemical materials transported by rail and addresses the potential risks associated with such transportation, particularly the risk of vapor cloud explosions (VCE). It emphasizes the need for a holistic, quantitative, and robust risk assessment model that incorporates factors triggering severe health loss and catastrophic consequences. The proposed model integrates *Bayesian networks for causality modeling of material release scenarios and fuzzy set theory for estimating health effects and severity impact coefficients*. The study considers risk factors such as population density, route distance from residential areas, and the availability of sensitive third parties. The model is applied to a real rail system for gasoline transportation in Tehran to evaluate its effectiveness. The research aims to provide comprehensive insights for risk-managed decision-making in the safe transportation of hazardous materials by rail, with a particular focus on VCE as the worst safety consequence.

Opportunities for future research:

- Future investigations into other types of fire and explosion risks and potential domino effects in the rail transportation of chemical materials.
- Extension of the Risk Assessment Model: The paper introduces a risk assessment model incorporating Bayesian networks and fuzzy set theory. Future work could involve refining and extending this model to encompass additional risk-triggered criteria, potentially incorporating advancements in modeling techniques or considering a broader range of risk factors.
- Comparative Analysis of Transportation Routes: While the study mentions the ability of the proposed risk model to analyze possible risks and design safe transporting routes, future research could delve into a comparative analysis of different transportation routes. This could involve considering factors like terrain, urbanization, and other environmental variables that may impact the safety of transportation routes.
- Integration of New Technologies: With advancements in technology, future research could explore the integration of emerging technologies, such as real-time monitoring systems, artificial intelligence, or predictive modeling, to enhance the accuracy and effectiveness of risk assessments in rail transportation of hazardous materials.
- Case Studies and Validation: Expanding the scope of case studies to include various geographical locations, different types of hazardous materials, and diverse rail systems can contribute to the validation and generalizability of the proposed risk assessment model.

Report Title: [Semi-quantitative risk assessment of commercial scale supply chain of hydrogen fuel and implications for industry and society]

Technical Journal/Source: Process Safety and Environmental Protection

Researchers/Research Organization: Health and Safety Laboratory, Harpur Hill, Buxton SK17 9JN, United Kingdom

Publication Date: 2021

Technologies examined: top-down hazard identification, frequency assessment.

Key findings:

The paper is based on a study conducted by the Health and Safety Laboratory (HSL) for the Department for Transport (DfT) regarding the safety aspects of bulk transport and storage of hydrogen as a fuel. The primary objective of the study was to identify the necessary knowledge and data for the development of a comprehensive risk assessment for hydrogen delivery and storage infrastructure. The methodology employed involved conducting a semi-quantitative risk assessment for a representative hydrogen delivery and storage supply chain. This assessment utilized top-down Hazard Identification (HAZID) brainstorming, consequence modeling with commercially available software, and the use of a risk matrix. The paper also discusses the identified gaps in hazard identification, consequence modeling, and frequency assessment that need to be addressed to develop a quantified risk assessment methodology. Additionally, the study compares hydrogen and liquefied petroleum gas (LPG) in terms of failure modes and the number of trips required to meet equivalent energy demand using data on current UK LPG consumption. The implications of using ammonia as a hydrogen carrier and the regulatory considerations for hydrogen fueling or storage sites are also explored in the paper.

The study identifies several knowledge gaps that must be addressed to develop a comprehensive risk assessment methodology for hydrogen. These include the lack of clarity about the components and detailed design of a hydrogen delivery and storage infrastructure, as well as challenges in modeling hydrogen flames, explosions, and phenomena in confined spaces. Additionally, the study highlights the need for failure rate data for hydrogen infrastructure components, tankers, and ignition probabilities for releases. Future work should address these gaps. Insights from the risk assessment include the classification of distribution storage and refueling sites, the increased delivery frequency required for liquid hydrogen compared to LPG, and the identification of more failure modes for hydrogen road tankers. The study suggests potential extensive hazard ranges from hydrogen catastrophic releases and highlights concerns about hydrogen fires in tunnels and potential damage to infrastructure. The use of ammonia as a carrier for hydrogen is discussed, with lower hazard ranges compared to hydrogen flash fires or vapor cloud explosions.

Opportunities for future research:

- Exploration of the risk associated with ammonia as a carrier for hydrogen.
- Investigation of engine efficiency in hydrogen-powered vehicles compared to conventional fuels.
- Consideration of potential hazards and safety measures for hydrogen transportation through rail.
- Examination of risk factors associated with increased deliveries if ammonia replaces conventional fuels with hydrogen.
- Further studies on failure modes and hazard ranges for hydrogen and ammonia road tankers

Report Title: Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors

Technical Journal/Source: Journal of Rail Transport Planning & Management

Researchers/Research Organization: University of Illinois at Urbana-Champaign

Publication Date: 2022

Technologies examined: Risk hot spots, semi-QRA.

Key findings:

The paper addresses safety concerns related to the operation of passenger and freight trains on shared-use rail corridors (SRCs), focusing on Adjacent Track Accidents (ATAs). ATAs occur when derailed equipment intrudes upon adjacent tracks and is subsequently struck by another train. The complexity and potential hazards of ATAs are particularly pronounced in SRCs. While previous research laid the groundwork for identifying and mitigating intrusion risks, a gap exists between current research on intrusion risk and a comprehensive risk assessment model for ATAs. The paper introduces an index-based, semi-quantitative risk analysis framework that evaluates the probability and consequences of ATAs. The model employs a new risk index system, considering infrastructure, rolling stock, and operational factors to assess the relative ATA risk among different track segments. The study includes a case study based on a modified real-world SRC to demonstrate and validate the model, identifying factors such as operating speed, containment, and derailment rates that significantly influence ATA risk. The model facilitates the comparison of relative ATA risks and the identification of high-risk locations (risk hotspots) on a railroad corridor. Additionally, it provides valuable information for future improvements in quantifying ATA risk and researching mitigation measures. The paper emphasizes the significance of this model in prompting more in-depth analyses and the implementation of risk mitigation measures for these high-risk locations.

Opportunities for future research:

- Passenger and Freight Train Accident Analysis: Conduct a comprehensive analysis of passenger and freight train accidents to consider differences in characteristics, rates, and affecting factors for accurate SRC risk assessment.
- Quantitative Analysis of Intrusion Probability: Extend intrusion probability quantification to include factors like curvature, grade, elevation, adjacent structures, and train speed using simulation and validated accident modeling.
- Effect of Intrusion Barriers: Investigate the relationship between the design of intrusion barriers and their impact on reducing intrusion probability and consequences to improve the SQRA model.
- Quantitative Train Presence Probability: Develop a quantitative model for train presence probability, considering parameters like distance, alerting systems, and braking capability, to enhance the accuracy of the comprehensive ATA risk assessment.

Report Title: Quantitative risk assessment of slope hazards along a section of railway in the Canadian Cordillera

Technical Journal/Source: Journal of the International Consortium on Landslides

Researchers/Research Organization: Renato Macciotta, C. Derek Martin, Norbert R. Morgenstern, and David M. Cruden

Publication Date: 13 January 2015

Report Title: Development of a Novel Quantitative Risk Assessment Tool for UK Road Tunnels

Technical Journal/Source: Fire (ISSN 2571-6255), special issue Current Advances on the Assessment and Mitigation of Fire Risk in Buildings and Urban Areas — 1st Edition, in the section “Fire Risk Assessment and Safety Management in Buildings and Urban Spaces.

Researchers/Research Organization: by Razieh Khaksari Haddad [1], and Zambri Harun [2]

1. London Bridge Associates Ltd., London SE1 1TY, UK
2. Faculty of Engineering and Built Environment, National University of Malaysia, Bangi 43600, Selangor, Malaysia

*Author to whom correspondence should be addressed.

Publication Date: 14 April 2023

Technologies examined: Underground passageways for motorists are provided through this cost-effective engineering solution, which allows for high traffic volumes. A crucial aspect of the operation of road tunnels is fire safety. Risk assessments have been established to ensure the level of safety in tunnels. As the existing quantitative risk analysis (QRA) models are inapplicable to assess the fire risk in UK road tunnels, this paper presents a novel QRA model, named LBAQRAMo, for UK road tunnels. This model consists of two main sections: quantitative frequency analysis, to estimate the frequency of fire incidents via an event tree; and quantitative consequences analysis, to model the consequences of fire incidents. LBAQRAMo covers the risk to tunnel users. The result of the risk analysis is the expected value of the societal risk of the investigated tunnel, presented via F/N curve. Another major result of this model is the estimation of the number of fatalities for each scenario based on the comparison between required safe egress time (RSET) and available safe egress time (ASET). Risk evaluation was carried out by comparison of the tunnel under study with the UK ALARP limit.

Quantitative Risk Assessment, Quantitative Frequency Analysis via Event Tree, F/N curve

Key findings: The benefits of the QRA model, LBAQRAMo, are:

- It has elements with high flexibility, and can be applied to almost every tunnel, ventilation, or traffic configuration. It can be used and supports decisionmakers to select safety measures for new tunnels or to upgrade measures for existing tunnels.
- New information can be implemented very easily.
- The impacts of important safety systems, their reliabilities, and the relationship between them can be included.
- The interaction between smoke and fire propagation inside the tunnel and the self-rescue operation can be modelled.
- The total distance of the evacuation path is calculated by considering both the longitudinal and lateral shares in the evacuation route.
- Traffic distribution: considering lane utilization factor for each lane based on total traffic flow of vehicles (veh/hr) in two-lane and three-lane tunnels.
- The results of the model include information about the distribution of different accident consequence classes such as F/N curves.

Opportunities for future research: The main limitations of this project are:

- Although LBAQRAMo has its limitations, identification of relevant limitations is crucial for a correct interpretation of the results and the methods employed.

- Quantitative measures must depend on the scope and accuracy of the defined measurement scale.
- Any errors in your setup or mistakes in execution can invalidate all your results. Even coming up with a hypothesis can be subjective, especially if you have a specific question that you already know you want to prove or disprove.
- There are no standards and universally accepted information for implementing this method.
- Only the lethal effects on humans have been of interest when analyzing the different scenarios, no consideration has been taken to material damage that might be caused because of the different scenarios that have been analyzed.

Report Title: A Quantitative Risk Assessment Model for Domino Accidents of Hazardous Chemicals Transportation

Technical Journal/Source: Processes, special issue Process Systems Engineering for Chemical Process Safety and Environmental Protection, in the section "Chemical Processes and Systems".

Researchers/Research Organization: by Jinhua Cheng, Bing Wang*, Chenxi Cao, and Ziqiang Lang

Department of Automation, East China University of Science and Technology, Shanghai 200237, China

*Author to whom correspondence should be addressed.

Publication Date: 10 May 2023

Technologies examined: When vehicles loaded with materials gather on a stretch of road, a potential domino accident might cause terrible incidents. This paper prompts a quantitative risk assessment (QRA) model to estimate the risk of multi-vehicle incidents. The model calculates the possibility of leakage and explosion of hazardous chemicals using a dynamic Bayesian network (DBN). For different types of hazardous chemicals, the model uses event trees to list different scenarios and analyzes the probability of domino accidents caused by each scenario. The F/N curve and potential loss of life (PLL) are used as an index to evaluate social risk.

Quantitative Risk Assessment, hazardous materials transportation, domino effect, dynamic Bayesian network, F/N curve, Computational Fluid Dynamics (CFD), Arial Locations of Hazards Atmosphere (ALOHA)

Key findings: This network and the vehicle state information uploaded by the vehicle terminal constitute a dynamic Bayesian network, which makes the prediction of accident frequency more convincing. The results show that driver status and weather conditions will increase the frequency of hazardous chemical accidents. Road type has a greater impact on risk because urban roads are more densely populated and have a greater traffic flow. The model also quantitatively assesses the risk of dominoes when multiple hazardous chemical vehicles gather.

Opportunities for future research: These results can provide guidance for enterprises and governments to prevent hazardous chemical transportation accidents.

Report Title: Development of a Bayesian Network-Based Accident Model for Hazmat Unit Trains

Technical Journal/Source: Technical Reports, Federal Railroad Administration

Researchers/Research Organization: Peter Johnson, Mahesh Raju Bailakanavar

U.S. Department of Transportation, Federal Railroad Administration

Publication Date: May 2022

Technologies examined: Researchers used artificial neural networks and data science approaches to identify predictable patterns, with a particular focus on unit train accidents, with the development of a Bayesian Network-Based Accident Mode.

Hazardous Materials, Rolling Stock

Key findings:

- The team concluded that due to the limitations of the available traffic data, the research would focus on building a Bayesian-based accident model using Railroad Accident/Incident Reporting System (RAIRS) data.
- Three different Bayesian networks were implemented then used a Random Forest algorithm to select the risk factors. Review of the model predictions found that train type did not have significant influence on the predicted accident cause. This is suspected to be due to the limited scope of the current model, which is built upon a subset of data comprising hazmat freight trains travelling on main track, 35 where a derailment occurred, and the cause was one of four specific cause groups: Wide Gauge (03T), Track Geometry (04T), Buckled Track (05T), and Broken Rail or Welds (08T). This limits the number of unit train accidents in this data set and the ability to identify differences in accident properties.

Opportunities for future research:

- To aid future research on the risk of hazmat transportation by unit train, improvements in accident and traffic data collection are needed, with unit trains being added to the RAIRS database.
- The team recommends that the collection of railroad operating statistics be expanded to provide total train-miles and car-miles by train type transporting hazmat. The Bayesian Network (BN)-based accident model has demonstrated potential to accurately predict accident cause, given information about the train and track. The team recommends that consideration is given to further developing the capabilities of the BN-based accident risk model by incorporating additional causes groups (e.g., mechanical and electrical, and human causes). In addition, inclusion of track maintenance inspection and repair data could enhance causal relationship learning.

Report Title: Risk Assessment Framework for Selecting the Safer Route for Hazmat Transportation Based on Accident Database and Vulnerability Models

Technical Journal/Source: ACS Chem. Health Safety. 2023, 30, 5, 302–317

Researchers/Research Organization: Nishat Tasnim, Mohammed Tahmid, Nusrat Jahan, and Sultana Razia Syeda Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka

Publication Date: August 21, 2023

Technologies examined: A quantitative risk assessment (QRA) framework to select the safest route for the transport of hazardous materials utilizing an accident database and human vulnerability models.

Quantitative Risk Assessment Hazardous Materials Transportation Routes Emergency Management Disaster Risk Reduction

Key findings:

The effectiveness of a number of risk reduction measures has been assessed to manage risks, and the results of the risk assessment have been spatially presented on a geographical map. This map will help decision makers to make routing decisions and identify route sections that are most at risk to take appropriate emergency response actions and allocate medical and support services during emergencies.

Opportunities for future research:

- The proposed method has been applied in a case study to assess the relative risks involved in LPG transportation along two different routes in Bangladesh and to identify the safer route.

Report Title: A dynamic domino effect risk analysis model for rail transport of hazardous material

Technical Journal/Source: Journal of Loss Prevention in the Process Industries, Volume 74

Researchers/Research Organization:

Esmaeil Zarei [a], Kamran Gholamizadeh [b], Faisal Khan [a d], Nima Khakzad [c]

a. Centre for Risk, Integrity and Safety Engineering (C-RISE), Faculty of Engineering and Applied Science Memorial University of Newfoundland, St. John's, NL, A1B 3X5, Canada
b. Center of Excellence for Occupational Health and Safety Engineering, Occupational Health and Safety Research Center, Hamadan University of Medical Sciences, Hamadan, Iran
c. School of Occupational and Public Health, Ryerson University, Toronto, Canada
d. Mary Kay O'Connor Process Safety Center (MKOPSC), Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, TX, 77843-3122, USA

Publication Date: January 2022

Technologies examined:

- Presents a risk analysis model to analyze domino effects in rail transportation of hazardous materials.
- It uses advanced probabilistic approach coupled with the Bayesian network.
- Range of accident scenarios i.e. pool fire, flash fire and fire ball, vapor cloud explosion and BLEVE are considered.
- The model provides a practical approach to analyze domino effect in transportation of hazardous materials.

Dynamic Bayesian network, Domino effect, Intuitionistic Fuzzy Set (IFS), and Fuzzy Analytical Hierarchy Process (FAHP)

Key findings:

The present study has proposed, as the first time, a new dynamic model to investigate the risk of domino effects in the rail transportation of hazardous material under uncertainty. This model also proposed a framework for advanced and comprehensive consequence analysis and probabilistic modeling of domino effect scenarios associated with Hazmat in rail transportation. The epistemic uncertainty involved in estimating prior failure probability and accident scenario occurrence is addressed.

Opportunities for future research:

- It is also worth noting that this study is conducted for the first time in the field of rail transport of hazardous materials. Accordingly, the authors assumed threshold values are valid enough for this study. However, the specialized proposing thresholds for rail cars can be investigated in future studies, and we reaffirm to take this limitation into account in the application of the study findings. Moreover, dealing with the aleatory uncertainty arisen from parameters randomness is required.

C12. Cybersecurity

Report title: Cybersecurity Considerations for Communication Based Train Control

Journal/Source: IEEE

Researchers/Research organization:

Italy CINI Cybersecurity Laboratory: Simone Soderi, Daniele Masti

University of Oulu: Matti Hämäläinen, Jari Iinatti

Publication date: August 2023

Keywords: Railway security, Jamming, TS 50701, Railway communications, Telecommunications security, Railway signaling

Technologies examined: Wifi communications, CBTC, Eurobalise

Key findings:

CENELEC TS 50701 is the first European government standard that aims to encompass process for cybersecurity risk management within the railway industry. It was stated that among practitioners CENELEC TS 50701 is an active field of discussion, especially when dealing with communication-heavy subsystems. This paper describes two cyber-attack scenarios against wireless Communication-based train control (CBTC) systems that can have potential safety concerns with respect to the framework described by CENELEC TS 50701. The paper specifically investigated the safety concerns of Jamming attacks and the common weak points regarding Vehicle to Infrastructure (V2I) communication based eurobalises. Jamming attacks can cause trains to have delays and stops to be missed which could potentially lead to collisions. Jamming attacks can also be done relatively easily with just public knowledge of the system, because of this, it is suggested that interference detectors are used to effectively identify disturbances and classify disturbances as faults or external actors.

There was an identified trend in applying general purpose wireless technology in intra-vehicular, Vehicle-to-vehicle (V2V), and Vehicle-to-Infrastructure (V2I). Nowadays, wi-fi communications technologies that are based on IEEE 802.11 (along with other standards) are often selected in CBTC for safety related applications such as V2V and V2I, however these general-purpose communications technologies typically lack industrial safety and security considerations during their design.

It was identified that there are issues and vulnerabilities around the conduits (a component that is part of the framework described in CENELEC TS 50701). The investigation concluded that the standards do not fully describe what is considered a conduit.

Opportunities for future research:

- The research team plans to continue research on novel high-fidelity hardware-in-the-loop simulation environments as a means to test and validate the proposal outlined in the report.
- The proposed mitigation measures require extensive experimental validation while considering new regulatory constraints and practical implications.

Report title: Deep Hybrid Learning Based Fault Diagnosis for Data Communication Systems in Communication-Based Train Control Systems

Journal/Source: IEEE

Researchers/Research organization: State Key Laboratory of Rail Traffic Control and Safety: Sen Lin, Li Zhu, Qingheng Zhuang

Publication date: November 2022

Keywords: Fault diagnosis, Radio frequency, Bit error rate, Feature extraction, Control systems, Data models, Hybrid learning

Technologies examined:

Key findings:

This paper proposed a Deep Hybrid Learning (DHL) method to identify faults within a Data Communication System (DCS). When fault information is extracted manually it is labor intensive and information can be lost. This project aims to mitigate information loss when extracting valuable information from faults. This paper highlights the advantages of utilizing the DHL model for fault diagnosis and shows how the simulation results for the proposed DHL model achieves substantial accuracy compared to traditional machine learning algorithms such as Decision tree and Bayesian network.

The proposed model uses a pre-trained Chinese Bidirectional encoder representation from transformers (BERT) deep learning model and the Random Forest model (combined is the DHL model) to automatically extract fault features from raw text logs and then classify the faults by the extracted features.

Opportunities for future research:

- Further investigation into other possible deep learning algorithms should be done to explore new methods for more effective DCS fault prediction tasks.

Report title: Advances in Computational Modeling of EMC/EMI Effects in Communication-Based Train Control (CBTC) Systems

Journal/Source: IEEE

Researchers/Research organization: Xingqi Zhang, Weibin Hou, Costas D. Sarris

Publication date: November 2021

Keywords: Geometry, Computational modeling, Control systems, Computational electromagnetics, Mathematical models, Communication networks, Time-domain analysis

Technologies examined: Communication Based Train Control Systems, Electromagnetic Interference

Key findings:

Communication-based train control systems need to operate in a variety of communications situation, including tunneled and open-air sections, within busy stations, and in areas that have wi-fi and cellular communication networks.

There is no model that can efficiently represent the electromagnetic compatibility and interference (EMC/EMI) issues, so this project investigates hybridizing several computational electromagnetic techniques to improve their overall efficiency.

This paper presents an overview of applicable standards, EMI scenarios for CBTC systems, and recent advances in hybridizing the Vector parabolic equation (VPE) method, Raytracing (RT), and the Finite-difference time-domain (FDTD) technique.

At the time of this paper, it was noted that advanced propagation methods based on FDTD, VPE, and RT methods were being developed to characterize radio wave propagation within the railway environment. The example of hybrid models demonstrated in this paper shows potential for using RT for complex station geometries, VPE for rail sections containing long tunnels, and full wave methods (FDTC in this paper) for the exterior and interior geometry of trains.

Opportunities for future research:

- Future extensions to this project could aim to include 5/6G systems, as well as millimeter-wave and THz frequencies.

Report title: Parameter Adaptive Research of Automatic Train Control Algorithm Based on Sliding Mode PID

Journal/Source: Sage Journals

Researchers/Research organization:

Shanghai Key Laboratory of Rail Infrastructure Durability and System Safety, School of Transportation Engineering: Ziwei Wang, Dongxiu Ou

Publication date: July 2023

Technologies examined:

Key findings:

This paper highlights a sliding mode proportional-integral-derivative (PID) control model that is optimized with back propagation (BP) neural networks. In the first part of the study the train operation model that considers response delay was constructed. In the second part, an analysis of existing research methods concluded that neural networks and sliding mode control techniques will be utilized for train speed control. Specifically, dynamic sliding techniques were used to optimize PID control.

During each control cycle for the PID error amount is checked to see if it exceeds the target optimization error. The difference between the actual train speed and the target train speed is used as the optimization target to iteratively adjust the PID control parameters. If the error requirement is satisfied the optimized parameters are output to the train control process.

This study utilized real operation data from urban rail transit to validate and simulate different control methods for the model. The results demonstrated how the sliding mode PID control model that utilized a BP neural network performed better with error distribution, average error value, and control variance under different simulation scenarios. It was also able to achieve better tracking and operation at the target speed. Overall, the described model has better adaptability and accuracy than within train operation tracking control.

Opportunities for future research:

- Further research into how the application can reduce resource and time cost needed to select sliding PID control parameters for actual operation should be conducted.
- Future technologies will likely require higher control requirements for train control algorithms so more research into the expansion of the proposed system may be needed.
- The algorithms proposed also have potential applications in optimizing vehicle control systems.

Report title: GNSS Jamming Detection and Exclusion for Trustworthy Virtual Balise Capture in Satellite-Based Train Control

Journal/Source: IEEE

Researchers/Research organization:

Frontiers Science Center for Smart High-speed Railway System: Jiang Liu, Bai-Gen Cai

School of Electronic and Information Engineering and the Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation: Jian Wang, De-Biao Lu

Publication date: September 2022

Technologies examined: Global Navigation Satellite Systems, Virtual Balise

Key findings:

For safety critical train control systems that utilize Global Navigation Satellite Systems (GNSS), jamming attacks are a major threat since they can disrupt the operations of the system. The concept of Virtual Balise (VB) enables a viable means to use GNSS and reduce the amount of physical balises needed.

To ensure the safety of VBs, jamming attacks need not pose a threat to their operation. As such, this paper presents a novel GNSS jamming detection and exclusion solution. The proposed method is an advanced architecture for a VB reader that incorporates an interference qualifier module (IQM), alongside a conventional GNSS-enabled VB framework.

The IQM detects and identifies any signal interference by examining the real and predicted GNSS pseudo-ranges. So long as the receiver is not completely disabled by an attack, the solution is able to identify the quality of available GNSS measurements and determine if it is viable.

The results from testing two typical GPS jamming attacks validate the tolerance of the proposed system and shows that the solution has the potential to protect against GNSS attacks within a satellite-based train control system that utilized VBs.

Opportunities for future research:

- This study will continue and focus on:
    - improving coverage to the additional satellite measurements over the pseudo-range
    - conducting more studies with different jamming signals beyond AM and coherent CW
    - Testing other GNSSs, such as Galileo and BeiDou
    - Conducting more tests with GNSS jammers and specific test instruments in real railway operations to optimize key parameters in the proposed solution.
    - Expanding the scope of research beyond just jamming attacks to include complicated interface modes and sophisticated GNSS spoofing attacks.
    - Developing a field demonstration for the train control system

Report title: Beyond Full Implementation: Next Steps in Positive Train Control

Journal/Source: National Transportation Safety Board

Researchers/Research organization: National Transportation Safety Board

Publication date: September 2023

Technologies examined: Positive Train Control

Key findings:

This report highlights the findings from an investigation, conducted by the National Transportation Safety Boards (NTSB), of the current Positive train control (PTC) and current PTC-related technologies and regulations. The investigation looked into the capabilities, limitations, safety goals, and safety performance of PTC.

The findings from this report include:

- Current PTC systems are able to enforce a fixed speed limit, however insufficient information regarding train location prevents PTC from effectively detecting and responding to potential train-to-train collisions while the train is operating under restricted speeds.
- While operating under restricted speeds in a permissive block, PTC must be able to ensure safe train separation. To achieve safe separation technologies that can reliably identify and locate the end of the train must be deployed so this information can be communicated to other trains.
- Technologies should be deployed for precision improvements in PTC and PTC-related technologies to help prevent or mitigate the severity of end of track collisions within terminals.
- For the interoperable electronic train management system, the switching mode software components require human intervention to activate PTC protection on the main tracks. This could result in the engineer leaving the PTC signal enforcement unnecessarily disables within 5 miles of the switching operation.
- Miscommunication between dispatcher and roadway workers can cause the working limits for PTC to be mistakenly removed. Removing working limits prematurely creates an unprotected work zone for personnel.
- Implementing technology that supplements verbal communication along with engineering controls can help improve the safety of work zones by improving work zone enforcement. These technologies will help mitigate the risks involved with potential miscommunication that could result in unauthorized or unsafe incursions within the set working limits.

Opportunities for future research:

- As a result of this investigation, the TSB makes the following recommendations:
  - Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.

- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Work with railroads to remove terminal exceptions currently granted under Title 49 *Code of Federal Regulations 236.1019* using available improved PTC-related technologies.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.
- Require railroads to implement technologies that eliminate the risk of miscommunication between dispatchers and roadway workers in charge regarding establishing working limits and PTC protection.

Report title: Formal Verification of the European Train Control System (ETCS) for Better Energy Efficiency Using a Timed and Asynchronous Model

Journal/Source: MDPI

Researchers/Research organization:
Faculty of Transport, Warsaw University of Technology: Andrzej Kochan, Juliusz Karolak
Institute of Computer Science, Warsaw University of Technology: Wiktor B. Daszczuk, Waldemar Grabski

Publication date: February 2023

Technologies examined: European Train Control System

Key findings:

The European rail traffic management system (ERTMS) and European train control system (ETCS) is the newest automatic train protection system and is being implemented all through the European Union with the goal of increasing energy efficiency and operational safety.

Currently verification techniques that use dynamic testing with actual rolling stick fail to verify all cases. As such, this paper presents a methodology and environment for the time-based verification of ETCSs.

In order to achieve errorless configuration of ETCS the proposed methodology will utilize the Integrated Model of Distributed Systems formalism and the temporal tool Dedan. These tools will allow the verification of specified conditions by analyzing all system runs at once. The formal model proposed is specifically designed for distributed systems and automated verification of real-time dependent systems.

The main contribution of the proposed model is the asynchronous and timed verification, since it:

- appropriately models the distributed nature of ETCS.
- allows the analyzation of time dependencies.
- allows the user to set the range of train velocities in which the operational scenario is valid.

In ETCS a device's operation is dependent on its current state and external signals acquired. This property alongside real-time analysis enables the actual behavior of interconnected devices to be observed.

Opportunities for future research:

- Future plans for this project include:
  - building a library of common ETCS system components to allow for the verification of large cases.
  - Incorporate timed verification into the Dedan tool for better presentation of counterexamples.
- The tool could be expanded to consider several consecutive trains for improved energy efficiency of the entire transportation system.

Report title: Train-Centric Communication Based Autonomous Train Control System

Journal/Source: IEEE

Researchers/Research organization: Haifeng Song, Shigen Gao, Yidong Li, Ling Liu, Hairong Dong

Publication date: July 2022

Technologies examined: Autonomous Train Control System

Key findings:

The development and integration of driverless train control systems are becoming more popular as a means to improve operational efficiency. The automatic train operation systems that are currently utilized operate under a framework where a ground control center generated network elements and movement authorities, making the systems automated but not autonomous.

This paper highlights the research done for an Autonomous Train Control System (ATCS) that aims to improve train movement coordination and efficiency. The paper discusses the systems structure, general operating scenarios, the data isolation breakdown, how data prediction and edge-based information fusion are applied to process real dynamic data (to estimate train speed and position), and how data fusion, modeling, and data-based control methodologies are used.

The goals of the ATCS includes:

- Running trains closer
- Dispatching trains faster
- Optimizing energy use
- Providing low-cost railway solutions
- Increasing safety

The ATCS enables ground resources to be used more efficiently since the train will be able to provide the following train the necessary information from the preceding train. To achieve this train-to-train and train-to-ground communication channels, a resource management unit, and an infrastructure controller will be used. Through the benefits of the mentioned on-board equipment and data systems, the train will be able to record more accurate real-time dynamic data and will have precise control when compared to current automated train control.

Opportunities for future research:

- The proposed system needs practical experimental data to validate its efficiency. The addition of real-world experimental data would enhance the research argument. As such, the future plans for this project include:
  - building a physical or digital twin platform that would obtain actual data through channel simulators and sensors.
  - Further discussion on the data-based model-free control algorithm.
- The above future plans should be investigated to see what has been done since the development of this report.

Report title: Methods for Applying Public Communication Lines to Communication-based Train Control Systems

Journal/Source: J-Stage

Researchers/Research organization: Train Control Systems Laboratory: Takayasu KITANO, Akihiro GION

Publication date: November 2023

Technologies examined: Communication-Based Train Control

Key findings:

This paper highlights a method for applying public communication lines to communication-based train control (CBTC). The goal of the proposed system is to reduce the amount of maintenance needed by reducing the amount of equipment, while still meeting the safety requirements.

The proposed system utilizes radio to transmit information between ground and on-board equipment. The trains position will be detected on-board, and the on-board equipment controls the train, which will reduce the amount of ground equipment needed to maintain operational safety. The system will be able to:

- Correct recognition of the train position by the on-board equipment
- Correct transmission of the train position, recognized by on-board equipment, to the ground equipment.
- Configuration of the route and setting of the movement authority, according to each train position, by the ground equipment
- Transmission of the set move authority to the set ground on-board equipment
- Creation of brake profiles according to the transmitted information

The system will need to apply countermeasures for third-party cyber-attacks to ensure the safety and security of the system. The main attacks identified included spoofing, tampering, and denial of service attacks. To mitigate many of the attacks, implementing a message authentication system is recommended.

Opportunities for future research:

- Future work will focus on the drafting of specifications and construction of a prototype for the described system.
- Further investigation on cyber-attack mitigation strategies needs to be conducted to ensure operational safety requirements are met.

Report title: Wireless Train Detection Based on Null-Filled UHF RFID Reader Antenna for Communications-Based Train Control

Journal/Source: IEEE

Researchers/Research organization:

University of Macau**:** Zi-Yu Pang, Kan-Weng Tam, Wai Son Kuan

Foshan University: Guan-Long Huang

Publication date: October 2023

Technologies examined: Axle counting system, ultra-high frequency technologies, Radio frequency identification systems.

Key findings:

This paper presents a novel Ultra high frequency (UHF) Radio frequency identification (RFID)-assisted axle counting system for wireless train detection. In the proposed system the train compartments will have RFID tag antennas attached to them. When a train travels across a signal indicator, the reader will detect the RFID tag and the acle counter will count the number of axles that have passed by. Traditional reader antennas have a blind reading zone that could potentially cause safety issues. To mitigate the blind reading zone this project proposes a new null-filled monopole UHF RFID reader antenna that eliminates the radiation blind reading zone at the antenna zenith. Traditional reader antennas are also directional and would not be compatible with the proposed system.

The new antenna described in this paper was developed using 3D printing out of polylactic acid which makes the antenna low-cost, lightweight, and easy to process. The antenna was demonstrated to have good performance, which shows its feasibility in an industry setting. The proposed RFID-assisted acle counting system also was shown to be low cost and have simple maintenance requirements.

It should be noted this report also offers a more technical overview of the proposed system, describing the structure of the proposed system, bandwidth, zenith gain, horizontal radiation gain, and other technical specifications.

Opportunities for future research:

- This research offers an additional axle counting system for railways, the best areas of application for this system should be conducted.
- Research into the cybersecurity aspects of the new system should be conducted.

Report title: ITC PTC interface control documents (ICDs)

- Positive Train Control Office-Locomotive Segment—Interface Control Document (ICD)

Standard S-9361

- Interoperable Train Control (ITC) Wayside-Locomotive Interface Control Document (ICD)

Standard S-9362

- Additional ITC PTC-related ICDs have been published by AAR, but those cited here are particularly relevant.

Journal/Source: AAR

Researchers/Research organization: ITC Committee

Publication date: 30 Dec 2021 for S-9361; 19 Jul 2023 for S-9361;

Technologies examined: Inter-segment messaging

Key findings:

These documents present highly relevant examples, potential templates, and reusable content that will be required to achieve interoperability among different railroads or suppliers' ETC equipment and also to achieve interoperability with ITC PTC.

Opportunities for future research:

- Determine what can be reused and what needs to be different between ETC ICDs and ITC PTC ICDs.
- Possibly perform similar analyses with respect to other train control systems, such as ETCS. However, for interoperability reasons, ITC PTC may take precedence in this analysis.

Report title: ITC PTC communications protocol specifications

- Edge Message Protocol, Standard S-9354
- Class C Messaging, Standard S-9355
- Class D Messaging, Standard S-9356

Journal/Source: AAR

Researchers/Research organization: ITC Committee

Publication date: 30 Oct 2018 for S-9354; 26 Aug 2022 for S-9355; 30 Oct 2018 for S-9356;

Technologies examined: Inter-segment communications protocols

Key findings:

These documents present highly relevant examples, potential templates, and reusable content that will be required to achieve interoperability among different railroads' or suppliers' ETC equipment and also to achieve interoperability with ITC PTC.

Opportunities for future research:

- Determine what can be reused and what needs to be different between ETC ICDs and ITC PTC ICDs.
- Determine the frequency bands, waveforms, and protocols to be used for ETC RF communications, which may be different than for ITC PTC.
- Possibly perform similar analyses with respect to other train control systems, such as ETCS. However, for interoperability reasons, ITC PTC may take precedence in this analysis.

Report title:

- Interoperable Train Control Wayside Interface Unit Requirements Standard S-9202
- Additional ITC PTC-related requirements specifications have been published by AAR, but the one cited here is particularly relevant.

Journal/Source: AAR

Researchers/Research organization: ITC PTC Committee

Publication date: 1 Aug 2014

Technologies examined: Functionality required for the wayside train control segment

Key findings:

This specification defines the wayside interface unit (WIU), which is a device that provides an interface to the wayside signal system to forward signal information to locomotive PTC segment in a vital manner. The WIU connects to, and monitors the states of, existing signal equipment, including signal lamps, switches, and hazard detectors.

A non-proprietary AAR specification for the ITC PTC locomotive segment is currently under development. PTC office segments are railroad or supplier-specific so there is no AAR standard for the office segment.

Opportunities for future research:

- Determine what can be reused and what needs to be specified differently for ETC vs. ITC PTC.
- Possibly perform similar analyses with respect to other train control systems, such as ETCS. However, for interoperability reasons, ITC PTC may take precedence in this analysis.

Report title: Higher Reliability and Capacity Train Control - DOT/FRA/ORD-22/30

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: 27 Dec 2019

Technologies examined: Safety and operational enhancements to PTC that could be applicable to ETC as well

Key findings:

This report describes the evolution envisioned for ITC PTC from its current state to Enhanced Overlay PTC (EO-PTC), Quasi-Moving Block (QMB) and Full Moving Block (FMB). Each of these advanced stages of PTC provides increases in safety and/or operational performance (e.g., headways and capacity).

Opportunities for future research:

- This report provides background for the specification documents cited herein for EO-PTC, QMB and FMB. Opportunities for future research are cited with the associated references.

Report title: Full Moving Block Concept and Requirements Specifications for Railroad Operations - DOT/FRA/ORD-24/03

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: 31 Aug 2022

Technologies examined: Safety and operational enhancements to PTC that could be applicable to ETC as well

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.
- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.

Two potential solutions to all of the safety issues cited immediately above, referred to as Quasi-Moving Block (QMB) PTC and Full Moving Block (FMB) PTC, are described and specified in this report. In addition, QMB and FMB can provide a reduction in headways and increase in rail line capacity.

Opportunities for future research:

- The specifications contained in the appendices to this report for the QMB and FMB enhanced modes of train control should be validated.
- Then these systems should be implemented and tested.

Report title: Advanced QMB/FMB Requirements and Algorithms

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: Pending

Technologies examined: Safety and operational enhancements to PTC that could be applicable to ETC as well

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.
- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.

Two potential solutions to all of the safety issues cited immediately above, referred to as Quasi-Moving Block (QMB) PTC and Full Moving Block (FMB) PTC, are described and specified in another report cited herein report. This report defines advanced requirements and algorithms that supplement the other report.

Opportunities for future research:

- The advanced requirements and algorithms for the QMB and FMB systems should be validated.
- Then they should be implemented and tested.

Report title: Office Safety Checker for Moving Block Train Control Systems - DOT/FRA/ORD-23/28

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: 11 May 2022

Technologies examined: Safety enhancements to PTC that could be applicable to ETC as well

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Complete and publish the results of current research into PTC technologies to prevent train-to-train collisions during restricted speed operations.
- Once the results of this research are available, develop a plan to implement any promising PTC technologies for train-to-train collision avoidance.
- Require that railroads adopt engineering controls that automatically return PTC to the active mode following switching operations.

Two potential solutions to all of the safety issues cited immediately above, referred to as Quasi-Moving Block (QMB) PTC and Full Moving Block (FMB) PTC, are found in another report referenced herein. QMB and FMB require "safety checker" functionality as specified in this referenced document.

Opportunities for future research:

- If ETC is to include QMB or FMB functionality, the specifications in the referenced report for the Safety Checker should be validated.
- Then the Safety Checker should be implemented and tested as part of a QMB or FMB implementation.

Report title: Development of Enhanced Overlay Positive Train Control (EO-PTC) - DOT/FRA/ORD-19/44

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date:

Technologies examined: An enhancement to PTC that improves operational performance

Key findings:

This report describes a simple proven modification to ITC PTC track data and operating rules that reduces train headways and increases line capacity.

Opportunities for future research:

- This alternative to baseline train control data configuration should be considered when evaluating potential performance for an ETC deployment.

Report title: Interoperable Employee-In-Charge Portable Remote Terminal (EIC-PRT)

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: January 2022

Keywords: Positive Train Control, PTC, Employee-in-Charge, EIC, Employee-in-Charge Portable Remote Terminal, EIC-PRT, work zone, electronic instructions

Technologies examined:

Key findings:

In the document "Beyond Full Implementation: Next Steps in Positive Train Control", the NTSB recommended:

- Require railroads to implement technologies that eliminate the risk of miscommunication between dispatchers and roadway workers in charge regarding establishing working limits and PTC protection.

A solution to address the above NTSB recommendation, referred to as Employee in Charge Portable Remote Terminal (EIC-PRT), is found in this report.

Collaborating with the North American railroad industry, MxV Rail developed systems engineering documents defining the EIC-PRT system, including interoperable requirements for the EIC-PRT, EIC server, and onboard segments. Additionally, MxV Rail and its subcontractors developed a prototype roadway worker terminal application per the interoperable requirements and tested the application to demonstrate compliance with the requirements.

Opportunities for future research:

- The EIC-PRT specifications should be evaluated for potential inclusion in the ETC specifications.

Report title: Positive Train Location: Final Report

Journal/Source: FRA

Researchers/Research organization: MxV Rail

Publication date: June 2018

Technologies examined: Onboard train location determination

Key findings:

This report along with similar reports from prior phases of the Positive Train Location (PTL) project describe a system and test results thereof that increases the accuracy and dependability of train positioning for use as part of systems such as PTC and ETC. It eliminates the potential for human error in determining which track a train occupies in multiple track scenarios that cannot be resolved by standard positioning systems. PTL can be used at both the front and rear of a train. In the case of rear-of-train implementation, PTL can determine where is the end of a train relative to a turnout or other track point of interest. PTL can also be integrated with QMB and FMB systems to provide safe train separation in following moves, e.g., when operating at or below restricted speed.

Opportunities for future research:

- A cost vs. benefits analysis should be performed for the potential use of PTL with ETC.

Report title: ITC PTC security requirements specifications

- S-9008 – PSA-2 Design Specification
- S-9009 – Certificate Requirements
- S-9010 – Data Protection
- S-9415 – Automated Certificate Update Process
- S-9416 – ITCSM Agent Requirements to Support PSA-2
- S-9418 – PSA-2 Gateway Requirements
- S-9419 – PSA-2 Back Office Application Requirements
- S-9420 – ITC Key Management Service
- S-9421 – WIU ITCSM Agent Requirements to Support PSA-2
- S-9504 – PSA-2 W-OPK File Service Requirements

Journal/Source: AAR

Researchers/Research organization: ITC Security Team

Publication date: S-9009 was published on 24 Oct 23. S-9010 was published on 24 Jul 19. The other security documents cited are out for comment in draft form and therefore are not yet published.

Technologies examined: Security requirements, certificates, key management, gateways

Key findings:

These documents address one of the greatest challenges for ETC security, namely, key management (for authentication and encryption). They also address other security-critical issues from an interoperability perspective.

Opportunities for future research:

- Security requirements should be developed for ETC that leverage similarities and address differences between ETC and ITC PTC and that address issues encountered during ongoing the implementation of these standards in ITC PTC deployments.

Report title: IEEE 802.15 WSN, Task Group 16t, Licensed Narrowband

Journal/Source: IEEE

Researchers/Research organization: IEEE Task Group 16t

Publication date: 20 July 2022

Technologies examined: Wireless data communications

Key findings:

This IEEE task group has developed a non-proprietary specification known as 802.16t for a versatile, RF band agnostic, data radio protocol that could possibly be used for ETC communications among base stations, locomotives and wayside devices. A non-proprietary radio protocol that is implemented by multiple vendors has the potential to result in lower cost products than a proprietary product developed specifically for ETC. On the other hand, a confidential proprietary radio protocol may present somewhat of a barrier to potential spoofers.

Opportunities for future research:

- This radio waveform and protocol (along with others, such as ITCnet) should be evaluated with respect to the needs of ETC to determine if it would suffice and satisfy security requirements.

Report title: DOP Geographical Distribution for the Galileo and GPS Constellations

Journal/Source: https://destevez.net/2020/01/dop-geographical-distribution-for-the-galileo-and-gps-constellations/

Researchers/Research organization: Daniel Estévez

Publication date: Unknown

Technologies examined: GPS and Galileo-based satellite positioning systems

Key findings:

Communications-based train control systems such as PTC and ETC depend upon an onboard location determination system (LDS). Satellite-based positioning is preferred over balise-based systems in many cases when many miles of track must be covered and cost is a significant consideration. The accuracy of a satellite-derived position estimate depends upon both the measurement geometry as represented by dilution of precision (DOP) values, and range errors caused by signal strength, ionospheric effects, multipath etc. This paper illustrates that satellite positioning accuracy can vary with latitude of the track, which is the only point of its being referenced here. Any further use of the results in this paper would first require validation or cross-verification with other reports.

Opportunities for future research:

- Investigation is needed into the effects of DOP upon satellite-based train positioning for the range of latitudes over which ETC will operate for each of the satellite systems under consideration. Balise-based positioning may be considered as an alternative.
- While DOP does not apply to satellite communications, geography does nonetheless play a role in the suitability (or lack thereof) of using satellite communications in train control. If satellite communication is considered for ETC, particularly in areas lacking supporting infrastructure (towers, electrical power, backbone or internet connectivity, etc.), geographic implications related to view angle from the ground will need to be analyzed in consideration of the high latitudes of Canadian railroads.

Report title: GPS Problem Report Status

Journal/Source: Navigation Center, United States Coast Guard, U.S. Department of Homeland Security
https://www.navcen.uscg.gov/gps-problem-report-status

Researchers/Research organization: Anyone in the world reporting a suspected incident of GPS service disruption, due to jamming, spoofing, or other cause.

Publication date: Ongoing

Technologies examined: Satellite-based positioning.

Key findings:

Various sources show that jamming and spoofing events do occur that can disrupt satellite-based positioning.

Opportunities for future research:

- Determine to what extent jamming and spoofing detection, reporting, and mitigation functions need to be designed in to ETC, for GPS as well as communication of other messages.

Report title: PTC Communications: Cybersecurity Technology Review and Concept of Operations - DOT/FRA/ORD-23/39

Journal/Source: FRA

Researchers/Research organization: Meteorcomm, L.L.C.

Publication date: December 2023

Technologies examined:

Key findings:

Researchers sought to determine how to improve the confidentiality of information passing through the PTC network without significantly affecting network performance. Phase 1 of the project reviewed requirements and assessed existing technologies. Phase 2 focused on implementation, migration, and deployment challenges. A recommendation to consider widely available algorithms covered by recognized open standards resulted in a project decision to focus on the National Institute of Standards and Technology Lightweight Encryption Algorithms and the ELLI algorithm covered by ISO/IEC 29192-4. Phase 3 identified technology gaps and areas for further research outside the scope of the project. Phase 4, the focus of this report, pulls together the work from Phases 1-3 to propose solutions to improve confidentiality, including a concept of operations for each solution.

Opportunities for future research:

- The findings and recommendations in this report should be considered to determine and achieve a satisfactory level of confidentiality for ETC communications.

Report title: Railway applications – Cybersecurity – CLC/TS 50701:2023

Journal/Source: European Standards s.r.o.

Researchers/Research organization: Commonwealth Standards Network (CSN)

Publication date: 2023

Technologies examined: Cybersecurity for railroad applications

Key findings:

The CLC/TS 50701:2023 standard deals with railway applications and their cyber security, providing guidance and specifications on how cybersecurity will be managed and the security assurance of systems and components/equipment. The objective of this standard is to provide guidelines and recommendations for the protection of information technology in railway systems against possible cyber threats. The standard contains several key aspects related to cyber security in railway applications:

- identification of threats and risks,
- protection of critical functions,
- incident management,
- safe development processes.

CLC/TS 50701 RAILWAY APPLICATIONS - CYBERSECURITY

Opportunities for future research:

- The guidelines in this standard should be considered to determine and achieve a satisfactory level of cybersecurity for ETC.

Report title: Automatic Train Control System and Method

Journal/Source: US Patent Office

Researchers/Research organization: Harris Corporation

Publication date: 27 Oct 1998

Technologies examined:

Key findings:

This patent describes a method for controlling the movement of multiple trains through a multiple-route railway with improved energy efficiency and reduced rail network congestion. Train movements are precisely monitored and orchestrated in accordance with a dynamic schedule that is determined through an evaluation of delivery requirements, coordination among all trains, speed restrictions, changes in conditions, and the effects of track topography and train consist on train response to brake and power application.

The basic concept is that a movement planner in the dispatch office plans the movements of all trains on the railway for at least 8 hours into the future, and continuously updates the schedule based on frequent reports (feedback) of actual train movements. The office system automatically sends time of arrival (TOA) targets via data radio to each train for critical milestones it is to meet along its route. Each train's onboard energy management system (EMS) cues the driver (whether human or automated) to follow a trajectory of train speeds to achieve its TOA targets in the most energy efficient manner feasible. As trains progress and some may deviate from the plan, revised or additional TOA targets are sent from the office to the affected trains.

Opportunities for future research:

- It is recommended that ETC system design incorporate the train scheduling, control and feedback method described in this patent (or something similar) or at least include the hooks to support this messaging and functionality in the future.

C13. Human Factors

Report title: Transport safety and human factors in the era of automation: What can transport modes learn from each other?

Journal/Source: Accident Analysis and Prevention

Researchers/Research organization: Eleonora Papadimitriou, Chantal Schneider, Juan Aguinaga Tello, Wouter Damen, Max Lomba Vrouenraets, Annebel ten Broeke

Publication date: September 2020

Technologies examined: Information sharing on automation for transport safety and human factors.

Key findings:

A systematic literature review was conducted to assess the conditions for deploying safe automation with respect to the human factors of the level of trust in automation, the impact on the driver's situational awareness (SA), the implications of takeover performance, and the role of experience and training for using automation. The study gathered literature on these human factors in the aviation, road, marine, and rail industries, looking for possible areas of knowledge transfer. In the rail sector, one paper on a Conrail train accident in Baltimore, 1987, suggested an under-reliance on automation. A 2014 paper on situational awareness showed that time pressure impacted the locomotive operator's situational awareness, even if they did not perceive it did. Little to no work was found on takeover performance or automation experience and training for the rail sector. Results from other sectors found unclear conclusions on mistrust in automation as it has led to both ignoring warning signs, but also faster reaction times in takeovers.

Opportunities for future research:

- Research on mistrust/under reliance on automation is needed to ensure rail operators are not mistrusting or over relying on systems like enhanced train control. Research should focus on the causes of this mistrust and how to alleviate them.
- Research on the speed at which different types of SA build up, hazard identification vs. speed of other vehicles, for example. This could provide information on how to best use and deliver automation to increase operator situational awareness.
- It is unclear how different levels of automation impact SA. Further research on how automation is delivered to the operator in-cabin could inform its use in a safer manner.
- Takeover performance in rail has not been studied and could better inform the transition between manual and autonomous operations in emergency situations.

Report title: What factors influence risk at rail level crossings? A systematic review and synthesis of findings using systems thinking

Journal/Source: Safety Science

Researchers/Research organization: Gemma J.M. Read, Jolene A. Cox, Adam Hulme, Anjum Naweed, Paul M. Salmon

Publication date: June 2021

Technologies examined: Systems thinking applied to risk at rail crossings.

Key findings:

A literature review of studies on rail crossing incidents was conducted to determine the factors that influence risk at rail crossings. Accident mapping was used to determine the factors from 6 different sources including government policy & budgeting; regulatory bodies and associations, local area government planning & budgeting, company management; technical & operational management; physical processes & actor activities; and equipment & surroundings. 88 studies were analyzed, and 3 accident maps were created. The four most common factors for influencing rates and severity of crashes were type of safety/warning device in place, train speeds, road features and road vehicle speeds. The most common factors for influencing unsafe and non-compliant road user behaviors came from the physical processes and actor activities, and equipment and surroundings levels. For influencing road user risk perception, attitudes and beliefs, young road users, and knowledge of the road rules pertaining to RLXs were the most common factors. Most studied focused on road users rather than pedestrians, leaving a gap in understanding of how factors of pedestrian behavior can increase rail crossing risk.

Opportunities for future research:

- Research into how factors of human behavior like visual, auditory, or mobility impairment; technology distractions; or various forms of transport (foot, bike, e-scooter, etc.) can impact rail crossing risk. This will become increasing important as urban areas get more densely populated.
- There is a large gap in knowledge in the relation between factors on different levels, for example how policy impacts, the physical attributes of the crossing (one of the most common risks influencing levels). More work should be done to apply systems thinking to the whole picture of rail crossings to see how factors combine to influence risk.
- Use of a many models approach, combined with systematic interventions is recommended to address this issue. This paper proposes a 5-stage agenda using various models to identify links between factors, design interventions, and model their impact over time.

Report title: The Impact of Commute Times on the Fatigue and Safety of Locomotive Engineers and Conductors

Journal/Source: FRA

Researchers/Research organization: Naomi J. Dunn, Susan Soccolich

Publication date: June 2023

Technologies examined: How operational decisions impact fatigue.

Key findings:

This study was conducted via survey results to determine the impacts of fatigue on locomotive engineers and conductors. The survey received 9,084 responses across the US. Self-identified highly fatigued locomotive engineers and conductors were twice as likely to experience fatigue related safety events, four times as likely to miss required stops, and 3.4 times more likely to have had a near miss. Just under 40% of participants were classified as being highly fatigued. Commute times over 1-hour, irregular work schedules like frequent switches from day to night shifts, and long-duration tasks all were identified as major contributors to high levels of fatigue.

Opportunities for future research:

- Research into scheduling interventions could help alleviate fatigue related incidents. Exploration of schedules which help reduce workers commute times, add consistency to their shift work, and decrease the need for long-duration tasks all could result in fewer incidents.
- As this research was conducted in the US, it may be worth exploring if the same findings are true for the Canadian railways, and if long-haul harsh-weather lines, like those across the Rockies, introduce any unique issues related to locomotive engineer and conductor fatigue.
- The use of wearables could offer valuable real-life information on how different tasks, shift, and commute times impact worker fatigue.

Report title: Delving Deeper: Applying Human Factors Analysis to Identify Factors Contributing to Railway Incidents

Journal/Source: Irish Rail, Trinity College Dublin

Researchers/Research organization: Nora Balfe, Kay Doyle

Publication date: 2021

Technologies examined: Use of three human factors analysis frameworks to identify factors contributing to incidents.

Key findings:

This paper conducts three human factors analyses on Irish railway operations. The first uses the (Accident mapping) Accimap and SPAD (signals passed at danger) hazard checklist, the second uses the Fatigue Risk Index (FRI), and the third considers possible performance shaping factors for an area prone to overspeeds. The three analyses are used to determine more information on root causes of operational issues and promote the use of human factors approaches. Although the paper focuses on a specific location, the lessons learned could be applied in inspections along Canada's railway. Their SPAD hazard checklist found issues with visibility, perception, signal association, read aspect, and interpretation. The FRI analysis suggested that those working on days that were meant to be rest days had a higher risk of feeling extremely fatigued during their shift. The overspeed analysis raised concerns of mental underload, speed differential, that it was a single line, and the rate of visual speed cues.

Opportunities for future research:

- The three analyses highlight the value in human factors analysis on top of regular investigations. There is potential for human factors to highlight issues that would not be found in standard investigations. Similar tests could be carried out on Canadian rail lines to determine if a similar benefit can be had from these human factors analyses here in Canada.
- The effect scheduling has on fatigue has come up again in this paper, bolstering the need for research on how scheduling changes can reduce the risk of extreme fatigue, and therefor incident risk.

Report title: Smart tools for railway inspection and maintenance work, performance and safety improvement

Journal/Source: Transportation Research Procedia

Researchers/Research organization: Christian Di Natali, Jouni Mattila, Antti Kolu, Pietro De Vito, Stephani Gauttier, Miquel Morata, Marta Garcia, Darwin Caldwell

Publication date: 2023

Technologies examined: The STREAM system which includes the OTA3M, a control platform adapted to existing excavators that provides autonomous multi-purpose operations enabling safe worker-machine collaboration, and the MMPE, a modular multi-tasking exoskeleton developed to assist track worker during heavy activities.

Key findings:

This paper pitches the STREAM system which hopes to leverage innovative rail technology to improve rail inspection and maintenance operations, taking physical load off workers. The On-Track Autonomous Multi-Purpose Mobile Manipulator (OTA3M) is meant to manipulate heavy rail infrastructure components and materials. The unit will be made by converting a hydraulic road-rail excavator into an on-track unit. The Modular Multitasking Powered Exoskeleton (MMPE) is meant to reduce musculoskeletal loading of railroad workers during manual handling tasks. A IoT network is proposed to be developed to allow data streaming from the OTA3Ms and MMPEs. STREAM aims to improve worker safety, cost reduction from time on task reduction, improved quality and accuracy of operations, lowering requirements for physical work.

Opportunities for future research:

- A 5-phase plan is proposed to develop the STREAM system: requirement definition, research and development, first assessment, iterative research and development, demonstration in a relevant environment and final assessment.
- This technology could potentially benefit from a market analysis, seeing what sectors would benefit from this the most, and who may be interested in the technology.

Report title: Opportunities for Wearable Technology to Increase the Safety of Rail Workers

Journal/Source: Transport Canada Innovation Centre, Factor Safe Solutions Ottawa

Researchers/Research organization: Daniel Blais, Adam Freed, Heather Colbert

Publication date: 2022

Technologies examined: Wearable technology for increasing safety of rail workers.

Key findings:

This paper covers findings from three exercises, a literature and market review of known human factors considerations of trackside and yard workers, and associated technologies; an analysis of the past 5 years of rail occurrences to determine incidents which could have been mitigated with wearables; and various expert interviews to validate findings and uncover new information. The literature review concluded that with proper implementation of wearable technologies, safety and efficiency improvements could be achieved in the Canadian rail industry. The incident analysis identified risks that could be mitigated if trackside and yard workers used wearables. Proximity detection systems, non-integrated wearables, and fatigue monitors systems were suggested as having potential to mitigate risks. As there are a variety of tasks, environments, workers, and wearables, it is unlikely a single approach will work, a hybrid approach would likely be more effective.

Opportunities for future research:

- A pilot study using the listed proximity detection systems, non-integrated wearables, and fatigue monitors systems should be conducted over a sufficient period to identify if the stated risk mitigations are achieved in the 11 priority occurrence types.
- In parallel with the pilot study, or following it, a Canadian deployment plan for wearable technologies should be drafted. It should outline which technologies should be used in which environments, a timeline for their deployment, and a proposed funding landscape.

Report title: Human performance in rail: determining the potential of physiological data from wearable technologies

Journal/Source: University of Nottingham

Researchers/Research organization: Abigail Fowler

Publication date: September 2023

Technologies examined: A wrist strap and chest strap to measure electrodermal activity, heart rate variability and mental workload.

Key findings:

This paper describes three studies and two literature reviews focused on how personal data from wearable physiological measures can be used to assess the Mental Workload (MWL) of staff in the rail industry. A simulation study measuring Electrodermal Activity (EDA) and Heart Rate Variability (HRV) provided individual data for MWL. EDA identified moments of realization, uncertainty, or strain due to time pressure. Average HRV had a strong negative correlation with average subjective workload, which could be used as a measure of workload. Interviews and surveys were conducted in place of a live trial. Trust emerged as a key factor in staff adoption, and EDA wrist straps were identified as the most acceptable wearable. Drawn from the results a Novelty of Events and Automatic State (NEAS) model was developed and proposed as a new perspective on MWL. It shows the impact workload has on individuals' performance and how physiological data can be used to identify this. The NEAS model could be used to tailor training, or shift breaks to individuals.

Opportunities for future research:

- A trial study should be conducted using EDA wrist straps to determine what extent individual physiological data changes over time.
- A pilot test of the NEAS model could provide valuable data on its effectiveness. A two-stage program could be used. The first stage would collect worker data to better understand individuals' performance related to workload. The second stage could implement individually tailored training and shift breaks, measuring operational performance to assess the program's effectiveness.
- Concern was raised with regards to trust, with tangible operational benefits identified as a way build trust. Research into how trust can be built, possibly with anonymity or transparency with workers, could benefit wearable implementation.

Report title: Digitalization of Railway Maintenance: A Situation Awareness Perspective

Journal/Source: International Conference on Applied Human Factors and Ergonomics

Researchers/Research organization: Phillip Tretten, Prasanna Illankoon, Olov Candell

Publication date: July 2021

Technologies examined: Using proper situation awareness interventions when implementing new digitization in railway maintenance.

Key findings:

This paper makes suggestions on how to address declining situation awareness (SA) in railway workers with an increase in digitalization of railway maintenance. Information overload is presented as a primary concern to SA, with data visualization and critical information being presented as under-explored solutions. Data uncertainty is mentioned as a source of mistrust in digital support by rail workers. AR and VR are an emerging area for maintenance digitalization that create concerns over decreased SA and visual and mental fatigue; a structured approach for its implementation is needed. With an increased used of autonomous inspection tools, the need for a user interface that collaborates well cognitively with maintenance workers is apparent. Rail workers are equipped with implicit knowledge related to sound and touch which can be difficult to convey.

Opportunities for future research:

- Work on how to effectively deliver information from digital sources to maintenance workers is needed. A study involving maintenance workers interacting with a variety of different user interfaces, measuring information retention, could inform how best to filter and visualize critical information.
- An implementation and training plan should be developed for more complex maintenance digitalization tools like AR.
- A deeper look, possibly involving workforce interviews, into how implicit knowledge could be intuitively relayed to a digital interface may make for more valuable use of these new digital tools.

Report title: Human reliability in railway engineering: Literature review and two bibliometric analysis of the last two decades

Journal/Source: Safety Science

Researchers/Research organization: Lorenzo Ciani, Guilia Guidi, Gabriele Patrizi

Publication date: July 2022

Technologies examined: A literature review identifying gaps in human reliability in the railway industry,

Key findings:

This paper reviews the use of Human Reliability Analysis (HRA), a systematic technique to assess human error probability, in the railway industry over the past 21 years. There exists a gap in innovative HRA methods specifically developed for the railway industry. The papers found in the literature review deal mainly with using HRA to find causes of past major railway incidents, and the adaptation and improvements of HRA techniques from other industries, for rail. The techniques here being the Cognitive Reliability And Error Analysis (CREAM), Human Error Assessment and Reduction Technique (HEART), and Success Likelihood Method (SLIM) methods. The industry has developed a solid background of experience in HRA and should be develop innovative techniques better suited for the railway industry.

Opportunities for future research:

- Development of a rail specific HRA method to better inform major incident investigation and human factor mitigation methods.
- Application of existing techniques to different types of rail workers to ensure consistent results across the industry (drivers, operators, maintenance, installation).

Report title: Task-induced fatigue when implementing high grades of railway automation

Journal/Source: Cognition, Technology & Work

Researchers/Research organization: Niels Bradenburger, Anja Naumann, Meike Jipp

Publication date: November 2019

Technologies examined: Quantitative fatigue assessment on train drivers and train operators under different grades of rail automation.

Key findings:

This paper outlines a simulator study that was conducted with 32 professional train drivers. While assessing fatigue with the Karolinska Sleepiness Scale and workload using the NASA-TLX (task load index), the grade of automation was manipulated. Fatigue increased significantly over a 2-hour work period. Intermediate grade automation induced significantly higher fatigue ratings than a high grade of automation. Workload scores were significantly higher for the high grade of automation. Workload at high automation grades was still in the underload level, but at an intermediate level. This is likely due to decreased need for continuous, monotonous visual monitoring, and the introduction of need to react timely to well defined system requests. The paper suggests high grades of automation may be used to tackle longstanding fatigue issues associated with train driving.

Opportunities for future research:

- The high-grade automation software was only a prototype and is subject to change with further regulations and development. A study which varies the interface of the automation software, and how tasks and alerts are delivered to the driver is needed to verify if workload is still at an intermediate level and positively offsets fatigue.
- Future studies should be longer term to identify if these decreases in fatigue levels are consistent, even as drivers become more familiar with high grades of automation.
- This study did not consider baseline fatigue levels of its participants. It is therefore recommended participants of future studies assess current fatigue levels 1 week prior to the study.

Report title: An Acquisition Approach to Adopting Human Systems Integration in the Railroad Industry

Journal/Source: Federal Railroad Administration

Researchers/Research organization: Gina Melnik, Emilie Roth, Jordan Multer, Hadar Safar, Matthew Isaacs

Publication date: February 2018

Technologies examined: General design advice for incorporating human factors.

Key findings:

This report defines how the rail industry can incorporate Human Systems Integration (HSI) into the design of railroad equipment and systems. It makes recommendations regarding planning, design, development, and evaluation of technical systems. The guidelines aim to reduce system safety risks and performance risks and minimize the required frequency of redesign related to human factors issues. Two forms of acquisition guidance are given, contractor proposal requirements that railroads can require their venders to fulfill, and general guidance which provides information on how to incorporate HSI into their processes.

Opportunities for future research:

- Rather than recommending further studies on the matter, this paper recommends the adoption of this approach, and recommends guidelines to railroad equipment vendors.
- Given this study was done by the FRA, it may be worth exploring how the guidelines might need to be adjusted for application in Canada and Worldwide.

Report title: Reducing Hazards Associated with Visual and Automation-Aided Track Inspections

Journal/Source: Federal Railroad Administration

Researchers/Research organization: Megan France, Gina Melnik, Hadar Safar, Jordan Multer

Publication date: May 2021

Technologies examined: Visual Inspection and both non-Autonomous and Autonomous Track Geometry Measurement System (ATGMS)

Key findings:

This study's objective was to identify factors that could lead to hazards during both manual and autonomous track inspection. The report analyzed three inspection systems, visual inspection, conventional TGMS, and ATGMS. These systems were analyzed using Systems Theoretic Process Analysis (STPA), a hazard analysis approach designed to examine complex sociotechnical systems. The major findings of the study pointed to need for stronger user-centered design; value of hands-on training, communication, and coordination; and a need to manage the impact of production and resource pressures on inspection and maintenance activities.

Opportunities for future research:

- The scope of the study did not include freight rail, repair and maintenance, or employee safety. A similar analysis of these sectors could provide valuable recommendations, and improvements.
- It was also recommended to applying this STPA approach to other inspection technologies. It provided valuable findings here and could do the same elsewhere.

Report title: Literature Review on Cognitive Impacts of In Cab Warning Systems

Journal/Source: Transport Canada and the Canadian Rail Research Laboratory

Researchers/Research organization: Mona Ahmadi Rad, Michael Hendry, Lianne Lefsrud

Publication date: May 2021

Technologies examined: In-cab warning systems.

Key findings:

The goal of this study was to review the cognitive impact of warning systems for train operators in locomotive cabs. It is meant to highlight any concerns and develop strategies to mitigate any potential negative impacts of these warning systems. The paper provides an overview of the warnings, categorizes and defines them, presents the human factor and usability implications, summarizes follow up actions to them, and analyses related reports. Results found in-cab warning systems to have a confusing array of controls. They were also found to potentially lead to mental under-load for the train operator, leading to less focus and awareness. Exploration of alarm related incidents found most to be a result of poor alarm design and management.

Opportunities for future research:

- The paper suggests a few areas of development involving consolidation of in-cab warnings, implementing an emergency braking response because of lack of response to in-cab warnings, and a potential redesign of alarm systems from a human factors standpoint.

Report title: The SPAR-H Human Reliability Analysis Method NUREG/CR-6883 INL/EXT-05-00509

Journal/Source: U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research Washington, DC 20555-0001

Researchers/Research organization: D. Gertman, H. Blackman, J. Marble, J. Byers, C. Smith / Idaho National Laboratory operated by Battelle Energy Alliance Idaho Falls, ID 83415

Publication date: August 2005

Technologies examined: Nuclear reactor oversight process

Key findings:

The Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method was developed, applied and updated in the development of nuclear power plant (NPP) models. Since that time, NRC staff analysts have been using this method to perform their risk-informed regulatory activities. SPAR-H consists of a two-step process to identify nominal human error probabilities (HEPs), and then modify those HEPs on the basis of summary-level performance shaping factors (PSFs) and dependence (the negative influence of a human error on subsequent errors). PSFs used in SPAR-H are: available time, stress/stressors, complexity, experience/training, procedures, ergonomics/HMI, fitness for duty, and work processes. Although the PSFs were originally developed for the nuclear industry, they are directly applicable to railroad safety risk assessment as well. This document presents the current version of the SPAR-H method, along with guidance, definitions, and comparisons between this and other contemporary HRA approaches and findings.

Opportunities for future research:

- SPAR-H has been successfully applied in safety case development to obtain FRA certification of safety-critical railroad systems, including a fully automated dispatching system. The method is proven and more quantitative than many other assessment methods. Because of this, it can be applied directly to new or modified railroad safety systems that must account for human factors and it is recommended for these types of applications.

Report title: Human Error Analyses Associated with Locomotive Cab Automation

Journal/Source: U.S. Department of Transportation, Federal Railroad Administration

Researchers/Research organization: Alion Science and Technology

Publication date: September 2022

Technologies examined: Positive Train Control (PTC) and Energy Management System (EMS)

Key findings:

To improve railroad safety and efficiency, automation is being introduced into the locomotive cab. This research addressed the potential for human errors that may occur during human-automation interaction with cab system automation displays. Specifically, the engineer and conductor examined the EMS known as "Trip Optimizer" (TO) and the Positive Train Control (PTC) systems while in operation in a lab. This research suggests that PTC and TO offer additional opportunities to support freight rail safety and enhance the efficiency of freight rail operations, but there is also potential for new opportunities for error. Based on the analyses in this research, the team suggested several mitigation strategies.

Opportunities for future research:

- Potential forms of human error that are specific to proposed new modes of train control (e.g., Enhanced Train Control [ETC]) and stages of automation (EMS and possibly more) should be comprehensively identified and quantified in terms of human error probability (HEP) and associated performance shaping factors (PSF).
    - Mitigations should be devised if/where there is unacceptable risk. Particularly salient events to analyze are the automatic transition of TO and/or PTC from active to inactive.
    - This project was based on the ITC PTC system and the TO EMS system deployed on U.S. railroads. Similar analysis is recommended that considers differences between these systems and the systems proposed for use in Canada.
- An examination of possible propagation of errors through the system with increased use of automation should occur.

Report title: The Expert Locomotive Engineer's Mental Model

Journal/Source: U.S. Department of Transportation, Federal Railroad Administration

Researchers/Research organization: General Electric (GE) Research and the Massachusetts Institute of Technology (MIT) Human Systems Lab

Publication date: August 2021

Technologies examined: Positive Train Control (PTC) and Energy Management System (EMS)

Key findings:

This project studied ways to improve the human-machine interface for the locomotive driving task and train handling with the assistance of advanced automation, considering both experienced engineers and those new to the job. The approach was to build-in and take advantage of expert drivers' knowledge and skills and the machine's ability to execute instructions more precisely than the engineer to provide better overall safety and efficiency.

This study paired volunteer expert freight engineers with novice subjects with very little knowledge of rail operations as the operating crew of a freight train. The subject pair drove two routes together in a locomotive simulator: one with the novice operator controlling the train (NAC, or "novice-at-the-controls") and the other with the expert engineer controlling the train (EAC, or "expert-at-the-controls"). In order to expose and understand all of the stimulus and actions involved in driving a train, the participant operating the train controls was unable to see the external environment, thus participants had to orally communicate necessary information to enable an appropriate control action.

Opportunities for future research:

- The creative method used in this project to identify what stimulus and actions are required for driving a train with good train handline can be applied to train assist and automation developments in Canada.

Report title: Using Cognitive Task Analysis to Inform Issues in Human Systems Integration in Railroad Operations

Journal/Source: U.S. Department of Transportation, Federal Railroad Administration

Researchers/Research organization: U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, Cambridge, MA 02142-1093

Publication date: May 2013

Technologies examined: Positive Train Control (PTC)

Key findings:

Railroad operations are undergoing rapid changes such as the introduction of positive train control (PTC) and energy management systems (EMS). Human Systems Integration (HSI) has been introduced to the railroad industry to help ensure these and other new technologies are optimally designed for safe and efficient use, to increase user acceptance and usability of the technology, as well as increase the likelihood that it is deployed successfully. This report provides guidance with respect to the need for HSI in the technology acquisition process, and more specifically, how to use Cognitive Task Analysis (CTA) methods and results as part of the HSI process.

This report draws on examples from CTAs previously conducted regarding PTC for locomotive engineers, conductors, dispatchers, and roadway workers. The information contained in the report serves as a lead-in to the kinds of insights that can be drawn from performing a CTA when introducing new technologies into railroad operations, as well as a starting point for the industry as far as identifying the likely emerging issues that need to be explored as a result of the introduction of new technology.

Opportunities for future research:

- It is recommended that the example PTC CTAs provided in the report be used as a starting point for performing CTAs regarding the "actors" (locomotive engineers, conductors, dispatchers, and roadway workers) who will interface with Enhanced Train Control (ETC) in Canada.
- The CTA process can also be applied to the introduction of other new technologies, such as EMS.

C14. Low Carbon Fuels

Report title: A Mini review on the Cold Flow Properties of Biodiesel and its Blends

Journal/Source: Frontiers – Bioenergy and Biofuels

Researchers/Research organization: M.A. Hazrat, M.G. Rasul, M. Mofijur, M.M.K. Khan, F. Djavanroodi, A.K. Azad, M.M.K. Bhuiya, A.A. Silitonga

Publication date: December 2020

Technologies examined:

Key findings:

This paper reviews and explains the various methods for improving the cold flow properties of biodiesel. The following methods are described and quantified based on their ability to lower cloud point (CP) and pour point (PP), which are two metrics for measuring cold flow performance.

- Winterization: controlled cooling of the fuel, removing the crystalized long-chain saturated fatty acid methyl esters (FAME) components when cooled. This method can reduce CP and PP between 5 to 10 C but can also decreases fuel yield between 5-15%.
- Fuel Additives: Many additives were discussed, but the most promising mentioned were Polymethyl acrylate (PMA) with a CP and PP reduction of 3C and 9C respectively, and ozonized vegetable oils with a CP reduction of around 15C.
- Blending with Conventional Diesel: various blends of diesel will have increasing CP and PP improvements as biodiesel is brought to lower percentages than B100.
- Branched-chain fatty acid methyl esters (BC-FAME): can be used to reduce the CP and PP of biodiesel, but no combustion tests have been done to quantify changes in performance.
- Blending of Biodiesels: blending biodiesels from different feedstocks can help created a desirable FAME profile.

The paper concludes by suggesting "In order to obtain both stable and improved low-temperature flow in biodiesel fuels, a combined methodology of blending for oxidation stability improvement and then the use of a CFI additive could be the most economical solutions."

Opportunities for future research:

- More field-based data on the effects of different feedstocks on biodiesels cold flow performance would help inform its use in the rail industry, especially during the winter months in Canada.

Report title: Literature Review and Experimental Testing of Hydrogen/Diesel Blends for Heavy-Duty Compression Ignition Engines Operating at Typical Locomotive Engine Load Conditions

Journal/Source: National Research Council Canada, Transport Canada Innovation Centre

Researchers/Research organization: Hongsheng Guo, Richard Frechette, Simon Lafrance, Brian Liko, Shuovik Dev

Publication date: June 2023

Technologies examined: Hydrogen-diesel co-combustion with direct and indirect injection of hydrogen, and an assessment of the GHG reductions.

Key findings:

This paper describes a literature review on the use of hydrogen-diesel co-combustion in locomotives, and experimental testing of engine operation with hydrogen-diesel co-combustion.

The literature review that co-burning the fuel reduces CO2, CO, and PM emissions, while increasing NOx emissions. Indirect and direct injection were compared, the first being cheaper with less control over fuel mixtures, and the latter has more control but requires a more expensive, intrusive modification of the engine. The details of any use of hydrogen-diesel are still very limited, with a technical readiness level of 2-3.

The experimental test involved operation of a hydrogen-diesel engine at 25%, 50%, and 75% engine loads, indirectly injecting hydrogen. The hydrogen energy fractions used at these loads were 50%, 40%, and 25% respectively. GHG reductions (mostly CO2) decreased near linearly with increasing hydrogen energy fraction, also significantly reducing PM and CO emissions. Cylinder peak pressure did increase with higher hydrogen energy fractions, limiting the ability to increase hydrogen percentage further. NOx emissions also increased.

Opportunities for future research:

The opportunities for future research were clearly stated in the conclusion as follows.

- More studies related to the economics and maintenance of hydrogen-diesel combustion for locomotive engines.
- More examples of hydrogen-diesel combustion being tested outside of lab demonstrations, to help address concerns on real-life integration, and.
- More examples of engine tests under real life climatic conditions (hot weather, cold weather, varying humidity, etc.).

Report title: Lignin-derived diesel fuel for rail application (Phase II): Final Report

Journal/Source: CanmetENERGY, Transport Canada Innovation Centre

Researchers/Research organization: Yi Zhang, Jacques Monnier

Publication date: June 2022

Technologies examined: Biofuel (lignin-derived), different blend ratios, and fuel additives.

Key findings:

This study aims to assess the feasibility of using lignin (a major component of wood) derived diesel fuels in current locomotives. Canmet Energy and CRB Innovations are working to turn lignin into renewable fuels, and this study determined that the fuel met locomotive fuel standards (CAN/CGSD-3.18-2010). Some characteristics of the fuel require modification; it is not conductive enough and will require an electrical conductivity improver additive; high concentration blends of lignin-diesel would require a lubricity additive; its cetane number is slightly below the required and it would need a cetane enhancer additive. The first two of these issues are also currently required for ultra-low sulfur diesel and should not be much of a concern.

Opportunities for future research:

- CanmetEnergy plans to optimize and scale up the production of lignin derived diesel. With this they will conduct engine tests to determine the emissions from locomotives using this fuel and its blends.

Report title: Evaluating the impact of using various biodiesel blends on the performance of diesel engine at variable load conditions

Journal/Source: IOP Conference Series: Material Science and Engineering

Researchers/Research organization: Mahmoud Abu-Zaid

Publication date: 2019

Technologies examined: Engine performance using B20 biodiesel from sunflower, palm, and corn oil feedstocks.

Key findings:

This study evaluated the effect B20 biodiesel (20% biodiesel, 80% diesel) from sunflower, palm, and corn oil feed stocks, effects the performance of diesel engines. The engine used was single cylinder, direct injection, with a 17:1 compression ratio. The following metrics were assessed:

- Torque: Due to its higher calorific value (its ability to produce thermal energy under combustion) diesel had the highest torque at all engine loads, where the biodiesel blends increased as engine load increased.
- Fuel consumption: Biodiesel blends consumed less at lower engine loads, as they were producing less torque.
- Brake specific fuel consumption: this measures the capability of the engine to convert fuel to power (measured in g/KWh). It was lower for all biodiesel blends, suggesting it is possibly more economically efficient.
- Brake thermal efficiency: this measures the ratio of brake power to thermal energy produced from fuel combustion. It was significantly higher for all biodiesel blends.
- Exhaust temperature: As expected these increases with an increase in engine load. The biodiesel blends had significantly lower temperatures at lower loads, approaching the diesel temperatures at full loads.

Opportunities for future research:

- It would be worth repeating these tests on a typical rail diesel engine to understand if these findings hold true for larger diesel engines. This same study could test various, higher biodiesel blends (B80-B100) to see if these effects are related to the blend ratio of the fuel.

Report title: A comprehensive review on the usage of the nano-sized particles along with diesel/biofuel blends and their impacts on engine behaviors

Journal/Source: "Fuel" Journal

Researchers/Research organization: M.S. Gad, Umit Agbulut, Asif Afzal, Hitesh Panchal, S. Jayaraj, Naef A.A Qasem, A.S. El-Shafay

Publication date: January 2023

Technologies examined: Engine performance of nano-additives, emissions, combustion characteristics, nanofuels.

Key findings:

Biodiesel show promising results for locomotive emissions reductions but issues with higher viscosity, lower calorific values, and clouding at low temperatures are inhibiting its use. These nano particle fuel additives (metals, metal oxides, and carbon-based materials on the scale of nanometers) can enhance the energy density of the fuels, though they increase its viscosity. Some other concerns are listed here:

- They are quite expensive; production cost or technology would need to improve for there to be widespread adoption.
- The particles can sink to the bottom of fuel tanks and can clog the fuel injection systems. The concentration at which this occurs is not yet known.
- Their effect on emissions is unknown.

Opportunities for future research:

Lots is still unknown about the proper use and effects of these nanoparticles as a fuel additive. The proper size, material, and concentration, their effect on emissions, and effect on fuel motion is unknown.

- A study comparing the effects of different materials and sizes of nanoparticle additives, at different concentrations could help inform their commercial use. This study would ideally measure the effects on fuel flow, any conglomeration or clogging caused by the particles, and the engine performance and emissions as a result of their use.

Report title: Effect of nano-fuel additive on performance and emission characteristics of the diesel engine using biodiesel blends with diesel fuel

Journal/Source: International Journal of Ambient Energy

Researchers/Research organization: S. Mahalingam, S. Ganesan

Publication date: April 2018

Technologies examined: Emission and performance assessment of nanoparticle additives in different concentrations in biodiesel (B20).

Key findings:

Unlike the other paper on nanoparticle fuel additives in this section, this study varies the concentration of nanoparticles and measures the effect on brake thermal efficiency, emissions, and brake-specific fuel consumption. The fuel used was a B20 diesel, with 20% rubber seed oil biodiesel blended with 80% pure diesel. The additive used was aluminum oxide at 10, 15, and 20ppm. The lowest concentration, 10ppm, was the most effective, producing the following results.

- The highest brake thermal efficiency compared to all other biodiesel blends (B20, B20 + 15ppm, B20 + 20ppm)
- 20% lower brake-specific fuel consumption compared to B20 with no additives.
- More complete combustion due to shorten ignition delay from the additives, leading to a decrease in CO emissions.
- Improved oxygen content in the fuel, decreasing hydrocarbon emissions.
- NOx emissions decreased with higher ppm of additives, though B20 + 10ppm still shows lower NOx emissions compared to pure diesel.

Opportunities for future research:

Similar to the other nanoparticle study in this section, this study only tests one ration of biodiesel on a single cylinder diesel engine. Hence, the same study suggested there applies here.

Report title: CO2 reduction in a common rail direct injection engine using the combined effect of low carbon biofuels, hydrogen and a post combustion carbon capture system

Journal/Source: Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

Researchers/Research organization: V. Edwin Geo, S. Thiyagarajan, Ankit Sonthalia, T. Prakash, Sary Awad, Fethi Aloui, Arivalagan Pugazhendi

Publication date: September 2021

Technologies examined: Emission and performance assessment of B20 biodiesel (lemon peel and camphor oil), hydrogen injection, and zeolite-based carbon capture.

Key findings:

This paper covers a unique study which utilizes several proposed emission reduction techniques on a single cylinder common rial direct injection engine. The tests use different combinations of biodiesel blends (B20 made from lemon peel oil and camphor oil), hydrogen intake injection, and a zeolite-based exhaust carbon capture system. Both emissions and performance metrics were measured for each system; CO2, particulate matter (smoke), and NO were measured for emissions; brake thermal efficiency, and brake specific energy consumption were measured for performance. The highest emissions reductions were achieved using B20 diesel from lemon peel oil with hydrogen intake injection, and a zeolite-based carbon capture system, with results as follows.

- A 39.7% reduction of CO2 emissions compared to pure diesel.
- Use of biodiesel and hydrogen injection increases NO emissions, though the addition of the zeolite carbon capture system drastically reduces them to about 20% below pure diesel.
- A significant reduction (49% from pure diesel) of smoke opacity due to lower viscosity and presence of oxygen.
- A large reduction of hydrocarbon emissions due to the hydrogen injection, though slightly increased by the back pressure of the carbon capture system.
- A few percent increase in efficiency, hindered by the backpressure of the carbon capture system.

Opportunities for future research:

- The study suggests that future research explore catalyst for carbon capture to be made from bio char to lower costs and make production more sustainable. A longer-term test, to see how carbon capture systems perform over time would be beneficial. This same study could include different, or possibly full-sized rail engines to see if the findings hold true. As with other studies, use of higher biodiesel blends (B80 to B100) should be explored.

Report title: Thermal barrier coated diesel engine running on biodiesel: a review

Journal/Source: International Journal of Sustainable Engineering

Researchers/Research organization: M. Mohamed Musthafa

Publication date: January 2017

Technologies examined: The use of thermal barriers to increase the benefits of biodiesel use.

Key findings:

This paper reviews the use of low heat rejection (LHR) engines to increase combustion temperature and discusses how this can be applied for more efficient use of biodiesel. The literature scan showed a unanimous increase in brake thermal efficiency and decrease in specific fuel consumption. All sources reported significant reduction of CO and hydrocarbons likely due to the higher oxygen content of biodiesel and the increased temperature from the LHR engine increases NOx emissions. Partially stabilized zirconia was found to be the best thermal barrier due to its "low thermal diffusivity, thermal conductivity, chemical stability and strong adherence to the substrate". The atmospheric plasma thermal spray is most used for making thermal barrier coating for these LHR engines.

Opportunities for future research:

Three main opportunities are listed in the review:

- Assessment of alternative lubricants that can withstand the higher temperatures in the combustion chambers.
- Optimization of the coating thickness to minimize stresses in service.
- More research on LHR engines in general is needed before adoption can be explored.

One point that was not mentioned, but that could be very beneficial to the use of biodiesel, is the use of LHR engines in cold weather. Using this coating may have the potential to eliminate concerns of biodiesel clogging at low temperatures, though this is yet to be explored and should be included in future research.

C15. Zero-emission rail propulsion technologies

Report title: Battery only electric traction for freight trains – A technical and operational assessment

Journal/Source: Journal of Rail and Rapid Transit

Researchers/Research organization: Fabio C. Barbosa

Publication date: March 2023

Technologies examined: Review of battery only electric traction for freight trains**.**

Key findings:

This paper reviews the current knowledge of Battery Only Electric Rail (BOER) as used in the freight industry. It presents the technical, operational, and environmental challenges and costs for implementation and operation. It raises challenges of the Li-ions range, size, and weight, all aspects that require further improvement. These battery performance issues also affect their charging speed, which is much slower than other hybrid vehicles. The infrastructure required for BOER should not be underestimated and is discussed further in the research opportunities. Shunt locomotives are a valuable pilot to BOER due to their proximity to urban areas, making emissions and noise reduction crucial. For addressing range concerns, regenerative braking was suggested as a way to increase range, citing an Australian pilot project which used the technology. Though BOER is considered an environmentally conscious technology, concerns still exist with the required energy usage and material lifecycle. The lifecycle can be split into three stages of manufacturing, use, and recycling. Issues with water usage, water quality impact, and worker safety still exist in manufacturing. Lack of guidelines for proper disassembly and recycling of these battery systems has potential cause for the process to release large quantities of pollutants.

Opportunities for future research:

- To address infrastructure concerns, a plan or implementation strategy should be drafted, considering "i) incremental power demand requirements and the grid capacity; ii) grid connection to charging points; iii) price negotiation with energy utility companies; iv) smart charging strategies policies, such as night charging and active management of BOER charging yards, as well as v) renewable energy contribution."
- A BOER shunt locomotive pilot project in North America could be a good opportunity to introduce the technology and infrastructure.
- Findings suggest that tests of regenerative braking devices on Canadian freight rail could identify if the technology is worth the cost and implementation concerns in North America.
- A lifecycle analysis of the materials required for the infrastructure and rolling stock of BOER could help inform the actual GHG reductions and environmental impact of country-wide adoption.

Report title: A Review of Developments in Electrical Battery, Fuel Cell and Energy Recovery Systems for Railway Applications

Journal/Source: University of Glasgow, Scottish Association for Public Transport

Researchers/Research organization: David Murray-Smith

Publication date: November 2019

Technologies examined: A review of zero-emissions propulsion vehicles and infrastructure with a focus on energy storage and regenerative braking.

Key findings:

This paper reviews recent developments in energy recovery in various forms like regenerative braking, use of supercapacitors, use of flywheels, and use of hydraulics. It also discusses developments in hybrid power vehicles, and potential design optimizations. Few pilot projects have used flywheels for energy storage and regenerative braking. They have shown how to improve acceleration, and decrease peak power demand, leading to cost savings. One project in the UK was able to achieve fuel savings of up to 10% using an on-board regenerative braking flywheel concept. Hydraulic transmissions have also proved effective in energy savings by reducing energy losses from engine to wheels. During deceleration, these transmissions can act as pumps to fill hydraulic accumulators. The pressure from the hydraulic accumulators can be used in acceleration, completing another form of regenerative braking. Supercapacitors, a more recently developed energy storage system, have delivered 30% energy savings, and 50% peak power reductions. A 2014 study in China used a rail-side charging system to charge supercapacitors on the train, taking only 30 seconds to charge the system. The 30 second charge gave them 4km of range and was repeated down the line (on a light rail system). These short charging times could make supercapacitors a possible replacement to catenary systems.

Opportunities for future research:

- Though this study provides valuable information on the use of energy storage systems, most of the research presented has been in the context of electrified light rail/public transit systems. Further research on how the Canadian freight industry can leverage these technologies is needed before determining whether they are valuable or feasible in Canada's net zero future.

Report title: Vibration-based degradation effect in rechargeable lithium-ion batteries having different cathode materials for railway vehicle application

Journal/Source: Engineer Failure Analysis

Researchers/Research organization: Pyeong-Yeon Lee, Seongyun Park, Inho Cho, Jognhoon Kim

Publication date: June 2021

Technologies examined: Vibration testing of different active materials in lithium-ion batteries.

Key findings:

This study aimed to simulate the complex vibration profile of railway vehicles to determine their effect on the degradation of cathode active materials in lithium-ion batteries. A standardized vibration profile: "IEC 61373: 2010 Railway application Rolling stock equipment – shock and vibration" was used to simulate a long-life test on components. The degradation of the cathode material was measured by "monitoring its resistance, capacity, and incremental capacity." Three different cathode materials were tested. In the electrical performance test, it was found vibration caused damage to the active materials in the battery, and performance was decreased in all vibration tests. In the incremental capacity analysis, which is "an electrochemical technology that analyzes battery degradation using changes in the voltage and capacity of the battery", batteries using Nickel Manganese Cobalt (NMC) active material were found to be the most resistant to vibrations, while batteries with Nickel Cobalt Aluminum (NCA) and Lithium Iron Phosphate (LFP) active materials were found to be more vulnerable to vibrations.

Opportunities for future research:

- The study offered no recommendation for further research, but based on the success of this test, it may be worth repeating the study for hydrogen fuel cells.
- Beyond selecting certain active materials in the battery, no methods are offered to mitigate the effects of vibration on batteries. Further research, possibly a literature review, on the mitigation methods for vibration damages in batteries could be informative in their implementation.

Report title: Research on Vibration Test Method of Hydrogen System in Fuel Cell Bus

Journal/Source: Journal of Physics: Conference Series

Researchers/Research organization: Ting Guo, Yue Xu, Guozhuo Wang, Shiyu Wu, Zhen Wu, Zhijun Wang, Rongliang Liang, Mingyue Zhou, Fang Wang

Publication date: 2023

Technologies examined: Developing vibration life cycle tests based on real life operational vibration data.

Key findings:

This studied gathered sensor data for a fuel cell bus currently in operation over two weeks of operation. The triaxial acceleration sensors were placed at multiple points on the bus's hydrogen system. This data was then used to create an accelerated bench test of the life cycle of the bus's hydrogen system. The rain flow count method was used to extrapolate the fatigue data and calculate fatigue over the system's life cycle. A fatigue plot showing the fatigue line for how many cycles the system can handle at different impulses, and an impulse response plot showing the vibration frequency at different impacts were produced. No information on how specific components were affected by the vibrations was given.

Opportunities for future research:

- Although this study is based on bus methods for establishing and accelerated life cycle bench test and processing the data for accurate fatigue and impact numbers, it could be useful for rail application. Equipping a hydrogen or battery locomotive with a similar sensor suite and developing a similar bench test and analysis procedure could inform the design of these battery and hydrogen rail systems.

Report title: Crashworthiness Evaluation of a Hydrogen Bus Fuel System

Journal/Source: International Journal of Automotive Technology

Researchers/Research organization: Jaeho Shin, Kyungjin Kim, Kyeonghee Han, Jeong Min In, Hyung-Jin Chang, Sojung Shim, Siwoo Kim

Publication date: October 2022

Technologies examined: [Note main technology being researcher/analyzed]

Key findings:

This study aims to analyze the crashworthiness of a bus with a roof-mounted fuel cell system. It focuses on static roll over testing of the bus, which may be applicable to rail given derailments often cause tipping of rail cars. The roll over test in this study was developed in accordance with several UN regulations on hydrogen vehicles. The bus was tilted beyond its equilibrium point on a raised platform, such that it would rollover making contact with its roof first. Accelerometers, and strain gauges were applied to critical components of the system like the tanks, valves, and fuel lines. Hydrogen sensors were placed near the system and in the cabin to determine leakage rates. Thermal imaging cameras were used to identify leaks outside the bus. A finite element model of the test vehicle was created to collect simulation data of the same test. The simulation data and experimental data showed good correlation. A sensitivity analysis of the simulated COG location was conducted. Changes in COG lead to changes in tank valve displacement in the rollover and the study suggest that verifying the COG of the real vehicle is important for accurate computational results.

Opportunities for future research:

- Although this study does not involve rail vehicles, this valuable comparison between simulated and experimental roll over tests could inform hydrogen rail crashworthiness testing. If it is possible to gather parameters of hydrogen rail vehicles, like their COG, it may eliminate the need for extensive experimental roll over testing, and a finite element model could be used to inform and iterate crashworthiness of hydrogen rail systems.
- Multiple models exist for rail dynamics during collisions. More work is needed to see which models could be combined with the findings from this study to begin work on modeling hydrogen incidents for rail.

Report title: Battery Train Fire Risk on a Steel Warehouse Structure

Journal/Source: Journal of Architectural Environment & Structural Engineering Research

Researchers/Research organization: Jasmine Mira, Nicole Braxtan, Shen-En Chen, Tiefu Zhao, Lynn Harris, Dave Cook

Publication date: July 2021

Technologies examined: Simulation of fire propagation among lithium-ion battery cells and nearby structures.

Key findings:

This paper aims to review the fire risk procedure for lithium-ion batteries. The subject of the study is a simulated lithium-ion battery fire that propagates to a nearby steel warehouse. The fire is simulated using Monte Carlo-based dynamic modeling and a finite element analysis is used to simulate the fire on the steel warehouse. The simulated battery stack is represented as a 50x10 matrix. The fire starts at a random cell and propagates based on a set probability, and the state of the neighboring cells. The test was ran 1,000 times with different assigned probabilities with the % of battery burned jumping from 1.5% to 89.4% from a probability increase of 0.2 to 0.4. Experts analyzed the steel warehouse and assigned fire risk scores for different sections of the warehouse, and a finite element analysis of the warehouse showed the damage the warehouse incurred for different fires. The outcome of the fire risk analysis was a set of specific fire protection strategies for the warehouse including use of fire protection material, sprayed fire resistive material, and blanket insulation.

Opportunities for future research:

- This fire analysis delivered a data-based fire protection strategy for this warehouse and could do the same for others. As pilot projects for lithium-ion trains begin, it would be valuable to implement these same tests at pilot sites to ensure proper fire protection strategies are in place.
- This paper does not mention the simulated battery capacity or voltage. Further research could determine the impact of battery size on fire risk.
- Controlled physical testing of battery fire propagation among cells may be useful to verify the probability-based model used in this study.
- A streamlined method of the fire simulation of nearby buildings may be required as mass adoption of lithium-ion battery locomotives means they will travel near many structures.

Report title: Techno-Economic Assessment of Battery Electric Trains and Recharging Infrastructure Alternatives Integrating Adjacent Renewable Energy Sources

Journal/Source: Sustainability - MDPI

Researchers/Research organization: Christoph Streuling, Johannes Pagenkopf, Mortiz Schenker, Kim Lakeit

Publication date: July 2021

Technologies examined: Lifecycle cost analysis of battery electric trains and their charging infrastructure with a focus on island charging systems and local renewable energy production and storage.

Key findings:

This paper proposes the use of battery electric multiple units (BEMU) to provide charging through an overhead line to battery electric freight vehicles. Combined with locally produced renewable electricity, the system is suggested as a package for zero-emission rail. The proposed model is applied to a regional German line, where the local renewable energy is produced using wind power and delivered from on-site battery storage. This setup is said to deliver a similar energy supply as grid consumption. A model-based approach was taken to assess the lifecycle costs (LCC). The intermediate island electrification proposed here had favorable LCC compared to full catenary electrification.

Opportunities for future research:

- Given this study was for a regional rail line in Germany, a feasibility study on the use of island charging infrastructure for Canadian freight lines with greater energy demands is needed. The same cost savings seen in this model may not hold true for longer, heavier freight lines in Canada.
- A feasibility study on local renewable energy storage systems is also required. Local wind power is not available along much of the Canadian freight lines and use of hydro and solar power should be explored as a substitute. Given the large upfront infrastructure costs this project would likely have, a partnership with power utilities and a preliminary analysis of different routes to find one most suitable for the project would be necessary to ensure the project's success.

Report title: Sizing BESS and On-site Renewable for Battery-electric Freight Rail Charging Station

Journal/Source: IEEE, Oregon State University

Researchers/Research organization: Vinson Guov, Derek Jackson, Manasseh Obi, Yue Cao

Publication date: October 2022

Technologies examined: [Note main technology being researcher/analyzed]

Key findings:

This paper presents the idea and required information for developing a fast-charging network for battery electric freight rail across the U.S. With fast charging stations drawing greater than 1MW of power, it can be too large a draw for the grid. To remedy this, the study suggests the use of on-site battery electric storage systems (BESS) and renewable energy sources. The tool and simulator proposed by the paper predict the size and cost of the network, making trade-off comparisons between multiple types of energy storage, renewable power sources, and power electronics. Two BESS are considered, Lithium-ion batteries (LIB) for their high specific energy, and redox flow batteries (RFB) for their scalability. Two renewables were considered, solar PV farms, and wind turbine farms. A dual active bridge converter (DAB) handles the Dc/DC power conversion, while a solid-state transformer (SST) rectifies the AC power from the grid. An energy management system is used to regulate the power draw from the grid and supplement it from the on-site BESS. Two, week-long MATLAB simulations demonstrated the capability of the fast-charging systems. One used RFB and a solar farm, while the other used LIB and a wind farm. Graphs were produced which indicated all the feasible combinations of BESS capacity and renewable source capacity. The pareto front, which is a line at which no component can be improved upon without sacrificing others, was slightly narrower (more defined) for the LIB/wind simulation, likely due to the uncertainty of solar energy generation.

Opportunities for future research:

- The paper offers a succinct suggestion for further simulation, "with results indicating Pareto optimal designs that can be used by a higher-level network train simulator to drive economic modeling of charging infrastructure to discover feasible pathways to decarbonizing freight rail in the U.S. or other parts of the world where applicable."
- The paper also recommends a longer than one-week simulation. Extending it to a year or more would give more accurate data for renewable energy production.

Report title: Hydrogen supply chain and refueling network design: assessment of alternative scenarios for the long-haul road freight in the UK

Journal/Source: International Journal of Hydrogen Energy

Researchers/Research organization: Ramin Raeesi, Christa Searle, Nazmiye Balta-Ozkan, Laura Marsiliani, Mi Tian, Phillip Greening

Publication date: January 2024

Technologies examined: A network of UK road freight hydrogen distribution with a focus on storage technologies and centralized hydrogen production. *Key terms: road freight, hydrogen supply chain, distribution network, hydrogen refueling station, underground storage of hydrogen, hydrogen powered HGV.*

Key findings:

This paper presents a hydrogen distribution and fueling network for long-haul road freight in the UK. A tool is developed to optimize the hydrogen network and provide managerial and policy-making insights. Some key findings quoted directly from the paper which I have abbreviated are as follows:

- Scenarios using blue and green hydrogen production tend to fully rely on blue hydrogen, ignoring green. Green hydrogen only scenarios raise the cost at the pump by 1.7 times.
- Bulk (underground) geographic storage save up to 65% on each kg of hydrogen at the pump.
- Price per kg of hydrogen is heavily reliant on the prevalence of hydrogen locomotives and the policies to support their adoption.
- A 5-day safety stock of hydrogen is needed for a reliable hydrogen supply chain.

Opportunities for future research:

- Recommendation for future research from the paper include repeating the study with more accurate hydrogen demand data (this study used energy conversion from currently used fuels); inclusion of pipeline and rail transport of hydrogen; and alternate, decentralized methods of hydrogen production (this study focused on centralized production.
- As this study is based on UK long-haul road freight, it is important to see how these findings can be adapted to Canada’s more remote freight rail network.

Report title: Battery Electric Locomotives & Battery Tenders: Operational & Infrastructure Challenges to Widespread Adoption

Journal/Source: ASME/IEEE Joint Rail Conference

Researchers/Research organization: Michael E. Iden

Publication date: June 2021

Technologies examined: A review of the current barriers that exist to battery electric locomotive adoption in the U.S. *Key words: AC diesel locomotive, battery electric locomotive, battery tender.*

Key findings:

This paper presents the barriers that exist to battery electric locomotive (BELs) adoption in the U.S. a 2.4MWh BEL is undergoing testing in the U.S. but the time at full throttle it is capable of is much lower than current diesel-electric locomotives. Battery Tenders (BTs) could supplement this lack of power but require retrofitting of ASC diesel electric locomotives. The paper identified a gap in knowledge in the size and power required for charging stations, along with the capacity in which on-board charging and regenerative braking systems can be used. The range of these BELs could be 1/12th that of diesel electric locomotives. The paper states that making a financial comparison between battery locomotives and fully electrified (catenary) rail is unfeasible at the moment due to large knowledge gaps in infrastructure, maintenance, and operational costs for BELs.

Opportunities for future research:

The final notes of the paper call for "significant engineering effort" on the research of current unknowns with regards to BELs and BTs. Further analysis is required to identify realistic market prices for manufacturing BELs and BTs as well as the supportive infrastructure. Few pilot projects of these technologies exist, and more of them will increase the knowledge of real-life performance and life cycle costs.

C16. Carbon life cycle of track materials and rolling stock

Report Title: [Life Cycle Cost, Energy and Carbon Assessments of Beijing-Shanghai High-Speed Railway]

Technical Journal/ Source: MDPI Sustainability Research Journal

Researchers/Research Organization: School of Engineering, University of Birmingham

Publication Date: Dec 2019

Technologies Examined: Life-cycle assessment, Energy Assumption analysis, Carbon emission calculation.

Key findings:

Construction Stage Impact

- The construction stage is identified as the primary contributor to carbon emissions and energy consumption in the lifecycle of the railway. This stage accounts for 64.86% of the total carbon emissions and 54.31% of the total energy consumption and is often omitted during emission calculations as the focus is on the emissions produced from operation.
- The significant environmental impact during this stage is primarily due to the extensive use of materials like cement, steel, and gravel. The energy-intensive processes of producing these materials, coupled with the emissions from transportation and construction activities, contribute heavily to the overall environmental footprint. Cement production is particularly carbon-intensive, largely contributing to the emissions during the construction phase. The calcination of limestone in cement manufacturing releases significant amounts of $CO2$.

Operation and Maintenance Stage

- Contributions to Emissions: This stage also plays a significant role in the life cycle environmental impact, contributing 31.60% to carbon emissions and 35.32% to energy consumption.
- Maintenance Activities: Regular maintenance activities, including part replacements and upkeep operations, contribute to ongoing emissions and energy use. This phase includes the maintenance of track infrastructure, rolling stock, and other operational components.

Opportunities for future research:

- Innovation in Construction Methods: Research can focus on developing less energy-intensive construction techniques.
- New Material Research: Future research can focus on developing new, more sustainable construction materials to replace or supplement traditional materials like cement and steel, which are major contributors to carbon emissions.
- More thorough Life Cycle analysis: opportunity to develop software tools that can model and predict the environmental impact of railway projects through a more complete scope.

Report Title: **Measuring Railway Infrastructure Carbon: A 'critical' in transport's journey to net-zero**

Technical Journal/ Source: EPSRC Energy Programme

Researchers/Research Organization: The University of Leeds Faculty of environment

Publication Date: 2022

Technologies Examined: Recycled Composite Sleepers, Fibre-reinforced Foamed Urethane (FFU) Sleepers, Solar PV Systems

Key findings:

This study focuses on a new way of assessing carbon lifecycles by approaching a "whole life carbon" (WLC) approach that encompasses all stages of rail infrastructure, including construction. This new assessment method is then used to evaluate the materials utilized and some possible alternatives, these include:

Comparison of Ballasted and Ballastless Tracks: The study highlights the differences in WLC impacts between ballasted and ballastless tracks. It's noted that ballastless tracks, while having a higher initial embodied carbon due to concrete usage, offer lower overall WLC mainly due to reduced maintenance needs.

Significance of Overhead Line Equipment (OLE): OLEs are identified as significant contributors to the WLC of rail infrastructure. The operational and maintenance phases of OLE are particularly carbon-intensive, indicating a need for more efficient designs or materials.

Innovative Sleeper Materials:

- Recycled Composite Sleepers: These are proposed as sustainable alternatives to conventional materials, utilizing recycled plastics and rubber. They are expected to reduce WLC due to their longer lifespan and use of recycled content.
- Fibre-reinforced Foamed Urethane (FFU) Sleepers: Represent another alternative with potential benefits over traditional materials, offering durability and a longer service life, although they are initially more carbon-intensive due to the manufacturing process.

Solar PV Systems at Stations: The study assesses the integration of solar PV systems to offset operational carbon emissions from station energy use. This approach aligns with the broader goal of reducing the carbon footprint of rail infrastructure operations.

Opportunities for future research:

- Investigate the long-term performance and environmental impact of recycled composite sleepers and FFU sleepers: Assessing their durability, maintenance requirements, and end-of-life disposal or recycling options.
- Efficiency Improvements in Overhead Line Equipment (OLE): Research more energy-efficient and low-carbon OLE systems, potentially incorporating advanced materials or innovative designs.

- Integration of Renewable Energy Sources research the effectiveness of solar PV systems at and their potential to contribute to the rail network's overall energy needs.

Report Title: **A carbon footprint analysis of railway sleepers in the United Kingdom**

Technical Journal/ Source: Transportation Research Part D: Transport and Environment

Researchers/Research Organization: Transportation Research Group, University of Southampton

Publication Date: 2020

Technologies Examined: Concrete Sleepers, Hardwood and Softwood Sleepers, Steel Sleepers, Under Sleeper Pads (USPs), and Incineration with Energy Recovery

Key findings:

The study presents a comprehensive analysis of the carbon life cycle of various railway sleeper materials, emphasizing their environmental impact in terms of greenhouse gas (GHG) emissions. The sleeper material is crucial as it significantly affects the overall carbon footprint of railway infrastructure, the findings for each sleeper material are as follows:

Concrete Sleepers: High-Traffic Scenarios: They excel in high-traffic conditions due to their extended service life, leading to reduced lifecycle GHG emissions and offering long-term financial benefits. Their durability makes them a practical choice for busy routes.

- Under-Sleeper Pads (USPs): The integration of USPs further enhances their lifespan and effectiveness.
- USPs often made of resilient materials like polyurethane or rubber, act as a buffer between the sleeper and ballast, reducing wear and extending the sleeper's life. This innovation could be a pivotal element in future railway infrastructure, potentially contributing to even greater environmental and economic efficiencies.
- Initial Emissions and End-of-Life Challenges: Despite these advantages, concrete sleepers have higher initial GHG emissions during manufacturing. End-of-life disposal and recycling of concrete sleepers remain a challenge that needs addressing to improve their overall environmental footprint.

Hardwood and Softwood Sleepers: Renewability and Environmental Impact: Both types are renewable resources. Hardwood sleepers perform better in high traffic conditions but have a shorter lifespan than concrete sleepers. Softwood sleepers are preferred in low traffic scenarios due to their superior environmental performance and lower GHG emissions in these conditions.

- End-of-Life Disposal Challenges: The primary environmental concern for timber sleepers is their end-of-life disposal. This phase can significantly impact their total carbon footprint, especially considering the methane emissions from landfilling.

Steel Sleepers: Steel sleepers, known for their durability, are less suitable for high-traffic conditions. They have a high carbon-intensive manufacturing process, leading to the worst GHG emission profile under increased traffic load. Their shorter service life in high-traffic scenarios necessitates more frequent replacements, further elevating their carbon footprint.

Opportunities for future research:

- Developing more sustainable end-of-life disposal and recycling methods for concrete and timber sleepers could significantly improve their environmental impact.
- Exploring the potential of innovative materials or composites for sleepers that combine the benefits of existing materials while minimizing their disadvantages.
- Further research into the long-term carbon sequestration capabilities of timber sleepers and the potential of carbon neutral USPs.

Report Title: **Life Cycle Assessment of Creosote-Treated Wooden Railroad Crossties in the US with Comparisons to Concrete and Plastic Composite Railroad Crossties**

Technical Journal/ Source: Journal of Transportation Technologies

Researchers/Research Organization: AquAeTer, Inc., Division of Sustainability

Publication Date: 2013

Technologies Examined: Life Cycle Impact Assessment (LCIA), Carbon Sequestration Accounting, Energy Recovery Analysis, and Sensitivity Analysis

Key findings:

This study provides a comprehensive life cycle analysis of railroad crossties, focusing on the carbon life cycle impact of materials and components used in creosote-treated wood, concrete, and plastic composite (P/C) crossties. The important highlights that address the carbon life cycle findings for each of the materials are as follows:

Service Life Impact on Carbon Lifecycle: The study assumes a service life of 35 years for creosote-treated crossties, 40 years for concrete ties, and 40 years for P/C ties. The extended service life of these materials impacts the total carbon footprint, as longer-lasting materials require less frequent replacement, reducing overall carbon emissions associated with manufacturing new ties.

End-of-Life Carbon Impact: The end-of-life stage of crossties plays a significant role in their overall carbon lifecycle. Creosote-treated ties that are recycled for energy recovery contribute to reducing the carbon footprint by offsetting fossil fuel use. In contrast, ties disposed of in landfills contribute to GHG emissions, particularly methane, a potent greenhouse gas.

Carbon Credits from Energy Recovery: The energy recovery from used creosote-treated ties, either through recycling or beneficial use, is credited against the total carbon footprint. This process involves using the ties as a fuel source in power plants, thereby reducing the dependency on fossil fuels.

Comparison with Alternatives: In comparison to concrete and P/C ties, creosote-treated wooden ties exhibit lower fossil fuel and water use, resulting in lesser environmental impacts including lower potential GHG emissions. The carbon footprint of concrete and P/C ties is increased due to the energy-intensive processes involved in their production and the lack of carbon sequestration benefits inherent in wooden ties.

Carbon Sequestration in Wood: The study highlights the importance of carbon sequestration in wooden ties. The growth of trees used for wooden ties naturally removes CO2 from the atmosphere, which is then stored in the wood for the duration of the tie's service life, effectively reducing the net carbon footprint.

Impact of Treatment Processes: The creosote treatment process for wooden ties, while contributing to GHG emissions during the treatment phase, extends the service life of the ties, leading to fewer replacements and, consequently, lower overall carbon emissions over the life cycle.

Opportunities for future research:

- Enhanced Creosote Treatments: Investigate improved formulations of creosote that are less environmentally damaging while retaining their preservative qualities. This could include research into bio-based or less toxic alternatives.

- Recycling and Repurposing of Wooden Crossties: Develop innovative methods to recycle and repurpose used wooden crossties, possibly in construction or other industries, to reduce waste.
- Sustainable Sourcing of Wood: Conduct research into more sustainable forestry practices for sourcing wood for crossties, ensuring minimal impact on ecosystems and biodiversity.
- Durability of Concrete Ties: Focus on enhancing the durability and longevity of concrete ties through material science innovations, potentially reducing their overall environmental impact over their lifecycle.

Report Title: Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks

Technical Journal/ Source: Environmental Impact Assessment Review

Researchers/Research Organization: Department of Transport Engineering and Infrastructure, Universitat Politècnica de València

Publication Date: 2020

Technologies Examined: ReCiPe 2008 Methodology, OpenLCA Software, Monte Carlo Simulations, Pedigree Matrix, and Service Life Analysis

Key findings:

This article focuses on evaluating the environmental impacts of different railway track substructures, particularly comparing ballasted and ballastless tracks. The study employs Life Cycle Assessment (LCA) methodology to assess these impacts over short, medium, and long-term service lives, using the ReCiPe (H) method, which is a life cycle impact assessment (LCIA) methodology used in Life Cycle Assessment (LCA) studies. It is designed to translate the emissions and resource extractions quantified in an LCA into a limited number of environmental impact scores, which represent the potential environmental harm.

Environmental Impact of Track Substructures: The study finds that ballasted tracks generally cause the lowest environmental impact for service lives of up to 75 years. Conversely, embedded track beds, a type of ballastless system, cause the highest environmental impacts, regardless of their service life.

Impact of Steel Production: A significant contributor to environmental impacts in the construction of track beds is steel production. This is particularly notable in embedded track systems, which require more steel.

Ballasted Tracks: Characterized by lower construction costs and good drainage performance but require regular maintenance.

Ballastless Tracks: Feature low maintenance costs, high availability, and longer service life but have higher construction costs and can be more challenging to repair.

Life Cycle Assessment Methodology: The study used a "cradle to grave" approach for LCA, considering raw material extraction, processing, transportation, construction activities, maintenance, and dismantlement.

Service Life Considerations: Different service lives (0, 25, 50, 75, 100 years) were analyzed. The study found that the environmental impact of ballasted tracks increases over time due to maintenance needs.

Opportunities for future research:

- Research into making ballastless track systems more environmentally friendly could be beneficial, especially given their advantages in maintenance and longevity. For example, further research on constructing ballastless systems with less steel by using composite materials.

- Research into enhancing steel recycling methods and reducing the environmental impact of steel production could significantly benefit railway infrastructure sustainability.
- Future studies could integrate LCCA to provide a more comprehensive understanding of the economic and environmental trade-offs between different track systems.
- Investigating how maintenance and renewal processes for different track systems affect environmental impacts, considering transport demand and future scenarios.

Report Title: **Life cycle assessment of rail freight transport in Belgium | Clean Technologies and Environmental Policy**

Technical Journal/ Source: Clean Technologies and Environmental Policy

Researchers/Research Organization: Chemical Engineering, PEPs Group- Products, Environment and Processes, University of Liège

Publication Date: 2020

Technologies Examined: Inventory Analysis Modeling, Electricity Supply Mix, Allocation of Shared Infrastructure, and Sub-System Analysis

Key Findings:

This article focuses on evaluating the environmental impact of rail freight transport in Belgium, with a specific emphasis on the carbon life cycle of track materials and rail infrastructure. It comprehensively analyzes the material consumption for track construction, including the substantial use of gravel, concrete, and steel in building tunnels, bridges, and tracks. The study also delves into the carbon implications of railway track components and infrastructure maintenance, highlighting the significant carbon footprint associated with material production, maintenance activities, and weed control measures.

Material Consumption for Track Construction: The use of large quantities of gravel, concrete, and steel for track bedding, tunnels, and bridges significantly contributes to carbon emissions from material extraction, processing, and transportation.

Railway Track Components: The production and use of steel for rails and concrete for sleepers involve high carbon emissions due to energy-intensive manufacturing processes.

Railway Infrastructure Maintenance: Maintenance activities, particularly those involving diesel consumption like rail grinding, lead to direct carbon emissions.

Environmental Impact of Infrastructure: The construction, maintenance, and disposal phases of railway infrastructure have a substantial carbon footprint, primarily due to the use of heavy materials and the energy required for these activities.

Weed Control in Maintenance: The use of herbicides can have indirect carbon impacts, considering the production, transportation, and application of these chemicals.

Opportunities for future research:

- Given the significant material demands in tunnel and bridge construction, future research can focus on design optimizations for reduced material use and enhanced durability.
- The article's emphasis on energy usage in railway infrastructure maintenance, such as diesel in rail grinding, highlights the potential for integrating renewable energy sources in these processes.
- The mention of herbicide use in maintenance underscores the need for research into more environmentally friendly weed management methods.

- The study’s analysis of materials in rails, sleepers, and fastening systems suggests opportunities to investigate recycling and reuse of these materials to reduce waste and emissions.

Report Title: **Potential for improving the environmental performance of railway sleepers with an outer shell made of recycled materials**

Technical Journal/ Source: Transportation Research Interdisciplinary Perspectives

Researchers/Research Organization: Politecnico di Milano, DICA (Department of Civil and Environmental Engineering)

Publication Date: 2020

Technologies Examined: Recycled Materials, RFID Technology, Vibration Dampening, Noise Reduction, and Electrical Isolation

Key Findings:

This article evaluates the Greenrail sleeper, an innovative railway sleeper with a pre-stressed reinforced concrete core and an outer shell of recycled materials. Using Life Cycle Assessment, it compares this sleeper to traditional concrete sleepers across various environmental and health impact categories. Key findings show that the Greenrail sleeper, under optimal conditions, offers significant environmental benefits, with potential reductions in impact ranging from 20% to 30% in most categories. The assessment includes the sleeper's production, installation, maintenance, and end-of-life phases.

Recycled Materials: Greenrail employs a mix of recycled plastics and elastomers to create their sleepers, reducing the demand for new raw materials.

RFID Technology: RFID tags embedded in the sleepers enable real-time tracking and monitoring of railway infrastructure, facilitating maintenance and reducing downtime.

Vibration Dampening: The sleepers are designed to absorb vibrations, leading to smoother train rides and less wear and tear on the tracks.

Noise Reduction: Greenrail sleepers minimize noise pollution, enhancing the environmental quality around railway lines.

Durability Enhancement: The use of recycled materials and innovative design increases the lifespan of these sleepers compared to traditional ones.

Electrical Isolation: Greenrail's sleepers provide improved electrical isolation, reducing the risk of electrical issues on the tracks.

Opportunities for future research:

- Research the long-term performance and durability of Greenrail's products. Assess how well they hold up under various conditions, including heavy train traffic and exposure to the elements, to ensure their effectiveness over time.
- Conduct cost-benefit analyses to determine the economic advantages of implementing Greenrail's technologies. Evaluate the upfront costs of installation versus the long-term savings in maintenance and environmental benefits.
- Investigate opportunities for optimizing the composition of Greenrail's materials. Explore alternative recycled materials or sustainable additives that can further reduce the environmental impact without compromising performance.

- Analyze the factors influencing the adoption of Greenrail's products in the rail industry. Identify barriers to entry and strategies to promote the widespread use of sustainable rail solutions.
- Ensure that Greenrail's products comply with relevant railway industry standards and regulations. Research any regulatory hurdles or requirements that need to be addressed for broader adoption.

Report Title: A Comprehensive Review on Metal Matrix Composites for Railway Applications

Technical Journal/ Source: Applied Science and Engineering Progress, Vol 15

Researchers/Research Organization: Department of Mechanical Engineering and Design, Alliance University, India

Publication Date: 2022

Technologies Examined: Powder Metallurgy, Friction Stir Processing, Ultrasonic-Assisted Casting, Spark Plasma Sintering, and Laser-assisted Additive Manufacturing

Key Points:

The article provides a thorough exploration of Metal Matrix Composites (MMCs) in the context of railway infrastructure. The focus is on how MMCs can improve the carbon life cycle of railway track materials and infrastructure. This encompasses considerations from manufacturing processes to end-of-life recycling.

Enhanced Durability and Reduced Maintenance: MMCs exhibit improved durability and require less maintenance compared to traditional materials. This contributes to a longer lifespan and a reduction in the frequency of replacements, thereby lowering the carbon footprint over the lifecycle of the railway infrastructure.

Recycling and Waste Management: The article discusses the importance of recycling and efficient waste management in the context of MMCs. The potential for recycling MMCs at the end of their lifecycle is a crucial factor in reducing overall carbon emissions.

Manufacturing Process: The production process of MMCs, including techniques like stir casting, powder metallurgy, and others, is explored. The environmental impact of these processes is considered, with an emphasis on finding more energy-efficient and lower emission manufacturing methods.

Lightweight and Energy Efficiency: The lightweight nature of MMCs leads to lower energy consumption during the operation of trains, contributing to a reduction in overall carbon emissions associated with the railway sector.

Innovative Fabrication Techniques: The research delves into various fabrication techniques for MMCs that can optimize material properties while minimizing environmental impact, such as microwave sintering and laser-assisted manufacturing.

Design for Sustainability: The paper underscores the importance of designing railway components with sustainability in mind, utilizing MMCs to create components that are not only high-performing but also have a lower environmental impact throughout their lifecycle.

Opportunities for future research:

- Extensive research is required to understand the long-term behavior of MMCs under various environmental conditions and stressors typical in railway applications.

- Researching the cost-benefit ratio of MMCs over their lifecycle, including manufacturing, maintenance, and end-of-life recycling costs, is crucial to determine their economic viability.
- Further research into optimizing the manufacturing processes of MMCs for large-scale production is needed to make them more cost-effective and environmentally friendly.
- Recycling and Reusability Studies: Investigating efficient methods for recycling MMCs at the end of their lifecycle is vital for sustainable integration into railway infrastructure.
- Understanding how MMCs perform under extreme weather conditions, high loads, and over long periods is crucial for ensuring safety and reliability.
- Research into how MMCs interact with, and can be integrated into, existing railway infrastructure without requiring extensive modifications is necessary.

Report Title: **Life Cycle Assessment of Construction and Demolition Waste from Railway Engineering Projects**

Technical Journal/ Source: Hindawi Computational Intelligence and Neuroscience Volume 2022

Researchers/Research Organization: School of Civil Engineering, Central South University, Changsha, China.

Publication Date: 2022

Technologies Examined: Process-Based LCA Model, Oracle Crystal Ball Software, Material Tracking Method, Statistical and Data Analysis Techniques

Key findings:

The article focuses on assessing the environmental impact of construction and demolition waste (CDW) in railway engineering projects. The study introduces a life cycle assessment model to estimate the volume of CDW throughout the entire lifecycle of such projects, categorizing the waste into four main sources: waste from off-site transportation, site operation wastage, discarded ballast from infrastructure, and waste from the repair and renewal of aging components. Using the Yun-Gui Railway as a case study, the model estimates that this project alone could generate between 175 to 311 million tons of CDW. The largest portion of this waste comes from discarded ballast, highlighting the need for improved waste management strategies in railway construction. The study emphasizes the importance of reducing material wastage in transportation and construction processes and suggests the need for comprehensive management of CDW in railway projects. Additionally, the article identifies specific materials like rubble, sand, and cement as major contributors to CDW, indicating areas for targeted waste reduction efforts. The research underlines the significant environmental impacts of railway projects and the necessity of enhancing CDW management for sustainable development in this sector.

Major Sources of CDW in Railway Projects: The study's breakdown of CDW sources includes specific examples like off-site transportation of construction materials (OSTCM) and site operation wastage (SOWCM). The most significant of these, discard ballast (DB) from roadbeds, bridges, and tunnels, is extensively analyzed. The sheer volume of discard ballast, often consisting of soil and gravel, is highlighted, underlining its environmental significance.

Environmental Impact and Management Strategies: The article emphasizes the need for strategically located waste disposal sites and effective landfill strategies, particularly for the management of discard ballast. It also suggests that construction practices be improved to reduce material wastage, indicating a potential for significant environmental benefits.

Material-Specific CDW Contribution: The research identifies primary CDW contributors such as rubble, sand, and cement, and quantifies their proportions (37.5%, 29.7%, and 15.9% respectively). These materials are marked as key targets for waste reduction strategies, given their substantial contribution to overall CDW.

Need for Comprehensive Management of CDW: The paper stresses the importance of enhancing CDW management, not only for environmental reasons but also for the sustainable development of railway infrastructure. It points to the continuous increase in CDW and its significant adverse environmental and socio-economic impacts.

Opportunities for future research:

- Research can focus on creating more sophisticated waste management systems, specifically tailored to handle the types of CDW identified in railway projects, such as discard ballast, and construction material wastage.
- Implementing technologies like AI (Artificial Intelligence), and blockchain for tracking the generation, movement, and disposal of CDW. This could lead to more efficient recycling and reduction strategies.
- Developing new, more sustainable construction materials or enhancing existing ones to reduce waste. Research could focus on materials that are more durable, easier to recycle, or have a lower environmental impact.
- Improving Life Cycle Assessment models to include more detailed assessments of environmental impacts, including carbon footprint, resource depletion, and biodiversity impacts. These models could be tailored specifically for large-scale infrastructure projects like railways.
- Utilizing Geographic Information Systems (GIS) and Building Information Modeling (BIM) to analyze the spatial distribution of CDW. This could help in planning waste management logistics more effectively and identifying optimal locations for recycling facilities.
- Investigating the potential for using CDW in other industries, such as using crushed concrete for road construction or using discarded ballast in landscaping.
- Regular Maintenance and Cleaning: Regularly cleaning the ballast to remove debris, organic matter, and small particles can prolong its life and reduce the need for replacement.
- Recycling and Reuse: Contaminated ballast can sometimes be treated or cleaned and then reused either within the railway system or in other construction projects. This approach minimizes waste and the need for new materials.
- Improved Construction Techniques: Utilizing modern construction techniques and materials that are more durable and less susceptible to contamination can reduce the frequency of ballast replacement.

Report Title: **Optimization of maintenance strategies for railway track-bed considering probabilistic degradation models and different reliability levels**

Technical Journal/ Source: Reliability Engineering & System Safety

Researchers/Research Organization: Department of Civil and Industrial Engineering (DICE), University of Pisa, Largo Lucio Lazzarino 1, Pisa, Italy

Publication Date: 2021

Technologies Examined: Markov Chains, Genetic Algorithms (GA), Multi-Objective Optimization, and Probabilistic Modeling

Key findings:

This study presents an innovative approach to optimize maintenance strategies for railway track-beds, focusing on balancing life cycle maintenance costs with track quality, while considering different reliability levels. Utilizing probabilistic degradation models based on Markov chains, the research effectively predicts the condition of railway tracks over time. Key geometric parameters like vertical and horizontal alignment are analyzed, acknowledging factors like ballast settlement. The application of Genetic Algorithms enables multi-objective optimization, aiming to minimize long-term maintenance costs and maximize track quality. This approach includes various reliability levels (75%, 85%, and 95%), allowing for maintenance scheduling based on the likelihood of meeting performance standards. Although the study doesn't directly measure carbon emissions, its methodology indirectly contributes to environmental sustainability in rail infrastructure management. By optimizing maintenance activities and extending the life of track materials, the study aids in reducing carbon emissions associated with material manufacturing and frequent maintenance operations, playing a crucial role in managing the carbon life cycle of railway infrastructure.

Probabilistic Degradation Models:

The degradation of vertical and lateral alignment (VA and HA) is modeled, considering factors like ballast settlement and deformation. Efficient prediction models like these can minimize unnecessary track repairs or replacements, thereby reducing the carbon emissions associated with frequent maintenance activities.

Multi-Objective Optimization Using Genetic Algorithms:

The application of Genetic Algorithms allows the study to find a balance between minimizing the life cycle maintenance costs and maximizing the track-bed quality.

This optimization takes into account the long-term costs (including environmental costs) and benefits of different maintenance strategies, which is crucial for sustainable rail infrastructure management.

Maintenance Strategy Optimization:

The research emphasizes the importance of planning maintenance activities to avoid rapid degradation of track quality. By optimizing these activities, the frequency and extent of maintenance can be reduced, leading to lower carbon emissions from machinery use and material manufacturing.

Life Cycle Assessment of Railway Infrastructure:

While the study does not directly measure carbon emissions, its approach contributes to the overall understanding of how to manage the lifecycle of rail infrastructure in an environmentally sustainable way. The optimized maintenance strategy proposed could potentially extend the life of track materials, reducing the need for new materials and the associated carbon emissions from material production and transportation.

Opportunities for future research:

- The probabilistic models used for maintenance optimization can be adapted to assess the lifecycle carbon emissions of various track materials. This would involve integrating environmental impact assessments into the decision-making process for maintenance strategy selection.
- Utilize the findings to optimize maintenance schedules not only for reliability but also for reducing carbon emissions. For instance, less frequent but more efficient maintenance activities could lead to lower overall carbon emissions by reducing machinery use and transport to and from maintenance sites.
- The probabilistic degradation models can guide the development of innovative maintenance techniques that are less carbon intensive. This could include the use of sustainable materials for track repairs or the adoption of less invasive maintenance methods.
- The models and methodologies from the article can be incorporated into broader sustainable transportation planning. This involves evaluating the carbon impact of entire railway systems, including the infrastructure and operations, and identifying areas where maintenance strategies can contribute to overall carbon reduction goals.
- Implementing IoT sensors and predictive analytics in railway infrastructure can minimize unnecessary maintenance, thereby reducing the carbon footprint. Predictive maintenance can be more environmentally friendly by targeting specific areas that need attention, reducing the waste of resources and materials.

Report Title: **Mechanical Properties of Coal Ash Particle-Reinforced Recycled Plastic-Based Composites for Sustainable Railway Sleepers**

Technical Journal/ Source: Polymers, Vol 12

Researchers/Research Organization:

Department of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology (UNIST), Korea

Publication Date: 2020

Technologies Examined: Twin-Screw Extrusion, Compression Molding, Scanning Electron Microscopy (SEM), and Mechanical Testing (tensile, compression, flexural tests)

Key Findings:

This study focuses on developing sustainable railway sleepers using municipal plastic waste and coal ash (CA). This innovative approach addresses environmental concerns by repurposing industrial by-products and waste materials, thereby contributing to the carbon lifecycle management of new track materials and infrastructure. The study demonstrates that composites made from recycled plastics and CA can meet the necessary mechanical requirements for railway sleepers. These findings are crucial in the context of reducing the carbon footprint associated with railway infrastructure materials. The research highlights the potential of using waste materials in a circular economy model, significantly impacting the environmental sustainability of railway systems. The successful application of these composites could lead to a reduction in the reliance on more carbon-intensive materials, aligning with global efforts towards sustainable and environmentally friendly transportation infrastructure.

Utilization of Waste Materials: The research emphasizes the use of municipal plastic waste and CA, a by-product of thermal power plants, in developing railway sleepers. This approach supports recycling and reduces the environmental footprint associated with waste disposal.

Sustainable Composite Development: The study successfully developed composites using recycled plastics and CA, demonstrating that these materials can meet the mechanical requirements for railway sleepers. This finding is significant in promoting sustainable materials in railway infrastructure, potentially reducing the carbon life cycle impact.

Environmental Benefits: By repurposing waste materials, the study contributes to a circular economy, which is crucial for reducing greenhouse gas emissions and the carbon footprint of railway infrastructure.

Mechanical Properties: The composites displayed suitable mechanical properties for railway sleepers, including tensile, compression, and flexural strength. This indicates the viability of these sustainable composites in real-world applications, potentially replacing more carbon-intensive materials.

SEM Analysis: The Scanning Electron Microscopy (SEM) analysis showed well-distributed fillers and smooth encapsulation in the matrix, contributing to the enhanced mechanical properties of the composites.

Opportunities for future research:

- Conducting long-term durability studies of these composites under real-world rail conditions, including exposure to weather, mechanical stresses, and potential chemical corrosion, would be valuable. This can help in understanding the long-term carbon implications of using such materials.
- Research could be directed towards optimizing the ratio of coal ash and plastic waste in the composites for maximum strength and minimum environmental impact, potentially reducing the carbon footprint further.
- Exploring efficient methods for recycling or safely disposing of these composites at the end of their lifecycle can further enhance their sustainability profile.
- Comparing the carbon lifecycle of these new composites with traditional materials like wood, steel, or concrete can highlight their environmental benefits or drawbacks, guiding future material choice decisions in railway infrastructure.
- Investigating the potential for integrating these materials in railway infrastructure that also utilizes renewable energy sources (like solar-powered tracks) could create a more holistic approach to reducing the carbon footprint of rail systems.
- Exploring the possibility of these composites acting as carbon sinks, thereby contributing to carbon sequestration, could be a novel area of research.

Report Title: Embodied greenhouse gas assessment of railway infrastructure: the case of Austria

Technical Journal/ Source: Environmental Research: Infrastructure and Sustainability, Volume 1, Number 2

Researchers/Research Organization: 1 Graz University of Technology, Rechbauerstrasse 12/II, Graz, Styria 8010, Austria

Publication Date: 2021

Technologies Examined: Track Maintenance and Construction Techniques, Reuse and Recycling Strategies, Alternative Fuels and Propulsion Systems, Energy and Emission Data Sources, Data Analysis for Predictive Maintenance

Key Findings:

The study assesses the life-cycle greenhouse gas (GHG) emissions of Austria's entire railway infrastructure, with a special focus on railway tracks. Employing a combination of methodologies, the research leverages the innovative 'standard elements' approach for a detailed analysis. This approach quantifies maintenance demands and service life (SL) of railway assets under various operational conditions by categorizing the network based on condition-affecting parameters. Through a thorough analysis of documented maintenance and renewal measures, the study identifies patterns in maintenance cycles, SLs, and the environmental impacts of different configurations and strategies. This methodology not only provides a comprehensive understanding of the degradation behavior of railway infrastructure but also assists in evaluating the environmental implications of diverse track compositions and maintenance approaches, thus facilitating a holistic assessment of the railway network's GHG emissions.

Overall GHG Emissions: Railway infrastructure causes 235,000 tonnes of CO2eq emissions per year, which is 0.3% of Austria's total emissions.

Railway Track: Accounts for 55% of the total GHG emissions in railway infrastructure.

Concrete Tunnels: Emit 16 times more GHG per kilometer per year than railway tracks but contribute only 22% of total emissions.

Comparison with Passenger Traffic Emissions: Infrastructure contributes an additional 141% of GHG emissions over emissions from passenger traffic, higher than previously anticipated.

Impact of Traffic Load and Curvature: Higher traffic loads and narrow curves significantly increase environmental impacts. The study analyzed different scenarios based on traffic density and track curvature.

Sleeper Types and Emissions: Comparison of different sleeper types (wooden, concrete, and concrete with under-sleeper pads) revealed that concrete sleepers with under-sleeper pads have the lowest environmental impact.

Economic Aspect of Emissions: For rails in a straight section with a 50-year SL and two grinding measures, GHG emissions cost €6500 per kilometer, about 5% of economic costs.

Opportunities for future research:

Investigating the potential for integrating renewable energy sources in railway infrastructure operations, such as solar-powered signals or wind energy for station operations, can further reduce the carbon footprint.

- Research into alternative materials for railway construction that have lower GHG emissions during production, use, and disposal can lead to more sustainable railway infrastructure.
- Exploring advanced maintenance technologies and strategies that reduce the frequency and intensity of maintenance activities can help in reducing the overall environmental impact.
- Development and adoption of low-emission or electric machinery for railway construction and maintenance can significantly reduce GHG emissions.
- Assessing the economic and policy implications of adopting more sustainable practices in railway infrastructure can provide insights into the feasibility and impact of such measures.
- Investigating the specific environmental impacts of HSR networks compared to conventional rail, considering factors like speed, frequency, and infrastructure requirements.
- Exploring how improvements in railway infrastructure can better integrate with other public transport systems to create a more cohesive and environmentally friendly transportation network.

Report Title: Selection and ranking of rail vehicle components for optimal lightweighting using composite materials - PJ Mistry, MS Johnson, UIK Galappaththi, 2021

Technical Journal/ Source: Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit

Researchers/Research Organization: PJ Mistry, Composites Research Group, Faculty of Engineering, University of Nottingham

Publication Date: 2021

Technologies Examined: FRP Composite Materials, Manufacturing Processes, Structural Design Techniques, Sandwich Panel Structures, Composite Rail Projects

Key Findings:

This study explores the potential of using fiber-reinforced polymer composites for lightweight construction in rail vehicles. The study, part of the ACIS UK project, developed a methodology to identify and prioritize components suitable for redesign using these composites. The focus was on enhancing rail vehicle efficiency and reliability while accommodating increased passenger capacity. The research addressed the need for lightweighting in the rail industry, considering the environmental implications and operational demands.

Methodology Development: The study introduced a three-step methodology for selecting and ranking rail vehicle components for lightweighting - Preliminary component ranking, evaluating economic potential for a composite component, and composite component evaluation.

Identification of Demonstrator Components: Five key components were identified for potential redesign with composites: cantilevered seat bracket, luggage rack module, intermediate end structure, body side structure, and roof structure. These were chosen for their potential in demonstrating the advantages of composites in terms of integration, lightweighting benefits, and commercial viability.

Mass Savings in Structural Components: The study estimated substantial mass savings with composite redesign in structural components:

- Intermediate end structures: 57% mass reduction.
- Body side structures: 47% mass reduction.
- Roof structures: 51% mass reduction.

Overall Impact on Rail Vehicles: The replacement of traditional materials with composites in these key areas was projected to significantly reduce the overall weight of rail vehicles. This reduction not only contributes to energy efficiency and lower CO_2 emissions but also reduces the impact on rail infrastructure, leading to lower maintenance and operational costs.

Opportunities for future research:

- Research into developing new or improved fiber-reinforced polymer (FRP) composites that offer enhanced environmental benefits, such as lower embodied energy or better recyclability, could significantly advance the sustainability of rail vehicles.

- Exploring more energy-efficient and less carbon-intensive manufacturing processes for composite components, which could reduce the environmental footprint of rail vehicle production.
- Developing effective strategies for the recycling or reuse of composite materials at the end of a rail vehicle's life, to minimize waste and conserve resources.
- Research comparing the environmental impacts of different material choices for rail vehicles, such as composites versus traditional materials like steel or aluminum, to guide more sustainable material selection.
- Investigating the integration of renewable energy sources in the manufacturing process of rail vehicle components to reduce greenhouse gas emissions associated with production.
- Focusing on the eco-design of rail vehicles, incorporating principles of sustainability and environmental friendliness right from the design phase.
- Studying the environmental impact of the maintenance and repair processes of composite components in rail vehicles, aiming to optimize these processes for sustainability.
- Research on the development of regulatory frameworks and standardization for the use of sustainable materials and processes in the rail industry.
- Investigating the broader environmental implications of lightweighting rail vehicles, including the impact on energy consumption, emissions during operation, and track wear.

Report Title: Embodied emissions in rail infrastructure: a critical literature review

Technical Journal/ Source: Environmental Research Letters

Researchers/Research Organization: University of Toronto

Publication Date: 2019

Technologies Examined: GHG Emission Analysis

Key Findings:

A comprehensive literature review of railroad GHS emissions was conducted by comparing 22 relevant papers with 57 case studies (hundreds more were excluded for various reasons). The literature review assessed multiple aspects of GHG emission analysis, including the scope of analysis, type of rail (Commuter, Freight, Heavy Rail Transit, High Speed Rail, Intercity, Light Rail, and Metro), location of study (North America, Europe, Asia), length of rail studied (0.3 km to 1318 km), functional units (passenger kilometer/mile travel (PKT), track kilometer traveled, overall construction length, vehicle kilometer traveled VKT, track mile traveled TMT, and others), and analysis methods (parametric, simplified, pseudo, process-based, and hybrid).

The literature review emphasized that an appropriate functional unit is important for comparisons because each functional unit can emphasize certain considerations. For example, comparing PKT of an at-grade direct route would inherently produce lower values than a PKT in mountainous territory, which requires curves and grades. The paper then proposed a functional unit of length that normalizes at-grade construction/operations.

Opportunities for future research:

- The literature review showed a lack of comprehensive railroad GHG emission studies specifically focused on North American freight or existing passenger rail. The large differences between rail mode and location puts in the question the ability for North American railroads to make strategic decisions based on the current literature. For example, many previous studies focused on new construction and decisions that would need to be made in that context (e.g. rail v. road; if rail was used, direct route with tunnels v. longer route without tunnels). This is not the most relevant for the majority of North American railroad lines. However, many of the values used in previous studies would be useful in a North American specific review.

Report Title: Carbon Footprint and environmental impact of Railway Infrastructure

Technical Journal/ Source: UIC Document

Researchers/Research Organization: Matthias Tuchschmid, IFEU, Oko-Institut

Publication Date: 2011

Technologies Examined: GHG Emission Analysis

Key Findings:

The study developed a comprehensive methodology for calculating the carbon footprint of European passenger and freight rail. This analysis included a wide range of conditions, ranging from: upstream processes (production of energy), vehicle fleet, track system, other buildings, and other modes. The analysis showed the largest carbon footprint generally came from train operations, but that could vary significantly by the electricity source. In all cases, rail passenger and freight traffic had significantly less carbon footprint than the roadway alternative.

Opportunities for future research:

- A comprehensive overview of the carbon footprint of Canadian/North American railways, since there are significant differences between European and North American rail infrastructure and operations. This can lead to strategic research decisions in the North American environment.

Calculate how practical changes in rail infrastructure, rolling stock, and operational practices could reduce the carbon footprint. This could allow for future strategic research decisions in the North American environment. Examples of areas could be manufacturing process (e.g. steel manufacturing) to renewals to end-of-life disposals.

C17. Decarbonization of rail maintenance activities

Report title: [IoT for predictive assets monitoring and maintenance: An implementation strategy for the UK rail industry]

Journal/Source: Automation in Construction, Vol 122

Researchers/Research organization: Big Data Enterprise and Artificial Intelligence Laboratory, University of West of the England, Bristol, United Kingdom

Publication date: 2020

Technologies examined: Internet of Things (IoT), Sensors and Devices, Predictive Maintenance Techniques, Remote Inspection Technologies, and Integrated Asset Data Management Platform.

Key findings:

This article presents a strategic approach centered on the implementation of Internet of Things (IoT), which is the network of physical objects or "things" embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet. This article aims to implement this technology in rail asset maintenance. This approach is particularly focused on the deployment of real-time condition monitoring, predictive maintenance, remote inspection techniques, and an integrated approach to asset data management. The development of this strategy was methodically grounded in qualitative research methodologies. This included conducting focus-group workshops with industry experts, performing thematic analysis, and employing conceptual modeling techniques. These methods collectively contributed to formulating a comprehensive and feasible IoT-based maintenance strategy, tailored to meet the current demands and challenges in the maintenance activities of the rail industry.

IoT Advantages: IoT offers real-time data collection and processing, enabling predictive maintenance that can significantly reduce maintenance costs and enhance safety.

Predictive Maintenance: Using IoT sensors and big data analytics, rail maintenance can shift from a reactive to a predictive approach, preventing breakdowns before they occur.

Data Integration: Integrating various data sources into a common data environment (CDE) is crucial. This facilitates cross-disciplinary data usage, enabling a comprehensive understanding of asset conditions.

Remote Inspection and Automation: Technologies like augmented reality and robotics, combined with IoT, can support remote inspections and potentially automate certain maintenance tasks, reducing risks for workers and improving efficiency.

Reduced Resource Use: Predictive maintenance reduces unnecessary inspections and repairs, conserving materials and energy.

Efficiency Gains: Better maintenance leads to more efficient train operations, contributing to lower fuel consumption and emissions.

Safety Improvements: Enhanced safety reduces the risk of accidents, which can have significant environmental impacts.

Opportunities for future research:

- Research into how IoT solutions can be scaled efficiently for large and complex rail networks.
- Developing standards for ensuring interoperability among different IoT devices and systems used in the rail industry.
- Investigating robust methods to secure the vast amounts of data generated and ensure privacy is maintained.
- Conducting detailed cost-benefit analyses to understand the economic implications of IoT deployment in rail infrastructure.
- Ensuring the reliability and durability of IoT sensors and devices in harsh rail environments.
- Researching advanced methods for real-time data processing and analytics to facilitate immediate decision-making.
- Studying how IoT can be seamlessly integrated with existing rail infrastructure and maintenance systems.
- Understanding the human factors, including the training needs of staff and user acceptance of new technologies.
- Assessing the environmental impact of implementing IoT in rail maintenance, including potential benefits and drawbacks.
- Examining the legal and regulatory considerations and implications of deploying IoT in public infrastructure.
- Further development and testing of predictive maintenance algorithms for higher accuracy and efficiency.
- Advancing remote inspection techniques, including the use of drones and AR, for safer and more efficient maintenance processes.
- Studying the long-term performance and maintenance needs of IoT systems in rail infrastructure.

Report title: [Sensors | Free Full-Text | Digital Twins for Managing Railway Bridge Maintenance, Resilience, and Climate Change Adaptation]

Journal/ Source: Sensors, Vol 23

Researchers/Research organization: Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham

Publication date: 2022

Technologies examined: Digital Twins (DTs), Building Information Modeling (BIM), Life Cycle Assessment (LCA), Greenhouse Gas Emissions Analysis, AutoCAD Revit Software, and Navisworks Software.

Key findings:

This study focuses on enhancing railway bridge maintenance through the integration of Digital Twins (DTs) and Building Information Modeling (BIM). Using the Minnamurra Railway Bridge in Australia as a case study, the research showcases the application of BIM for detailed life cycle analysis, enabling efficient and proactive maintenance strategies. A key element of the study is the adoption of Life Cycle Assessment (LCA) within the BIM framework, allowing for a comprehensive evaluation of the environmental impacts, particularly in terms of greenhouse gas emissions, linked to maintenance activities. The study effectively demonstrates how DTs can optimize maintenance management by providing dynamic, real-time visualization of the bridge's condition, facilitating better decision-making and resource allocation. Additionally, the incorporation of climate data into the DT model underscores the importance of adapting maintenance practices in response to changing environmental conditions, ensuring the long-term resilience and sustainability of railway infrastructure.

GHG Emissions Assessment: The study successfully integrates the estimation of GHG emissions in the BIM model, highlighting that steel, the primary material in the MRB, contributes significantly to total emissions. This insight emphasizes the need for material choices and construction practices that are more environmentally friendly.

Maintenance and Resilience Management: DTs provide a dynamic platform for visualizing and managing maintenance activities. Effective maintenance, guided by accurate and real-time data from DTs, can reduce material wastage and optimize repair and replacement schedules, contributing to lower carbon footprints.

Cost and Environmental Impact: The integration of cost and environmental data into the DT model allows for a comprehensive assessment of the economic and ecological sustainability of maintenance activities. This approach promotes more efficient resource utilization and lower GHG emissions.

Climate Change Adaptation: By incorporating climate data into the DT model, the study addresses the challenges of adapting railway infrastructure to changing environmental conditions. This is crucial for reducing the environmental impact of maintenance activities and ensuring the long-term sustainability of the railway system.

Opportunities for future research:

- Further research is needed to refine DT and BIM models for accuracy and reliability in various environmental and operational conditions. Validation studies comparing DT predictions with actual bridge maintenance outcomes would be crucial.
- Studies on the integration of real-time environmental and weather data into DT models are necessary. This would help in understanding how changing climatic conditions affect railway infrastructure and maintenance needs.
- Research on scaling these technologies for different types of railway bridges and infrastructure is needed. This includes understanding how DT and BIM can be adapted for various designs, materials, and geographical locations.
- Comprehensive research on the economic aspects, including the cost-benefit analysis of implementing DT and BIM in railway maintenance, is crucial. This would help in understanding the financial implications and potential savings.
- Further studies on the durability of materials used in railway construction under different maintenance scenarios modeled by DTs would be valuable. This includes extending the lifecycle analysis to cover longer periods.
- Research on the integration of these technologies into current maintenance workflows and their impact on the workforce is important. This includes training needs and changes in maintenance practices.
- Exploration of the necessary policy and regulatory changes required to support the implementation of advanced technologies like DT and BIM in railway infrastructure maintenance.

Report title: [Sustainability | Free Full-Text | Adapting Railway Maintenance to Climate Change]

Journal/ Source: Urban Sustainability: Safety and Maintenance in Future Transportation Infrastructure

Researchers/Research organization:

Operation and Maintenance Engineering, Luleå University of Technology, 97187 Luleå, Sweden

Publication date: 2021

Technologies examined: Qualitative Research Methodologies, Data Collection Strategies, Risk Assessment Models, Predictive Maintenance Models, Big Data Analytics, Machine Learning Algorithms, and Geographic Information System (GIS) Analyzers

Key findings:

This article focuses on the challenges and necessary actions for adapting railway maintenance to climate change. It highlights the need for increased awareness and understanding of climate impacts on railway infrastructure. The study reveals that railway infrastructure is susceptible to various climate-related events like extreme temperatures, floods, winds, lightning, and permafrost, which can significantly impact its operation, safety, and economic viability.

Awareness and Data Utilization: There is a general awareness of the impacts of climate factors on railway systems, but more work is needed to quantify these effects. While climate data sources and models are available (e.g., from the Swedish Meteorological and Hydrological Institute - SMHI), their full potential is not being tapped due to unawareness of tools, costs, and knowledge gaps.

Risk Assessment: Limited assessments have been conducted to identify specific risks and consequences related to climate change. Identified risks include rail buckling, bridge scouring, signaling system failure, and inadequate drainage capacity.

Adaptation Strategy: About 50% of organizations involved in the study have planned or implemented general adaptation strategies to climate change impacts. Suggested strategic solutions include better stormwater management, improved maintenance of drainage systems, and education and skill development.

Barriers to Implementation: The implementation of climate adaptation strategies faces several barriers, including lack of knowledge and resources, lack of coordination among organizations, and high investment costs.

Adaptation and Maintenance Debt: The concept of adaptation and maintenance debt is discussed, emphasizing the gap between current and required adaptation and maintenance activities in transport infrastructure. The study underscores the need for effective climate adaptation approaches, including awareness programs, risk mapping, vulnerability assessment, maintenance planning, and emergency response planning.

Regulatory and Technological Actions: Effective guidelines and regulations are crucial for designing and constructing railway infrastructure that considers climate change parameters.

Additionally, utilizing new monitoring technologies and systems is essential for adapting to climate changes and enhancing emergency response systems.

Opportunities for future research:

- Detailed quantitative studies to assess the direct and indirect impacts of climate change on railway infrastructure. This includes developing models to predict the severity and frequency of climate-related incidents and their effects on railway maintenance.
- Research into advanced maintenance technologies that are resilient to climate change impacts. This includes exploring new materials, methods, and tools that can withstand extreme weather conditions and reduce maintenance frequency and costs.
- Development of predictive maintenance models using big data analytics and machine learning. These models can forecast potential issues in railway infrastructure caused by climate change, allowing for proactive maintenance interventions.
- Investigating new design standards and practices for railway infrastructure that are resilient to the impacts of climate change. This research should focus on the entire lifecycle of infrastructure components under varying climate scenarios.
- Studies focused on the sustainability of maintenance operations, including the environmental impact of different maintenance strategies and the carbon footprint associated with maintenance activities.
- Research into risk management frameworks and adaptation strategies for railway maintenance in the context of climate change. This includes developing guidelines for risk assessment and decision-making processes for maintenance planning.
- Economic analysis of different maintenance strategies under climate change scenarios. This research would help in understanding the cost-effectiveness of various adaptation measures and maintenance approaches.

Report title: **Investigations of Exhaust Emissions from Rail Machinery during Track Maintenance Operations (mdpi.com)**

Journal/Source: Energies, Vol 14, MDPI

Researchers/Research Organization:

Institute of Combustion Engines and Powertrains, Poznan University of Technology, 60-965 Poznan, Poland

Publication date: 2021

Technologies examined: Portable Emissions Measurement System (PEMS), Non-dispersive infrared sensor (NDIR), On-board diagnostics (OBD) system, Diesel Oxidation Catalyst (DOC), and Diesel particulate filter (DPF)

Key findings:

This article focuses on the decarbonization of rail maintenance activities, particularly examining exhaust emissions from specialized rail vehicles used in track maintenance. The study is significant because, unlike passenger and cargo locomotives, there's limited data on emissions from these types of rail vehicles under actual operating conditions. The researchers aim to introduce Real Driving Emissions (RDE) tests into the homologation procedures for rail vehicles, as is already done for Light-Duty Vehicles (LDV) and Heavy-Duty Vehicles (HDV).

Research Context and Objective: The study investigates exhaust emissions from two specific rail maintenance vehicles in Poland, emphasizing the need for improved emission testing under real-world conditions. The vehicles tested include a track geometry vehicle and a clearance vehicle.

Testing Methodology and Equipment: Emissions of CO2, CO, HC, NOx, and PM were measured using Portable Emissions Measurement Systems (PEMS). The study provided detailed technical specifications of the vehicles and the measurement equipment used.

Results and Analysis: The results showed significant differences in emissions between the two vehicles. The track geometry vehicle, with newer engine technology (Stage IIIB), showed higher emissions of NOx and PM compared to the older clearance vehicle (Stage II). However, the overall environmental performance of the newer vehicle was better when considering emissions relative to distance covered.

Emission Standards and Compliance: The study highlighted discrepancies between real-world emissions and those measured under lab conditions, suggesting that current emission standards might not accurately represent actual operating conditions. The newer vehicle exceeded NOx and PM emission limits under real-world conditions, raising concerns about the effectiveness of current emission standards.

Annual Emission Estimates: The article also estimated annual emissions based on the operational distances of the vehicles. It noted that the highest emissions were from NOx, with the diagnostic vehicle emitting significantly more than the clearance vehicle.

Opportunities for future research:

- Expanding the scope of emissions testing to include a wider range of rail maintenance vehicles and machinery. This would provide a more comprehensive understanding of the emissions profile across different types of equipment used in rail maintenance.
- Conducting long-term studies to observe the emissions of rail maintenance vehicles over their operational lifespan. This could help in understanding how emissions change as vehicles age and how maintenance practices impact emissions.
- Investigating the feasibility and emissions impact of alternative fuels (such as biofuels, hydrogen) and propulsion systems (like battery-electric or hybrid systems) for rail maintenance vehicles.
- Researching and developing more advanced emission control technologies, such as improved diesel particulate filters and selective catalytic reduction systems, specifically tailored for rail maintenance vehicles.
- Studying how operational changes can reduce emissions, such as optimizing routes and schedules to minimize idling and running times or employing predictive maintenance to keep engines running more efficiently.
- Analyzing the impact of stricter emission standards and regulations on the rail maintenance sector. This includes studying the feasibility and impact of implementing standards similar to Euro VI (for road vehicles) for rail vehicles.
- Exploring the use of renewable energy sources in rail maintenance activities, such as solar-powered maintenance facilities or the use of wind or solar power for electric rail vehicles.
- Developing and refining real-world emissions monitoring techniques, similar to the PEMS used in the study, to continuously track and manage the emissions from rail maintenance operations.

Report title: Experimental and Theoretical Evaluation of Side Tamping Method for Ballasted Railway Track Maintenance

Journal/ Source: Transport Problems Vol 14

Researchers/Research organization:

TU Dresden, Institute of Railway Systems and Public Transport

Publication date: 2020

Technologies examined: Scale model experiments, Photogrammetric measurements, Theoretical finite element modeling (FEM), Mohr–Coulomb failure criterion, and Non-destructive testing methods.

Key findings:

The article investigates the ballast layer of railway tracks, a critical yet vulnerable component that often leads to the deterioration of track geometry. Focusing on the cost implications and efficiency of various tamping methods, the paper thoroughly examines the impact of these methods on the maintenance expenses associated with ballasted tracks. Specifically, it delves into the intensive particle breakage that occurs during corrective tamping, a significant factor in high maintenance costs. The study extensively explores side tamping technology using both theoretical and experimental approaches. It employs a scale model of the ballast layer, complemented by photogrammetric measurements, to analyze the material transport process during side tamping. Additionally, the research incorporates a theoretical finite element model (FEM), which is corroborated by the experimental findings. This comprehensive analysis reveals that side tamping could be an effective and versatile method, potentially serving as a universal solution applicable across various superstructures, thereby optimizing maintenance processes and costs.

Ballast Layer Maintenance: The ballast layer is identified as a critical component in railway tracks, prone to deterioration and causing geometry destabilization. Its maintenance is vital but often leads to high costs due to intensive particle breakage during tamping.

Evaluation of Tamping Methods: Different machine tamping methods are evaluated for their effectiveness and impact on maintenance costs. This evaluation is crucial in understanding how these methods can be optimized to reduce the frequency and intensity of maintenance activities, thereby contributing to decarbonization.

Side Tamping Technology: The study focuses on side tamping technology, exploring its potential to reduce maintenance costs and its effectiveness in the material transport process. This method is analyzed through experimental models and photogrammetric measurements.

Finite Element Model (FEM): Theoretical modeling using FEM is used to validate experimental results, providing a comprehensive understanding of the effectiveness of side tamping technology.

Decarbonization Potential: The paper suggests that optimizing tamping methods, particularly through side tamping, can significantly reduce the frequency and intensity of maintenance. This leads to less energy use and lower carbon emissions associated with maintenance activities, contributing to the broader goal of rail maintenance decarbonization.

Opportunities for future research:

- Conduct extensive field tests of side tamping technology under various real-world conditions to validate its effectiveness and durability over time.
- Assess the environmental impact of side tamping, including a comprehensive life cycle analysis to understand its full carbon footprint compared to traditional methods.
- Perform detailed cost-benefit analyses comparing side tamping with conventional tamping methods, taking into account the long-term savings in maintenance costs and reduced environmental impact.
- Research the scalability of side tamping technology for different types of railway systems, including high-speed rails, heavy freight lines, and urban tramways.
- Investigate how side tamping can be integrated with existing railway maintenance infrastructure and practices, including potential modifications to machinery and training requirements for personnel.
- Research the impact of side tamping on different types of ballast materials and track structures to understand its applicability across diverse railway systems.
- Develop and refine tamping techniques and equipment based on side tamping principles to enhance their efficiency and effectiveness.
- Study the long-term effects of side tamping on the overall lifespan of rail infrastructure, including tracks, sleepers, and ballast layers.

Report title: [Experimental and Numerical Investigation on Repairing Effect of Polymer Grouting for Settlement of High-Speed Railway Unballasted Track]

Journal/Source: Applied Sciences Vol 9

Researchers/Research organization: School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China

Publication date: 2019

Technologies examined: Polymer grouting, Laboratory material testing, Finite Element (FE) modeling (ABAQUS software), Elastic modulus testing, Stress-strain curve analysis, and multi-rigid body vehicle modeling.

Key findings:

This study investigates the use of polymer grouting to repair and lift subsided high-speed railway unballasted track structures. Laboratory tests assessed the expansion force and stress-deformation of different density polymers. A finite element model analyzed the mechanical characteristics under varying conditions. Results showed that polymer material, compared to traditional cement slurry, effectively handles dynamic train loads, demonstrating similar stress values to complete subgrade surfaces. The study highlighted the effectiveness of polymer grouting in rail maintenance, potentially reducing the carbon footprint and offering a sustainable, cost-effective solution.

Innovative Repair Method: The study explores the use of a two-component, non-aqueous reactive polymer material for lifting and repairing subsided track slabs. This method is rapid and has a broad application scope, making it suitable for high-speed rail maintenance.

Laboratory Testing and Finite Element Modeling: The expansion force characteristics and stress-deformation curves of different density polymer materials were tested in a laboratory setting. Furthermore, a three-dimensional finite element model of a high-speed railway train and ballastless-track subgrade was developed using ABAQUS to analyze the mechanical characteristics under various repair materials and conditions.

Comparison with Cement Slurry Repair: The research shows that under dynamic train loads, the stress value of polymer repair material is less than that of cement slurry. This indicates that the polymer material can effectively handle the stresses associated with high-speed train operations, similar to the complete subgrade surface.

Effects of Polymer Density and Layer Thickness: The study finds that varying the density and thickness of the polymer affects the stress variation between the polymer filling layer and complete pavement. Within a certain range, increasing the thickness of the polymer is beneficial, but beyond this range, the thickness has little effect on force variation.

Environmental and Economic Implications: Polymer grouting as a repair method aligns with the objectives of decarbonization in rail maintenance. It potentially reduces the carbon footprint by offering a more efficient, durable, and less resource-intensive solution compared to traditional methods like cement slurry. Additionally, the study suggests that excessive thickness of polymer may not be cost-effective, highlighting the importance of balancing environmental and economic factors.

Broad Applicability in Rail Maintenance: Given the success of polymer grouting in this context, the method has potential applicability in various railway maintenance scenarios, contributing to more sustainable practices in the rail industry.

Opportunities for future research:

- Research should focus on the long-term performance and durability of polymer grouting under various environmental conditions and prolonged stress from railway operations.
- Conducting extensive field tests on actual railway tracks will provide real-world data on the effectiveness and practical challenges of using polymer grouting in track maintenance.
- Comprehensive studies are needed to assess the environmental impact of polymer materials, including their life cycle, recyclability, and potential ecological risks.
- Detailed cost-benefit analyses comparing polymer grouting with traditional methods are essential to evaluate the economic viability and potential savings in maintenance costs.
- Research on the compatibility of polymer grouting with different track and subgrade materials, as well as its interaction with other railway infrastructure components, is crucial.
- Impact on Train Dynamics: Studying the influence of repaired tracks using polymer grouting on train dynamics, ride quality, and noise levels will provide insights into operational impacts.
- Continued research into advanced polymers with enhanced properties, such as increased strength, faster curing times, or reduced environmental impact, could further improve the application.

Report title: [A Critical Review of Sensors for the Continuous Monitoring of Smart and Sustainable Railway Infrastructures]

Journal/Source: Sustainability vol 12

Researchers/Research organization:

Laboratory of Construction Engineering, University of Granada

Publication date: 2020

Technologies examined: Strain Gauges, Piezoelectric Sensors, Fiber-Optic Sensors, Geophones, and Accelerometers.

Key findings:

This article reviews smart sensor technologies for continuous monitoring of railway infrastructures. It emphasizes the transition from traditional track testing to real-time monitoring using advanced sensors, enhancing preventive maintenance and optimizing infrastructure resources for sustainable railway operation. The study evaluates various sensor types (strain gauges, piezoelectric sensors, fiber-optics, geophones, and accelerometers), assessing their suitability for monitoring different railway track failure modes. It highlights their capabilities in detecting deformations, stresses, and accelerations, offering insights for tracking railway degradation. This approach contributes to predictive maintenance, reducing costs and enabling smarter, sustainable railway infrastructure.

Advancements in Sensor Technologies: The article acknowledges significant advancements in sensor technologies that enable real-time and continuous monitoring of railway infrastructure, marking a substantial evolution from traditional track testing methods.

Improvement in Preventive Maintenance: With these smart sensors, preventive maintenance of railway tracks can be significantly improved. This leads to enhanced optimization of infrastructure resources, making the railway systems smarter and more sustainable.

Assessment of Various Sensors: The study critically assesses different types of sensors for continuous monitoring, such as strain gauges, piezoelectric sensors, fiber-optic sensors, geophones, and accelerometers. Each sensor type is evaluated based on its capabilities to monitor various railway track failure modes.

Detection of Track Failures: The sensors are found capable of accurately measuring parameters like deflections, deformations, stresses, and accelerations. This ability is crucial for detecting and tracking various forms of railway track degradation.

Application in Predictive Maintenance: The application of these sensors plays a pivotal role in transitioning from corrective to predictive maintenance. This shift is significant for minimizing maintenance costs and facilitating the early detection of potential pathologies.

Case Studies and Implementations: The article presents various case studies and practical implementations of these sensor technologies. These examples illustrate how different sensors have been effectively used in real-world scenarios for railway track monitoring.

Opportunities for future research:

- One of the primary areas for future research is enhancing the economic viability of these sensor technologies. Making these sensors more cost-effective will be crucial for their widespread adoption in railway infrastructure monitoring.
- Further research is needed to assess and improve the long-term durability and reliability of these sensors in various environmental conditions and under continuous operational stress.
- Research into how these advanced sensors can be integrated with existing railway infrastructure and maintenance systems is necessary. This includes studying compatibility, communication protocols, and data integration.
- Studies to understand the scalability of sensor deployment across extensive rail networks are required. This includes evaluating the logistics, cost implications, and maintenance requirements of large-scale sensor implementations.
- With the increase in data from continuous monitoring, there is a need for advanced data analysis techniques and tools. Research in big data analytics, machine learning, and AI for predictive maintenance could provide significant insights.
- Further research into the calibration and standardization of sensors to ensure consistent and accurate readings across different types of railway infrastructure is necessary.
- Continuous improvement and innovation in sensor technology, including higher sensitivity, smaller size, and lower power consumption, would make these systems more practical and efficient.

Report title: **Smartphone’s Sensing Capabilities for On-Board Railway Track Monitoring: Structural Performance and Geometrical Degradation Assessment**

Journal/Source: Advances in Civil Engineering 2019 Ed

Researchers/Research organization:

Transportation Department, National Laboratory for Civil Engineering (LNEC), Lisbon

Publication date: 2019

Technologies examined: Smartphones, MEMS (Micro-Electro-Mechanical Systems) accelerometers, STMicroelectronics LSM330DLC inertial module, Sensor Log application, GNSS (Global Navigation Satellite System), Inertial Measuring System (IMS), Laser distance sensors, Wi-Fi and cell phone network (for data transmission), Data analytics software, and Machine learning algorithms (for advanced data analysis).

Key findings:

This article explores an innovative approach to railway track monitoring using smartphones. The study focuses on using the acceleration sensors in smartphones to assess the structural performance and geometric degradation of railway tracks. The authors conducted experiments on a Portuguese railway line, comparing smartphone data with traditional track geometry records. The research demonstrates a high correlation between the standard deviations of track longitudinal level and the vertical accelerations measured on-board a train. This approach presents a cost-effective, efficient alternative to traditional methods and could significantly contribute to maintenance planning and asset management in railways.

Innovative Monitoring Approach: The study proposes using smartphones’ sensors for continuous monitoring of railway track conditions, offering a more frequent and cost-effective alternative to traditional inspection vehicles.

Experimentation and Data Analysis: Experiments were conducted on an 11-km stretch of a Portuguese railway line. Acceleration measurements inside a passenger train were recorded using a smartphone and compared against traditional track geometry records.

High Correlation with Traditional Methods: The study found a strong correlation (cross-correlation values between 0.85 and 0.97) between the standard deviation of the track's longitudinal level and the vertical accelerations measured by the smartphone.

Identification of Critical Situations: The smartphone-based approach effectively identified locations with significant track defects, such as transitions zones, rail joints, turnouts, and other discontinuities. These areas showed higher rates of track degradation.

Contribution to Maintenance Planning: This method could enable earlier detection of track malfunctions, leading to more efficient maintenance planning and improved asset management.

Potential for Crowdsourced Monitoring: The research suggests the possibility of implementing a crowdsourced system for track monitoring, utilizing data collected from passengers’ or crew members’ smartphones.

Enhancing Railway Infrastructure Management: The approach aligns with modern asset management strategies in railways, providing a complementary tool to existing practices and contributing to the overall improvement of railway infrastructure management.

Opportunities for future research:

- Further research is needed to improve the accuracy and reliability of data collected from smartphones. This includes refining sensor calibration, data filtering techniques, and algorithms for more precise track irregularity detection.
- Developing standardized protocols and validation methods for smartphone-based measurements is crucial. This ensures consistency in data collection and interpretation across different devices and railway networks.
- Research on how smartphone-based monitoring can be integrated with existing railway infrastructure management systems is necessary. This includes compatibility with current track inspection and maintenance practices.
- Longitudinal studies are required to understand the long-term performance and durability of smartphone-based monitoring under various operational and environmental conditions.
- Implementing advanced data analytics and machine learning algorithms can enhance the interpretation of complex datasets, improving the prediction of track degradation and maintenance needs.
- Studies on the scalability of the technology for extensive railway networks, including urban and high-speed lines, are important. This also includes research on efficient deployment strategies and cost-benefit analyses.
- Addressing security and data privacy concerns is crucial, especially when considering a crowdsourced approach that involves data collection from passengers' or crew members' devices.
- Research on optimizing the hardware and software for this specific application is necessary. This includes custom-designed smartphone apps or dedicated devices with enhanced sensing capabilities.

Report title: **Improved performance of ballasted tracks under impact loading by recycled rubber mats**

Journal/Source: Transportation Geotechnics Vol 21

Researchers/Research organization: Center for Geomechanics and Railway Engineering (CGRE) and ARC Training Centre for Advanced Technologies in Rail Track Infrastructure (ITTC-Rail), University of Wollongong Australia

Publication date: 2019

Technologies examined: Rubber Energy Absorbing Drainage Sheets (READS), Large-scale drop hammer impact testing equipment, Piezoelectric accelerometer, Dynamic load cell, High-speed camera, and Data acquisition system.

Key findings:

This article focuses on enhancing the resilience of railway ballast tracks, particularly at transition zones such as bridges and road crossings, which are prone to rapid degradation due to dynamic and high-impact forces. The key solution proposed is the use of Rubber Energy Absorbing Drainage Sheets (READS), made from recycled tires. These sheets, when placed beneath the ballast layer, help in distributing the load over a wider area, attenuating the load over a longer duration, thus reducing maximum stress and energy transfer to the ballast and other substructure components. This results in reduced plastic deformation and degradation of the track substructure.

Reduced Ballast Degradation and Deformation: The inclusion of Rubber Energy Absorbing Drainage Sheets (READS) manufactured from recycled tires beneath the ballast layer significantly reduced ballast degradation and deformation at transition zones such as bridge approaches and road crossings.

Load Distribution and Attenuation: READS effectively distribute the load over a wider area and attenuate the load over a longer duration. This results in decreased maximum stress and reduces the energy transferred to the ballast and substructure components.

Impact of Subgrade Type: The study conducted tests on both soft and stiff subgrades to evaluate the load-deformation response of ballast with and without READS under various impact loads. The results indicated that READS is beneficial in both scenarios, but its effectiveness varied with subgrade stiffness.

Reduced Permanent Deformation: The laboratory tests showed that the inclusion of READS led to significantly less permanent deformation of the ballast, irrespective of the subgrade type.

Attenuation of Load Magnitude and Vibration: READS not only reduced the dynamic impact load transferred to the ballast layer but also significantly attenuated the magnitude of the load and vibrations transmitted to the underlying subgrade layers.

Sustainability and Cost-Effectiveness: The use of recycled rubber mats as READS presents an environmentally friendly and cost-effective alternative for enhancing the performance and longevity of railway tracks, especially in high-impact and high-stress areas.

Opportunities for future research:

- Conducting long-term field tests under various climatic and operational conditions to validate the laboratory results and assess the durability and performance of the READS in real-world settings.
- Investigating the performance of READS on a wider range of subgrade materials and conditions, including varying soil types, moisture content, and compaction levels.
- Examining the effectiveness of READS under different types of train loads, including passenger, freight, and high-speed trains, to ensure versatility and applicability across various railway systems.
- Investigating the scalability of producing READS from recycled materials and the challenges associated with consistent quality and supply.
- Exploring how READS can be integrated with existing railway infrastructure, including compatibility with current maintenance practices and equipment.
- Studying the impact of READS on track geometry, including alignment and stability, and their interaction with rail dynamics.
- Testing the performance of READS under extreme weather conditions, such as heavy rain, snow, and extreme temperatures, to ensure reliability in all operating environments.

Report title: State-of-the-Art Review of Ground Penetrating Radar (GPR) Applications for Railway Ballast Inspection

Journal/Source: Sensors Vol 22

Researchers/Research organization: Infrastructure Inspection Research Institute, China Academy of Railway Sciences Co., Ltd., Beijing 100081, China

Publication date: 2022

Technologies examined: Ground-Penetrating Radar (GPR), LiDAR, Drones, Machine Learning Algorithms, Signal Processing Techniques, and Data Fusion and Analysis

Key findings:

The article discusses the findings related to the application of Ground-Penetrating Radar (GPR) in rail maintenance. It presents various studies and research on GPR's effectiveness in assessing track conditions, including track geometry, ballast quality, and subgrade stiffness. The document highlights the role of moisture content in affecting rail materials. It also discusses technological advancements in GPR systems and techniques. Overall, the findings emphasize the utility of GPR as a valuable tool for non-destructive evaluation of rail infrastructure, enabling better maintenance and ensuring the safety and efficiency of railway systems.

Assessing Track Geometry: GPR has been used effectively to assess track geometry conditions. For instance, the article mentions the use of GPR to measure rail wear, gauge widening, and cross-level irregularities. This allows rail operators to identify areas needing maintenance and ensures the safe alignment of tracks.

Ballast Quality Evaluation: GPR is employed to evaluate ballast quality and discusses a study using GPR to identify ballast fouling, which helps in maintaining proper drainage and preventing deterioration of the track structure.

Subgrade Stiffness Impact: The document discusses how GPR can quantify the impact of subgrade stiffness on track quality and the development of geometry defects. This insight is crucial for understanding the relationship between subgrade conditions and track geometry.

Moisture Content Influence: Moisture content plays a significant role in rail material properties. The article mentions a study that used GPR to characterize track substructure using different frequencies. It highlights the influence of moisture content on GPR data and its importance in assessing rail conditions.

Railway Ballast Assessment: GPR is used for railway ballast condition assessment. The article continues to discuss studies that focus on using GPR to assess the condition of railway ballast, including its density and quality.

Utility of Multi-Frequency GPR: The document emphasizes the utility of multi-frequency GPR systems. For example, it discusses the use of multi-frequency GPR for quantifying ballast fouling conditions, providing a more comprehensive assessment of track conditions.

Water Content Estimation: GPR has been used to estimate soil and ballast water content. The article mentions studies that employed GPR to estimate water content in soil and ballast layers, aiding in understanding drainage and moisture-related issues.

Advancements in GPR Technology: The document highlights advancements in GPR technology and its practical applications in rail maintenance. For instance, it discusses the technology evaluation and implementation of GPR in railway maintenance.

Opportunities for future research:

- Research should focus on integrating GPR with other advanced technologies, such as LiDAR and drones, to provide a more comprehensive assessment of railway infrastructure. Combining data from multiple sources can improve the accuracy of condition assessments.
- Developing advanced data fusion and analysis techniques to process the large volumes of data generated by GPR and extract meaningful insights. This includes the development of machine learning algorithms for automated defect detection and predictive maintenance.
- Research into signal processing techniques tailored specifically for railway applications. This includes noise reduction, improved depth penetration, and the development of algorithms for distinguishing between different types of defects and materials.
- The establishment of standardized procedures and guidelines for GPR data collection, interpretation, and reporting in the railway industry. This will ensure consistency and reliability in the use of GPR for maintenance.
- Investigating real-time monitoring capabilities of GPR systems to provide instant feedback to railway operators. This can help in proactive maintenance and minimizing downtime.
- Understanding the impact of environmental factors, such as temperature, moisture, and soil composition, on GPR data accuracy and reliability. Research should focus on mitigating the influence of these factors.
- Conducting comprehensive cost-benefit analyses to assess the economic feasibility of implementing GPR-based maintenance strategies. This includes evaluating the return on investment and long-term cost savings.
- Field validation studies to verify the accuracy of GPR measurements and calibration of GPR systems for specific railway conditions. This will ensure that GPR data aligns with ground truth conditions.

Report title: [Evaluation of CO2 emissions from railway resurfacing maintenance activities - ScienceDirect]

Journal/Source: Transportation Research Part D: Transport and Environment Volume 65

Researchers/Research organization: School of Computing, Engineering and Mathematics, University of Western Sydney, Kingswood, Penrith 2751, New South Wales, Australia

Publication date: 2018

Technologies examined: Carbon footprint, Greenhouse gas emission, Railway resurfacing, Strategic maintenance, and Construction management.

Key findings:

This study is among the first to discuss the CO2 emissions of railway maintenance activity, specifically, ballasted track resurfacing. The vast field data collection for this study included travel distances, working distances, fuel consumption, and construction techniques from resurfacing equipment (diesel-engine tamping machines, ballast regulators, and ballast stabilizers). Diesel's embodied energies were used to convert fuel use to a kg CO2/m. Analysis revealed that among the resurfacing equipment, tamping machines released the most CO2, followed by ballast stabilizers and regulators, in that order.

Machinery Emissions:

Tamping machines were found to emit the most CO2, followed by ballast regulators and stabilizers. Tamping machines processed 4.25 meters of track per liter of diesel, ballast regulators 6.51 meters, and ballast stabilizers 10.61 meters. Over a 1000 km track, tamping machines emitted 628,675 kg CO2, ballast regulators 414,985 kg, and stabilizers 251,727 kg.

Comparative Study with Previous Research: The study compared its findings with previous research, noting significant differences in CO2 emission estimates. This discrepancy was attributed to the use of broad assumptions in earlier studies and the lack of detailed field data.

Parametric Study for Future CO2 Emissions: A parametric study projected future CO2 emissions from railway resurfacing. It considered different scenarios over 20, 50, and 100 years, providing essential insights for long-term planning and decarbonization strategies, the findings are as follows:

For 1,000 km of Track Annually:

- In 1 year: 1,295,387 kg CO2.
- Over 20 years: 25,907,740 kg CO2.
- Over 50 years: 64,769,350 kg CO2.

For 2,000 km of Track Annually:

- In 1 year: 2,581,500 kg CO2.
- Over 20 years: 51,630,000 kg CO2.
- Over 50 years: 129,075,000 kg CO2.

For 5,000 km of Track Annually:

- In 1 year: 6,453,750 kg CO_2.
- Over 20 years: 129,075,000 kg CO_2.
- Over 50 years: 322,687,500 kg CO_2.

Opportunities for future research:

- Investigating the use of alternative fuels (like biodiesel) or renewable energy sources (like solar or wind power) for powering resurfacing machinery. This research could explore the feasibility, cost implications, and environmental benefits of such alternatives.
- Studying the development and deployment of hybrid or fully electric resurfacing machinery. Research could focus on the efficiency, operational challenges, and long-term environmental benefits of these technologies compared to traditional diesel-powered equipment.
- Exploring new methods and technologies for railway track maintenance that are less energy intensive. This could include automated systems, advanced materials for track construction, or innovative engineering techniques that require less frequent maintenance.
- Conducting comprehensive life-cycle assessments (LCAs) of railway maintenance activities. This would involve evaluating the environmental impact of these activities from cradle to grave, including the production of machinery, operation, and end-of-life disposal or recycling.
- Researching ways to optimize the scheduling and routing of maintenance activities to minimize fuel consumption and CO_2 emissions. This could involve the use of advanced analytics, machine learning algorithms, or simulation models.

Report title: Interactive reinforcement learning innovation to reduce emissions in ralway infrastructure maintenance

Journal/Source: Development in the Built Environment

Researchers/Research organization: Jessada Sresakoolchai, Sakdirat Kaewunruen (Uni of Birmingham)

Publication date: 2023

Technologies examined: Carbon footprint, Greenhouse gas emission, Railway maintenance, Strategic maintenance, and machine learning.

Key findings:

Carbon emission is one of the primary contributors to global warming. The global community is paying great attention to this negative impact. The goal of this study is to reduce the negative impact of railway maintenance by applying reinforcement learning (RL) by optimizing maintenance activities. Railway maintenance is a complex process that may not be efficient in terms of environmental aspect. This study is the world's first to use the potential of RL to reduce carbon emission from railway maintenance. The data used to create the RL model are gathered from the field data between 2016–2019. The study section is 30 km long. Proximal Policy Optimization (PPO) is applied in the study to develop the RL model. The results demonstrate that using RL reduces carbon emission from railway maintenance by 48%, which generates a considerable amount of carbon emission reduction and reduces railway defects by 68%, which also improves maintenance efficiency significantly.

Paper also listed emissions from various track maintenance activities, including tamping, rail grinding, ballast cleaning, sleeper replacement, rail replacement, fastening replacement, and ballast unloading. This also includes the CO2 from the electricity but also the component CO2 emissions. This shows the material CO2 is significantly greater than emissions from the machines themselves.

Maintenance Activity	CO2 from Electricity	CO2 from Material	Total CO2
Tamping	3.56E-4	-	3.56E-4
Rail Grinding	2.29E-3	-	2.29E-3
Ballast Cleaning	2.67E-3	6.16E-6	2.67E-3
Sleeper Replacement	1.15E-4	8.68	8.68
Rail Replacement	1.91E-5	66.6	66.6
Fastener Replacement		36.04	36.04
Ballast Unloading	4.55E-2	-	4.55E-2

*All emissions in kg*CO2e per foot

Opportunities for future research:

- Investigating the use of alternative fuels (like biodiesel) or renewable energy sources (like solar or wind power) for powering resurfacing machinery. This research could explore the feasibility, cost implications, and environmental benefits of such alternatives.

C18. Alternative fuel and battery tender cars

Report title: Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards

Journal/Source: Federal Railroad Administration, Sandia National Laboratories

Researchers/Research organization: Brian D. Ehrhart, Leonard E. Klebanoff, Jamal A. Mohmand, Cheri Markt

Publication date: June 2021

Technologies examined: Included for info on adapting LNG (liquified natural gas) standards for hydrogen tenders. *Keywords: Hydrogen, alternative fuel, fuel cell, rail car, propulsion, rail, rolling stock, railroad.*

Key findings:

This report includes plenty of valuable information on the adoption of hydrogen fuel cells in the rail industry and the related, useful standards. It has been included in this section for the section on hydrogen fuel tenders and the adaptation of standard M-1004 from LNG to compressed hydrogen or cryogenic liquid hydrogen (LH2). There are numerous sections of M-1004, their key findings are listed below.

Inner tank:

- For compressed hydrogen the inner tank liner can be aluminum or a polymer.
- For LH2 the inner tank liner can be 316 or 304 stainless steels. Room temperature hydrogen would usually cause embrittlement with 304 stainless, but the cryogenic temperatures mitigate this. Various other materials are listed for cryogenic use.
- LNG tanks are designed for durability while compressed H2 tanks are designed for manufacturability and H2 diffusion. M-1004 needs to be revised to accommodate gaseous hydrogen technology.
- LH2 tanks can be thinner as Lh2 is much lighter than LNG. M-1004 should be revised to accommodate LH2 technology.

Impact testing temperature:

- A gap exists for impact testing at cryogenic temperatures. Further work is needed to determine if this can happen at 77K (using liquid nitrogen), extrapolating data to the 21K that liquified hydrogen would be kept at.

Jacket design:

- The suggested LNG tank jacket thickness (0.5625in) is about double common LH2 tank jackets (0.25in). This change may offer some heat transfer concerns and should be explored further.

Access to inner tank:

- M-1004 specifies physical access is needed for LNG tanks, but any physical access to LH2 tanks would cause significant icing and require evacuation of the tanks. Physical access requirements to LH2 tanks would cause significant operational issues and should be reassessed.

Pipe Jacketing for tenders:

- Pipe jacketing for cryogenic pipes should be vacuum jacketed and be able to withstand the max internal and external pressure it will be subjected to, even at emergency pressure release. Vapor seals should be used on the inner vessel, and expansion joints should support the outer jacket.

Pressure release devices (PRD):

- Given vacuums aren't used on compressed hydrogen systems, new requirements need to be written for PRD use on gaseous hydrogen tanks.
- For LH2 tanks, two PRDs must be used on each tank to allow for maintenance of one, or in the case of freezing.

Leak detection:

- For LNG, leak detection is based on lower explosion limit (LEL). For hydrogen it should be based on the lower flammability limit (LFL) as this will prevent both fires and explosions. For hydrogen the LFL is 4% by volume fuel/air mix, and 5% for methane. 25% LFL should be used as the shutoff limit for hydrogen.

Heat exchanger:

- Heat exchangers are needed to warm up the fuel for LH2 use. Currently 2 heat exchangers are used for LNG, but the required amount and power of heat exchangers for LH2 is unknown. It should be defined in hydrogen tender design.

LNG Return:

- Return lines used for returning unused LNG to the tanks are not needed for hydrogen systems as they use fuel on demand. These can be removed.

Protective housing for tank car-style tenders:

- M-1004 currently specifies that protective housing should be watertight and vented. More detail is needed on whether this needs to be passive or active (mechanical) ventilation.

Refueling:

- M-1004 currently describes a general "tender refueling station", this should be broken into Lh2 delivery trailers and fixed hydrogen facilities. Trailer setups come with unique concerns like grounding and fuel line breakaway, not present in fixed stations.

Fueling interface:

- The lower fueling temperature must be modified to accommodate the 21K that LH2 must be kept at.

Venting of car body:

- M-1004 offers no specification on how venting the car body is achieved. This is very important in H2 uses to prevent dangerous accumulation of gas. The tank car should have an open roof to the outside air that is weather/precipitation proof.

Dynamic design considerations:

- The temperature for material selection in the dynamic design considerations must be lowered to 21K.

Wire conduit and harnesses:

- M-1004 specifies that tender wiring must not come in contact with liquids. For wires on the inside of the tender, the wire conduit must be gas tight to protect from any gaseous hydrogen.

Grounding/bonding:

- The train cars are not necessarily grounded through the tracks as suggested in M-1004. The train cars and LH2 refueling trailer need to be grounded separately, to the same ground. Done properly the grounding will prevent sparking of fuel vapors caused by discharged static electricity.

Nitrogen purge assembly:

- Nitrogen is used to purge LNG systems as it will not liquefy at the temperature of LNG. Nitrogen can continue to be used for gaseous hydrogen applications, but not for Lh2, as it would liquify. The procedure for purging LH2 systems would be to use nitrogen to displace the oxygen at ambient temperatures, the use hydrogen to displace the nitrogen.

Leak detection:

- M-1004 suggest visually and audibly checking for leaks, which is insufficient for all but the largest leaks. Hand-held combustible gas detectors should be used for inspection purposes.

Opportunities for future research:

- The key findings above identify multiple gaps in the current LNG tender standards (M-1004). Future research should look explore the gaps identified for modifying M-1004 for hydrogen tenders and make changes where needed.

Report title: [Highway-Rail Grade Crossing Collision Test of a Fuel Tender]

Journal/Source: Federal Railroad Administration

Researchers/Research organization: Francisco Gonzalez, Melissa Shurland

Publication date: November 2021

Technologies examined: *Keywords: Fuel tender, alternative fuels, impact testing, finite element analysis, FEA, hazardous materials.*

Key findings:

This paper outlines a collision test of an 80,000-pound dump truck (on rail tracks) and a fuel tender at 43mph. The tender was a double-walled tank designed to carry LNG and was constructed in accordance with the Association of American Railroad (AAR) standard M-1004. The impact caused derailment of both the fuel tender and the adjacent cars, but the tender remained upright and maintained its vacuum with no LNG leaks. The locomotive fuel supply valve successfully shut off after the impact. To compare, and FEA model was developed including a deformable model of the fuel tender, dump truck, locomotives, and track infrastructure.

Opportunities for future research:

- The research team will compare the physical test results with the FEA model for validation, updating the FEA model with actual impact conditions like temperature, pressure, and speed. Further updates may be made to the model to better reflect the test outcomes.
- This test could be modified for a similar hydrogen tender car to see how a different tender design under different temperatures and pressures reacts to impact. This could be done using nitrogen in a hydrogen tender car.
- The design for this tender, and its related standard seem to have done a good job mitigating impact damage. Future research should look at how this standard and design could be adapted for alternative fuel tenders.

Report title: Safety-Centric Design in Hydrogen Tenders for Mainline Freight

Journal/Source: Federal Railroad Administration

Researchers/Research organization: CNG Motive

Publication date: May 2023

Technologies examined: Hydrogen and battery tenders.

Key findings:

This is a pdf of a PowerPoint presentation given by CNG motive on safety-centric design considerations for hydrogen tenders. There does not seem to be any supporting documents, though the presentation offers some valuable design considerations. Identifying relevant standards (M-1004 and NFPA2) and crashworthiness design cases, they list several design considerations and tradeoffs, albeit with little context.

Opportunities for future research:

- Further discussion with CNG motive on their hydrogen tender research findings could provide more context to this source.

Report title: Tank Car Fire Failure Assessment using Combined Models

Journal/Source: CanmetMATERIALS (CMAT), Transport Canada

Researchers/Research organization: Jonathan McKinley, Jis Xue, Bruce W. Williams, Su Xu

Publication date: September 2021

Technologies examined: Tank cars carrying flammable liquids, FEA of tank car material fire resistance.

Key findings:

This paper aims to assess the risk of pool fires when transporting flammable liquids via rail tank car. To gather data on the flammability of these tank cars, CMAT conducted tensile and creep-rupture tests of the two most common tank car steels. Using the data from these material tests, FEA software was used to analyze these tank cars at high temperatures. This developed into a specific model for tank car failures in pool fire conditions. Verifying it with the FEA model, a computational model was then developed to estimate time to failure in these scenarios. In 34 simulations, all lasted at least 100 minutes, with only two failing (a blocked pressure release valve, and lack of thermal protection) within the 716-minute run time.

Opportunities for future research:

- The paper notes that there is not enough data to compare the CMAT model with the Analysis of Fire Effects on Tank Cars (AFFTAC) model. As they currently produce different results, further investigation is recommended.
- A project which modifies this model to align with a hydrogen tender design based on the results of the FRA/Sandia labs report on standard M-1004 for hydrogen tenders would offer valuable information on their fire resistance.

Report title: DECARB: Battery Powered Trains: Route to Enter into Service (T1195) – Hazard Analysis Phase

Journal/Source: Rail Safety and Standards Board (RSSB)

Researchers/Research organization: Martin Brown, ARUP

Publication date: January 2021

Technologies examined:

Key findings:

The RSSB wrote this paper on hazard analysis, along with a literature review, a high-level overview of their operational concept, a route map, and a hazard record to outline their approach to enter battery powered trains into service in the UK. The hazard analysis paper is being included as it is possibly the most transferable to the North American industry, but the other papers are certainly of value. 2 workshops were held with industry technical experts to identify hazards and hazard mitigation strategies. Each hazard identified at the first workshop was given an overall risk score (likelihood+severity) and added to the hazard record (separate excel sheet). The second workshop looked at existing standards, legislation, directives, or codes of practice from the UK rail industry, or other battery industries that could be used to mitigate the identified hazards. The output of this was added to the hazard record, concluding in 60 hazards identified with relevant mitigation measures included, noting any gaps that will require further analysis.

Opportunities for future research:

- This paper is presented as a high-level analysis of the hazards and mitigation methods for battery powered train adoption. Future research should look at how these guidelines can be applied to the North American rail industry, and how they may need to be adjusted for certain routes and infrastructure.

Report title: Application and limitation of batteries and hydrogen in heavy haul rail using Australian case studies

Journal/Source: Journal of Energy Storage

Researchers/Research organization: Ruth Knibbe, Damien Harding, Emily cooper, Jonathan Burton, Sheng Liu, Zhilal Amirzadeh, Roger Buckley, Paul A. Meehan

Publication date: December 2022

Technologies examined: *Keywords: Heavy haul locomotives, Decarbonization, Energy modelling, Lithium-ion battery, Fuel Cell, Techno-economic, Hydrogen.*

Key findings:

This paper provides valuable insights into the decarbonization of heavy haul rail and suggests the use of a battery tender or a hydrogen tender. The energy required for heavy haul operations was estimated and a model was created to better understand the energy and battery sizing needs. Lithium iron phosphate (LFP), nickel manganese cobalt (NMC) and lithium titanium oxide (LTO) batteries were considered based on cost, energy density, and lifespan, with LFP batteries identified as the most suitable. The three platforms identified for decarbonization are as follows "i) a battery electric locomotive for low-energy demands, which can be coupled with either ii) a battery electric tender for medium energy demands or iii) a hydrogen fuel cell electric tender for higher energy demands." These models were concluded based of a combination of the energy model and a future-looking techno-economic analysis. 17MWh was identified as the threshold for when the hydrogen tender was more feasible than the battery electric tender.

Opportunities for future research:

- As this is an international study, it would be worth adjusting the model and analysis to North American railways to see if similar conclusions can be drawn for American infrastructure and rolling stock.

For questions or comments on this document, contact chris_pinney@aar.com

.

MxV Rail

(formerly TTCI)

350 Keeler Parkway
Pueblo, Colorado USA 81001

A subsidiary of the Association of American Railroads (AAR)

www.mxvrail.com