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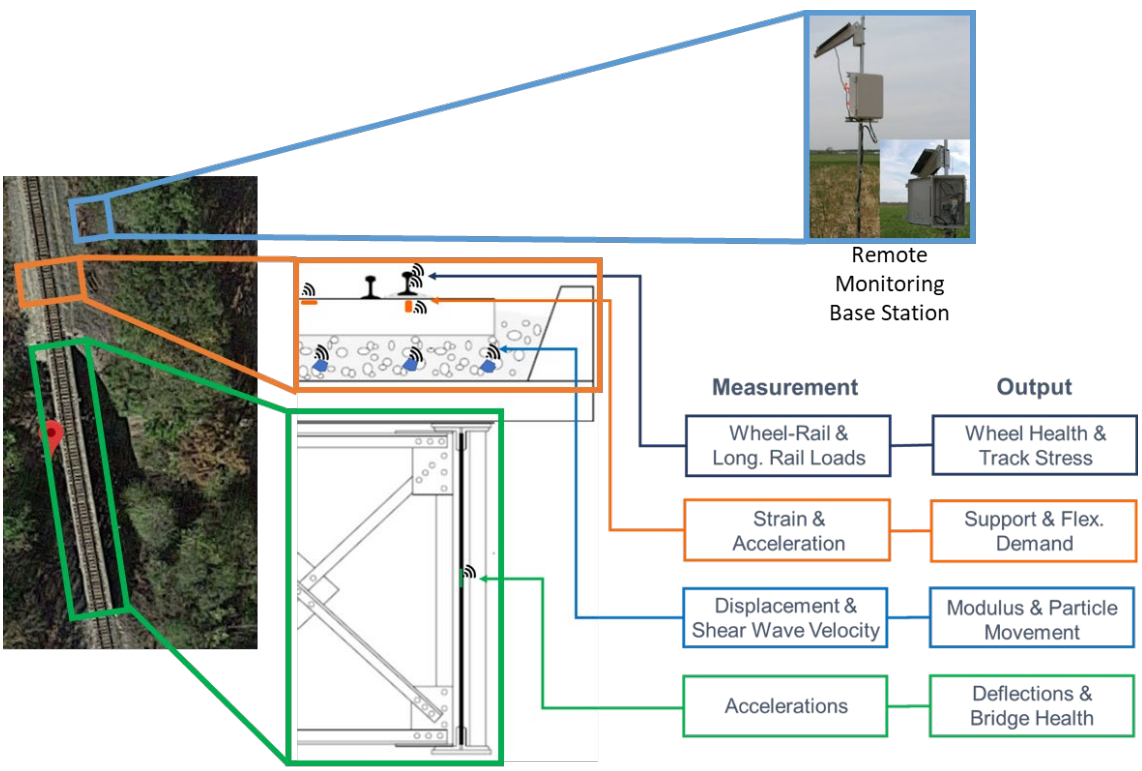
Smart Track: Wireless, Continuous Monitoring of Track Conditions



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13. ABSTRACT (Maximum 200 words)
The mission of the Smart Track research project is to improve the rail industry's ability to answer critical safety- and maintenance-related questions on track infrastructure by monitoring and predicting track health. This mission will be accomplished through the development and implementation of embedded, wireless, "smart" infrastructure technologies capable of autonomously transmitting state-of-repair exception reports. This Phase 1 effort was conducted by University of Illinois between April 2020 and April 2021. This report summarizes the development of a conceptual design for future Smart Track development and deployment. The conceptual design study included a review of FRA track-caused accident data, the development and execution of a focused industry survey to assess industry track inspection priorities and current needs, and an analysis of the type of track conditions that can be measured or detected with modern sensor technologies – and their impact on rail safety. The team also evaluated current wireless communication architectures to provide a fully wireless solution for field data acquisition. The project concluded with a SWOT analysis and the development of a gap analysis to understand any remaining laboratory developmental work before full site design and field installations.

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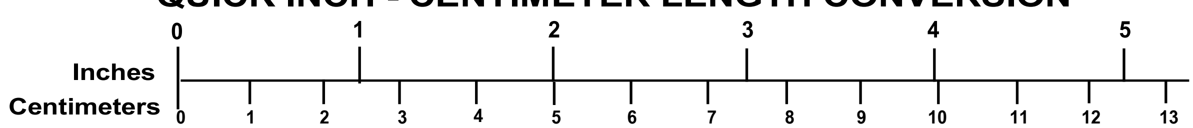

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Executive Summary

The mission of the Smart Track research project is to improve the rail industry's ability to answer critical safety- and maintenance-related questions on track infrastructure by monitoring and predicting track health. This mission will be accomplished through the development and implementation of embedded, wireless, "smart" infrastructure technologies capable of autonomously transmitting state-of-repair exception reports. The University of Illinois at Urbana-Champaign conducted this Phase 1 effort between April 2020 and April 2021.

This report summarizes the development of a conceptual design for future Smart Track development and deployment. The scope included a review of Federal Railroad Administration (FRA) track-caused accident data, an industry survey to assess track inspection priorities, and an analysis of track conditions that can be measured with modern sensor technologies. The team also evaluated current wireless communication architectures to provide a fully wireless solution for field data acquisition. The project concluded with a strengths, weaknesses, opportunities, and threats (SWOT) analysis and developed a gap analysis to understand any remaining laboratory developmental work before full site design and field installations.

The combined analysis of the FRA database and the survey responses produced a prioritized list of target areas for smart instruments and the types of information needed from these locations.

- Open Track and Curves: Lateral displacement, longitudinal loads, and deflections
- Special Trackwork: Impact loads
- Bridges and Approaches: Rail loads, deflection, vertical displacements, and impact loads
- Substructure: Fouling and deflection
- Crossties: Support condition and stresses

Wireless communications technology options are presented, as is a design architecture proposed for sensor management within the field site, between the field site and the Cloud, and between the collected data and the end users.

The SWOT identified many strengths related to the modular nature of wireless smart sensors, as well as opportunities related to filling gaps associated with other forms of automated track inspection. Many of the weaknesses or threats are institutional and can be overcome by a clear depiction of the expectations of Smart Track.

The report concludes with a refined list of target locations for Smart Track installation, measurement requirements, sensor selections, and a technical gap analysis to communicate the state of development of these systems toward the Smart Track objective. Proposed future work consists of developing and deploying a mock laboratory test setup to validate instrumentation and communication protocols required to achieve the objectives of this project, as discussed previously. Phase 2 will also involve the finalization of site design and installation with an industry partner railroad in terms of methods by which smart infrastructure components will be deployed and monitored during the start-up phase.

1. Introduction

The University of Illinois at Urbana-Champaign (Illinois) conducted this Phase 1 research project between April 2020 and April 2021.

1.1 Background

Based on recent history, wireless and embedded sensors could solve or mitigate multiple infrastructure-related safety and maintenance challenges. A review of the Federal Railroad Administration (FRA) accident database revealed that 24 percent of total derailments in 2017 were associated with track-focused cause codes. Many track-caused derailments could have been prevented by knowing the relationship between a component's stress state and the median time to failure at that stress state. This indicates that improvements in infrastructure monitoring and exception reporting are needed to supplement current track inspection technologies.

There are technological and financial limitations to achieving wide scale deployment of smart infrastructure components. On a commercial scale, Wheel Impact Load Detector (WILD) sites have proven successful at improving the wheel health of the North American interchange fleet (D.H. Stone et al., 1992; Stratman et al., 2007). While other wayside inspection systems have been successfully deployed (e.g., truck performance detectors), most focus on mechanical challenges, are wired, and are only deployed at strategic locations. Therefore, the need exists to develop wireless, smart infrastructure technologies that could be deployed collectively or individually to address safety-related challenges and reduce the number of infrastructure-related derailments.

In addition, many novel sensing technologies have been developed and deployed over the past decade to answer individual questions about various challenges, components, and layers of the track sub- and superstructure (R. Bischoff et al., 2009; Tutumluer et al., 2012; Chen et al., 2013; Mishra et al., 2014; Stark & Wilk, 2016; Sussmann et al., 2017; Jeong et al., 2019; Y. Liu et al., 2019; Spencer et al., 2021). In parallel, wireless technologies have continued to evolve and battery life has increased, partially due to reduced energy needs. There is an opportunity to couple these together for smart infrastructure technologies that could provide powerful, vertically integrated systems with multiple devices within the rail domain to autonomously communicate the track stress state.

1.2 Objectives

The objective of the Smart Track research project is to improve the rail industry's ability to answer critical safety- and maintenance- related questions related to the track infrastructure (both superstructure and substructure) by monitoring, assessing, and predicting track health. This objective will be achieved through the development and implementation of embedded, wireless, smart infrastructure technologies capable of autonomously transmitting state-of-repair exception reports. This will serve the rail industry by both increasing safety and improving infrastructure reliability. A conceptualized Smart Track site is shown in Figure 1.

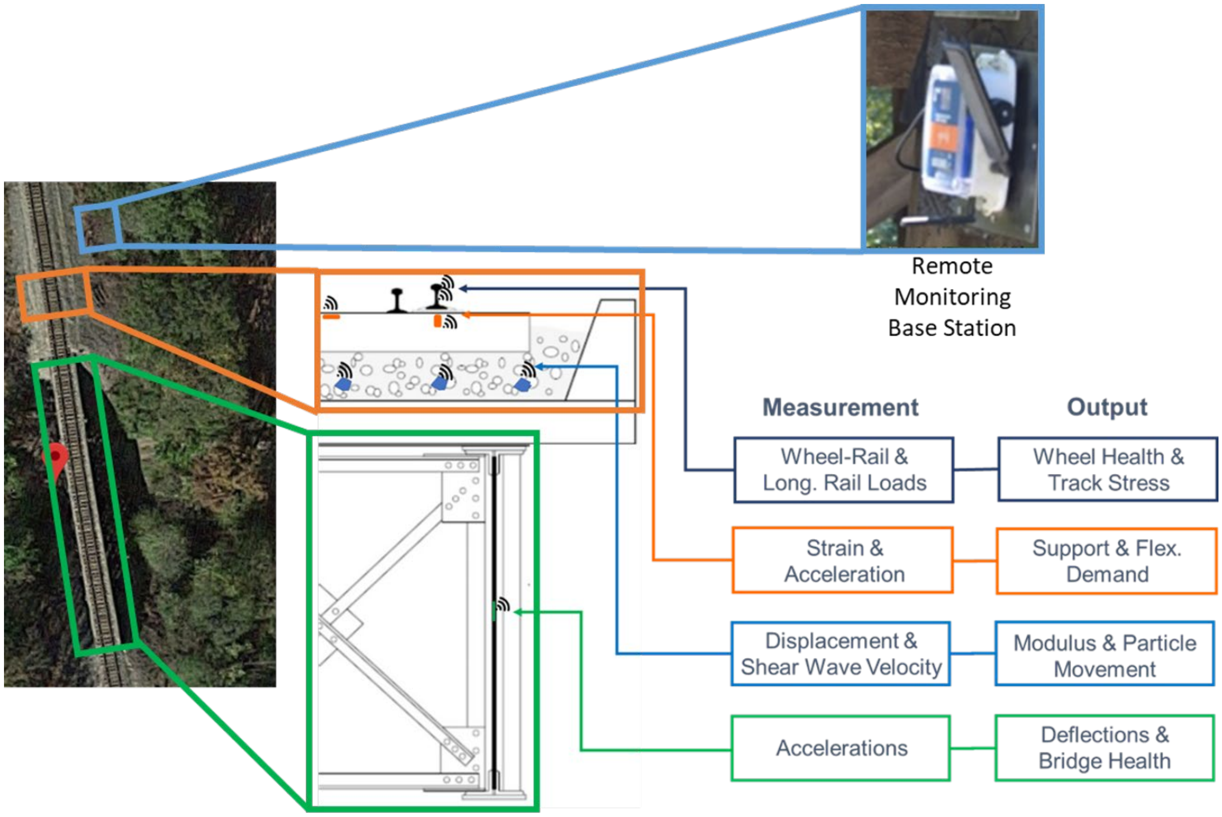

Figure 1: Possible Smart Track sensor integration and layout

Expected outcomes and impacts from the broader Smart Track research program are as follows:

- Multi-faceted outcomes for each area within the track structure given "smart" infrastructure provides actionable information at one or more of the following levels:
  - **Safety –** Identification of immediate concern(s) related to the safe operation of trains and health of the track infrastructure.
  - **Maintenance –** Provision of data to help plan track maintenance, also accompanied by a risk index or method to rank urgency.
  - **Design –** Provision of data and information that guides future design of the railway track and its components.
- Short-, medium-, and long-term effects of this project can also be quantified in terms of their impact on the safety and efficiency of the rail industry:
  - **Short-Term –** Safety exception reporting (primary project objective) and further validation of instrumentation to quantify track component deformations and stresses, increasing individual sensors TRL and improving the overall system's functionality.
  - **Medium-Term –** Improved understanding of mean time to failure for components within the track structure and advancement of wireless technology and exception reporting methods to serve the broader rail infrastructure community.
  - **Long-Term –** Use of data mining and other forms of data analytics to develop trends related to the performance of the infrastructure and its influence on safety.

- Modular system that has stand-alone "smart" infrastructure technologies that can be used in tandem or as individual devices to answer specific safety, maintenance, or design questions:
    - **Module 1: Track Superstructure Technologies –** Designed to quantify the health of the track superstructure (rail, fastening systems, crossties, and immediate crosstie support) and infer the health of the track substructure and wheelsets.
    - **Module 2: Bridge Health Module –** Designed to quantify the health of bridge components, to assess both superstructure and substructure health.
    - **Module 3: Track Substructure and Technologies –** Designed to quantify the stress state, modulus and deformation, and therefore and health of track transitions and substructure (ballast, sub-ballast, and substructure).

1.3 Overall Approach

Phase 1 of the Smart Track project focuses on the development of a conceptual design to guide future development. A conceptual design will help facilitate the development and execution of a field experimentation plan by developing and refining a list of questions to guide the technology development.

The conceptual design includes a technology readiness gate review encompassing the instrumentation hardware, communication protocols, and data collection software. Relevant data from each discrete smart infrastructure component was evaluated and a means to integrate the data collection and system communications explored. The Smart Track project team developed standardized communication protocol and data transfer methods through a common gateway to ensure successful device time synchronization.

The Smart Track project team was made up of transportation and structures faculty, staff, and students within the Rail Transportation and Engineering Center (RailTEC) at Illinois. These parties understand railroad superstructure and substructure track behavior as well as design and monitoring of smart sensors for structural health monitoring applications. Additionally, the project team included technical staff from the Illinois Department of Computer Science, with expertise in communications systems architecture.

1.4 Scope

The scope of this Phase 1 project was limited to the development of a conceptual design plan. The conceptual design plan included the following components:

- Review and analysis of FRA track-caused accident data to prioritize inspection locations.
- Web-based survey of railway industry experts to prioritize inspection locations.
- Linking of FRA accident data to industry survey responses to provide prioritized list of inspection locations and guiding questions to addressed with Smart Track instrumentation.
- Technology readiness gate review encompassing the instrumentation hardware, communication protocols, and data collection software.
- Development of standardized communication protocol and data transfer methods through a common gateway to ensure successful device time synchronization.
- SWOT analysis of the Smart Track concept and process for implementation.

Future project phases will focus on instrumentation, data collection, and exception reporting.

1.5 Organization of the Report

This report summarizes the development of a conceptual design for future Smart Track development and deployment. The scope included a review of FRA track-caused accident data, an industry survey to assess track inspection priorities, and an analysis of track conditions that can be measured with modern sensor technologies. (Section 2).

The conceptual design also included evaluation of current methods for establishing wireless communication architecture to provide a fully wireless solution for data acquisition from heterogeneous sensors at a proposed field site (Appendix C). This evaluation also included documentation of a proposed wireless communication architecture by which the track can communicate condition information and discussion of requirements for critical system elements (e.g., communication among sensors at site, connectivity with Cloud, battery life, etc.) (Section 3). The project concluded with the execution of a SWOT analysis (Section 4) and the development a gap analysis (Section 5) to understand any remaining laboratory developmental work before full site design and field installations.

2. Track Inspection Priorities for Smart Monitoring

Implementing smart monitoring technologies first requires prioritizing track inspection needs. A risk-based analysis of North American track-caused accidents was carried out using the FRA accident database. In addition, industry experts gave Illinois researchers their opinions related to track inspection priorities. The following sub-sections describe the details of both steps.

At the onset of this project, researchers developed an initial list of guiding questions based on expected locations and conditions of interest for sensing technologies (Table 1). This methodology provided initial guidance to the project and was later revised based on the results from the FRA accident database review and the industry expert survey.

Table 1: Initial list of guiding questions

Track Structure Location	Guiding Question (the Why?)	Result of Answering Question / Action	Specific Measurements	Output	Implications P=Primary Purpose A=Added Value		
					Safety	Maint.	Design
Rail	What are the impact loads imparted into the track structure and their associated risk?	Investigate rolling stock health? Add resilient track layer?	Vertical Load	Wheel Health Monitoring and Track Stresses	P	A	A
	Is there a longitudinal rail stress management problem (possibly obtain RNT risk data)?	Add anchors? Change fastening systems? De-stress rail?	Longitudinal Load		P	A	A
Crosstie and Support	Has the capacity of the concrete crosstie been compromised or exceeded? What is the stress imparted onto the ballast and does it exceed the track strength?	Replace crosstie? Tamp track?	Bending and/or Accelerations	Support and Flexural Demand		P	A
Ballast and Substructure	Has track strength been exceeded? Is there adequate vertical support, lateral stability, and resistance to settlement?	Tamp track? Ballast shoulder cleaning vs. undercutting? Future ballast design improvements?	Particle Movement	Modulus and Sub-Structure Stability	P	A	A
	Is the ballast modulus adequate for proper density & substructure support?	What should future design/maintenance thresholds be?	Shear Wave Velocity			A	P
	Has track drainage, and thus strength, been compromised?	Immediate or mid-term remediations required?	Moisture Content			P	A
Bridge Deck and Support	What is the global health estimate of the structure and assessment of its operational safety?	Does bridge require maintenance, slow order, or closure?	Mid-Span Deflections	Bridge Health	P	A	A

2.1 Analysis of FRA Track-Caused Accident Data

The publicly available FRA accident database allows anyone to assess safety-critical railroad track conditions. While the specified accident causes depend on the thoroughness and accuracy of each accident's investigation documentation, these data are provided by individual railroads and can prove useful in identifying trends. Using the FRA's database, an analysis of the track-related accidents that occurred during the last two decades was performed.

2.1.1 Data Selection – Relevant FRA Accident-Cause Codes

FRA requires reporting of all "Rail Equipment" accidents or incidents that have material damage above a given threshold ($10,700 for calendar year 2020). The research team's review of FRA accident data considered accidents from main lines and sidings only. These are the locations where Smart Track instrumentation would most likely be implemented and should generate the greatest safety and economic benefits. The data used in this analysis includes accidents reported by all railroads from 1996 to 2018. Only track-caused accidents were considered, which included the FRA accident codes listed below.

Roadbed Defects

T001 Roadbed settled or soft
T099 Other roadbed defects

Infrastructure Damage Causes

T002 Washout/rain/slide/flood/snow/ice damage to track
T401 Bridge misalignment or failure
T402 Flangeway clogged
T403 Engineering design or construction

Wide Gauge

T110 Wide gauge (due to defective or missing crossties)
T111 Wide gauge (due to defective or missing spikes or other rail fasteners)
T112 Wide gauge (due to loose, broken, or defective gage rods)
T113 Wide gauge (due to worn rails)

Track Geometry (excluding Wide Gauge)

T101 Cross level of track irregular (at joints)
T102 Cross level of track irregular (not at joints)
T103 Deviation from uniform top of rail profile
T104 Disturbed ballast section
T105 Insufficient ballast section
T106 Superelevation improper, excessive, or insufficient
T107 Superelevation runoff improper
T108 Track alignment irregular (other than buckled/sunkink)
T199 Other track geometry defects

Buckled Track

T109 Track alignment irregular (buckled/sunkink)

Rail Defects at Bolted Joints

T201 Broken Rail – Bolt hole crack or break
T211 Broken Rail – Head and web separation (within joint bar limits)

Joint Bar Defects

T213 Joint bar broken (compromise)
T214 Joint bar broken (insulated)
T215 Joint bar broken (noninsulated)
T216 Joint bolts broken or missing

Broken Rails or Welds

T202 Broken Rail – Base
T203 Broken Rail – Weld (plant)
T204 Broken Rail – Weld (field)
T207 Broken Rail – Detail fracture from shelling or head check
T208 Broken Rail – Engine burn fracture
T210 Broken Rail – Head and web separation (outside joint bar limits)
T212 Broken Rail – Horizontal split head
T218 Broken Rail – Piped rail
T219 Rail defect with joint bar repair
T220 Broken Rail – Transverse/compound fissure
T221 Broken Rail – Vertical split head

Other Rail and Joint Defects

T299 Other rail and joint bar defects

Turnout Defects – Switches

T307 Spring/power switch mechanism malfunction
T308 Stock rail worn, broken, or disconnected
T309 Switch (hand-operated) stand mechanism broken, loose, or worn
T310 Switch connecting or operating rod broken or defective
T311 Switch damaged or out of adjustment
T312 Switch lug/crank broken
T313 Switch out of adjustment because of insufficient rail anchoring
T314 Switch point worn or broken
T315 Switch rod worn, bent, broken, or disconnected
T319 Switch point gapped (between switch point and stock rail)

Turnout Defects – Frogs

T304 Railroad crossing frog worn or broken
T316 Turnout frog (rigid) worn or broken
T317 Turnout frog (self-guarded) worn or broken
T318 Turnout frog (spring) worn or broken

Misc. Track and Structure Defects

T404 Catenary system defect
T205 Defective or missing crossties

T206 Defective spikes or missing spikes or other rail fasteners
T217 Mismatched railhead contour
T222 Worn rail
T223 Rail condition – Dry rail, freshly ground rail
T301 Derail, defective
T302 Expansion joint failed or malfunctioned
T303 Guard rail loose/broken or mislocated
T305 Retarder worn, broken, or malfunctioning
T306 Retarder yard skate defective
T399 Other frog, switch, and track appliance defects
T499 Other way and structure defect

2.1.2 Risk Analysis of Track-Caused Accident Data

Three metrics were used to identify the most critical track conditions that lead to accidents: frequency, number of cars derailed, and the composite metric of the two to represent average severity. The frequency of accidents relates to their probability of occurrence while the number of cars derailed is a proxy for the severity of each accident. Consequently, the quotient of the two provides an estimate of the average severity of each accident cause, a method that has seen widespread use in other rail applications (Barkan et al., 2003; Lin et al., 2020; X. Liu et al., 2012, 2013; Wang et al., 2020). Among the top five most frequent accident causes, *wide gauge due to both defective/missing crossties* (1st) and *fasteners* (5th) combined account for 24% of all accidents in the 23-year period evaluated and represents an average of 44 accidents per year (Figure 2). Completing the list are accidents due to: *switch point wear and breakage* (2nd) with 430 accidents, an average of 19 per year, and *broken rail due to both detail fracture from shelling or head check* (3rd) and *transverse/compound fracture* (4th) combining for 481 accidents, an average of 21 accidents per year.

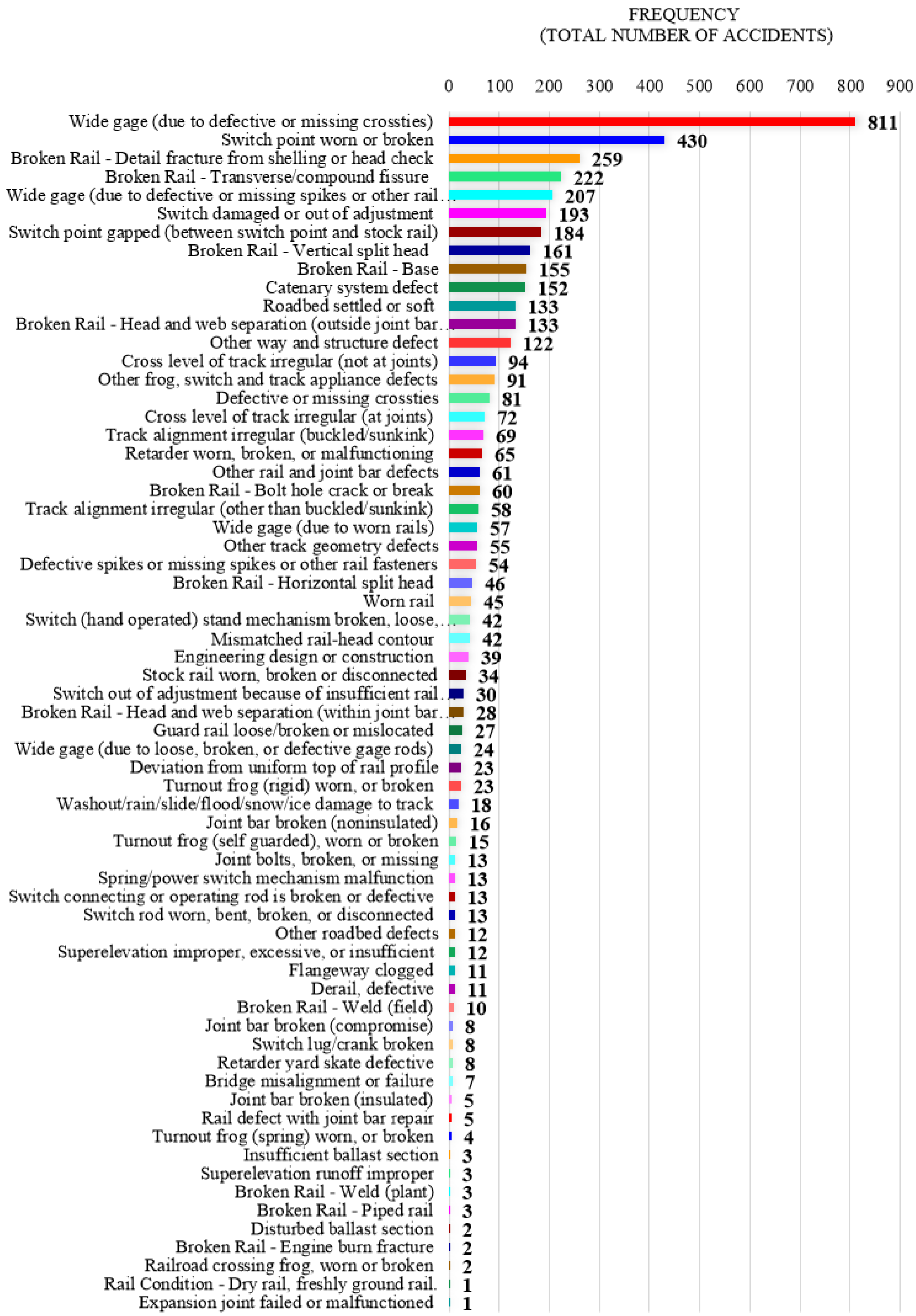

Figure 2: Frequency-based ranked track-caused FRA accident data from 1996 to 2018

When considering the types of accidents with most severe consequences, the picture is less revealing (Figure 3). The top five categories are:

1. Turnout frog (spring) worn or broken
2. Broken rail (weld)
3. Broken rail (engine burn fracture)
4. Track buckling
5. "Other" rail and joint bar defects

Except for the "other" category, it is intuitive that these accident causes could have led to severe derailments. But this level of information is insufficient for our track monitoring purposes. For example, there have only been 10 reported accidents involving *broken rail weld* and 2 reported accidents involving *broken rail due to engine burns* in the past 23 years. Although severe, the rate of occurrence is low.

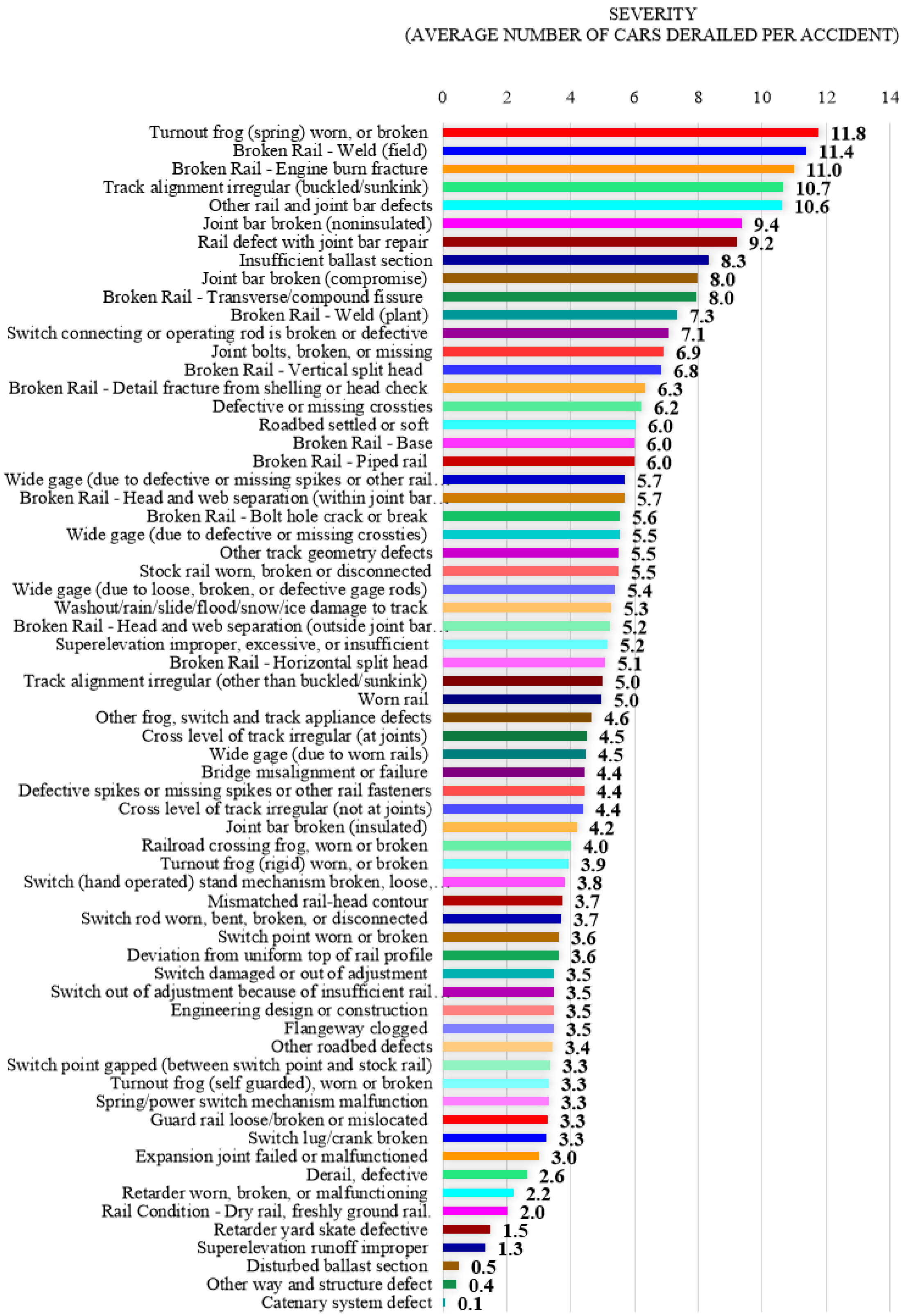

Figure 3: Severity-based ranked track-caused accident data from 1996 to 2018

A more comprehensive analysis considers both frequency and severity, as shown in Figure 4. Dashed "iso-car" lines first presented by Wang et al. (2020) represent constant risk, while frequency and severity are still displayed on the x and y axes.

Based on this risk analysis, the top five monitoring priorities should be:

1. Wide gauge due to defective or missing crossties
2. Broken rail due to transverse/compound fracture
3. Broken rail due to detail fracture or head check
4. Switch point worn or broken
5. Wide gauge due to defective or missing spikes or other fasteners

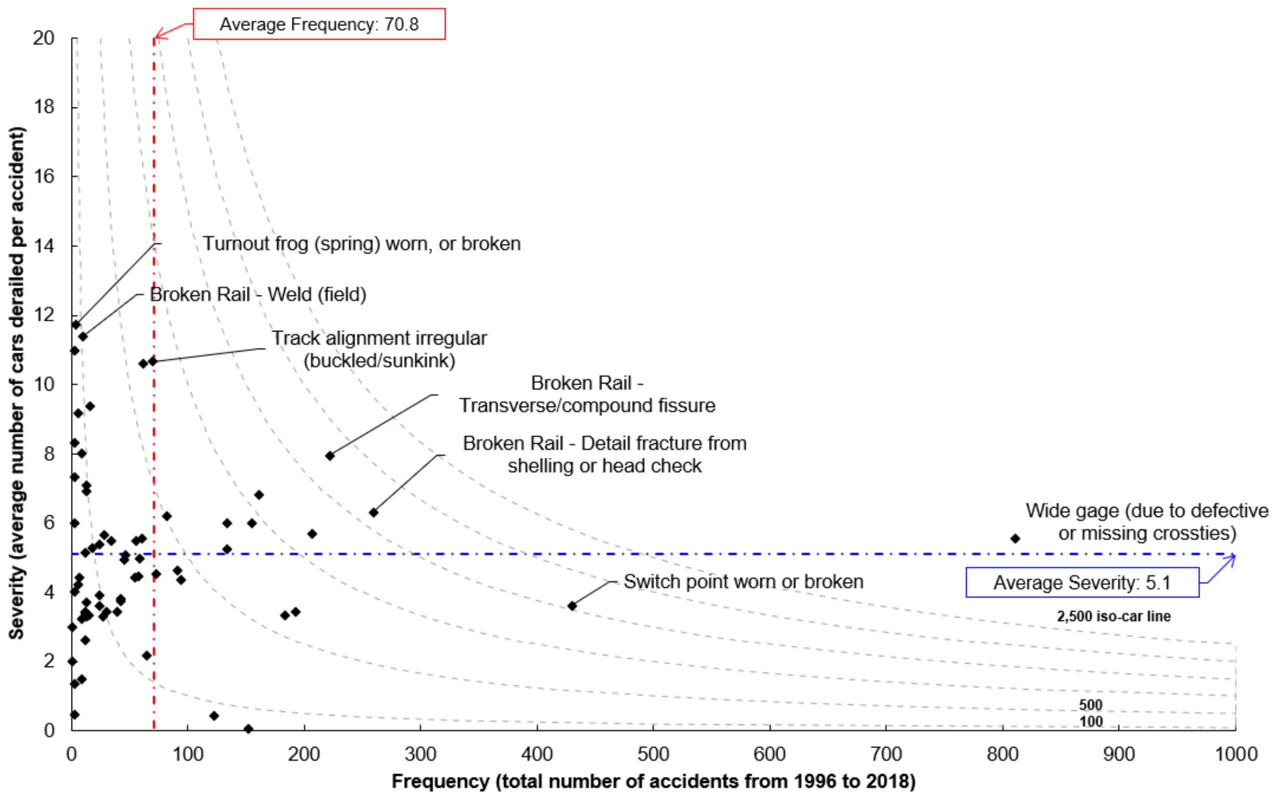

Figure 4: Frequency-severity graph for track-caused accidents between 2000 and 2019

2.2 Industry Survey on Track Inspection Priorities

The project team developed a survey to supplement its review of FRA accident data and gain insight into the rail industry's priorities. The objective of the survey was to collect information about infrastructure data of greatest relevance to railroads to help ensure infrastructure is in a state of good repair.

The survey comprised nine questions, including six multiple choice/scoring and three short-answer questions. The survey was deployed in both online and paper format, with the bulk of respondents using the online response option. The complete survey is included in Appendix A: Smart Track Industry Survey Questions.

The primary goal of the survey was to provide Smart Track project leadership with insights from key railroad industry decision makers and track health experts as to the most relevant information for active (and proactive) maintenance decision making. The survey was distributed to a wide range of rail industry professionals representing employees from Class I and regional railroads, suppliers of track infrastructure components, FRA staff, and others.

In total, researchers collected 50 individual responses from 33 unique organizations (Table 2). A summary of all the responses along with discussion of trends are presented in the subsequent sections, and comprehensive documentation of all responses is included as Appendix B: Detailed Smart Track Industry Survey Responses.

Table 2: Summary of organizations and individuals responding to Smart Track survey

Company	Responses
Amtrak	1
ASLRRA	1
BJTU	1
BNSF Railway	1
Changeis	1
Chicago Transit Authority (CTA)	1
CN	1
CN Railway	2
CSX Transportation	1
FRA	12
Genesse & Wyoming, Inc.	2
HDR	1
Holland Lp	1
Istanbul University - Cerrahpaşa	1
KCS	1
Lake State Railway Company	1
Loram MOW, Inc	1
Metro Link St. Louis	1
MoDOT Rail Safety	1
Norfolk Southern Railway	1
ProRail	1
Public Authority	1
Retired	1
Southern CA Reg. Rail Auth. (Metrolink)	2
SWJTU	1
Tampere University	1
U.S. DOT/Volpe	1
University of Illinois	1
University of New Mexico	1
US Army Corps of Engineer	2
voestalpine Nortrak	2
Vossloh Fastening Systems America	1

2.2.1 Locations of Greatest Interest for Wireless Monitoring

To develop an infrastructure monitoring plan, researchers first needed to identify locations and components of greatest interest. Given fixed and operating costs associated with remote base stations and knowing what areas were more conducive for gathering relevant and actionable information was a fundamental step in prioritizing project locations.

Respondents reviewed 13 types of candidate instrumentation locations:

- Open Track
- Bridges
- Bridges Approaches
- Mud Spots
- Insulated Joints
- Turnout – Switches
- Turnout – Frog
- Grade Crossing
- Curves
- Plug Rail (Rail Neutral Temperature (RNT) Management)
- Recently Disturbed Track
- Areas of Poor Subgrade
- Slide Fence/Slope Stability

For each possible location, respondents scored the importance of the size of the deployment (i.e., focused or mass) and the period of monitoring (i.e., short- or long-term). Scores ranged from 1 to 5, representing low and high importance, respectively. For this research, mass deployment represents instrumentation of every (or every other) component, whereas focused deployment represents instrumentation approximately once per subdivision.

To better visualize the results of this first question, a scatter plot was generated with four quadrants representing the aggregate results between deployment size and period of monitoring (Figure 5). The x-axis represents period of monitoring, ranging from short-term (i.e., negative) to long-term (i.e., positive). The y-axis represents the size of deployment, ranging from focused deployment (i.e., negative) to mass deployment (i.e., positive). For each location, the x-value was determined by subtracting the average score for short-term from the average score for long-term. Similarly, the y-value for each location was determined by subtracting the average score for focused deployment from the average score for mass deployment. This procedure generated the x-y coordinate for each location of interest.

Results presented in Figure 5 provide high-level insight into the collective opinion of respondents with respect to the size of deployment and the length of monitoring. Bridge structures and approaches, as well as slide fences, were seen to be distinct examples of long-term mass deployments. In contrast, recently disturbed track was observed as a location best suited for short-term deployments, with a slight preference toward larger scale deployments.

Figure 5: Scatter plot for importance of size and length of deployment for each location

2.2.2 Components or Structures of Greatest Interest for Wireless Monitoring

The survey contained questions to identify the relative level of interest in monitoring specific components using wireless monitoring. These questions did not specify deployment size or length. Respondents scored the importance (between 1 and 5) of 8 different component/structure alternatives:

- Rail
- Fasteners
- Crossties
- Special Trackwork
- Substructure (Ballast/Sub-ballast/Subgrade)
- Bridge Superstructure
- Bridge Substructure
- Cut/Embankment

Respondents were also given the option to select “Other” as an answer where they could use a text box to specify a component that was not listed. Details of these responses can be found in Appendix B: Detailed Smart Track Industry Survey Responses.

A summary of results for this question is presented in Figure 6. Rail, special trackwork, and bridge superstructure received the highest average scores and ranked as the top three candidates for wireless monitoring.

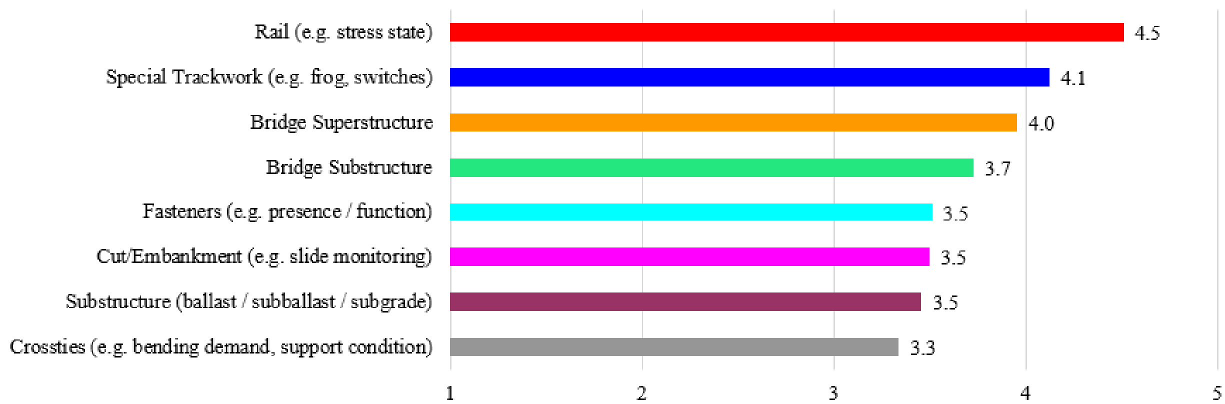

Figure 6: Scores for components of most interest for wireless monitoring

2.2.3 Safety and Maintenance-Critical Measurements (and Resulting Information)

Survey respondents were asked to score specific information related to each component or structure. The responses to this question helped in sensor selection for a given application. Specifically, respondents were asked, *"If you were able to continuously monitor the following elements of your track structure, what information would be most valuable?"* Specific measurements were requested for the five components/locations below:

- Rail
- Crosstie
- Substructure
- Special Trackwork
- Structures

To ensure the significance of the specific conclusions obtained in this section, results were analyzed holistically, by company type, and by area of expertise (structures, substructure, and track). The team determined that there was no trend specific to individual companies that was different than the overall trend observed. When evaluating responses based on areas of expertise, there were deviations noted in the results (as compared to a review of the entire dataset). A summary of the results (both overall and for each area of expertise) are presented in Figure 7.

For rail and crosstie responses, the overall results agreed with individual categories of experts. Differences were primarily observed for structures experts' responses which scored most information higher than the overall average, indicating an increased interest in instrumentation.

The overall results indicated fouling and settlement to be the most relevant information. However, substructure experts' responses pointed to moisture content and ballast particle movement as the most pertinent information in this location of the track. The trends for special trackwork responses were similar across all areas of expertise. Similar trends were observed for all structures-related responses, with vertical and lateral displacements obtaining the highest scores. These observations underscore the importance of evaluating results by area of expertise to reduce the influence of answers from individuals not as familiar with a given focus area.

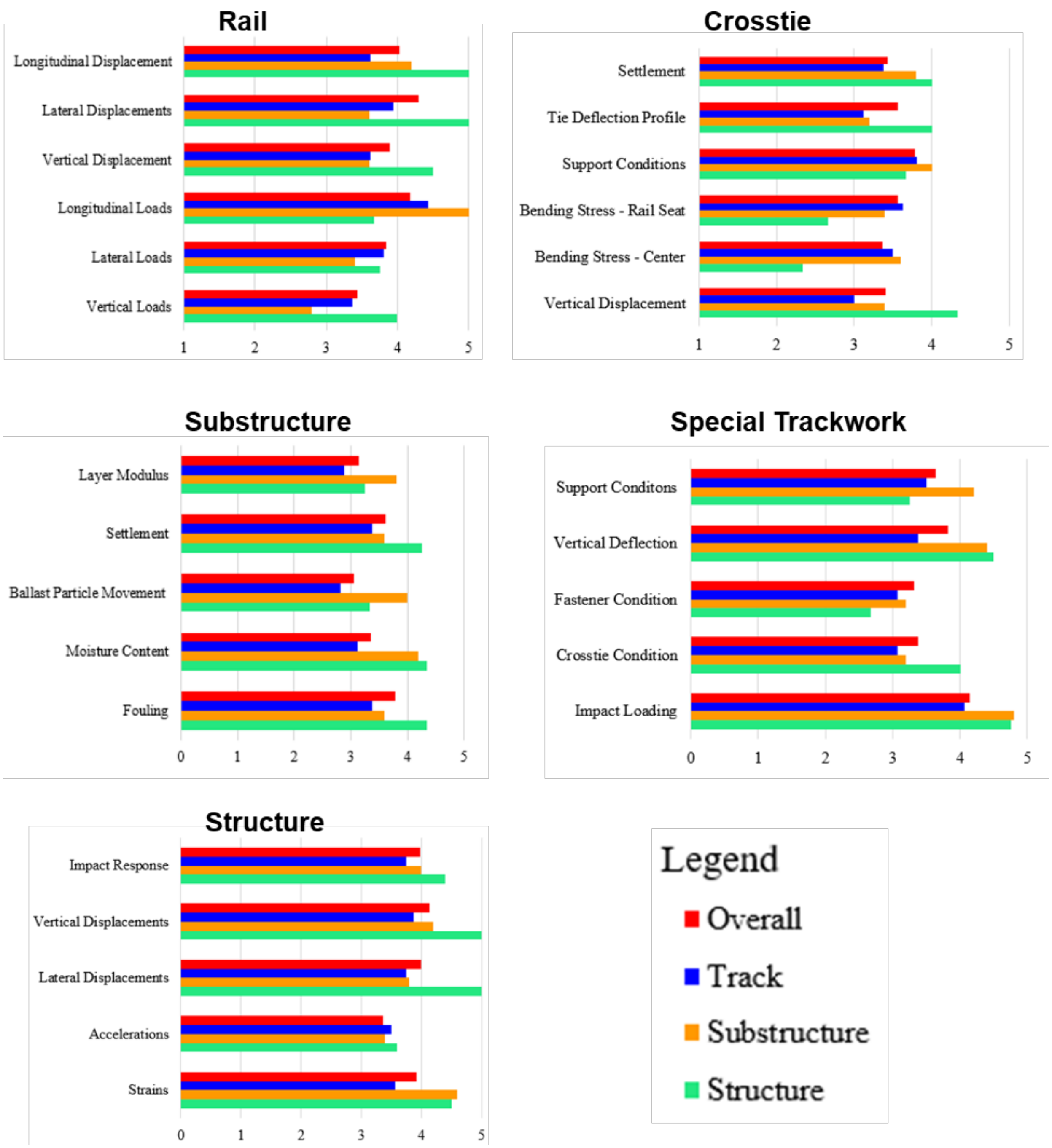

Figure 7: Most valuable information for various elements of track infrastructure with responses filtered by respondent area of expertise

To gather additional data about critical measurements that would aid in maintenance decision making, the following question was asked, *"For the following maintenance activities, what information on the health of the track structure would best guide your prioritization of the following maintenance activities?"*

A matrix of seven different maintenance activities and seven types of information were provided with multiple selections per activity allowed. The results are summarized in Figure 8 based on percentage of respondents for each information.

	Rail Relay	Rail Grinding	Crosstie Replacement	Surfacing	Undercutting Shoulder Cleaning	Bridge Superstructure Repair	Bridge Substructure Repair	Overall
Ballast Particle Movement	3%	9%	13%	49%	66%	5%	8%	**22%**
Crossties Stresses	14%	9%	85%	26%	17%	21%	13%	**27%**
Crossties Support Condition	28%	14%	85%	56%	44%	16%	21%	**38%**
Deflection	25%	14%	36%	62%	39%	84%	90%	**51%**
Fouling Moisture	6%	9%	28%	69%	95%	5%	26%	**35%**
Rail Displacements	64%	40%	33%	36%	22%	47%	41%	**40%**
Rail Loads	83%	80%	18%	10%	5%	53%	41%	**40%**
Track Modulus	19%	14%	36%	49%	44%	39%	38%	**35%**

Figure 8: Matrix of most valuable information for informing various maintenance activities

2.2.4 Necessary Deployment Size to Provide Decision Making Information

Respondents were asked, *"For the following elements of your track structure, which areas would you desire mass deployment versus focused deployment?"* Additionally, respondents could select one or both options. A preference for mass deployment was indicated for rail stress only (Figure 9, Table 3). For structures, the results indicated a mix of preferences between mass and focused deployment. For all the other locations, a focused deployment was preferred.

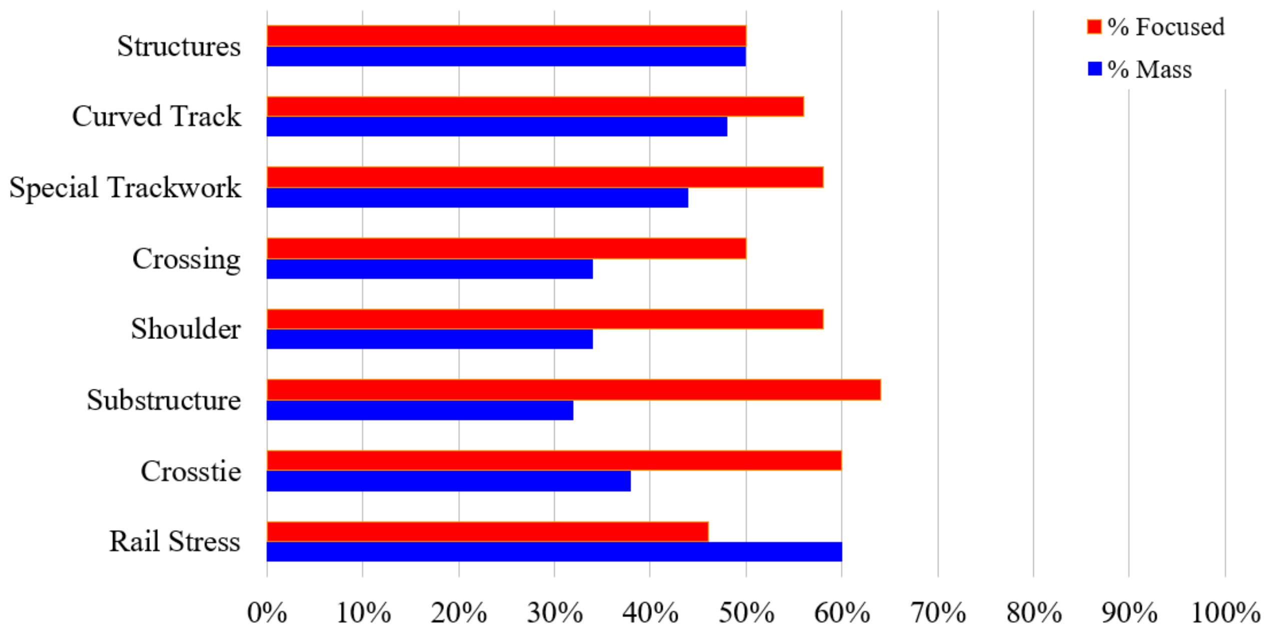

Figure 9: Size of the deployment needed for decision making

Table 3: Numerical count of responses for size of deployment needed for decision making

	Focused Deployment	Mass Deployment	Total Answers
Rail Stress	23	30	**53**
Crosstie	30	19	**49**
Substructure	32	16	**48**
Shoulder	29	17	**46**
Crossing	25	17	**42**
Special Trackwork	29	22	**51**
Curved Track	28	24	**52**
Structures	25	25	**50**

2.2.5 Survey Findings and Discussion

To avoid potential bias in the survey responses and gain additional insight, three open-ended questions were included to allow respondents to express general thoughts and other considerations they felt were valuable to the Smart Track research effort. Responses were reviewed by the research team and some general response trends extracted.

A subset of recurring topics brought up in these responses include:

- RNT and Rail Stress were important parameters for de-stressing prioritization.
- Crosstie data were commonly seen as desirable for informing subgrade work decisions.
- Ballast data were considered essential for informing undercutting and drainage improvement decisions.

Respondents identified several areas that outputs from the Smart Track project could aid end users in decision making processes. These included gaining a better understanding of track problems, securing a more concrete basis for supporting decision making, and the possibility of creating a method to rank and optimize maintenance activities. Some respondents provided words of caution and identified possible difficulties that could arise during field instrumentation. These included the complexity of covering a large railroad network, how to properly optimize sensor location, and how to ensure precision when installing sensors. Other respondents indicated they were seeking additional technology to apply to their daily activities, such as Internet of Things (IoT)-based maintenance, real-time data, and reporting software and applications that Class II and III railroads could more easily implement.

Finally, some monetary questions and concerns were raised. This survey was developed without considering instrumentation costs as a limitation, therefor economic aspects should be evaluated in subsequent project phases to ensure feasibility. As an initial step, Section 5 of this report provides initial cost estimates for proposed deployments.

A few conclusions can be drawn from the survey results:

- No significant variability in responses were observed across company type, indicating consistent opinions between practitioners, government, and technical professionals.
- When considering responses by specific areas of expertise, negligible differences were observed compared to the overall responses.
- Rail, special trackwork, and bridge superstructure were the components that respondents were most interested in monitoring.
- In terms of size of deployment, turnout switches and frogs, and plug rails were preferred choices for mass deployments – while curves and track substructure were the commonly suggested for focused deployment.
- Fouling/moisture, crosstie stresses/support, deflections, and rail loads were of greatest interest for use in maintenance decision making.

The survey provided valuable insights as to what types of measurements were desired at each location. A summary is provided below, by component:

- Bridges and Approaches: Rail loads, deflection, vertical displacements, and impact load
- Special Trackwork: Impact loads
- Rail: Lateral displacement, longitudinal loads, and displacements
- Substructure: Fouling and deflection
- Crossties: Support condition and stresses

2.3 Combined Assessment of FRA Data and Survey Responses

Using results from the review of FRA accident data and trends from the industry survey, a normalized bubble chart was created by combining the scatter plot results and locations shown in Figure 5 with the corresponding accident severity (i.e., total number of cars derailed) for each location as shown in Table 4. Thus, for the normalized bubble chart (Figure 10), the size of the bubble indicates the total number of derailed cars that could be related to that specific location, while the x and y axis coordinate positions represent length and size of deployment, respectively.

Table 4: Total number of cars derailed related to specific location

Location	Code	Description	Number of derailed cars
Open Track	T109	Track alignment irregular (buckled/sunkink)	7856
	T299	Other rail and joint bar defects	
	T205	Defective or missing crossties	
	T111	Wide gage (due to defective or missing spikes or other rail fasteners)	
	T110	Wide gage (due to defective or missing crossties)	
	T108	Track alignment irregular (other than buckled/sunkink)	
Bridges	T401	Bridge misalignment or failure	34
	T302	Expansion joint failed or malfunctioned	
Mud Spots	T001	Roadbed settled or soft	845
	T099	Other roadbed defects	
	T104	Disturbed ballast section	
Insulated Joints	T299	Other rail and joint bar defects	994
	T101	Cross level of track irregular (at joints)	
	T214	Joint bar broken (insulated)	
Turnout - Switch	T310	Switch connecting or operating rod is broken or defective	3873
	T308	Stock rail worn, broken or disconnected	
	T399	Other frog, switch and track appliance defects	
	T309	Switch (hand operated) stand mechanism broken, loose, or worn	
	T314	Switch point worn or broken	
	T311	Switch damaged or out of adjustment	
	T313	Switch out of adjustment because of insufficient rail anchoring	
	T319	Switch point gapped (between switch point and stock rail)	
	T307	Spring/power switch mechanism malfunction	
	T312	Switch lug/crank broken	
Turnout - Frog	T318	Turnout frog (spring) worn, or broken	797
	T308	Stock rail worn, broken or disconnected	
	T399	Other frog, switch and track appliance defects	
	T316	Turnout frog (rigid) worn, or broken	
	T317	Turnout frog (self guarded), worn or broken	
Curves	T111	Wide gage (due to defective or missing spikes or other rail fasteners)	5743
	T110	Wide gage (due to defective or missing crossties)	
	T106	Superelevation improper, excessive, or insufficient	
	T108	Track alignment irregular (other than buckled/sunkink)	
	T107	Superelevation runoff improper	
Plug Rail (RNT Management)	T109	Track alignment irregular (buckled/sunkink)	1384
	T299	Other rail and joint bar defects	
Recently Disturbed Track	T109	05T - Buckled Track	736
Areas of Poor Subgrade	T001	Roadbed settled or soft	845
	T099	Other roadbed defects	
	T104	Disturbed ballast section	
Slide Fence / Slope Stability	T002	Washout/rain/slide/flood/snow/ice damage to track	95

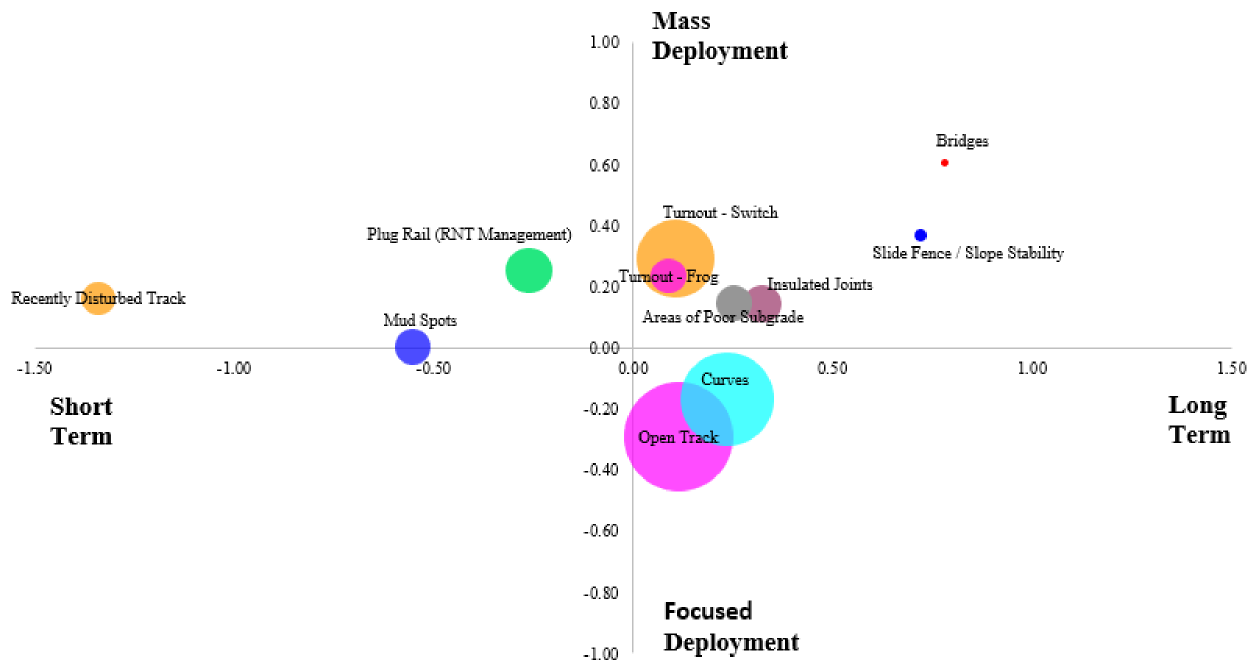

Figure 10: Normalized bubble chart combining FRA accident data and survey results

Based on the outcomes from the first two stages of the project (i.e., FRA accident database review and industry survey), some of the priorities and assumptions included in Table 1 were revised, and an updated list is presented in Table 5. Not only were questions/measurements added or removed from the previous locations, but a new track location (i.e., special trackwork) was added based on survey responses.

Conclusions regarding the best locations and measurements for deployment of smart sensor technologies were developed, which include:

- Open Track and Curves: Lateral displacement, longitudinal loads, and deflections
- Special Trackwork: Impact loads
- Bridges and Approaches: Rail loads, deflection, vertical displacements, and impact loads
- Substructure: Fouling and deflection
- Crossties: Support condition and stresses

Table 5: Updated list of guiding question based on analysis of FRA accident database and industry survey results

Track Structure Location	Guiding Question (the Why?)	Result of Answering Question / Action	Specific Measurements	Output
Rail	~~What are the impact loads imparted into the track structure and their associated risk?~~ What are the lateral displacements found in a specific location of the track and their associated risk? Is there a longitudinal rail stress management problem (possibly obtain RNT risk data)?	~~Investigate rolling stock health?~~ ~~Add resilient track layer?~~	~~Vertical Load~~	Wheel Health Monitoring and Track Stresses
		Modify track structure to increase lateral resistance? Are the crib and shoulder ballast sections reasonable?	Lateral Displacement	
		Add anchors? Change fastening systems? De-stress rail?	Longitudinal Load	
Crosstie and Support	Has the capacity of the concrete crosstie been compromised or exceeded? Has crosstie deflection been excessive? What is the stress imparted onto the ballast and does it exceed the track strength?	Replace crosstie? Tamp track?	Bending and/or Deflection	Support and Flexural Demand
Ballast and Substructure	Has track strength been exceeded? Is there adequate vertical support, lateral stability, and resistance to settlement?	Tamp track? Ballast shoulder cleaning vs. undercutting? Future ballast design improvements?	Particle Movement Layer Modulus Shear Wave Velocity Moisture Content Fouling	Modulus and Sub-Structure Stability
	Is the ballast modulus adequate for proper density & substructure support?	What should future design/maintenance thresholds be?		
	Has track drainage, and thus strength, been compromised?	Immediate or mid-term remediations required?		
Bridge Deck and Support	What is the global health estimate of the structure and assessment of its operational safety? Are eccentric loads in double track bridges causing excessive lateral displacements?	Does bridge require maintenance, slow order, or closure?	Mid-Span Deflections Impact Loads Lateral Displacements	Bridge Health
Special Trackwork	Are there excessive impact loads? Are there significant changes to the track geometry at these locations?	Replacement of switch and/or frog? Tamp track?	Impact Loading Settlement	Special Trackwork Conditions

3. Wireless Communication Architecture

This sections details Illinois' efforts to design an effective wireless communication infrastructure to support Smart Track sensor communication at field sites and to communicate field site data to end users. In parallel with the prioritization of components and locations within the track structure that are in greatest need of monitoring (Section 2), the project team undertook a survey of wireless communications technologies. This assessment was divided into two categories: 1) technologies for communication within the Smart Track field site and 2) communication between the field site and the Cloud, where the acquired data is to be stored, processed, and evaluated.

The researchers surveyed wireless communications technologies deemed most suitable for supporting future Smart Track field sites. The suitability assessment was based on the typical characteristics of the sensor technologies and the data transport requirements of the various sensor modalities proposed to be included in the field site.

Further details on the survey of wireless communications technologies can be found in Appendix C: Survey of Wireless Technologies.

3.1 Within Smart Track site

Based on a range of metrics, Bluetooth Low Energy (BLE) and IEEE 802.15.4 were identified as the most broadly suitable technologies to support communication needs within the field site. They are similar technologies designed for similar use cases, and provide an excellent balance in power-performance, and high flexibility and configurability. Their main drawback – a relatively short transmission range – can be compensated with range-extension circuitry.

Long Range Radio (LoRA) is not suitable for use in applications that require the transmission of the complete high-resolution data collected by the sensors due to its very limited bandwidth. However, given the capabilities of smart sensors to process data on-board, LoRA may have a role in deployments where only high-level aggregate data needs to be transmitted, e.g., only maximum vibration levels or significant deviations from historical norms.

WiFi covers the other side of the power-performance tradeoff compared to BLE and 802.15.4, offering meaningfully higher bandwidth at the cost of proportionally higher power consumption. WiFi may be required for certain field site deployments where data is generated at very high sampling rates and full dataset extraction is required.

3.2 Smart Track Field Site-to-Cloud

While many communications solutions can be employed to connect the field site to the Cloud, cellular stands out as the most broadly applicable, cheapest, and best-supported by third-party communications service providers. Alternate technologies would generally be considered only when cellular coverage is inadequate.

With 3G technologies nearing phase-out and their 5G counterparts still in its early adoption stage, 4G LTE is overwhelmingly the most appropriate option at the time of the development of this report and for the near future. Inexpensive, low-power cellular modems are readily available that can be added to embedded devices to provide 4G LTE connectivity in a modular fashion, requiring only a modest development effort for most wireless smart sensor (WSS) platforms. Bandwidth provided by a 4G LTE modem should be sufficient, since local communication technologies within the field site would act as the bottleneck, limiting the total data exfiltration rate, rather than the cellular connection.

In remote areas with poor cellular coverage, satellite connectivity is generally the next-best option. New satellite constellations are currently being deployed that offer the promise of ubiquitous and inexpensive network access. The Smart Track field site can take advantage of this emerging technology to replace cellular connectivity. However, at the time of this report, this option is inferior to 4G LTE by both cost and bandwidth metrics.

Another notable alternative, the mobile base station, provides an attractive option for certain types of monitoring deployments. While not suitable for near-real-time emergency notifications (due to the significant data collection latency) or full raw sensor data transmission (due to the short upload window), it does not require or depend on any third-party connectivity service, such as cellular, satellite, or wired internet, allowing the railroad to maintain all monitoring data within its private network. This option also lowers costs to end users by not requiring ongoing charges for connectivity or data usage.

3.3 Proposed Architecture

Providing end-to-end wireless connectivity for a Smart Track monitoring field site encompassing numerous and diverse sensors is nontrivial. Due to the breadth of sensor modalities that can be included in a potential deployment and their significant variability in the data transport requirements, no single wireless technology is expected to cover the full range of functionality required for interconnecting these sensors. The limited power availability (e.g., rechargeable batteries, solar panels) and the resulting need to use energy-efficient communication methods, which typically feature lower bandwidth, places additional constraints on the selection of optimal communication technologies in this setting.

This section lays out a proposed communications architecture for a wireless Smart Track field site. The design is informed by the survey of wireless communications technologies, their key parameters, and relative strengths and weaknesses as detailed in Appendix C: Survey of Wireless Technologies. Additionally, the design choices are guided by the previously identified list of questions that the monitoring system is expected to answer (Table 5), while meeting the specific requirements of sensors capable of providing such information. The method to estimate the aggregate expected bandwidth usage for the field site's suite of monitoring instrumentation is also presented, based on the number and type of monitoring devices included within a particular deployment.

3.3.1 Survey of Instrumentation Requirements

Before making specific recommendations, the project team first assessed the different types of sensors available to monitor track, substructure, and bridge structures.

Based on the conducted survey of the railroad industry and prior track and structure monitoring experience, the team identified the following metrics of interest for each infrastructure component:

- *Rail:* Lateral displacement, longitudinal load
- *Crosstie and support:* Bending, deflection

- *Ballast and substructure:* Particle movement, layer modulus, shear wave velocity, moisture content, fouling
- *Bridge deck and support:* Mid-span deflection, impact loads, lateral displacement
- *Special trackwork:* Impact loading, settlement

Collecting such a diverse set of measurements requires making use of several distinct sensor types. Sensors include different forms of accelerometers and strain gauges as well as more specialized sensor devices. These include:

- *Concrete strain gauges.* For concrete crosstie bending moment instrumentation, typically between one and three sensors are installed per instrumented crosstie, with sampling rates up to 1 kHz.
- *Rail-mounted strain gauges.* For rail longitudinal load instrumentation, up to six sensors can be expected to be installed per field site, with sampling rates up to 2 kHz.
- *Accelerometers (crosstie).* For impact monitoring instrumentation, a small number of high precision accelerometers are used, with sampling rates up to 2 kHz.
- *Potentiometers.* For direct measurement of displacements, a small number of potentiometers can be installed, with sampling rates up to 500 Hz.
- *Smart Rocks.* For measuring several ballast properties, wireless Smart Rock sensors can be embedded throughout the ballast layer, sampling at up to 500 Hz.
- *Bender elements.* For shear wave measurement instrumentation, 6-12 bender elements are embedded in the ballast and subballast layers, with sampling rates ranging up to 80 kHz.
- *Accelerometers (bridge).* For lateral displacement and impact monitoring, 3-6 triaxial accelerometers need to be installed for a typical bridge, sampling at up to 100 Hz.

For most sensor types, data measurement occurs in an event-driven fashion: when a train passes the Smart Track field site. Typical measurement durations range from 1–10 minutes, depending on the length and speed of the train. Additionally, some sensors (e.g., bender elements), require baseline measurements in the quiescent state. Combining this information with the typical sampling rates and numbers of sensors per field site, one can estimate both the specific bandwidth needs for each sensor type and the aggregate bandwidth needs of the field site as a whole for field site to Cloud communication).

Table 6 summarizes the key properties and requirements of the proposed instrumentation types. The table highlights the importance of edge computing to reduce the volume of generated data at the source, which dramatically improves latency and energy efficiency. For example, sending a fast Fourier transform of the acceleration measurement from a passing train instead of the time history can reduce the volume of data that must be transmitted by almost two orders of magnitude. Also note is that the relatively high sampling rates required preclude the use of many wireless sensor and IoT platforms not specifically designed for high-fidelity data acquisition.

Table 6: Key requirements for the proposed instrumentation types

Sensor Type	Measurement	Sampling Rate (kHz)	Raw Data Size (MB)	Processed Data Size (kB)	Connection Type	Additional Requirements
Analog strain gauges	Loads, bending moments	2	0.8	<10	3-wire, 4-wire	Wheatstone bridge, autobalancing, temperature compensation
Analog accelerometers	Impacts	2	0.8	<10	2-wire	
Potentiometer / LVDT	Displacement	0.5	0.2	<10	4-wire	
Bender elements	Modulus	80	10	n/a	2-wire	Waveform generator and amplifier for transducer element
Smart Rocks	Particle movement	0.5	0.2	n/a	Wireless (BLE)	
Bridge accelerometers	Displacement	0.1	0.2	<10	Wireless (IEEE 802.15.4)	

The key to creating an efficient and versatile communications architecture that can support a variety of instrumentation combinations for the Smart Track field site is to treat *sensor bandwidth requirement* as the minimum suitability criterion for choosing a set of candidate wireless technologies for that sensor type (Hoang et al., 2020). Subsequently, it is possible to select a candidate among these based on *energy efficiency* and *versatility* (i.e., capability to support multiple sensor types using a single communications technology). The minimum bandwidth requirements are identified in Section 4.1. For most sensor types, low-power wireless technologies intended specifically for embedded devices (i.e., BLE and IEEE 802.15.4) satisfy these requirements. Both radios are also relatively energy-efficient, with similar power consumption in both transmitting and receiving modes.

The much higher sampling rates of the bender element field sensors translate into similarly high bandwidth requirements (Kang et al., 2021). Transmitting that much data using the relatively low-bandwidth 802.15.4 or BLE radios loses the benefit of energy efficiency; the relatively low power drawn by the radio itself becomes overwhelmed by the power needed to keep the wireless nodes powered on for the much longer duration needed to transmit the sensor data. For this reason, WiFi becomes the more power-efficient option for this sensor type; however, 802.15.4 and BLE remain feasible as somewhat less efficient fallbacks. Additionally, the more complex sensing functionality of the bender elements requires a more powerful processor than is typically available on low-power embedded devices used in most wireless sensors. Combined, these factors call for the use of a custom wireless data acquisition platform (DAQ) platform that can provide the suitable sensing functionality for the bender elements and can incorporate WiFi and/or 802.15.4 radios.

When it comes to versatility, two of the identified sensor types already have complete wireless sensing implementations: Smart Rocks (S. Liu et al., 2017), which use BLE for communication, and bridge monitoring systems (based on Xnode Smart Sensors), which use 802.15.4 radios (Spencer et al., 2017; Fu et al., 2019). The remainder of the sensors are analog devices, requiring connection to a wireless DAQ module to provide wireless connectivity. The Xnode Smart Sensor platform can also be used as a 5-channel wireless DAQ, with up to 3 strain sensor channels and 2 analog sensor channels available per node. Thus, the 802.15.4-based wireless sensor platform can cover the bulk of the communication needs within the field site, excluding Smart Rocks and bender element sensors.

The aggregate bandwidth requirements of all the sensors within the field site inform the choice of the communication technology for interconnecting the field site with the Cloud. As identified in Section 3, cellular communication provides the most versatile option within the cellular coverage area. Specifically, 4G LTE currently offers the best balance of bandwidth and coverage within the continental U.S. A low-power cellular modem can provide the interconnect between wireless sensor devices within the Smart Track field site and the cloud back end that provides the data management and user interface functionality. Figure 11 presents a schematic view of the proposed end-to-end wireless communication architecture.

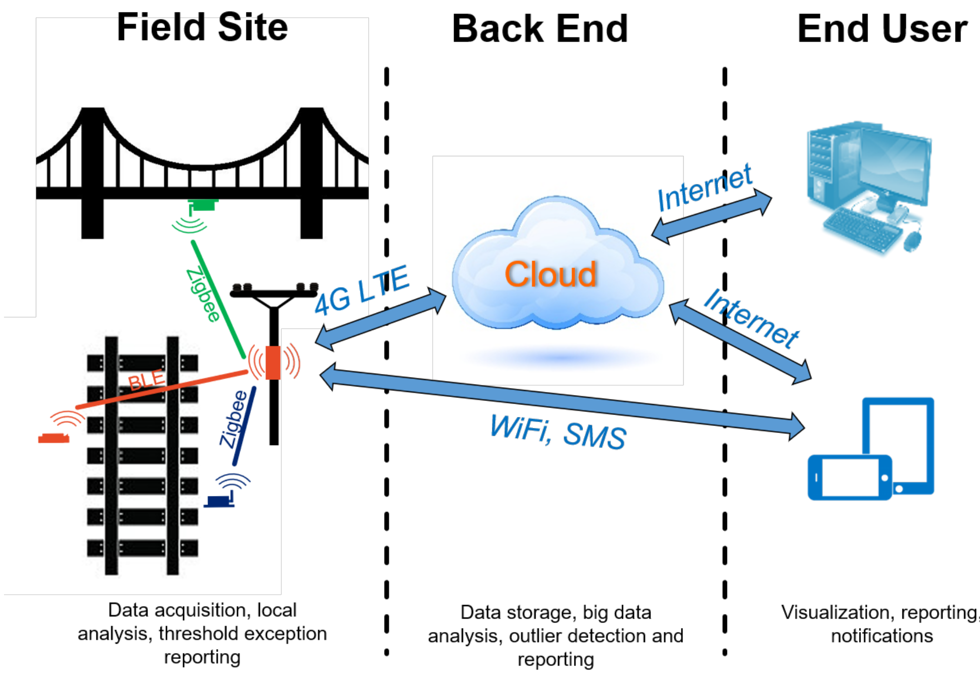

Figure 11: Overview of proposed end-to-end wireless communication architecture

The sensors within the field site will be interconnected via energy-efficient BLE and 802.15.4 radios. A 4G LTE cellular modem will provide remote access connectivity for the field site. A scalable Cloud-based data management system with provide data collection, categorization, analysis, and a web-based user interface. Optionally, direct communication between handheld mobile devices (smartphones, tablets) and the field site can be supported to provide users physically present at the field site direct access to the information. The following sections elaborate the specific design choices for each component of the Smart Track monitoring system.

3.4 Wireless Communications Solutions

The following wireless communication solutions are proposed for each sensor type.

3.4.1 Strain Gauges, Accelerometers, Potentiometers

These are traditional analog sensors that are widely used for a variety of monitoring applications (Tutumluer, 2014; Edwards et al., 2017; Wilk et al., 2017; Edwards et al., 2020). Some WSS platforms, e.g., the Xnode Smart Sensor, can connect such analog sensors, in effect turning the WSS node into a small wireless DAQ. A hardened breakout box (Figure 12) facilitates this integration and allows for housing external circuitry that may be required by some sensors, e.g., Wheatstone bridges for strain gauges. Once integrated with a WSS node, the analog sensors can be treated exactly the same as the WSS node's integral sensors with respect to time synchronization and data transmission. Figure 13 illustrates the schematic view of the proposed integration of these sensor types with the Smart Track field site.

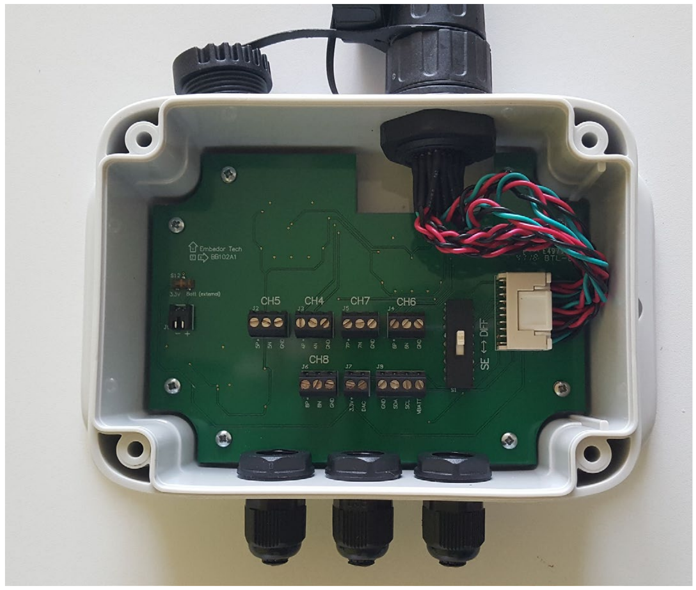

Figure 12: Breakout box for interfacing analog wired sensors with a WSS platform

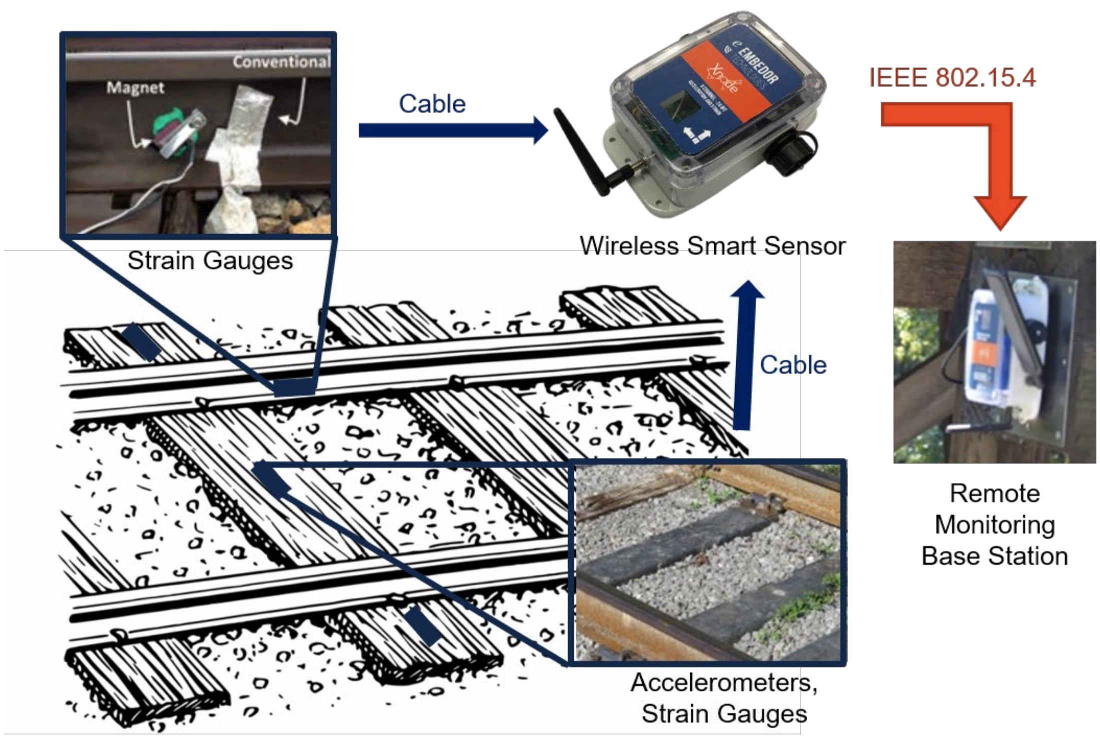

Figure 13: Track superstructure instrumentation plan (strains and accelerations)

3.4.2 Smart Rocks

These sensors comprise a wireless network of several distributed sensors, using BLE for communication with the Smart Rock gateway (S. Liu et al., 2017). Two options exist for integrating Smart Rocks and similar wireless sensors into the Smart Track field site. First, a Bluetooth radio can be added to the field site's gateway, and the functionality of the Smart Rock gateway can be replicated on that platform. This requires a significant development effort. The second option is to keep the Smart Rock gateway and its functionality, while interconnecting it with the WSS gateway by means of a wired serial connection (USB, UART). The two gateways would need to be physically collocated. This is the proposed choice for a first pilot implementation, due to the considerably lower technical risk. Figure 14 illustrates the schematic view of the proposed integration of Smart Rocks with the Smart Track field site.

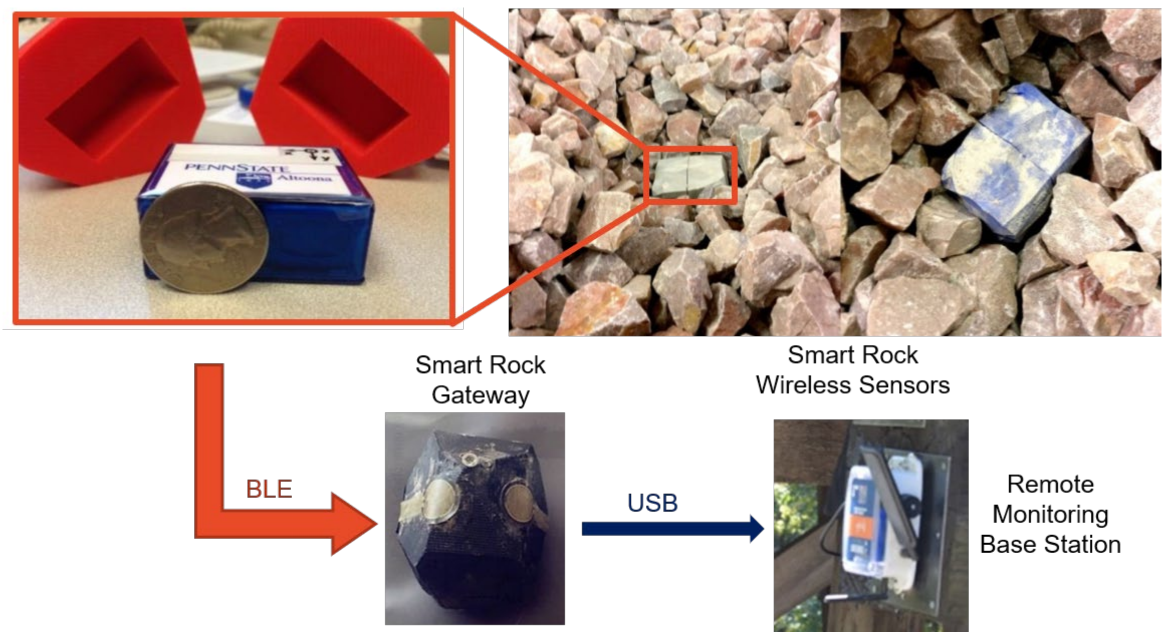

Figure 14: Track substructure instrumentation plan (displacement) (adapted from S. Liu et al., (2017))

3.4.3 Bender Elements

Bender elements require additional, relatively complex data acquisition functionality in order to perform sensing (Kang et al., 2021). This involves first using a signal generator to drive a signal through the BE frame, then sample the resulting output signals at a high frequency using filters, amplifiers, and an oscilloscope. To be compatible with the vision of a portable Smart Track field site, this data acquisition hardware must be replaced with a more compact, wireless DAQ node, which implements the requisite functionality. The capability of small, low-power, single-board computers such as Raspberry Pi to implement similar functionality has been demonstrated. Figure 15 presents the proposed method of integration of bender elements with the Smart Track field site using such a wireless DAQ node. Note that the wireless DAQ must be developed to meet the specific requirements of the BE sensors, including signal quality and sampling rate.

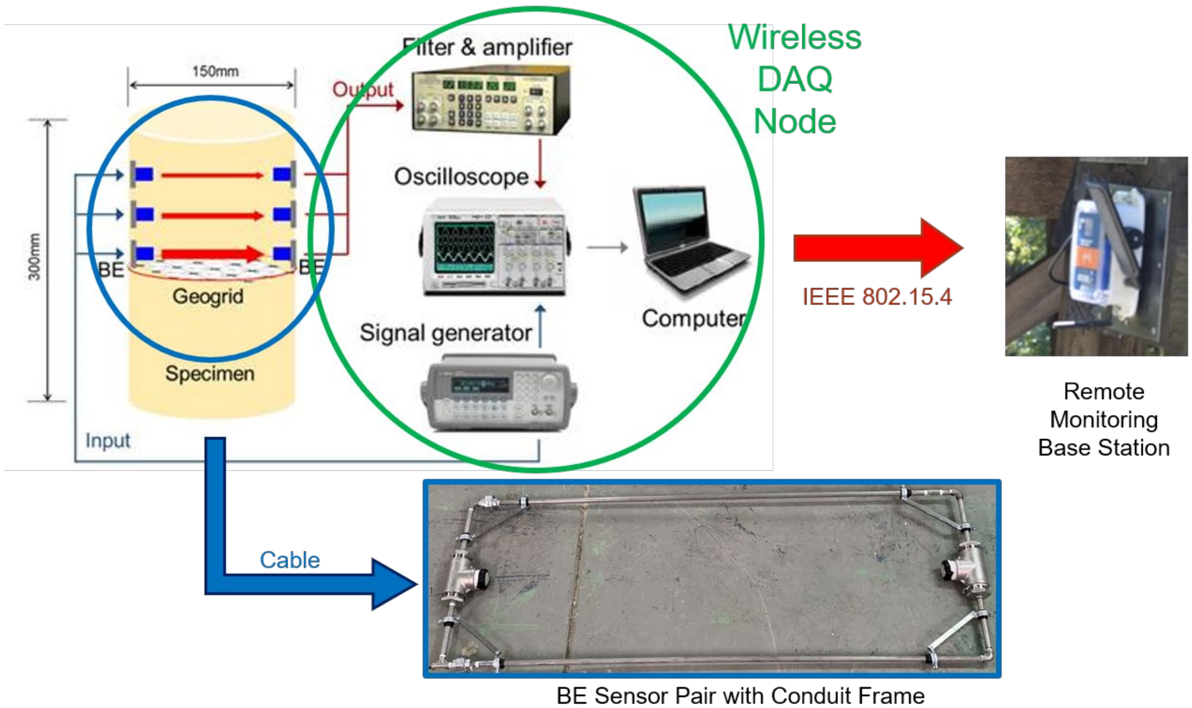

Figure 15: Track substructure instrumentation plan (shear wave velocity) (adapted from Kang et al., (2021)

3.4.4 Accelerometers

WSS-based bridge acceleration and displacement measurement systems using IEEE 802.15.4 radios for communication have been previously developed and deployed successfully (Fu et al., 2018). Integrating such WSS monitoring solutions into the Smart Track field site is straightforward: the deployed sensors connect wirelessly to the WSS gateway, performing the necessary time synchronization and data acquisitions functions over the common radio. Figure 16 illustrates the schematic view of the integration of WSS-based bridge monitoring sensors with the Smart Track field site.

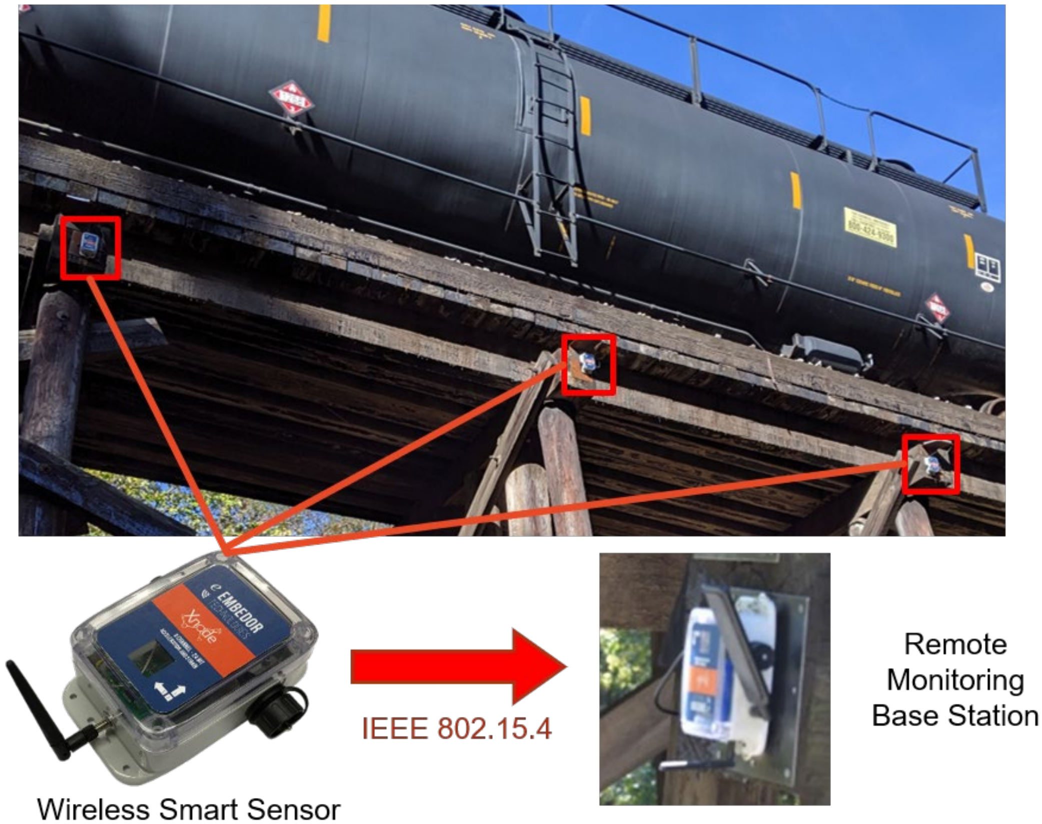

Figure 16: Bridge instrumentation plan (acceleration and displacement)

3.5 Field Site-to-Cloud Communication Architecture

The next element in the data-to-user pipeline is to extract the data from the Smart Track field site and send it to a remote data repository for storage and processing purposes. Due to the typical remote location railroad bridges, a long-range communication method for this data retrieval process is necessary. The project team proposes to make use of the readily available 4G LTE technology and infrastructure for this purpose.

A commercial, low-power, 4G LTE cellular modem (e.g., Sierra Wireless HL7588 LTE-CAT4) can be integrated with an existing WSS platform such as the Xnode Smart Sensor to provide cellular connectivity. The modem connects to the WSS via a UART serial bridge and GPIO pins for control while being powered by the WSS's main battery. The modem enables 4G LTE connectivity from major network providers, 3G fallback, 50 Mbps upload speed, and 150 Mbps download speed, and firmware over-the-air reprogramming.

Energy-efficient remote data uploading can be accomplished. Assuming no solar panel exists to generate renewable power, a 2 percent duty cycling scheme for data uploading can provide over 50 days of connectivity on a single 10,000 mAh lithium-ion battery. With lower duty cycles, and correspondingly longer data access latencies, operational life can be extended up to 1 year. The addition of solar panels can extend operational life to several years, limited primarily by the degradation of the lithium-ion batteries.

In addition to remote connectivity, a cellular modem can also provide auxiliary functionality, such as time synchronization (NimbeLink Corp, 2020). Using the cellular network and the internet, various tasks requiring precise timing (second-accuracy precision) and scheduled data uploading can be realized. The network timekeeping task reads the time provided by the network, adjusts the clock of the gateway node, and propagates the timestamp to the WSSs in the network by rebroadcasting the timestamp data.

3.6 Cloud-based Data Management and User Interface

The final component of the data-to-user pipeline is to manage and visualize data at the front end. A Cloud-based server with efficient data aggregation, management for timely storage and queries, and providing processed data to assist engineers with decision making can help make the information collected by a Smart Track field site accessible to railroad personnel.

Figure 17 illustrates the proposed data architecture and connectivity among its subcomponents. This server would actively wait for data from the sensor network through a Message Queuing Telemetry Transport (MQTT) data broker. Once the broker collects these data, another MQTT client, which subscribes to the topic of the data, will process and decode the raw data and then store it in respective databases for further analysis. Finally, the processed data is presented and ready to be queried at the front end of the web-based user interface.

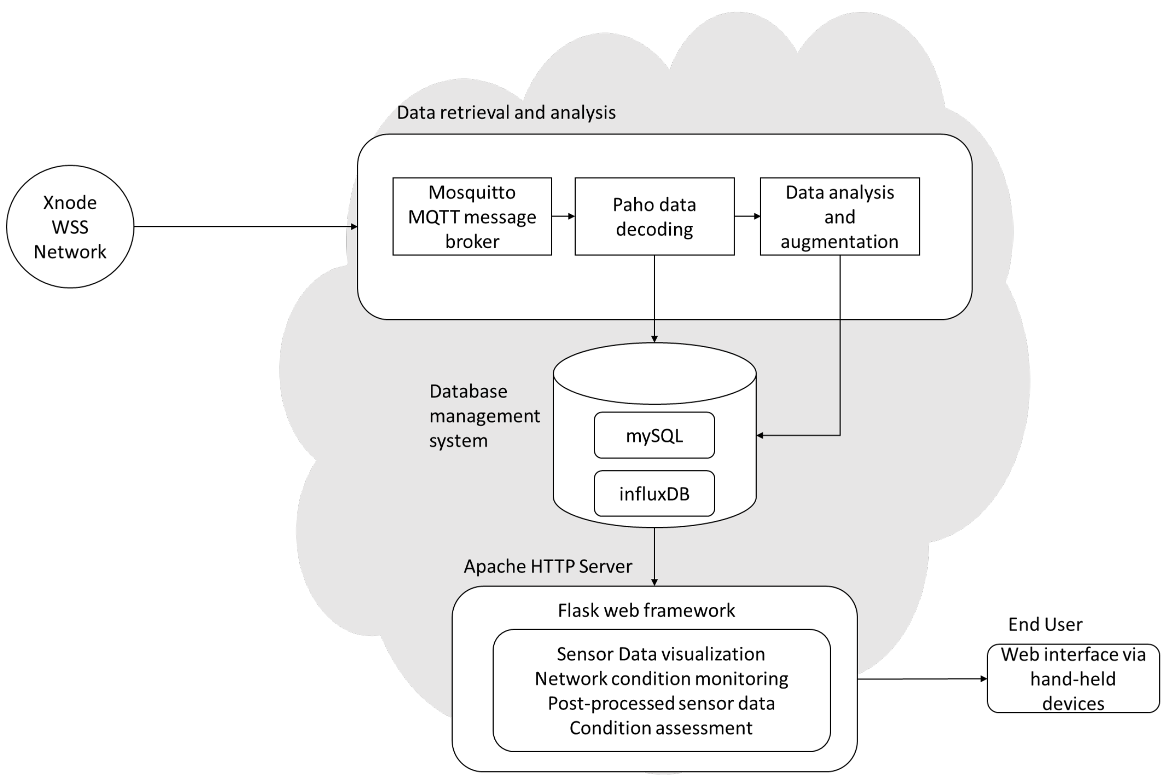

Figure 17: Cloud-based data management, computing, and visualization platform schematic

MQTT is an extremely lightweight message protocol running over TCP/IP. This protocol is suitable for a low-power embedded system like WSSs by consuming little power and minimizing the code footprint. The MQTT protocol follows a publish/subscribe (pub/sub) scheme. This scheme contains clients that can publish (send) and subscribe (receive) to messages of one or multiple topics. All clients are connected to a message broker, which receives the messages from the publisher and distributes them to the subscribers according to their subscribed topics

A data broker can be realized using the open-source MQTT implementation Mosquitto. The subscriber can be set up using the open-source MQTT implementation Eclipse Paho-MQTT in Python to make use of the scientific computing libraries for post-processing. The publisher on the gateway node can be implemented using the same Eclipse Paho-MQTT library, acting as an MQTT encoder for the sensor data before being published to the broker over TCP/IP using the 4G LTE modem.

To ensure proper performance for management and to serve time for all types of data collected from the monitoring system, in addition to the popular relational DBMS MySQL to handle non-sensor data, a separate time-series database (TSDB) is also required. A TSDB enables multiple distinguished properties in handling time-series data, including fast range queries, high write performance, data compression, scalability, and usability. Among the options, InfluxDB, an open-source schema-less database, is the most popular choice for TSDB, and thus, was chosen as the project team's proposed solution for time-series data storage. Both database systems can be developed to work as MQTT subscribers through a Python data parser. Any dataset obtained from the sensor network is distributed to the parser.

A web interface granting ubiquitous access to the data is crucial to support direct access to the field site data and any assessment results (Figure 18). This platform can be implemented via a web server hosted using the micro web framework Flash written in Python. This web server has direct access to the MySQL and InfluxDB databases by using the MySQL connector and InfluxDB library. Thus, users can interact with the data by querying on the web by selecting a row in the database table. In response to the queries, the time series record can be presented in graph and map format, showing both time-history and location data. In addition to the monitoring data, network condition, containing voltage and current measurements, can also be presented so that the engineers with access to the web server can check for the last known state of the network. The web server can be hosted using the widely used Apache server framework.

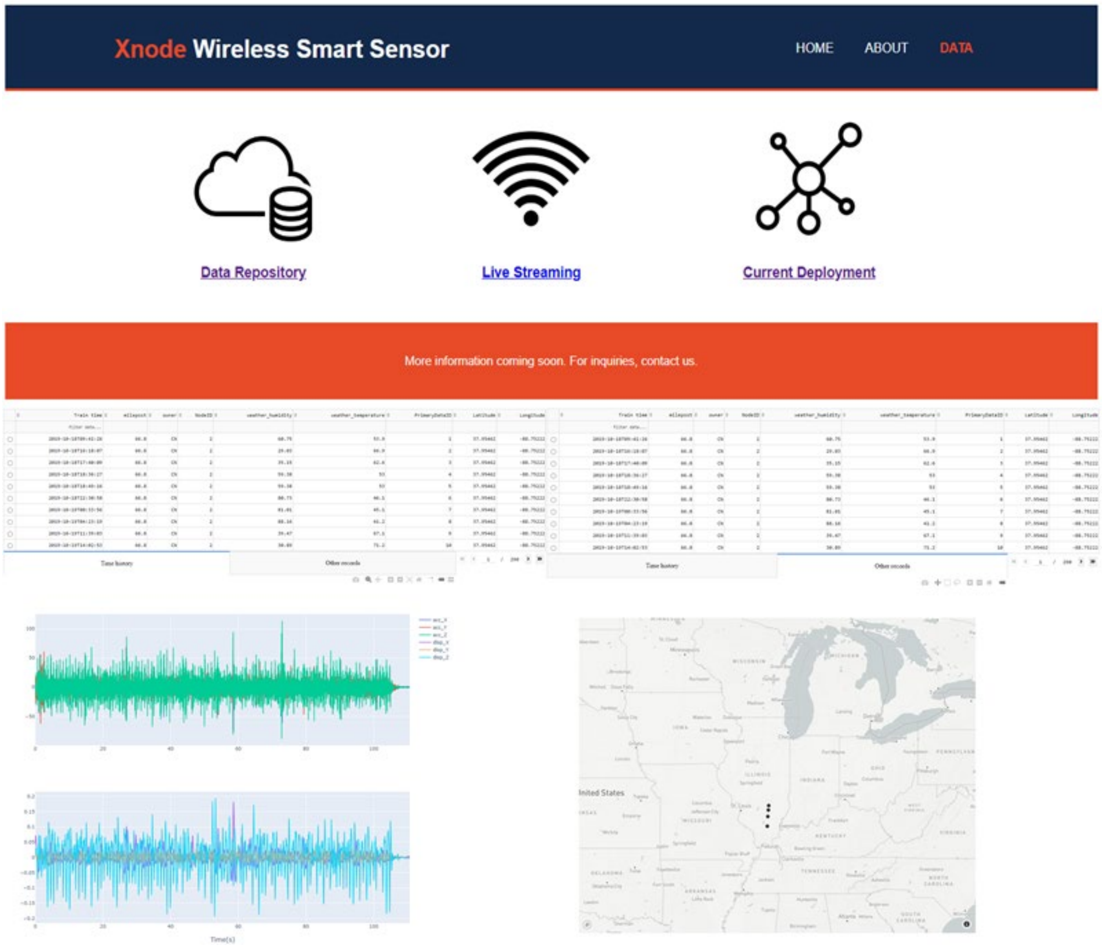

Figure 18: Mock-up of proposed data-to-user interaction web interface

4. Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis

The project team conducted a strengths weaknesses, opportunities, and threats (SWOT) analysis to holistically evaluate the proposed Smart Track instrumentation and monitoring strategy. Table 7 summarizes the Smart Track SWOT analysis, including solutions to possible weaknesses and threats, where appropriate.

Table 7: SWOT analysis of smart track WSS approach

Category	Topic	Explanation
Strengths	Economic advantage	WSS are an inexpensive (and further reducing in cost) way of acquiring a large volume of data remotely. WSS reliability continues to increase; thus, there is less need for personnel dedicated to maintaining the sensors, and contractors have less need to access infrastructure for installation and maintenance.
	Integration with existing track inspection systems	Autonomous track inspection technologies, including autonomous track geometry measurement systems (ATGMS), have increased in their level of coverage and effectiveness. Smart Track WSS methods mesh with ATGMS and other track inspection systems – by filling voids with focused deployments (e.g., bridge structures or special trackwork).
	Track availability and intrusiveness	Limited need to foul track for installation and monitoring; further decreased by the wireless nature of Smart Track.
	Flexibility	Possibility of modular deployment of sensors to address specific concerns and evaluate specific assets, without significant instrumentation deployment in field. Incremental addition of instrumentation is “cheap.”
	End user installation and monitoring	As individuals become more familiar with smart technologies, the opportunity exists for end user deployment and monitoring, providing further buy-in.
Weaknesses	Communication availability	Difficulties of achieving reliable site-to-Cloud communications in remote locations (lack of cellular service) [*possible solutions: range extended cellular, satellite (space-based for IoT systems)*]. Possibly overcome through integration of fixed sites with

Category	Topic	Explanation
Weaknesses		ATGMS for data collection.
	Network reliability	Reliability or wireless connection and wireless systems – what to do when connectivity is lost? [*possible solution: need plan for node being offline / when we don't get the data we plan to get*].
	Lack of coverage (narrow vs. broad deploy)	Infeasible to install sensors throughout the entirety of a network. Possibility of having problematic locations without sensors (missing key locations with defects) [*possible solution: use these findings to optimize future sensor placement, when possible*].
Opportunities	Innovation	The rail industry is adopting autonomous inspection technologies, including rail-bound systems like ATGMS. Smart Track could leverage should leverage ATGMS systems as a source of additional track data and as a platform from which to wirelessly collect smart track data.
	Supporting AI advancement	Play a role in collecting data to support broader AI advancements related to track maintenance (e.g., a dozen FRA-funded projects are currently underway).
	Maintenance prioritization	Feed into automated processes for prioritizing and focusing maintenance activities at both the component (crosstie), structure (bridge), and network (comparison to other subdivisions) levels.
	Leverage other public data	Use of publicly or private relevant databases for acquiring precipitation, temperature, rail temperature, CWR-SAFE, etc.
	Cost benefit	Very scalable system of instrumentation; depends on the size of the railroad and their annual budget and the size of deployment.
Threats	Institutional challenges	Railroads find their status quo more efficient, are slow to adopt changes (partially reduced through the use of ATGMS and success in establishing new FRA rules regarding inspection).
	Regulatory implications	There may be a risk (real or perceived) to the adoption of this technology related to possible inclusion of new regulations. Recent evidence suggests this is diminishing (e.g., rail flaw rule).

Category	Topic	Explanation
Threats	Other inspection platforms	Significant advancements of other types of inspection systems and platforms – typically deployed on a continuous basis longitudinally along the track – could diminish the value of Smart Track.
	Cost-benefit proposition	Barriers to entry may exist, especially for short line and regional railroads. Thus, Smart Track advantages are likely dependent on the size of the of the railroad and volume of traffic being moved (lower unit cost of sensing).

4.1 Key Findings

Relevant takeaways from the SWOT analysis:

- Strengths abound, and the rail domain is a tremendous application for smart sensors and the broader Smart Track concept for sensor deployment. The sensors can be deployed modularly, with sensor economies of scale increasing with the size of deployment.
- Opportunities exist for the integration of Smart Track modules with existing automated inspection systems such as ATGMS. This can occur at two levels – 1) capturing data that would otherwise not be captured to further fill out the set of tools needed to automate track inspections and 2) using the ATGMS vehicle platform to collect Smart Track data.
- Many of the weaknesses and threats are institutional and are best overcome by clear articulation of the expectations of Smart Track (and wireless sensing in general). It is critically important to identify what wireless smart sensing can (and cannot) contribute in inspecting and assessing rail infrastructure assets.

5. Conclusion and Future Work

Revisiting Table 5 from Section 3, that combines the results of the analysis of FRA accident data and expert survey, the Smart Track team produced a final version of measurements for track instrumentation (Table 8). These are organized by location within the track structure, proposed guiding questions, and specific measurements obtained.

Table 8: Final list of instrumentation locations and measurements

Track Structure Location	Guiding Question(s)	Measurements
Rail	What are the loads imparted into the track structure? What are the lateral displacements found in a specific location of the track and their associated risk? Is there a longitudinal rail stress management problem (possibly obtain RNT risk data)?	Vertical Load Lateral Displacement Longitudinal Load
Crosstie and Support	Has the capacity of the concrete crosstie been compromised or exceeded? Has the crosstie deflection been excessive? What is the stress imparted onto the ballast and does it exceed the track strength?	Bending and/or Deflection
Ballast and Substructure	Has track strength been exceeded? Is there adequate vertical support, lateral stability, and resistance to settlement? Is the ballast modulus adequate for proper density & substructure support? Has track drainage, and thus strength, been compromised?	Particle Movement Layer Modulus Shear Wave Velocity Moisture Content Fouling
Bridge Deck and Support	What is the global health estimate of the structure and assessment of its operational safety? Are the eccentric loads in double track bridges causing excessive lateral displacements?	Mid-Span Deflections Impact Loads Lateral Displacements
Special Trackwork	Are there excessive impact loads? Are there significant changes to the track geometry at these locations?	Impact Loading Settlement

Based on project findings and building on Table 8, a summary of required attributes of the most common forms instrumentation and their associated costs are provided in Table 9. The cost per unit column indicates the fixed cost of the instrument and its installation cost for each type of measurement. The priority column provides a qualitative assessment of the urgency of deployment of a given form of instrumentation at each specific track location (1 being the highest priority).

Table 9: Summary of instrumentation requirements and priorities

Track Structure Location	Measurement	Instrumentation	Units / Site	Cost / Unit (USD)	Priority (1-3)
Rail	Vertical Load	Strain Gauges	4	$1000	1
	Lateral Load	Strain Gauges	4	$1000	2
	Longitudinal Load	Strain Gauges	1-20	$650	1
Crosstie and Support	Bending Moment	Surface Strain Gauge	3-30	$250	2
	Displacements	Potentiometer Accelerometer	5-24	$500 $600	3
Ballast and Substructure	Particle Movement	Smart Rocks	10	$2,900	1
	Layer Modulus Shear Wave Velocity	Bender Elements	4	$2,000	2
	Moisture Content	Moisture Probe	4	$600	1
Bridge Deck and Support	Mid-Span Deflections, Impact Loads, and Lateral Displacements	Accelerometer	4-6	$5,000-$7,000	1
Special Trackwork	Impact Loading	Accelerometer	2	$1000	1
	Settlement	Potentiometer	2	$500	3

Additionally, the method of sensor communication, its status, and future needs (gap analysis) are included in Table 10 for each instrumentation type. The predominant need was to develop wireless capability for many of the forms of field instrumentation that have been demonstrated via past and existing wired deployments.

Table 10: Instrumentation status, gap analysis, and future needs

<table>
<tr><th rowspan="2">Instrumentation</th><th rowspan="2">Measurement</th><th rowspan="2">Commun-ication</th><th rowspan="2">Required Data Rate (Hz)</th><th colspan="2">Current Status</th><th rowspan="2">Future Need</th></tr>
<tr><th>Level of Development</th><th>TRL</th></tr>
<tr><td rowspan="4">Strain Gauges</td><td>Vertical Load</td><td rowspan="4">Analog</td><td rowspan="4">2,000
(Less for Long. Loads)</td><td rowspan="4">Wired successfully deployed – many locations</td><td>8</td><td>Wireless capability</td></tr>
<tr><td>Lateral Load</td><td>7</td><td>Wireless capability</td></tr>
<tr><td>Longitudinal Load</td><td>7</td><td>Wireless capability & large-scale field demo</td></tr>
<tr><td>Bending Moment</td><td>7</td><td>Wireless capability</td></tr>
<tr><td>Potentiometer</td><td>Displacements and Settlement</td><td>Analog</td><td>2,000</td><td>Wired successfully deployed – many locations</td><td>6</td><td>Wireless capability</td></tr>
<tr><td rowspan="3">Accelerometer</td><td>Displacements</td><td rowspan="3">Wireless (802.15.4)</td><td rowspan="3">100-200</td><td rowspan="3">Wireless prototypes successfully deployed</td><td>8</td><td>Hardening, robustness</td></tr>
<tr><td>Impact Loads (Bridge & Special Trackwork)</td><td>7</td><td>Event classification, data analysis</td></tr>
<tr><td>Mid-span Deflections</td><td>8</td><td>Hardening, robustness</td></tr>
<tr><td>Smart Rocks</td><td>Particle Movement</td><td>Wireless (Bluetooth)</td><td>500</td><td>Wireless prototypes successfully deployed</td><td>7</td><td>Long term demonstration. Battery life improvements</td></tr>
<tr><td>Bender Elements</td><td>Layer Modulus Shear Wave Velocity</td><td>Analog</td><td>80,000</td><td>Wired successfully deployed – many locations</td><td>6</td><td>Wireless capability</td></tr>
<tr><td>Moisture Probe</td><td>Moisture Content</td><td>Analog</td><td>10</td><td>Wired successfully deployed – many locations</td><td>8</td><td>Wireless capability</td></tr>
</table>

5.1 Communication System Conclusions

Based on the needs identified in the industry survey and the resulting forms of instrumentation that are needed (summarized above), this project identified IEEE 802.15.4 as the wireless technology best-suited for intra-site communication and 4G LTE cellular as the preferred means for field site-to-Cloud communication. The notable advantages of IEEE 802.15.4 include a good balance of energy efficiency, communication range, and available bandwidth. 4G LTE stands out as the most broadly applicable, among the cheapest, and best-supported by third-party communications service providers. Alternate technologies (WiFi, Bluetooth, satellite, mobile base station) would generally only be considered when the above solutions are not an option.

5.2 Gap Analysis – Future Work

Several gaps remain in the current state of readiness of the technologies encompassing the proposed Smart Track field site, which must be addressed prior to a Phase 2 deployment. The following gaps and associated research tasks to address them have been identified.

5.2.1 Instrumentation Development

- *Integration of new analog sensing equipment.* External accelerometers and strain gauges must be integrated with a WSS platform, e.g., Xnode Smart Sensor, for wireless data acquisition. While platforms like the Xnode support connecting external analog sensors, certain sensor types, in particular strain gauges, require additional signal conditioning circuitry and software support (auto-balancing, shunt calibration, temperature compensation) for accurate and meaningful data collection.
- *Interfacing the above WSS platform with other complex sensing systems.* Smart Rocks and bender elements are not in the same category as traditional analog sensors, as the data acquisition process is significantly more complex. Their integration with an external wireless sensor network is a nontrivial task.
    - For wireless sensors (e.g., Smart Rocks), which come with their own wireless network and gateway node, the preferred integration point is between the two gateways. This can be accomplished by means of a physical serial connection between the devices, such as a USB or UART serial interface. The interface hardware and associated software need to be developed.
    - For bender elements, the complexity lies on the data acquisition side, where a combination of a signal generator, an oscilloscope, a signal conditioner, and a DAQ system is currently used. These hardware components will need to be replaced with a portable embedded device, e.g., a single-board computer (SBC), with the appropriate data acquisition functionality implemented in software. Integration with the chosen WSS platform needs to be performed via a compatible radio module (IEEE 802.15.4) or a wired serial interface (USB, UART) for the SBC.

5.2.2 Communications within Field Site

- *Optimization of energy and bandwidth consumption*. Employing unoptimized sampling, processing, and data transport methods can be expected to quickly drain the embedded devices' batteries. This is a particular concern in winter when battery efficiency suffers due to low ambient temperatures and reduced daylight for solar panels to recharge. To extend the operating life of the Smart Track field site and increase the fidelity and timeliness of data acquisition, communication protocols and associated software should be optimized for burst data transmission. This is especially important for intra-site communication, where both bandwidth and energy reserves are significantly limited.
- *Validation and testing of the communication system.* Communication among the different device types within the field site must be thoroughly tested to validate functionality and performance. This testing must cover performance under adverse conditions that are likely to manifest at some deployment sites: low signal strength, no line-of-sight between devices, presence of outside wireless interference (e.g., WiFi).

- *Stability testing of integrated system.* Once the data acquisition and communication components of the field site have been integrated, the system should undergo extensive stability testing in the laboratory before deployment. The primary objectives of this testing are to uncover incompatibilities and adverse interaction effects among the system's subcomponents and validate its stable long-term operation under realistic conditions.

5.2.3 Field Site to Cloud Communications

- *Validation and testing of field site-to-Cloud communication.* As with intra-site communication, the proposed 4G LTE cellular communication solution should undergo rigorous testing to validate performance and functionality.
- *Data management framework development.* Once the data from the field site has been transmitted to the Cloud, it should be appropriately organized and stored for long-term access and data processing. This includes storing and managing the raw sensor data, results of edge processing, and metadata (location, weather information, etc.).
- *Data processing and visualization interface.* To make the collected data and processed monitoring results accessible to end-users, the information must be presented in an intuitive and role-appropriate manner: allowing access to the full raw data to researchers in order to develop more advanced analysis methods, while focusing on high-level analysis results and condition-based alerts for railroad personnel.

5.3 Next Steps

The objectives of and deliverables of future, follow-on Smart Track work include:

- Conduct laboratory validation of instrumentation and communications system.
- Deploy and operate mock field site demonstration in laboratory.
- Conduct energy and bandwidth usage optimization to meet targets (iterative process).
- Develop final field instrumentation and experimentation plans (building on Phase 1).
- Modular installation of "smart" infrastructure on Class I industry partner.
- Conduct at least 6 months of initial data collection (test mode).
- Conduct at least 6 months of follow-on data collection (revenue service demonstration).
- Technology transfer and frequent interaction with end users in the rail industry.
- Coordination with industry on outputs (exception reporting) from Smart Track modules.

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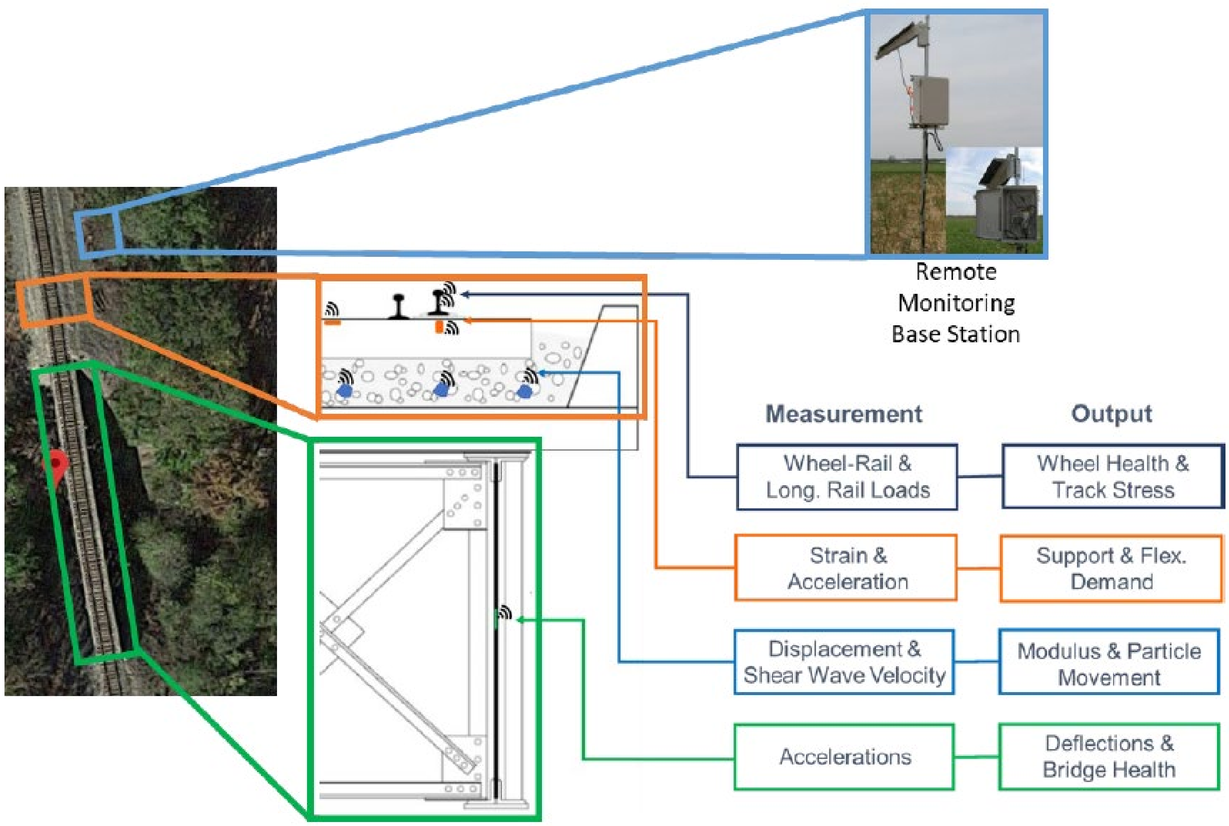
Appendix A: Smart Track Industry Survey Questions

SMART TRACK RESEARCH PROGRAM SURVEY

This survey was designed to help the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign collect information about which track infrastructure data are of greatest relevance to rail infrastructure designers, maintainers, and operators to ensure the infrastructure is maintained to a good state of repair. The Smart Track project scope includes the development of a conceptual design plan for wireless wayside monitoring of the track structure that will self-enunciate challenges as they arise. While not exhaustive, the figure below depicts sensor data collection from an instrumented track section including a railroad bridge and approach site as well as example measurements and resulting health monitoring output for various track structure components.



This survey seeks to answer the following questions about the primary objectives in the identification and prioritization of smart infrastructure:

1) What locations of the infrastructure are the best candidates for wireless monitoring (e.g., turnouts, grade crossings, etc.)?
2) Which track components/structures are the best candidates for wireless monitoring (e.g., bridges, rail, crossties, substructure, etc.)?
3) What are the most critical measurements and resulting information for safety or maintenance prioritization (e.g., crosstie displacements, longitudinal rail stress, etc.)?
4) What is the size of the deployment needed to provide sufficient information for decision making (e.g., every component vs. every subdivision)?

All answer fields are in table format; please place your cursor in the appropriate location and type your answer. In multiple-choice questions, type an "X" in the box next to your answer or a number (1-5) in ranking questions.

Please contact J. Riley Edwards at jedward2@illinois.edu with any comments or questions. Thank you in advance for your time and assistance!

Name: ______________________________

Email: ______________________________

Company: ______________________________

Company Type ______________________________

Title: ______________________________

1) If you could continuously monitor the health of your track, what <u>locations on your network</u> would be valuable to monitor to evaluate the short or long-term performance of your infrastructure (Score 1-5; 1 = low importance, 5 = high importance)?

Short Term	Continuous	
______	______	Open Track
______	______	Bridges
______	______	Bridge Approaches
______	______	Mud Spots
______	______	Insulated Joints
______	______	Turnout - Switch
______	______	Turnout - Frog
______	______	Grade Crossings
______	______	Curves
______	______	Plug Rail (RNT Management)
______	______	Recently Disturbed Track
______	______	Areas of Poor Subgrade
______	______	Slide Fence / Slope Stability
______	______	Other (Please elaborate below)

____

2) If you were able to deploy "Smart Technology" to monitor the health of your track structure, what <u>locations on your network</u> would be most valuable to monitor (Score 1-5; 1 = low importance, 5 = high importance)?

Mass (e.g., every component, every other component, etc.)	Focused (e.g., once per subdivision)	
______	______	Open Track
______	______	Bridges
______	______	Bridge Approaches

______	______	Mud Spots
______	______	Insulated Joints
______	______	Turnout - Switch
______	______	Turnout - Frog
______	______	Grade Crossings
______	______	Curves
______	______	Plug Rail (RNT Management)
______	______	Recently Disturbed Track
______	______	Areas of Poor Subgrade
______	______	Slide Fence / Slope Stability
______	______	Other (Please elaborate below)

____

3) If you were able to continuously monitor the health of your track structure, which <u>areas or components</u> would be most valuable to monitor (Score 1-5; 1 = low importance, 5 = high importance)?

______ Rail (e.g., stress state)

______ Fasteners (e.g., presence / function)

______ Crossties (e.g., bending demand, support condition)

______ Special Trackwork (e.g., frog, switches)

______ Substructure (ballast / subballast / subgrade)

______ Bridge superstructure

______ Bridge substructure

______ Cut/Embankment (e.g., slide monitoring)

______ Other (Please elaborate below)

____

4) If you were able to continuously monitor the following elements of your track structure, what <u>information</u> would be most valuable? (Score 1-5; 1 = low importance, 5 = high importance)?

A) Rail

____ Vertical Loads
____ Lateral Loads
____ Longitudinal Loads (related to RNT)
____ Vertical Displacement
____ Lateral Displacements
____ Longitudinal Displacement
____ Other (Please elaborate below)

____

B) Crosstie

____ Vertical Displacement
____ Bending Stress – Center
____ Bending Stress – Rail Seat
____ Support Conditions
____ Tie Deflection Profile
____ Settlement
____ Other (Please elaborate below)

____

C) Substructure

____ Fouling
____ Moisture Content
____ Ballast Particle Movement
____ Settlement
____ Layer Modulus
____ Other (Please elaborate below)

____

D) Special Trackwork

____ Impact Loading
____ Crosstie Condition
____ Fastener Condition
____ Vertical Deflection
____ Support Conditions
____ Other (Please elaborate below)

____

E) Structures

____ Strains
____ Accelerations
____ Lateral Displacements
____ Vertical Displacements
____ Impact Response
____ Other (Please elaborate below)

____

5) For the following elements of your track structure, which areas would you desire widespread deployment of instrumentation (e.g., every crosstie, turnout) vs focused deployment (e.g., one installation per subdivision) (Check all that apply).

	Widespread	Focused
Rail (stress state/loads)	☐	☐
Crosstie (health and support)	☐	☐
Substructure (strength/capacity)	☐	☐
Shoulder (drainage)	☐	☐
Crossing (support)	☐	☐
Special Trackwork (impacts)	☐	☐
Curved Track	☐	☐
Structures (condition)	☐	☐
Other (Please elaborate below)	☐	☐

____

6) For the following maintenance activities, what *<u>information</u>* on the health of the track structure <u>would best guide your prioritization of the following maintenance activities</u>? (multiple *information* selections per activity are allowed)

	Rail Loads	Rail Displa-cement	Crosstie Stress	Crosstie Support Condition	Fouling/ Moisture	Ballast Particle Movement	Deflection	Track Modulus
Rail relay	☐	☐	☐	☐	☐	☐	☐	☐
Rail grinding	☐	☐	☐	☐	☐	☐	☐	☐
Crosstie replacement	☐	☐	☐	☐	☐	☐	☐	☐
Surfacing	☐	☐	☐	☐	☐	☐	☐	☐
Undercutting / shoulder cleaning	☐	☐	☐	☐	☐	☐	☐	☐
Bridge superstructure repair	☐	☐	☐	☐	☐	☐	☐	☐
Bridge substructure repair	☐	☐	☐	☐	☐	☐	☐	☐
Other (Please elaborate below)	☐	☐	☐	☐	☐	☐	☐	☐

____

7) Please provide any specific details on how you would use the above information?

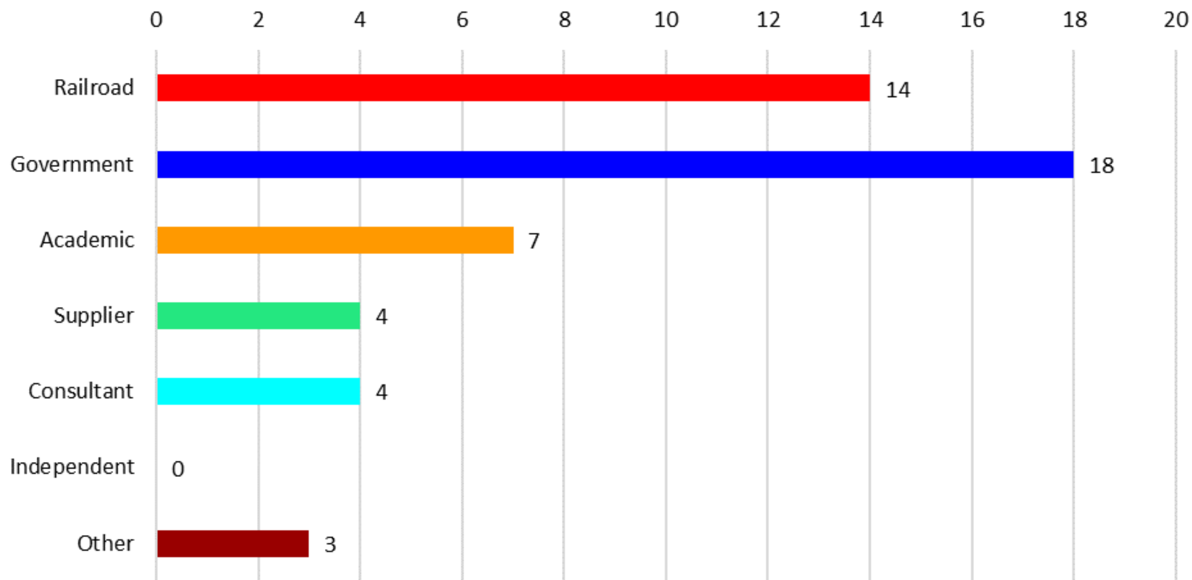
8) Fill in the blank question: If only I had ____X____ data and information, I would be able to make better ____Y____ decisions. These will help us formulate our instrumentation priorities. Please provide as many answers as you would like.

X	**Y**

9) Do you have any other comments or ideas you would like to share with us?

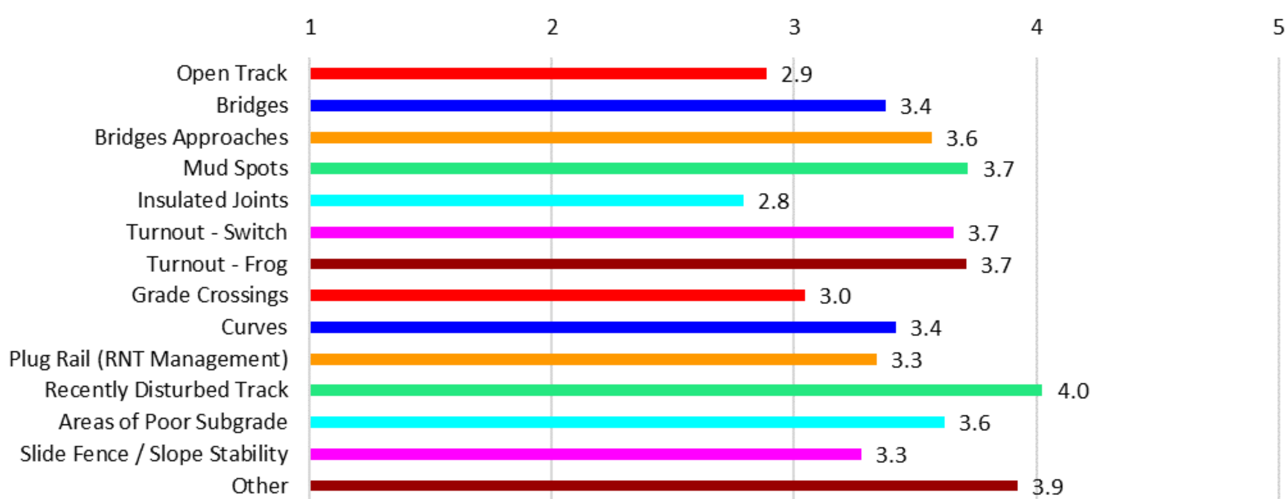
Appendix B: Detailed Smart Track Industry Survey Responses

- **Company type:**



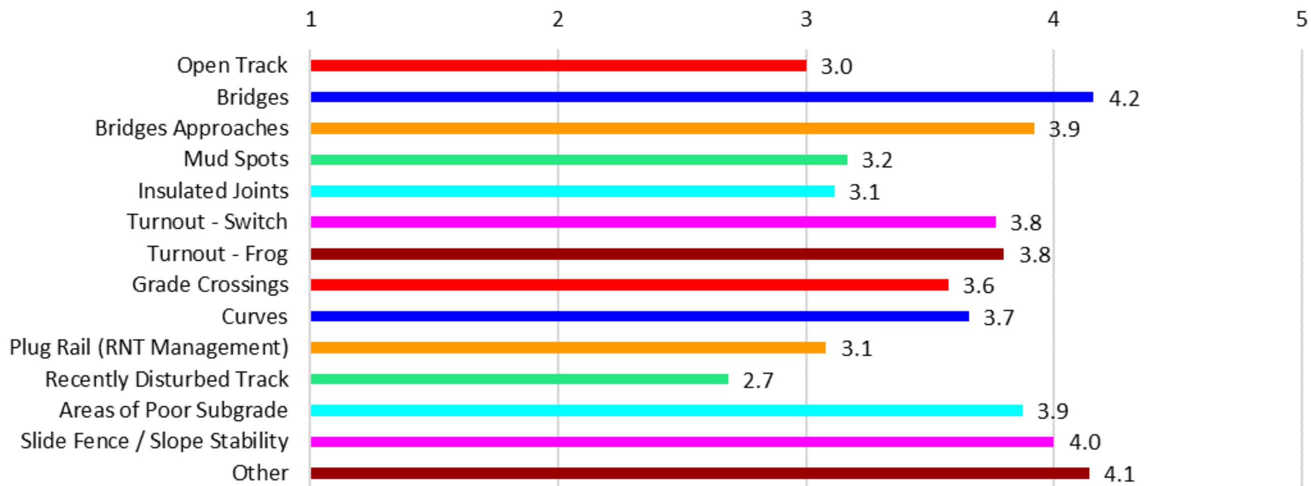
1. **If you could monitor the health of your track, what locations on your network would be valuable to monitor to evaluate the Short-Term and Continuous performance of your infrastructure (Score 1-5; 1 = low importance, 5 = high importance)?**

    a. **Short Term (e.g., days, weeks, a few months).**



Other responses: Areas where poor lateral strength was measured with GRMS and water accumulated locations for potential surface issues; Low priority on this list are high priority long term; Rail Fasteners (clips and plates) stresses, strains and rotational moments; Wood tie condition; Railroad crossties; Track geometry; Locked in RNT at recent track work; Fault lines, slide areas, sensitive areas based up on risk associated with the consequences of a derailment at this location, e.g., river gorges, scenic byways, highly populated urban areas.

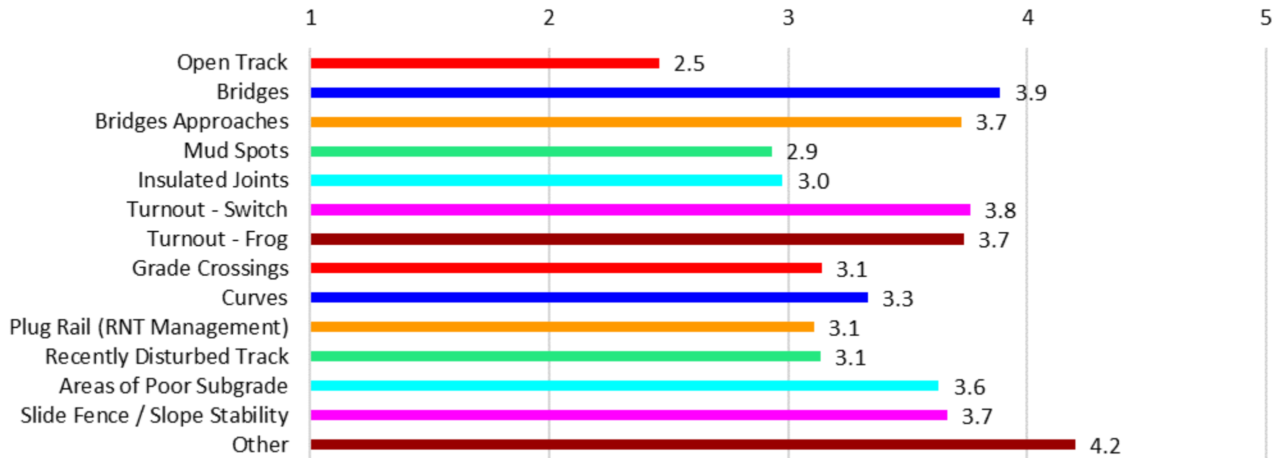
b. Continuous (i.e., permanent).



Other responses: Entrance to tunnels; Floods: culverts and washouts; Poor drainage locations; Tunnels; Spot check actual rail temperature every few miles continuously; Rail fasteners; Railroad crossties; Crossing diamonds; Track geometry; Fault lines, slide areas, sensitive areas based up on risk associated with the consequences of a derailment at this location, e.g., river gorges, scenic byways, highly populated urban areas.

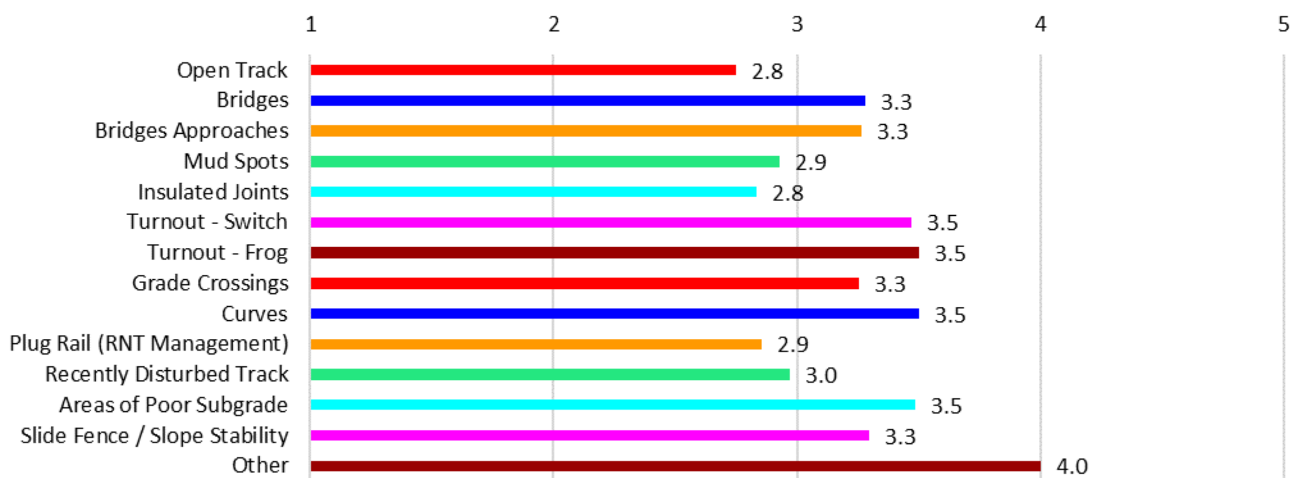
2. **If you were able to deploy "Smart Technology" to monitor the health of your track structure, what <u>locations on your network</u> would be most valuable to monitor (Score 1-5; 1 = low importance, 5 = high importance)?**

    a. **Mass deployment (e.g., every component, every other component, etc.).**



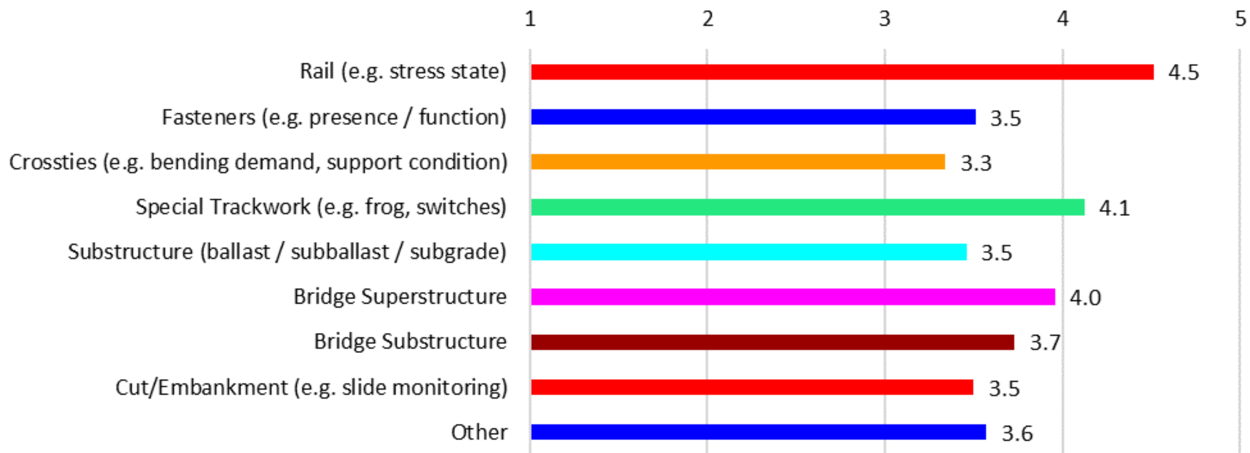
Other responses: Not yet designed longitudinal thermal stress sensors located near fixed objects; Dynamic gauge widening on sharp curves; Rail fasteners; Crossing diamonds; Track geometry; Plug rail and recently disturbed track, areas of concerns of poor subgrade, near passenger platforms and other places with frequent brake applications.

    b. **Focused deployment (e.g., once per subdivision).**



Other responses: Sleepers in track and S&C; Floods: culverts and washouts; Not yet designed longitudinal thermal stress sensors located near fixed objects; Rail fasteners; Plug rail and recently disturbed track, areas of concerns of poor subgrade, near passenger platforms and other places with frequent brake applications.

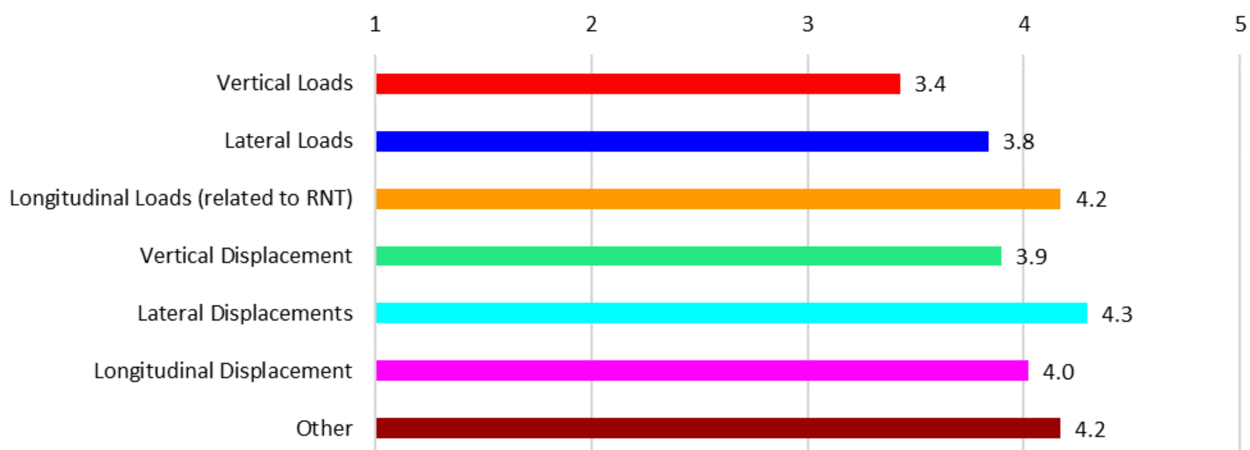
3. **If you were able to continuously monitor the health of your track structure, which <u>areas or components</u> would be most valuable to monitor (Score 1-5; 1 = low importance, 5 = high importance)?**



Other responses: Entrance to tunnels; Rail fasteners measurement to include dynamic gauge widening; Track geometry.

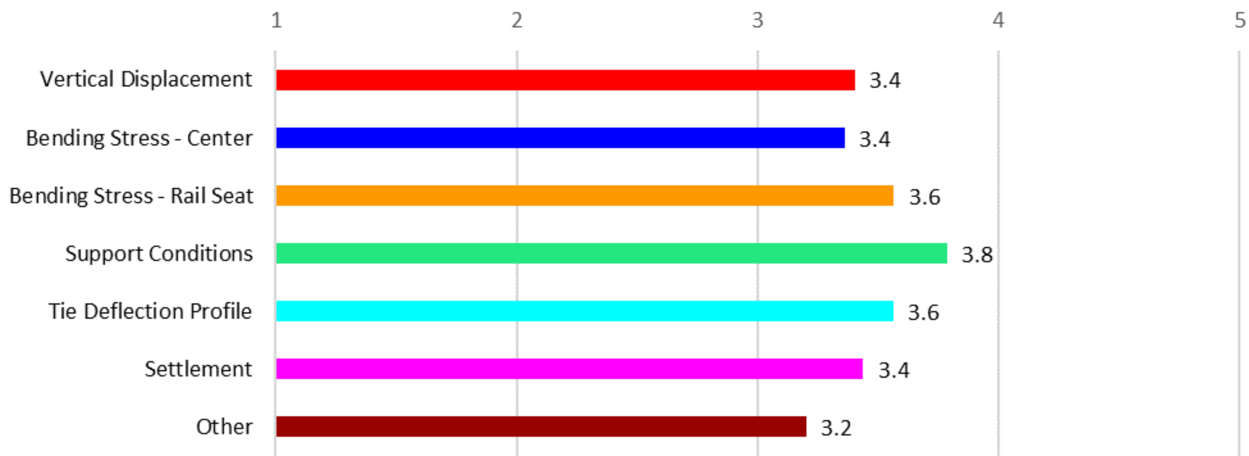
4. **If you were able to continuously monitor the following elements of your track structure, what <u>information</u> would be most valuable? (Score 1-5; 1 = low importance, 5 = high importance)?**

   a. **Rail**



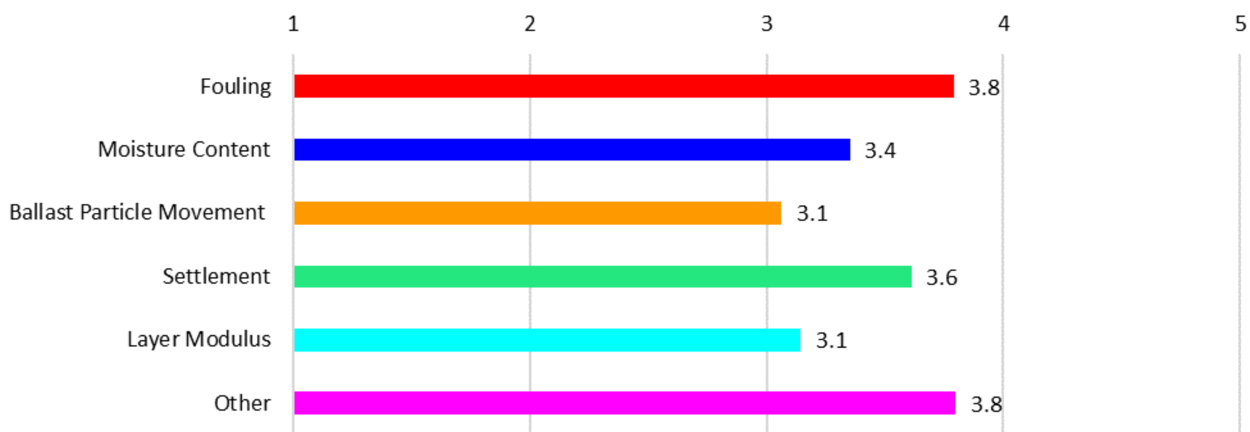
Other responses: Rail fatigue and stress; Temperature; Lateral displacement to include tipping and base widening; Temperature all these events happen.

b. Crosstie



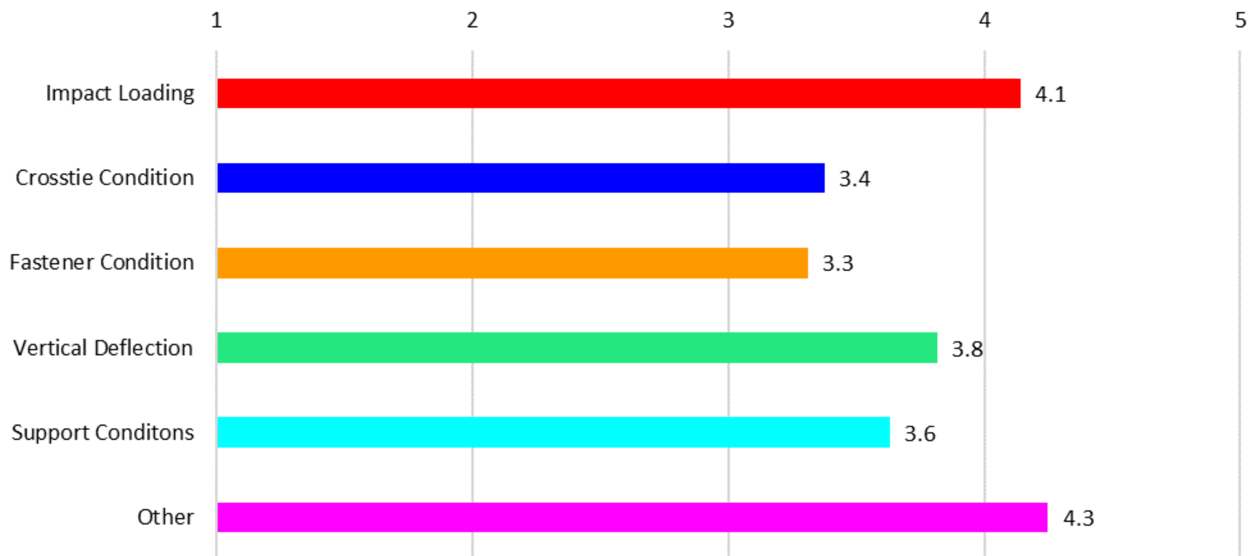
Other responses: Fastening system component stresses; Tie deflection to include gauge restraint measurement.

c. Substructure



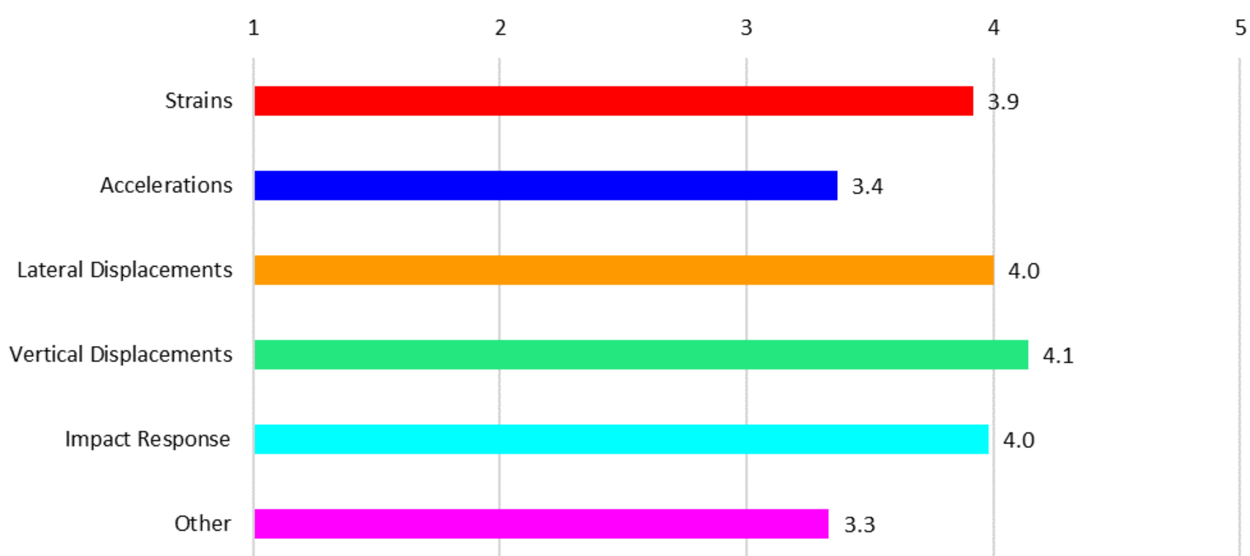
Other responses: Compressive forces/density; Moisture content as GPR or other technology to monitor for changes from prior condition; Fill saturation.

d. Special Trackwork



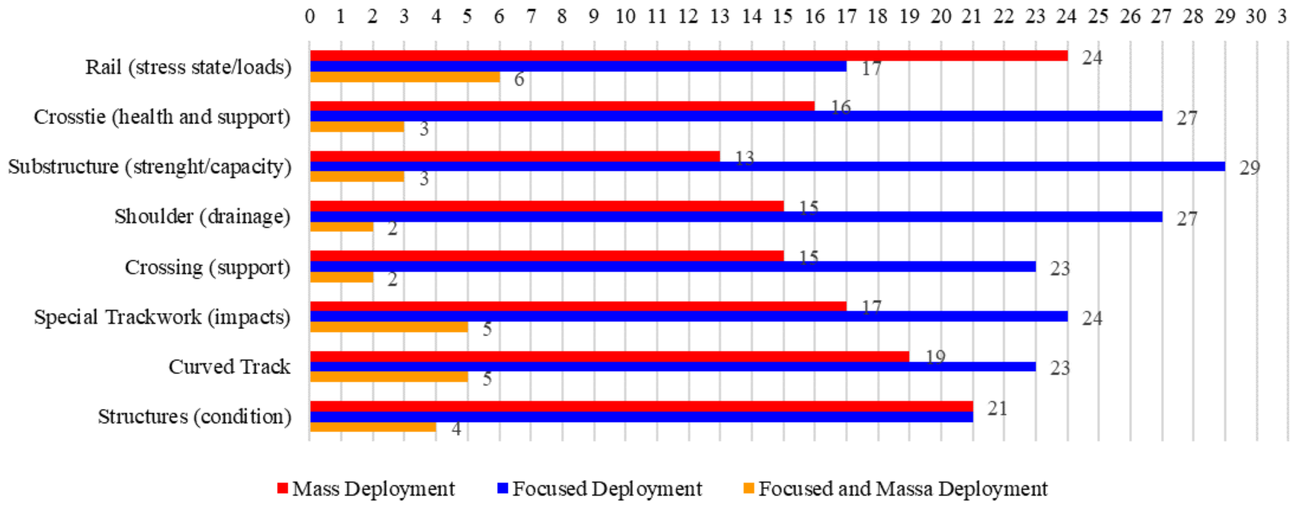
Other responses: Lateral loading of diverging route to check for overspeed or alignment issues; Locked in RNT.

e. Structures

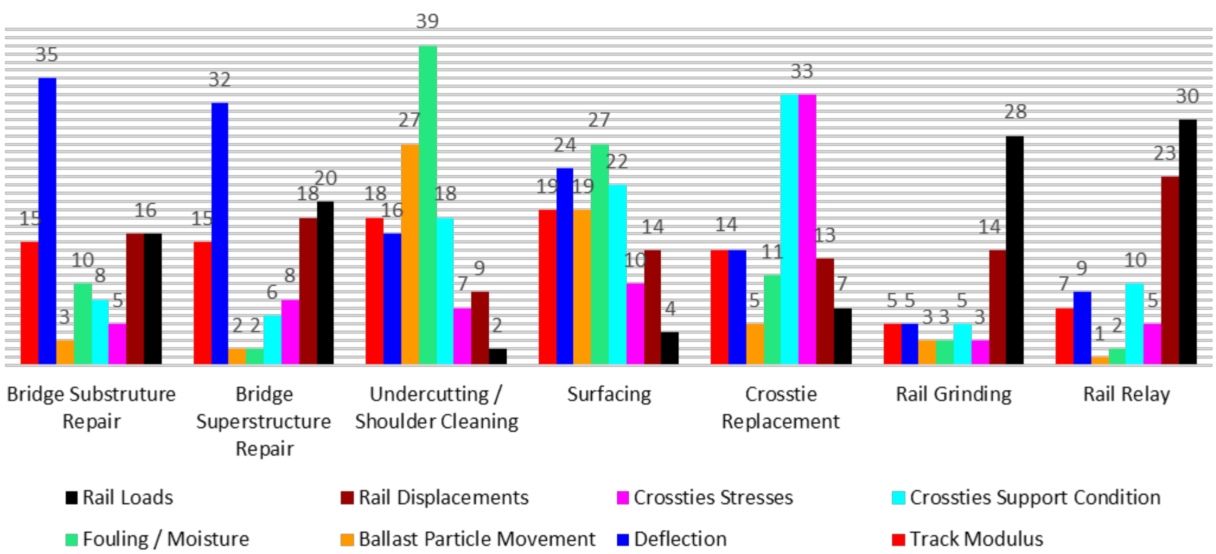


Other responses: Acceleration to monitor for earthquakes, impact to monitor for broken rail or wheel overloads.

5. **For the following elements of your track structure, which areas would you desire mass deployment (e.g., every component, every other component) vs focused deployment (e.g., once per subdivision) of instrumentation?**



6. **For the following maintenance activities, what information on the health of the track structure would best guide your prioritization of the following maintenance activities? (multiple selections per activity are allowed).**



7. Please provide any specific details on how you would use the above information.

- This information would be utilized to locate weak locations within the track system enhancing prioritization for maintenance and capital budgets.
- Rail relay or rail grinding cannot be timed based on those alternatives. Wear and surface faults are more critical indicators. Crossties are usually also visually broken before need for replacement. Ballast replacement can be based on fouling index. Weak subgrade can be seen as high deflection, which usually leads fouling on ballast and sub-ballast layers.
- These data would help better inform the intelligent distribution of maintenance activities. (I know, not very specific, but I do not make maintenance decisions.)
- Track geometry info usually is also important in these decisions - I would use track geometry data with the above measurements to prioritize maintenance
- I would consolidate the data obtained to prioritize my maintenance practices and focus on the critical areas based on the data and budget.
- Rate of changes of track modulus over time would correlate to ballast/subgrade condition, thresholds for this rate of change could trigger different maintenance actions. Structure deflections over time under comparable loads would indicate changes in the structural behavior and therefore merit Change in crosstie stresses and modulus could indicate deterioration of resilience on fastening components, demanding replacing pads Stresses on crossties could indicate loss of prestress which leads to cracked ties and then replacement.
- Deflection measurement will provide insight on the overall bridge behavior and excessive deflection means that a particular bridge requires continuous monitoring.
- Land slides and/or washouts by put out restrictions in sufficient time.
- Data received from this kind of monitoring would be useful in the planning of short term and long-term maintenance. It could also help to create focus inspection practices.
- To modify maintenance intervals to achieve the most cost-effective solutions to track maintenance while protecting against potentially unsafe conditions.
- The hardest things to monitor are what changes gradually, repeatable continuous monitoring can suggest trajectories of deterioration to guide remedial action. The second use for widespread monitoring it to detect surprises such as sudden changes in RNT and actual rail temperature, moisture in ballast and subgrade, dynamic gauge widening, impacts from breakouts of pieces of rail ends and frogs and from engine burns, and earthquakes.
- I do not have much experience from the maintenance side of our business, however from observation I have chosen the above choices with the following reasoning: For immediate responses, the above choices would be the best data to have in order to know when maintenance is required or to plan focused preventative maintenance for each track component. Long term, more data on the degree of ballast fouling (or/and ballast particle movement) and the associated locations on our system, along with the track modulus in these locations, could provide a better understanding of the root cause of the degradation of all track components.

- Most maintenance activities would benefit from rail/ track displacement data.
- Tamping.
- Determine slow orders. Order special inspections. Evaluate different solutions for similar problems. Maintenance / capital planning.
- Allow for a better planning and budgeting evaluation for work.
- We would like to think that we place the track where we want it to be. We only set it up where we would like for it to be, and the train forces move the track structure to a place where it best handles the given situation it operates in. Some of these movements are beneficial, some are not. Without extensive knowledge about how the track structure really handles the forces we apply to it. We are not making intelligent discussions about how to install and maintain track to a level that we get maximum reliability vs return on investment. For example, Continuous Welded Rail when you ask most railroaders what their main concern is, they say Buckled Track. They are completely wrong; it is about finding that perfect RNT that balances both Buckles and Pull-Apart. That one issue effects everything else noted in this survey.
- Monitoring rail neutral temperature (RNT) in given areas prone to buckles/pull-apart, or areas of plug rail installation could allow for better planning to make RNT adjustments prior to conditions of likely buckles and pull-apart. I would like to monitor subtle or sudden changes to the track structure from failing subgrade, failing hillsides, or structure bents.
- The monitoring of the combination of track on the bridge approach and bridge ends (first 30 feet +/-) could help determine what impact/additional loading on the bridge ends occurs from poor approach track conditions.
- Having access to the data above would allow the railroad industry to better monitor the development of defective conditions. This information would be useful in understanding the rate at which each type of condition develops under different circumstances, such as tonnage or climate. This would also allow for preventative maintenance in the early stages of defect development.

8. Fill in the blank question: If only I had ____X____ data and information, I would be able to make better ____Y____ decisions. These will help us formulate our instrumentation priorities. Please provide as many answers as you would like.

X	Y
lateral displacements in curves	curve rail/fastener replacement
real-time access and ability to select	safety and maintenance
crosstie	replacement
RNT	rail adjustment
Additional	Judgement

X	Y
At/along track locations where track stiffness changes, approach and exit track deflection data	Track condition and dynamic impact force assessment,
maintenance	replacement
true	wiser
Long Term rail base deflections	Evaluate insulator post thickness loss
crosstie condition	production tie replacement
strain	bridge superstructure
more filtered	prioritized
real time data	remedial action plan
rail stress	destressing
RNT	Destressing prioritization issues
Track Modulus	Ballast cleaning, drainage
Tie deterioration	Walking inspection locations
more accurate	budget
Thermally induced longitudinal rail stress near fixed objects	When to adjust rail to remove unsafe condition
Rail loads, lateral and vertical	Authorized speed for trains and super elevation
Rail clip and rail plate stresses and strain data.	Better understand the possible root cause of resulting plate rotations and rail clip breaks.
Concrete crosstie image	Concrete crosstie replacement
ballast moving	tamping
Tie conditions (wood)	Capital replacement
Temporary Joint compressive & tinsel forces.	What are the average forces they can handle?
Inexpensive RNT strain gauges to apply at every temporary repair	Improved RNT management timing/prioritizing adjustments
Bridge approach/bridge end condition	Maintenance
Lateral Loading	Inspection
real-time rail wear rates	rail replacement plans
ballast	undercut/replacement
ballast fouling	ballast cleaning and undercutting
Accurate	Prioritized
Subgrade instrumentation (depth and breadth) with accelerometers	Ability to assess the extent (depth and breadth) of effective subgrade and ground mass contributing to system excitement under dynamic forces
life expectancy	replacement
Long term crosstie stresses	Refine tamping cycles

X	Y
acceleration	bridge superstructure and substructure
usable	prioritized
layover/run over run data	prepare and plan our work
geo hazard warnings	stop train derailments
Ballast fouling and moisture content	undercutting prioritization
RNT	Slow Orders, Destressing
Excessive lateral movement in curves	Walking inspection focus
Change of stress factors in bridge components over abutment	Monitor for component failure to prevent critical system failure
Actual rail temperatures, continuously	Choice of RNT by location, monitor for first wave of summer heat to order daily visual inspections and precautionary speed restrictions
Ballast particle movement, ballast fouling and overall condition of track substructure.	Better understanding of the degree and rate of track component deterioration.
Concrete crosstie image	Infer support conditions and decide if subgrade work is necessary
crosstie cracks	adding ballast
Diamond impact loads	Schedule maintenance, replacement, and evaluate types of solutions
Locked in RNT readings at Plug installs	would know where my workforce has setup problems
Inexpensive/lo-fi slide monitoring	Expand "slide fence" significantly
Vertical Loading	Inspection
rail longitudinal stress measurements	destressing plans
rail	replacement
RCF crack depth	rail grinding
Sound measurements in service (frequency and intensity)	Correlations of track qualities with spectra of sound generated along the track
wear	maintenance
Rate of ballast fouling	Refine allowable stresses on track
tilt	bridge substructure
modulus	track design
Turnout condition / degradation	preventive maintenance
Longitudinal rail movement	Rail adjustment
Dynamic Gauge Widening	Replacement crosstie program

X	Y
Loading forces resulting from trains. (vertical, lateral, rotational forces from wheels)	Better choices in what types of product to install to support the loading and provide a smoother ride to customers.
crosstie support	adding ballast
Manganese frog / material performance	Not all manganese is equal however evaluating the difference quantitatively has not been done
Lateral curve movement in CWR	What is normal radial breathing and what is excessive
Actual Speed	Limiting speed
turnout	repair or to replace
behavior	development
deflection	bridge superstructure and substructure
Crosstie conditions	Program replacement scheduling
Dynamic Gauge Widening	Choice of types of fasteners and crossties
How rail shoe and contact rail interact upon impact with each other.	Limit the amount of arcing that may occur upon contact between the two surfaces.
Longitudinal rail creep at fixed points	Alert to potential track buckle situations
RNT	Inspection and remedial action
Rail wear	Program replacement scheduling
Ballast and subgrade moisture content, changes	Remedial embankment and drainage restoration
Monitor rail condition in dead zones	Alert to rail problems where signal current does not work
A hand-held method to measure stress state of rail.	be able to calculate a RNT
Quickly & easily deployable deflection measurement	surfacing
Monitoring tools that non-engineers could easily use and understand	day-to-day (i.e., non-capital) maintenance
Track inspection car results in time series	maintenance
Rail Displacements	Maintenance
Crosstie Stresses	Capital
Crosstie Support Conditions	Scheduling

9. Do you have any other comments or ideas you like to share with us?

- The challenge with wayside monitoring is figuring out where to put the measuring equipment. To capture the first signs of track distress may require instrumenting the entire railroad. And what frequency of instrumentation would that mean - every 10 feet on tangents, every 5 feet on curves, every switch and frog, every bridge and crossing approach? The overwhelming majority of measurement devices will work their entire life and not report anything of concern. So then do we concentrate on instrumenting known high-risk locations, such as mud spots, weak subgrades, fatigued or battered rail, and rail with suspected RNT issues? We are better off fixing these spots than merely monitoring their progressive decline. I think the more effective way to monitor track conditions is via a vehicle-based measurement system. Vertical rail acceleration (impact), vertical displacement and lateral acceleration are a part of well-established technology that does an excellent job assessing the condition of open track, turnouts, crossings, and bridges. Of course, there are some parameters that you have mentioned that cannot be measured by a vehicle, including RNT, ballast moisture content, ballast particle movement.

- I am focused on bridge testing and have experience in bridges, I did not want to express my opinion on track related issues and mislead the survey.
- Site monitoring is always difficult given a large network. We have a multitude of platforms to measure / monitor track already to help us make maintenance and capital decisions.
- While completing the survey I noticed there was not anything noted concerning Tunnel structures at various areas of Mountainous Regions. Would suggest getting feedback from FRA's Bridge group concerning questions in regards to bridge structures, etc; for a fair assessment with regard to the bridge structures questions in the survey.
- Acoustic monitoring was not mentioned, perhaps it can indicate when rail corrugation is becoming a problem or when lubrication is failing (e.g., flange squeal suddenly higher). Some way to monitor switch point wear would be valuable. Some way to measure differential displacement of rail ends in insulated joints may be an early intervention opportunity before visual inspection discovers failed adhesive and fasteners. Impact detectors at highway underpasses may prevent trains from traversing damaged bridges.
- It seems that there is room for using cameras/images to maximize the use of data provided and make better decisions.
- IoT based maintenance.
- Many of these solutions are available however they are not cost effective or practical in real business life.
- I am forwarding this survey to Al Cloutier Retired Amtrak and Peter Wright retired Amtrak. Both senior MOW engineering.
- Develop useful reporting forms (apps) that class II and Class III railroads can use during their normal activities that creates useful research material. I have seen many presentations where the researchers reference railroad data. Well, I look at and field verify railroad data all the time, across all US railroads. I know just how bad that data is, and it is getting worse. Make it easy, and as cheap as possible. The improved data you would get from those advances in reporting will pay off in tremendous ways.
- Perhaps a cheaper way to monitor some of the issues above, alignment in particular, could be more cheaply accomplished with numerous wayside devices (RFID?) read by an

autonomous car/inspection vehicle instead of expensive instruments placed at few locations. This could be especially useful in areas with significant curve breathing over an extended segment of track.

- Turnouts are a good point of monitoring, specifically in the frog section and at the switch point. At this point the switch condition could be monitored in addition to crosstie and ballast health.
- It is difficult to use a survey such as this to capture direct needs from the railroad. I would suggest a round table discussion to elaborate on capabilities and needs.

Appendix C: Survey of Wireless Technologies

In parallel with the prioritization of components and locations within the track structure that are in greatest need of monitoring (Sections 2 and 3), the project team undertook a survey of wireless communications technologies.

The use of wireless communications technologies for sensing has been explored by industry and academia for over two decades. However, only recently has the technology matured sufficiently for large-scale, robust, and ubiquitous wireless sensor deployments to become commercially feasible. Driven by advancements in electronics, battery, and radio transmission technologies, the development of small, low-power WSSs has provided an alternative to traditional wired instrumentation. By removing the need for running signal wires from the data acquisition system to the physical sensor, WSSs offer the potential to dramatically reduce installation and maintenance costs of the monitoring systems. Additionally, onboard processing capabilities of smart sensors allows for enhanced functionality and improved efficiency.

This section surveys wireless communications technologies deemed most suitable to supporting future Smart Track field sites. The suitability assessment was based on the typical characteristics of the sensor technologies and the data transport requirements of the various sensor modalities proposed to be included in the field site.

This assessment was divided into two categories: 1) technologies for communication within the Smart Track field site and 2) communication between the field site and the Cloud, where the acquired data is to be stored, processed, and evaluated.

1. Suitability Assessment Criteria

Several key features and metrics were identified to determine the suitability of communications technologies for use in the field site. Smart Track researchers classified these into primary and secondary groups. Primary metrics related to the functional requirements of the system and determine whether a technology was suitable to the task. Secondary metrics largely addressed non-functional requirements and help to differentiate between technologies within a group identified by the primary metrics. Finally, the application requirements determined and defined the ranges of the metrics needed to support the desired functionality.

1.1 Primary Metrics

Bandwidth, transmission range, and power consumption are the primary metrics used to assess wireless communications technologies. These metrics are independent of specific sensing technologies and their purposes and serves to divide communications technologies into different classes based on the combination of these parameters (e.g., long-range and high-bandwidth vs. low-power and short-range).

- *Bandwidth.* Bandwidth is defined as the amount of data transferred per unit time. To be suitable for use in the Smart Track field site, the technology must provide sufficient bandwidth to transmit the data generated by the sensors within a reasonable amount of time. Note that the bandwidth achievable in practice is always lower than the theoretical maximum bandwidth due to protocol overheads and data loss due to external interference.
- *Transmission range.* The transmission range determines the maximum distance between a sensor and a base station that a signal of sufficient strength can reach the receiver to

successfully transmit data. Since a typical field site is expected to span tens to hundreds of meters, maximum communication range is a key differentiator of suitability.

- *Power consumption.* Power consumption refers to the amount of energy needed to power the radio device. Since most WSSs are battery-powered, energy is a finite resource. Even if it is periodically replenished (e.g., via solar panel charging), the battery capacity determines the amount of energy available to power communication over a particular timeframe. Limited energy availability is the distinguishing feature of most wireless sensors and is the reason why communications technologies are created specifically to support low-power wireless devices, in addition to general-purpose communications technologies widely used in other types of devices.

1.2 Secondary Metrics

Secondary criteria can also be used to evaluate communications technologies. Once a group of technologies is found to be suitable by the primary metrics, consideration of secondary metrics further refines the selection of technologies that best meet the needs of a specific application.

- *Cost and availability.* Ideally, the radio hardware and communications services should be inexpensive and widely available commercially.
- *Frequency spectrum.* The frequency spectrum determines the bandwidth and transmission range of a technology, but also has secondary effects such as interference with outside signal sources and the ability of the signal to penetrate obstacles such as walls.
- *Antenna size.* While most technologies commonly in use have relatively small antennas, certain technologies and use cases require antennas much bigger in size.
- *Latency.* Latency refers to the length of time between when data is generated at the sensor to when it becomes available off-site. Due to the use of duty-cycling to save power, many wireless technologies can have significant latency beyond that determined by the amount of data generated and the bandwidth.
- *Future-proofing.* As technologies age, hardware implementing them becomes scarce and difficult to acquire, and communications services may stop supporting that technology entirely.
- *Value-added features*. Some devices provide additional features that either offer enhanced functionality not available elsewhere or improved efficiency, e.g., radios with hardware support for encryption and/or data compression.

1.3 Application Requirements

Future Smart Track field sites may contain dozens of smart sensor nodes, with multiple sensor channels per node encompassing different sensor modalities, sampling rates, power requirements, and data transport needs. Accelerometers and strain gages are the most common forms of instrumentation proposed for installation within the field site. These devices generate analog data at sampling rates ranging typically between 100 and 2,000 Hz. For a typical high-resolution sensor, that translates to 120 kB to 2.4 MB of data generated per sensor channel for a train crossing event lasting 5 minutes. This amount of data is negligible compared to streaming high-resolution video, yet it is several orders of magnitude higher that the design workloads for many IoT devices, which often generate data at the rate of a few bytes per minute. A radio with a bandwidth of at least 100 kbps, and ideally higher than that, is needed to extract data from tens of sensor channels spread across multiple devices within a reasonable time interval after the passage of a train.

The required transmission range to cover the length of a typical field site has to be over 100 m, and ideally longer than that, as transmission range in practice can vary significantly from the theoretical range, which is usually quoted as communication range under ideal conditions. These deviations can be due to the presence of nearby vegetation, which absorbs radio waves, or due to data loss caused by external signal interference.

For power consumption, typical radio transmitters designed for low-power wireless nodes have current draw during transmission and reception ranging from 15 to 50 mA. However, certain range-extended radios can have significantly higher power consumption, as much as 300 mA, trading off power efficiency for transmission range. The power consumption of a wireless radio must be matched by the battery capacity available on the smart sensor node.

2. Communication within the Field Site

Table A-1 provides a summary of the communications technologies that can be employed for communication between smart sensors within the field site and a local base station. After surveying the available communications technologies, the project team identified those most suitable for field site deployment by using the suitability assessment criteria outlined above.

Table A-1: Wireless communication technologies matrix for communication within field site

Wireless Technology	Metrics						
	Bandwidth (kbps)	Max Range (m)	Current Draw (mA)	Transceiver Cost ($)	Antenna Size	Latency	Additional Considerations
Bluetooth (BLE)	125 - 2,000	100	15	2 - 4	Small	Low	
IEEE 802.15.4	250 - 2,000	50	15 - 35	2 - 4	Small	Low	Protocol variety, hardware encryption and compression
IEEE 802.15.4 (range-extended)	250 - 2,000	1,200	150	3 - 5	Small	Low	Protocol variety, hardware encryption and compression
LoRa	0.2 - 5	10,000	20 - 135	5 - 15	Small	High	Adjustable range vs. power and bandwidth tradeoff
WiFi (2.4 GHz, 5 GHz)	11,000 - 900,000	150	150 - 300	10 - 15	Small	Medium	Potential interference with other WiFi networks

Communications Technologies

- *BLE.* BLE is a versatile low-power radio and protocol stack designed for small personal electronic devices but also widely used for wireless sensor connectivity. It is cheap, widely available, and offers a good tradeoff between bandwidth and power consumption. The transmission range of most available BLE chips is relatively short; however, range extension circuitry can be used to extend the range at the cost of power consumption.
- *IEEE 802.15.4.* This low-power wireless radio encompasses a range of higher-level communication protocols including Zigbee, 6LoWPAN, and WirelessHART. Designed for the IoT and a wide range of embedded devices, 802.15.4 offers similar bandwidth, range, and power characteristics to BLE. However, the much wider selection of available hardware and higher-level protocols make 802.15.4 among the most versatile solutions for wireless smart sensor communication.
- *LoRA.* An abbreviation for long range radio, LoRA is a relatively new technology that has emerged to support IoT and Smart City applications. As its name implies, it features a

significantly longer communication range, up to 10 km, than other low-power wireless communications technologies. The tradeoff is significantly reduced bandwidth, at under 5 kbps, which limits the application of LoRA to only a subset of the functionality expected to be used at the field site.

- *WiFi.* Perhaps the best-known wireless communication technology, WiFi is ubiquitous. It is used for connecting everything from personal computers, handheld devices, and industrial electronics. Today, WiFi technologies span a range of wireless frequencies that can offer significant bandwidth. However, shorter range and much higher power consumption set WiFi aside from technologies developed explicitly for low-power embedded systems. Certain applications (e.g., streaming video from a webcam), require WiFi due to the high bandwidth needs that may not be satisfied by lower-power alternatives. A larger battery and solar panel may be required to support WiFi for communication with embedded smart sensor nodes.

2.1 Suitability Assessment

Based on a range of metrics, **BLE** and **802.15.4**, were identified as the most broadly suitable technologies to support communication needs within the field site. They are similar technologies designed for similar use cases and provide an excellent balance in power-performance and high flexibility and configurability. Their main drawback, a relatively short transmission range, can be compensated with range-extension circuitry.

LoRA is not suitable for use in applications that require the transmission of the complete high-resolution data collected by the sensors due to its very limited bandwidth. However, given the capabilities of smart sensors to process data on-board, LoRA may have a role in deployments where only high-level aggregate data needs to be transmitted, e.g., only maximum vibration levels or significant deviations from historical norms.

WiFi covers the other side of the power-performance tradeoff compared to BLE and 802.15.4, offering meaningfully higher bandwidth at the cost of proportionally higher power consumption. WiFi may be required for certain field site deployments where data is generated at very high sampling rates and full dataset extraction is required.

3. Communication between the Field Site and the Cloud

Table A-2 provides a summary of the communications technologies that can be employed for communication between the field site's base station and the Cloud. These technologies are typically less specialized compared to the low-power communication modes discussed in Section 3.2, and their selection would be generally dictated less by a specific combination of features and more by availability at the location of the field site.

For satellite technologies in particular, a large variety of offerings targeting IoT applications have emerged, providing for a wide range of solutions with different bandwidth and power consumption parameters and at a range of prices for both the communication hardware and data plans.

Table A-2: Wireless communication technologies matrix for communication between field site's base station and the Cloud

Wireless Technology	Metrics						
	Bandwidth (Mbps)	Coverage Area	Current Draw (mA)	Transceiver Cost ($)	Antenna Size	Latency	Additional Considerations
Cellular (3G/4G)	7	High	100 - 200	<50	Small	Low	3G nearing obsolescence
Cellular (4G LTE)	150	High	100 - 200	<50	Small	Low	Backwards compatible with 3G/4G
Cellular (5G)	30 - 250	Limited	Varies	<50	Small	Low	New technology, limited availability, future-proof
Satellite	Limited	Global	Varies	100 - 500	Large	Medium	Additional bandwidth usage-based costs
Local Internet	10 - 1,000	N/A	N/A	N/A	N/A	Low	Not available at many field site locations
Mobile Base Station	Limited	N/A	N/A	N/A	N/A	Extreme	Bandwidth dependent on speed of train

3.1 Communication Technologies

- *Cellular.* Cellular communication is primarily used for cell phone connectivity. It also hosts a wide range of IoT and embedded devices that require internet connectivity. Cellular technology is continually evolving, with a range of devices and protocols currently in use:
  - *3G/4G.* These are older technologies that offer significantly lower bandwidth compared to more recent alternatives. In the U.S., 3G connectivity will begin to be phased out soon, making it a poor choice for a future-proof solution.
  - *4G LTE.* It is the most widely used connectivity option for modern devices, offering significant bandwidth, good power consumption performance, extensive commercial hardware and services availability, and a good geographic coverage footprint.
  - *5G.* This is the emerging standard for the next-generation cellular connectivity solution. At present, however, 5G coverage is extremely limited, and the bandwidth/power consumption ratio is generally much worse compared to 4G LTE. While 5G technologies may become suitable for the task of providing field site connectivity in the future, at present there is little compelling reason to select 5G technology.
- *Satellite.* While cellular communication covers large portions of the continental U.S., certain remote locations may have limited or no cellular coverage. Satellite communication provides an alternative for such cases. While typically a substantially more expensive option, new satellite networks currently being deployed offer the promise of cheap and ubiquitous satellite communication in the near future.
- *Local internet connection.* At certain locations, a wired connection to the internet is available, e.g., via Ethernet or WiFi. In these cases, it generally becomes the cheapest and most reliable connectivity option for the field site base station.
- *Mobile base station.* A railroad-specific solution, in some circumstances it may be suitable to mount a mobile base station on a traditional geometry car, ATGMS car, or hi-rail vehicle that periodically collects data from the field site as the vehicle traverses its location. While obviating the need for permanent connectivity between the field site and the Cloud, this solution dramatically increases the latency in retrieving the data, making it less suitable for exception notification and emergency reporting use cases.

3.2 Suitability Assessment

While all the communications solutions listed above can be employed to provide field site connectivity to the Cloud, **cellular** stands out as the most broadly applicable, cheapest, and best-supported by third-party communications service providers. Alternate technologies would generally be considered only when cellular is not an option due to coverage issues.

With 3G technologies nearing phase-out and their 5G counterparts still in early adoption stage, **4G LTE** is overwhelmingly the most appropriate option at the time of the development of this report and for the near future. Inexpensive, low-power cellular modems are readily available that can be added to embedded devices to provide 4G LTE connectivity in a modular fashion, requiring only a modest development effort for most WSS platforms. Bandwidth provided by a 4G LTE modem is expected to be sufficient, since the local communication technologies within the field site would act as the bottleneck limiting the total data exfiltration rate, rather than the cellular connection.

In remote areas where cellular coverage is lacking or very poor, **satellite** connectivity is generally the next-best option. New satellite constellations are currently being deployed that offer the promise of ubiquitous and inexpensive network access intended to support IoT devices. The Smart Track field site can take advantage of this emerging technology to replace cellular connectivity. However, at the time of this report, this option was strictly inferior to 4G LTE by both cost and bandwidth metrics.

Another notable alternative, the **mobile base station** provides an attractive option for certain types of monitoring deployments. While not suitable for near-real-time emergency notifications (due to the significant data collection latency) or full raw sensor data exfiltration (due to the short upload window), it does not require or depend on any third-party connectivity service, such as cellular, satellite, or wired internet, allowing the railroad to maintain all monitoring data within its private network. This option also lowers costs to end users by not requiring ongoing charges for connectivity or data usage.

Abbreviations and Acronyms

ATGMS	Automated Track Geometry Measurement Systems
BLE	Bluetooth Low Energy
CN	Canadian National (Railway)
DAQ	Data Acquisition
FRA	Federal Railroad Administration
IEEE	Institute of Electrical and Electronics Engineers
LoRa	Long-range radio (Wireless Communications Protocol)
RailTEC	Rail Transportation and Engineering Center
SBC	Single Board Computer
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TRL	Technology Readiness Level
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus
WILD	Wheel Impact Load Detector
WSS	Wireless Smart Sensor