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Reducing Hazards Associated with Visual and Automation-Aided Track Inspections

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14. ABSTRACT
Railroads are increasingly using automated track inspection technologies to augment the work of track inspectors in support of safety and productivity. The current study documents a human factors hazard analysis intended for both railroads and others interested in understanding hazards associated with track inspection, with and without the use of automation. The report makes recommendations to mitigate potential risks associated with railroad systems using only visual inspection, as well as potential risks associated with railroad systems using automated track inspection technologies along with visual inspection.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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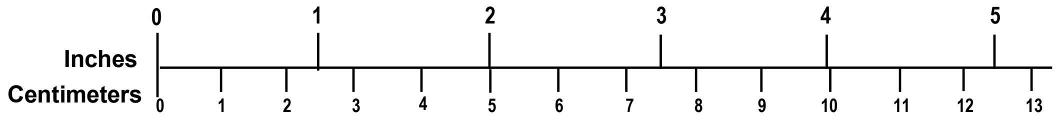
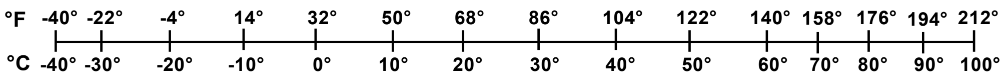
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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The team would also like to thank the subject matter experts who contributed to this effort by sharing their knowledge, reviewing sections of this report, or suggesting relevant literature and new ideas to the research team. In particular, the team thanks Don Wilson and Brian Marquis.

Lastly, the team would like to thank the Federal Railroad Administration’s Research, Development and Technology’s former Track Division Chief, Gary Carr, and the Track Division’s Engineer Robert Wilson for their guidance and feedback throughout this project.

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Executive Summary

As the use of automation in track inspection grows, the railroad industry can benefit from understanding how automated technologies impact the safety and effectiveness of the inspection process. To achieve this understanding, the Federal Railroad Administration (FRA) asked a team of human factors researchers from the U.S. Department of Transportation's Volpe National Transportation Systems Center (Volpe) to study both visual and automation-aided inspection processes from February 10, 2018, to March 31, 2020. This work took place at Volpe, with the exception of site visits to three passenger railroads for data collection. This study's objective was to identify factors that could lead to hazards during both visual and automation-aided track inspections and identify recommendations to address those factors. The Volpe team focused on track inspection processes that use automated track geometry measurement technology because they are the most widely-used forms of automation-aided track inspection in both freight and passenger rail environments.

The Volpe team considered three sociotechnical systems, where "sociotechnical system" refers to the combination of people, technologies, and actions and feedback that make up a railroad's inspection process. To reflect current inspection practices and allow for the analysis of human-automation interactions, all three sociotechnical systems include a visual inspection component. The three sociotechnical systems included in the hazard analysis were:

1. **Visual Inspection sociotechnical system**: A railroad inspection system where visual inspection is the sole mode of inspection used to find track issues and no automated inspection technologies are used to supplement the process
2. **Conventional TGMS & Visual Inspection sociotechnical system**: A railroad inspection system where both visual inspection and a conventional track geometry measurement system (TGMS) (i.e., a staffed "geometry car") are used to find degraded track conditions
3. **aTGMS & Visual Inspection sociotechnical system**: A railroad inspection system where both visual inspection and autonomous track geometry measurement systems (aTGMS) (i.e., an unstaffed, locomotive-mounted system) are used to find degraded track conditions

The team analyzed each of these three sociotechnical systems using Systems Theoretic Process Analysis (STPA), a hazard analysis approach designed to examine complex sociotechnical systems, including how both human and technological components can impact safety. Data collection consisted of reviewing relevant literature, speaking to track inspectors and managers at three passenger railroads, and consulting with other subject matter experts (e.g., FRA track inspectors, labor union representatives, other track inspection researchers, and automated technology manufacturers). The team used this information to identify and document how the track inspection process works, including the role of the inspector, the role of the automation, and the types of human-technology interaction required. The team also learned and documented what railroads do once a defect is found and how the inspection process fits into the broader track lifecycle, which includes inspection, maintenance, and operations.

To capture this information, the Volpe team created a functional model of each sociotechnical system, which the team used as the basis for the STPA hazard analysis. During the analysis, the team identified how each action in the inspection process could lead to undesirable conditions, or hazards. Then the team developed a comprehensive set of scenarios that describe how combinations of factors could potentially lead to undesired events, or accidents. By identifying ways to address contributing factors from these scenarios, the team developed a set of recommendations railroads can use to assess and strengthen their current inspection processes and safety measures.

Major themes that emerged from these recommendations include the need for strong user-centered design when incorporating new technologies, the value of hands-on training, the importance of communication and coordination, and a need to manage the impact of production and resource pressures on inspection and maintenance activities.

Railroads can use these recommendations to assess their practices and mitigate potential risks, thereby strengthening the safety of their current inspection process. Although the team developed these recommendations to address potential risks associated with visual inspection and track geometry measurement systems, railroads may use them as a baseline when assessing future inspection technologies.

For future work, researchers may consider turning their attention to freight railroads, to the repair and replacement part of the maintenance process, or to employee safety during inspection and maintenance, all of which were outside the scope of the current work. Additionally, it may be valuable to apply STPA to other, more novel inspection technologies to identify and mitigate potential risks while the automated technology is still developing and evolving. This would also allow researchers to examine how broadly the recommendations in this report can be applied to technologies beyond TGMS.

1. Introduction

As the use of automation in track inspection grows, the railroad industry can benefit from understanding how these technologies impact the safety and effectiveness of the inspection process. In particular, it is important to understand how these new technologies affect the roles of track inspectors and other workers, and how railroads can best integrate humans and technology within the inspection process.

To achieve this understanding, the Federal Railroad Administration (FRA) asked a team of human factors researchers from the U.S. Department of Transportation's Volpe National Transportation Systems Center (Volpe) to study both visual[1] and automation-aided inspection processes. The Volpe research team gathered data on these processes, developed models for the human-technology interactions within them, and conducted a systematic analysis to identify risk factors and develop recommendations for railroads to improve their inspection processes.

This report is intended for both railroads and research audiences interested in understanding hazards associated with track inspection, both with and without the use of automation.

1.1 Background

To maintain track safety, railroads inspect their infrastructure to identify defects and degraded track conditions that occur over time. Most track inspection is performed by human inspectors, but as new automated inspection technologies are developed, railroads are beginning to rely on automation more heavily. Automation offers potential benefits, such as increasing the speed of track inspections and enabling the detection of track conditions that are difficult for human senses to detect. However, humans and automated technologies both have strengths and limitations that shape the track inspection process, and changes to railroads' existing processes may introduce new hazards.

1.1.1 Visual Inspection

FRA regulation specifies the required frequency for track inspections for each track class (Electronic Code of Federal Regulations, 2020). The track class specifies the speed at which trains can operate safely, with higher track classes indicating higher maximum operating speeds. As track class increases, the requirements for track become stricter and inspections occur more frequently. Railroads must inspect track classes 4 through 8 twice weekly, and lower classes of track once or twice weekly, depending on how much traffic operates over those tracks. Track other than main line and sidings requires less frequent inspection.

To accomplish these inspections, the Code of Federal Regulations (CFR) specifies that railroads may inspect "on foot or by riding over the track in a vehicle at a speed that allows the person making the inspection to visually inspect the track structure for compliance" (49 CFR § 213.233(b)). This report refers to such inspections as "visual inspections."

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[1] This document refers to human inspection as "visual" inspection. This type of inspection is commonly understood to encompass the use of other senses as well and so is not exclusively visual. However, the term "visual" is used in the FRA regulation and is the term used by industry professionals when referring to inspection conducted by a human.

1.1.2 Automation-Aided Inspection and Track Geometry Measurement Systems

The CFR also allows railroads to use "mechanical, electrical, and other track inspection devices" to supplement visual inspection (49 CFR § 213.233(b)). Railroads have been using some form of automated inspection technology since the 1970s. Currently, all U.S. Class I railroads use some form of automated inspection technology for track geometry, rail profile, or gage restraint measurement (Carr, Tajaddini, & Nejikovsky, 2009).

The most common automated track inspection technologies, and the ones focused on in this report, are track geometry measurement systems (TGMS) (Al-Nazer, Raslear, Wilson, & Kidd, 2017; Al-Nazer, et al., 2011). In a 2011 survey of track workers, 96 percent of respondents indicated that their railroad supplements main line visual inspections with TGMS, and over 75 percent of inspectors receive reports from TGMS (Stockton, 2011).

The prevalence of TGMS use may be due in part to Federal regulation. For track classes 6 and above, the CFR requires railroads to use TGMS in addition to visual inspections (49 CFR § 213.333). For class 6 track, the CFR requires TGMS inspection at least once per calendar year. It requires more frequent TGMS use for classes 7, 8, and 9.

Although the CFR does not require such inspections for lower track classes, many railroads choose to use TGMS and other automated track inspection technologies to supplement visual inspections. These supplementary inspections have many potential benefits, including:

- Taking measurements that would be cumbersome or impossible by hand
- Identifying problem areas quickly to help focus visual inspections
- Providing consistent data so railroads can monitor changes over time (Berry, Nejikovsky, Gilbert, & Tajaddini, 2008; Edwards, et al., 2009; Cabrera & Vargas, 2013)

As the capabilities of automated inspection technologies increase, railroads seek new ways to use these automated technologies to improve safety, increase productivity, and reduce costs. Some railroads use frequent TGMS inspections to reduce the frequency of their visual inspections, which the CFR permits if railroads petition FRA and receive a waiver (49 CFR § 213.317).

Many automated track inspection technologies, such as conventional TGMS "geometry cars," still require staffing and track time to collect and process the information. Therefore, although they do provide detection support, they do not alleviate the challenges associated with obtaining track time for inspections (except in cases where the railroad requests a waiver for reduced visual inspections).

More recent automated track inspection technologies use instruments mounted on revenue trains to collect data and reduce the engineering department's need for track time. The information processing that took place while the track geometry vehicle was operating over the track takes place remotely after the data has been collected. The industry refers to TGMS technologies of this type as "autonomous" track geometry measurement systems (aTGMS). These automated technologies can operate without obtaining track time and do not require a dedicated onboard operator (Carr, Tajaddini, & Nejikovsky, 2009).

1.1.3 Human-Machine Interactions in Track Inspection

It is important to understand how the use of inspection technologies can change the track inspection process and the role of railroad employees. The most obvious impacts are on the track inspectors themselves, who now have an additional source of data to consult, which may reduce their workload and help them complete their tasks more quickly (or, create additional workload through required verifications). However, these changes also impact the track supervisors, managers, and dispatchers who are involved in coordinating track inspection activities. Furthermore, the use of technology can introduce new roles, like data analysts and technology operators.

This study seeks to understand the risks to introducing technology (specifically**,** TGMS and aTGMS) and increasing the complexity of the track inspection process. It also seeks to model the current visual inspection process and identify the risks associated with visual inspection to provide recommendations for railroads that have yet to introduce additional automation.

Understanding the hazards associated with both visual and automation-aided inspections can help in designing future track inspection processes that optimize the capabilities of human and technology for the benefit of safer and more efficient track inspection.

1.2 Objectives

This study's objective was to identify factors that could lead to hazards during both visual and automation-aided track inspections and identify recommendations to address those factors.

This study attempts to answer questions such as:

- What hazards are associated with the visual inspection processes?
- What hazards are associated with the use of new inspection technologies?
- How do changes in human-technology interactions impact safety?
- How can railroads mitigate these hazards associated with track inspection?

The Volpe team selected TGMS as a case study because it is one of the most widely used forms of automation-aided track inspection in both freight and passenger rail environments. Given that even small railroads may use TGMS in some capacity, and many railroads are moving toward greater use of TGMS, this choice lends itself to developing recommendations that are relevant across the industry. Many of the recommendations can apply to other types of automated inspection technology besides TGMS.

To reflect the variety of ways that automated inspection technology can be used, the team examined two types of TGMS:

- Conventional TGMS, which is mounted on a train that is not in revenue service and requires an onboard staff to operate it and review the data as it is collected
- aTGMS, which is an unstaffed type of TGMS that is mounted to revenue service trains and sends data to be reviewed offsite

For each of these inspection technologies, the Volpe team examined not only the inspection technology itself, but also the context in which it operates, called a "sociotechnical system." As shown in Figure 1, a sociotechnical system is a collection of people, technology, and organizational processes which interact with one another to accomplish a shared purpose.

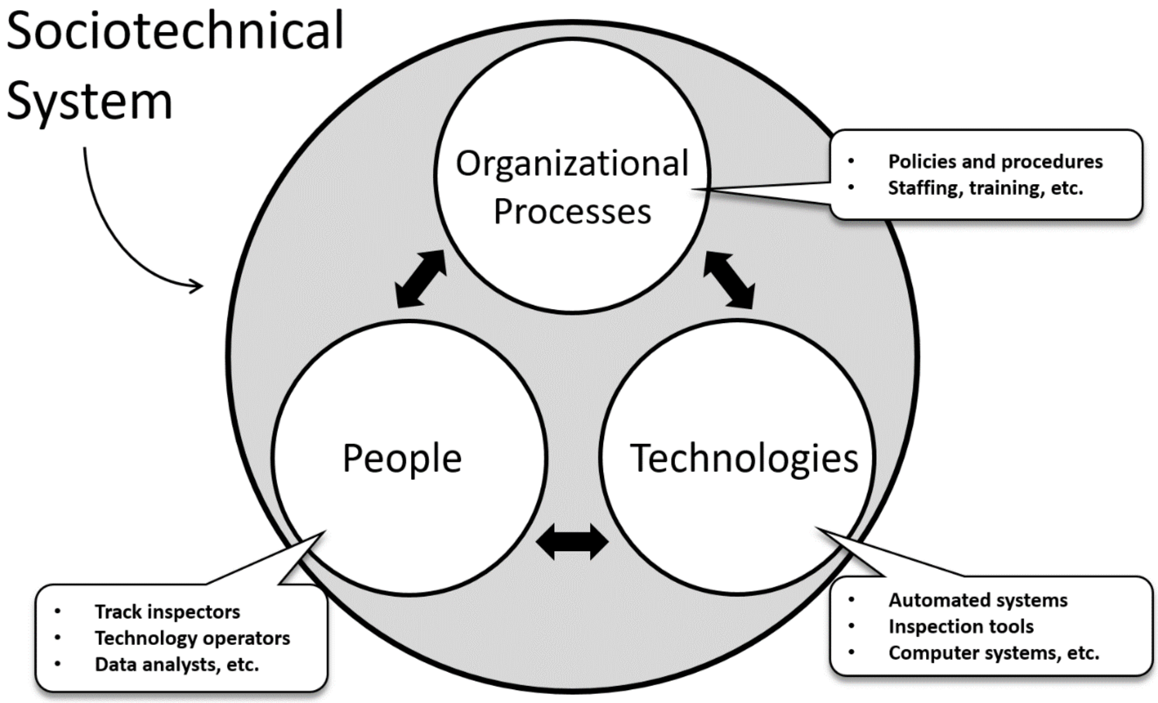

Figure 1. Simple model of a sociotechnical system

The term "system" can have multiple meanings, so this report attempts to reduce the possibility of confusion by specifying the type of system referred to as often as possible.

- Where the team refers to a sociotechnical system, the word "sociotechnical" will generally be included.
- Where the team refers to a type of technology, such as TGMS, the team will generally try to replace the word "system." For example, "automated technology" instead of "system" or "automated system."
- Where a specific other type of system is referred to, the team will often try to include the type of system to aid in understanding. For example, "a data-logging system" or "an information technology (IT) system."

When modeling track inspection sociotechnical systems that used one of the two types of TGMS, the Volpe team assumed that these automated technologies were used in conjunction with visual inspection. This reflects current usage of these technologies at the railroads the team visited, and allows the team to examine how the automation interacts with visual inspection processes.

After comparing these sociotechnical systems against each other and against a sociotechnical system that only uses visual inspections, the team developed recommendations to strengthen current track inspection processes, including facilitating successful interactions between humans and technology.

1.3 Overall Approach

The overall approach for this study included four main activities: data collection, modeling, hazard analysis, and developing recommendations.

1. **Data Collection**. The Volpe team collected data from several sources to support identification and documentation of the track inspection process. The team's data collection efforts included:
    a. Reviewing relevant literature
    b. Speaking to employees at three passenger railroads
    c. Consulting with subject matter experts (e.g., FRA track inspectors, labor union representatives, other track inspection researchers, and inspection system manufacturers)
2. **Modeling**. Following data collection, the Volpe team created a functional model for each of the three sociotechnical systems being studied, to use as the basis for the hazard analysis. These models capture what the team learned about the role of the inspector, the role of the automation, and the types of human-technology interaction required. The team also sought to understand how the inspection process fits into the broader track maintenance lifecycle (i.e., inspection, repair and/or replacement, and operations).
3. **Hazard Analysis**. The team used a systems-based hazard analysis method called Systems Theoretic Process Analysis (STPA). STPA is a method that can be used to systematically identify potential risks, particularly those related to human-technology interactions. Using STPA, the team:
    a. Identified contributing factors that could lead to undesirable conditions
    b. Developed a comprehensive set of scenarios that describe how combinations of sociotechnical system factors could potentially lead to undesired events or accidents
4. **Developing Recommendations**. Lastly, the team generated recommendations to address the contributing factors identified in the STPA scenarios. This report includes those recommendations, which railroads can use to assess and improve their current inspection processes.

1.4 Scope

Though the track maintenance process and lifecycle encompasses much more than detection of track defects, this analysis focused on hazards associated with detecting and reporting defects, rather than prioritizing and performing maintenance. Therefore, the team includes some discussion of maintenance only when directly related to the study's focus (e.g., maintenance sometimes performed by inspectors). This decision enabled the team to perform a deeper analysis on the inspection portion of the track maintenance lifecycle. The Volpe team directed its efforts on inspection technologies associated with TGMS because it is currently the most widely-used form of automation-aided inspection.

Similarly, this analysis was primarily focused on identifying scenarios that could lead to unsafe events during operations (e.g., derailments due to unaddressed track defects). There are other hazards associated with track inspection, such as injuries to track workers, damage to equipment, or an undue economic burden imposed by inspection activities, but these are beyond the study's scope and not examined in detail in this report.

As previously noted, this study focused on two variations of TGMS. The inclusion of these two variations may reflect, to an extent, the variation in how other automated technologies are used in the railroad industry. Therefore, some of this study's findings will be relevant to other forms of automation-aided inspection; however, given that the team's data collection focused on TGMS, railroads should use their judgment when applying this report's recommendations to the use of other automated technologies.

Lastly, track class and type of service (passenger or freight) impact the requirements for inspection frequency and the permissible thresholds for track conditions. However, for the purposes of this study, the team determined that examining the human-automation interactions within the track inspection process did not require differentiating between these contexts. To gather data on the two variations of TGMS examined in this study, the team visited railroads that used TGMS and aTGMS to conduct their interviews and observations, without consideration for track class or type of service. As a result, the team collected data from passenger railroads only. The Volpe team expects that the findings of this study would be relevant to freight railroads; however, there may be some differences in how inspection processes are handled in freight operations.

1.5 Organization of the Report

This report is divided into nine sections, as follows:

- Section 2 provides additional information about the research context.
- Section 3 describes the study's research methodology, including data collection, model development, and the STPA hazard analysis.
- Section 4 describes the track inspection process and presents a general model that applies to both visual and automation-aided inspections.
- Section 5 presents a comparison of three sociotechnical systems that the team used for their hazard analysis, including functional models of each sociotechnical system.
- Section 6 describes sociotechnical factors that impact track inspection, using examples from interviews with railroad employees.
- Section 7 provides recommendations for addressing potential risk factors in visual and automation-aided sociotechnical systems based on the team's hazard analysis.
- Section 8 discusses the study findings, including a comparison of the strengths and weaknesses of both visual and automation-aided inspections.
- Section 9 presents the study's conclusions and suggestions for further research.

2. Research Context

This section provides additional context and background for the reader to understand visual and automation-aided track inspection processes. It discusses the following topics:

- **Defects and maintenance conditions**. What are the thresholds that railroads use to identify degraded track conditions? What is required by regulation?
- **The visual inspection process**. How inspections are typically accomplished? What factors affect inspectors' ability to perform their jobs?
- **Automated track inspection technology**. What are some of the benefits and drawbacks of using automated track inspection technology? How automated are these technologies?
- **Systems perspectives on track inspection**. What does it mean to take a systems perspective? Why is this relevant to track inspection?

2.1 Defects and Maintenance Conditions

Degradation of track and other rail infrastructure typically occurs gradually over time as a result of normal operations and environmental conditions. Sometimes degradation may occur more quickly due to exceptional events (e.g., severe weather or environmental conditions, or abnormal train-track interactions).

Railroads conduct track inspections to identify degraded track conditions so that the railroad can repair or replace components when necessary, or adjust their operations to fall within safe limits given the current conditions.

Degraded track conditions that require the railroad's attention fall into two broad categories:

1. *Safety defects*: Track conditions that exceed the FRA safety regulations for a given track class.[2] A safety defect requires that the railroad takes immediate action to address it. This may involve restricting the speed at which trains and equipment can travel over the track (i.e., reducing the track class so that the condition is within the threshold for the new track class, and no longer considered a defect). It may also be addressed by removing the track from service or repairing the track.
2. *Maintenance conditions*: Track conditions that do not exceed thresholds set by FRA safety regulations, but exceed the maintenance standards that railroads set for themselves. The actions that a railroad takes in response are similar to those for a safety defect. However, the railroad has more discretion about when to act and how to respond.

FRA lays out compliance requirements for the inspection process in 49 CFR Part 213–Track Safety Standards. Conditions that do not comply with these standards are referred to as defects. There are 21 categories of defects listed in Subparts B through F of 49 CFR Part 213, summarized in Table 1. This means that the inspector has numerous defects to search for simultaneously. When the inspector identifies a defect, immediate action is required.

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[2] For simplicity, this report uses the term "exceeds regulations" to refer to any conditions that do not meet the regulatory standards.

Table 1. Categories of defects included in 49 CFR Part 213

Roadbed Defect	Track Geometry Defect	Track Structure Defects	Track Appliances & Track Related Devices Defects
• Drainage • Vegetation	• Gage • Alinement • Curves; Elevation and Speed Limitations • Elevation of Curved Track; Runoff • Track Surface	• Ballast • Crossties • Rail-End Mismatch • Rail Joints • Torch-Cut Rail • Tie Plates • Rail Fastenings • Turnouts & Track Crossings • Switches • Frogs • Spring Rail Frogs • Self-guarded Frogs • Frog Guard Rails & Guard Faces; Gage	• Derails

In addition to looking for immediate safety risks that exceed the FRA safety standards, inspectors also search for degraded conditions that do not meet railroad-established maintenance standards. By identifying and acting on these maintenance conditions before they become defects, railroads have more flexibility in how and when to address them. By setting their own standards for maintenance that are stricter than FRA's standards, they address potential hazards earlier and reduce the potential risk for an adverse event. Dictating stricter thresholds than FRA requires allows railroads to decide when to repair or replace degraded track conditions that are not yet defects in a way that minimizes the impact on revenue service.

The railroad's maintenance standards may also consider factors besides safety that can impact their operations. For example, passenger railroads care about ride quality and how it impacts their passengers. Railroads also monitor lower-level degraded track conditions as part of a capital planning strategy. Capital planning enables railroads to maximize their limited resources and minimize the impact on revenue services.

2.2 Visual Inspection Process

FRA requires railroads to visually inspect track on a regular basis, with the required frequency dependent on the track class and operating speed.[3] For the most common track classes in passenger and freight operations, railroads must inspect the track twice a week.

Railroads employ track inspectors who perform visual inspections in two ways:

1. Walking the track
2. Operating a hi-rail vehicle to travel along the tracks

Inspectors may use just one of these methods or a combination of the two depending on their territory characteristics and the time available for inspection. Some railroads inspect track infrastructure like high-speed turnouts and complex interlockings on foot. Railroads with very large territories and frequent train movements are more likely to inspect track via hi-rail because the inspector cannot cover the territory on foot within the available time.

To make this inspection manageable, railroads assign each track inspector responsibility for a section of track, (i.e., the inspector's territory). Territories vary in size depending on complexity (e.g., switch inspections, number of tracks) and the type of inspection method used to cover it (i.e., on foot vs. hi-rail). Over time, track inspectors get to know their territory, which helps them identify vulnerable areas (e.g., track curves, grade crossings, locations near bodies of water).

Inspectors typically work 8–10 hour shifts, but they frequently work beyond the scheduled workday, sometimes working on rest days (Al-Nazer, et al., 2011). As part of the inspection process, inspectors document their findings and may perform minor repairs. Waiting for track time and traveling between locations takes up additional time. These tasks take away time from performing inspections (Al-Nazer, et al., 2011).

The amount of territory an inspector can cover depends on considerations such as the inspection method (e.g., hi-rail or on foot), the number of curves on the track, the type of rail (e.g., jointed or continuous welded), weather and track visibility, and time constraints. Time constraints contribute to time pressure that can hinder the inspectors' ability to detect defects effectively (Al-Nazer, et al., 2011).

In a report of survey findings, the Brotherhood of Maintenance of Way Employes Division (BMWED) described a high-pressure work environment for track inspectors. Some inspectors feel pressure from management to avoid overtime, as well as pressure from dispatchers to limit track occupancy time and minimize slow orders. In some cases, track inspectors may feel discouraged from reporting too many issues that the railroad will have difficulty addressing quickly. Many inspectors indicated that they felt their territory was too large to inspect in the time available, and that time spent on repairs limited their ability to complete inspections. Some indicated that having a second qualified inspector available could improve the quality of inspections (Stockton, 2011).

Training is also a significant concern for track inspectors. The BMWED survey indicated an opportunity for "succession planning" as experienced track inspectors retire (Stockton, 2011). Wolf (2019) writes: "a new generation of railroaders is upon us, and the need for training and

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[3] 49 CFR Part 213.317 allows for railroads to request a waiver for these requirements. For example, if a railroad uses TGMS sufficiently often, FRA may permit the railroad to reduce the frequency of visual inspections.

understanding is paramount." Al-Nazer et al. (2011) described several issues that could be improved through standardized training and minimum training requirements, including uncertainty regarding appropriate speeds for hi-rail inspections, and challenges detecting defects like loose bolts which are detectable through non-obvious visual or auditory cues.

While a multi-pronged approach is needed to address these challenges to the visual inspection process, some can be improved upon through the use of additional technologies to supplement visual inspection.

2.3 Automated Track Inspection Technologies

Automation offers many potential benefits, including fast, consistent data collection, avoidance of human errors and risks like distraction, and increased overall safety (Woodland, Menon, & Blanchard, 2015). Railroads began using automated inspection technologies in the 1970s, and researchers have credited automation with a reduction in derailments over the past few decades (Carr, Tajaddini, & Nejikovsky, 2009).

A wide range of technologies exist to detect different types of track defects. Table 2 provides examples of some of these technologies.

Table 2. Examples of automated track inspection technologies

Name	Description	Purpose
Track Geometry Measurement System (TGMS)	Specially equipped "geometry cars" used to measure track geometry in a loaded condition	Characterizes vertical and lateral deviation, gage, and cross-level measurements
Machine-vision	Uses algorithms to examine images or light detection ranging (LIDAR) data	Identifies surface defects for later visual review by a human
Gage Restraint Measurement System (GRMS)	Measures gage deviation under a lateral load	Measures gage strength and identifies weak ties or fasteners
Ground penetrating radar (GPR)	Uses electromagnetic waves to examine layers of track structure	Identifies ballast and sub-structure issues that may lead to settling and later affect track geometry
Vehicle-track interaction systems (VTI)	Accelerometers placed on the rail car body (above suspension) and truck (below suspension)	Indicates dynamic forces input into track structure, to identify areas at higher risk of deterioration

2.3.1 Benefits of Using Automation

Railroads may seek to automate aspects of their track inspection processes for many reasons. The two largest reasons are: (1) making more efficient use of resources and (2) enhancing safety through the detection of degradation or defects that humans may miss.

Automated inspection technologies can collect large volumes of data with a high degree of accuracy and consistency, and when used with sufficient frequency, they can provide a means for railroads to more efficiently monitor track condition over time. Railroads can use this type of data to identify trends and make strategic decisions regarding when to perform maintenance

(Carr, Tajaddini, & Nejikovsky, 2009; Cabrera & Vargas, 2013; Berry, Nejikovsky, Gilbert, & Tajaddini, 2008; Edwards, et al., 2009).

In some cases, where automated technologies have greater sensitivity to detecting minor degradations than human inspectors, these technologies can allow railroads to detect conditions earlier than visual inspection. By detecting these issues before they become safety defects, railroads gain flexibility in deciding when and how to address them. Lester (2019) notes that automated inspection technologies including TGMS have provided railroads with a better understanding of track conditions and facilitated improvements to the maintenance process. Specifically, the author describes a shift from reactive maintenance (replacing assets that have failed) to preventive maintenance (replacing components that may fail), and describes how automation can facilitate predictive maintenance, or using track condition data and to more accurately understand when to replace components.

Railroads also use automated inspection technologies to guide or supplement visual inspections. Evolving technological capabilities have made it possible to identify defects that prior automated technologies could not detect. For example, automated technologies have been developed using video data and machine vision (Berry, Nejikovsky, Gilbert, & Tajaddini, 2008; Cabrera & Vargas, 2013; Edwards, et al., 2009). Such technology developments have been particularly beneficial for difficult-to-detect defects like joint bar defects, rail seat abrasion, and torch cut rail (Berry, Nejikovsky, Gilbert, & Tajaddini, 2008). Given that regulations require the inspection of 21 elements, some of which are difficult to detect by human inspection alone, there may be significant benefits to developing this capacity for automated technologies to support humans in detecting these types of defects.

If automation is used to support the human in accomplishing the required inspection tasks, it may reduce time pressure on inspections and supplement the limitations of sensory capabilities and cognitive resource limitations, such as fatigue. By highlighting problem areas, the data from automated inspections may reduce the track time required for visual inspection (e.g., by allowing inspectors to complete inspections more quickly) and lessen the impact on revenue service (Berry, Nejikovsky, Gilbert, & Tajaddini, 2008; Edwards, et al., 2009). Alternately, if inspectors spend the same amount of time inspecting, using the automated inspection data may allow them time to examine other issues more thoroughly by freeing up cognitive resources.

Railroads can also provide data from automated inspections to maintenance crews to help them locate components in need of repair or replacement (Cabrera & Vargas, 2013), potentially reducing time burdens for maintenance tasks. If the automated inspection output contains sufficient information to share directly with maintenance crews, this may also reduce the burden on inspectors who would otherwise need to identify and document those defects during visual inspections.

To further reduce the track time required for inspection, there is an emerging trend toward automated inspection technologies that are mounted directly to revenue service vehicles and do not require a dedicated operator. The industry refers to such technologies as “autonomous” (Carr, Tajaddini, & Nejikovsky, 2009).

2.3.2 Complexities of Using Automation

Automated track inspection technologies collect more data than ever before. However, introducing such automated technologies can lead to new challenges. It is beyond the scope of this report to cover all the complexities of using track inspection automation; however, the current section covers some of the complexities addressed in prior research and which are relevant to the current study.

Automated technologies can allow for faster data collection with fairly high accuracy. Al-Nazer et al. (2017) found no overall difference in detection rates between visual hi-rail inspections and TGMS inspections. However, there are some differences in the types of conditions these technologies are sensitive to, compared to visual inspection. Researchers in the same study found that TGMS may be more sensitive to track geometry safety defects, while human inspectors may be more sensitive to conditions requiring maintenance (Al-Nazer, Raslear, Wilson, & Kidd, 2017).

There can also be costs associated with placing too much focus on reduction of false alarms: namely, increasing the rate of misses (i.e., failure to detect a degraded track condition). Al-Nazar et al. (2017) noted that both visual hi-rail inspections and TGMS inspections may be biased toward indicating that there is no defect. This behavior may be influenced by prior observations: the frequency of defects was low for this study, which lowers inspectors' and operators' expectations that a defect will be present, potentially biasing them toward non-detection. However, detection rates can also be shaped by the incentives set by the railroad, either intentionally or unintentionally. If a railroad places a greater value on avoiding misses, this will lead to more false alarms. If they instead place a greater value on avoiding false alarms, this will lead to more misses. Therefore, railroads teach both inspectors and technology operators to use appropriate detection criteria based on what the railroad considers acceptable rates for both misses and false alarms (Al-Nazer, Raslear, Wilson, & Kidd, 2017).

For some emerging automated technologies, such as the use of video and advanced image processing to inspect joint bars, it can be difficult to strike an acceptable balance of misses and false alarms given current technological capabilities. Technology developers are working on improving detection algorithms to address these limitations (Berry, Nejikovsky, Gilbert, & Tajaddini, 2008).

An additional challenge for automated inspection is the requirement for visual verification of defects. Given that railroads typically require visual verification, the possibility of more frequent data collection could lead to an increased workload for track inspectors, with respect to these verifications (Carr, Tajaddini, & Nejikovsky, 2009). This is because current regulations require the inspector to perform verification during, or in addition to, their regularly-scheduled inspections. If railroads do not require verification, they risk unnecessary impacts on revenue service, or creating additional workload for maintenance-of-way (MOW) crews who they send to repair defects that are actually false alarms.

Lastly, it is important to note that automated inspections have a more limited scope than visual inspection when it comes to the types of defects they can detect. Visual inspectors can look for all 21 defect categories in the CFR (see Table 1) simultaneously. In contrast, each automated inspection technology is designed to identify one or more specific track conditions. Put another way, the automation is designed to specialize in detection of a specific track condition and can often detect degradations before human inspectors can find them. Human inspectors can detect a broader variety of degraded conditions and consider the track conditions holistically. Sometimes multiple automated inspection technologies are incorporated on a single vehicle, but there is currently no technology that integrates data across every type of track condition the way that human inspectors can.

2.3.3 Levels of Automation in Track Inspection

Technology advocates are sometimes quick to suggest that automation can replace humans. Humans and automation can interact in many ways beyond a complete substitution of technology for humans. Humans and automation can also share or trade-off in the performance of tasks, allowing the automation to augment the capabilities of humans, relieve them of excessive workload; act as a backup to human actions, or replace some subset of the tasks a human normally performs (Sheridan & Verplanck, 1978). Parasuraman and Sheridan (2000) describe possible interactions between humans and automation, and identify four processes that technology could support.

- **Information acquisition**: This is the process of gathering information from the environment. In humans, it involves sensation and perception; in automated technologies, it involves collection of data using sensors.
- **Analysis**: This is the process of making inferences about the gathered information. In automated technologies, it may involve manipulating the data and presenting summaries or predictions to the user.
- **Decision making**: This is the process of selecting from available alternatives. In automated technologies, the computer may help narrow or select among options.
- **Action**: This is the process of carrying out the decisions made in the previous step. In automated technologies, the technology can reduce the manual effort to perform required actions.

The technologies used to support track inspectors may assist with any of these four processes. Figure 2 illustrates how visual (i.e., non-automated), automation-aided inspection processes, and "fully autonomous" processes use differing degrees of automation at each of these stages.

Current automation-aided inspections use technology for information acquisition and analysis, using a combination of sensors and detection algorithms. However, they still rely on humans to verify the findings, review the data, and decide on actions to take. Humans are also involved in taking any necessary actions.

While some automated track inspection technologies are referred to as "autonomous," due to their capacity to operate without direct, ongoing involvement from an operator, this reflects their potential, rather than current usage. A truly autonomous inspection technology would acquire track data without any instruction, then analyze it, make decisions, and take action without human input. This is reflected by the dotted, light blue line in Figure 1. The purpose of including this theoretical automated technology is not to advocate for removing humans from the inspection process. Rather, it is to emphasize that current inspection technologies still involve a significant human role, especially in decision-making and action execution.

Similarly, it is inaccurate to suggest that visual inspection is performed without technology. Visual inspections use technology to aid in the inspection process, particularly during information acquisition and action stages, where inspectors and maintenance crews rely on technology to help them take measurements and perform repairs.

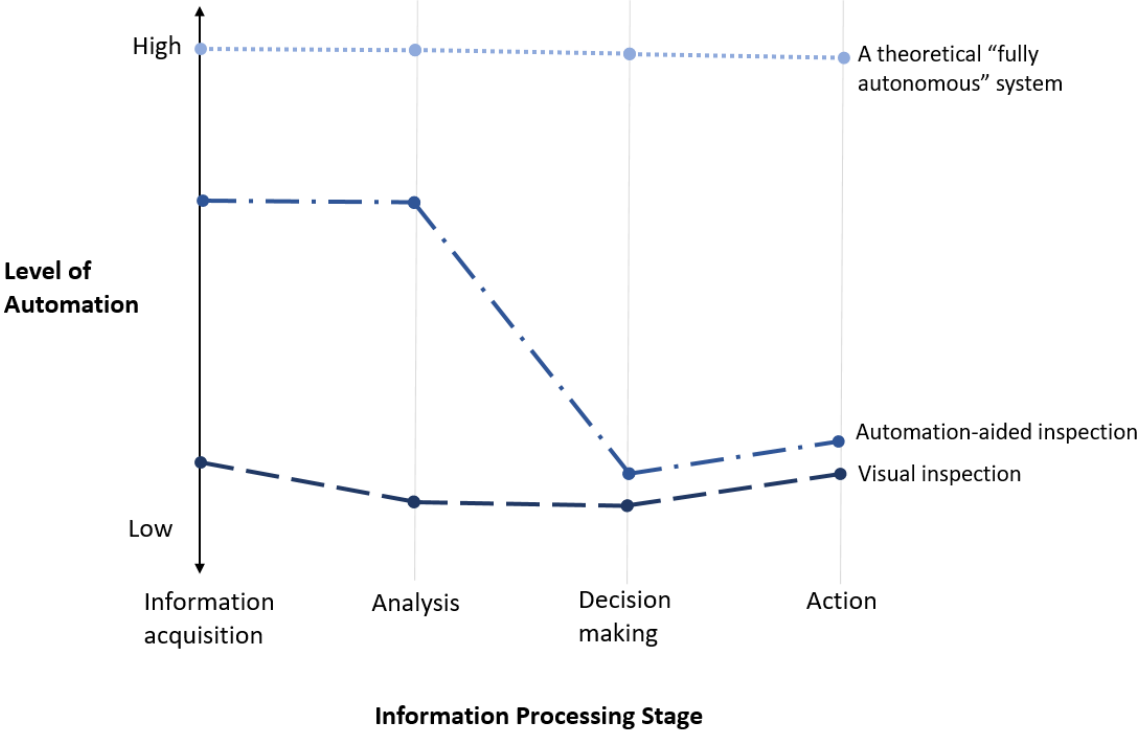

Figure 2. Degree of automation of various track inspection methods (Parasuraman, Sheridan, & Wickens, 2000)

It is a false dichotomy to suggest that inspection is performed either "with or without" technology. In reality, during each of the four stages in Figure 2, the degree of automation can range along a spectrum. Parasuraman, Sheridan, and Wickens (2000) identified 10 possible levels of automation for decision-making and action execution, listed below:

1. The computer offers no assistance. The human must take all decisions and actions.
2. The computer offers a complete set of decision/action alternatives.
3. The computer narrows the selection down to a few.
4. The computer suggests one alternative.
5. The computer executes that suggestion if the human approves.
6. The computer allows the human a restricted time to veto before automatic execution.
7. The computer executes automatically, then necessarily informs the human.
8. The computer informs the human only if asked.
9. The computer informs the human only if it, the computer, decides to.
10. The computer decides everything and acts autonomously, ignoring the human.

Considering this list of possibilities, one could easily envision automation-aided technologies that strike a different balance than the one depicted in Figure 2. However, for this report, the Volpe team uses "automation-aided" to refer specifically to inspections where sensors and computers aid in information acquisition and analysis.

Differences may also exist between technologies at similar levels of automation. For example, automated track inspection technologies can vary by:

- **Method of travel**. For example, some are pulled by a locomotive, some are self-propelled, and some are mounted to a revenue service vehicle. Some are rail-bound, while others are implemented using hi-rail vehicles.
- **Use of track time**. Some require track time, while others, like those mounted to revenue service vehicles, do not. Depending on whether the vehicle is rail-bound, it may have more or less flexibility in use of track time.
- **Staffing**. Some require onboard technicians or operating crews, while others (again, typically those mounted to revenue service vehicles) do not.
- **Analysis process**. Some use more advanced algorithms to analyze data and dismiss anomalies, while others require a greater degree of human review. The location of the analyst(s) may also vary.

In the present hazard analysis, the Volpe team examined rail inspection processes utilizing two types of track geometry measurement technology, conventional TGMS and aTGMS, in an attempt to capture some of the varied ways that automated inspection technology can be implemented across the railroad industry. However, the team recognizes that additional variations of automated inspection technology exist, particularly with respect to emerging technologies. In some cases, the team's findings may be cautiously extended to other automated technologies which bear similarities to conventional TGMS or aTGMS (e.g., regarding whether these technologies are or are not staffed, where and when the data are analyzed, etc.), while in other cases, unique approaches to implementing inspection technology may merit further research.

2.4 Systems Perspectives on Track Inspection and Hazard Analysis

The track inspection and maintenance process is a complex sociotechnical system involving the interaction of human, technology and the organization (e.g., the railroad). The challenges of track inspection and detecting degraded track conditions in a timely manner result from the interactions of these three elements. To identify the factors that contribute to hazards associated with track inspection requires examining not just the individual elements but the interactions between these elements as well. For this reason, the hazard analysis method adopts a systems perspective.

A systems perspective is one that examines not only a technology or process, but also the context in which it operates. Particularly, a "sociotechnical" systems perspective examines social, organizational, and environmental or regulatory factors that influence the behavior of people and technologies within a system.

While many researchers have described challenges associated with visual and automation-aided inspection processes, as well as strengths and weaknesses of each, these studies typically focus on the individual and task level, and touch only briefly on social, organizational and regulatory issues. Additionally, automation studies commonly reflect on the drawbacks of visual inspection without discussing the unique strengths that experienced track inspectors bring to the process.

A study by Read, Naweed, and Salmon (2019) took a high-level systems perspective of rail transport in Australia and modeled the control and feedback mechanisms among actors responsible for managing safety. From this model, they inferred that improved feedback, more formal controls at higher levels of the sociotechnical system, and greater focus on understanding normal activity–rather than focusing only on failures–would be beneficial for improving rail safety.

In another study, Naweed, Young, and Aitken (2019) used systems-theoretic methods (i.e., analyses based on systems theory) to examine safety incidents involving track workers and lookouts. They observed that these incidents involved factors at organizational, social, task, and individual levels. In particular, they described the pressures that the railroads experience to maintain infrastructure while expanding their service capacity. Their recommendations for improving track worker safety included training in non-technical skills to address social dynamics and distraction, as well as designing or redesigning technology to reduce hazards. While their study does not specifically address hazards related to unaddressed track defects, the premise of examining safety issues from a systems-perspective applies to track inspection tasks.

Researchers have also applied systems-theoretic methods to other problems in the rail domain, including conducting a hazard analysis of run through switch events (Safar, Roth, Multer, & France, 2019) and modeling interactions within railroad sociotechnical systems that may lead to stop signal overruns (Multer, Safar, Roth, & France, 2019). Building on this prior body of work, the present study applies a systems-theoretic hazard analysis method, STPA, to examine the track inspection process from a sociotechnical perspective.

3. Methodology

This section describes the Volpe research team's data collection and analysis activities.

3.1 Data Collection

The team began by using data from multiple sources to identify and document how the track inspection process works, including reviewing relevant literature and conducting interviews with passenger railroad employees and other subject matter experts.

3.1.1 Literature Review

The team began by gathering and synthesizing literature related to the track inspection process, including the use of automation. The literature included FRA technical reports and presentations, articles in scientific and trade journals, and sources from related domains, such as the Federal Transit Administration's research reports on the use of automation-aided inspection in rail transit. Additionally, the team considered research that described systems approaches to safety in the railroad industry, a growing area of interest, to understand how similar research has been done on processes other than track inspection.

The information gathered during this literature review is summarized in Section 2 and incorporated into the model of the track inspection process in Section 4.

3.1.2 Passenger Railroad Interviews

Following the literature review, the Volpe team conducted site visits and interviewed employees at three passenger railroads, all of which use visual inspection and automation-aided TGMS inspection processes. Table 3 summarizes the types of inspection at each railroad, as well as the interviews and observations that the team conducted at those railroads.

Table 3. Summary of data collection activities by railroad

Railroad	Types of inspection	Interviews	Field observations of technology
Railroad 1	Visual, TGMS	Chief Engineering Officer, Track Department Director, Track Geometry Engineer, Senior Engineer, Roadmasters, and Track Inspectors.	TGMS ride-along
Railroad 2	Visual, TGMS	Division Engineer, Senior Engineers, Assistant Engineers, Track Supervisors, and Track Inspectors.	No observations made
Railroad 3	Visual, TGMS, aTGMS	Deputy Director of Track Maintenance, Manager of Track Geometry, Assistant Chief Engineers, Track Supervisors, and Maintenance Foremen / Track Inspectors.	No observations made

The Volpe team conducted separate group interviews with management, supervisors, and track inspectors.[4] During these semi-structured interviews, the employees described how they do their work, the technology they use to perform this work, and their interactions with others in the railroad that support the track inspection process. Since the track inspection process is part of maintaining the railroad infrastructure, interviews also touched on maintenance activities and how they interact with the track inspection process. Appendix B includes the question sets the Volpe team used to conduct interviews.

At Railroad 1, the Volpe team rode onboard a conventional TGMS geometry car during an inspection and spoke with the railroad's Track Geometry Engineer and two onboard TGMS technicians. For all three railroads, the Volpe team reviewed documents used in the track inspection process, including inspection logs and data outputs from conventional TGMS and aTGMS.

3.1.3 Interviews with Subject Matter Experts

In addition to collecting data during site visits, the Volpe team also spoke to several track inspection subject matter experts to improve the team's understanding of the track inspection process.

The subject matter experts interviewed included:

- FRA regional employees, including FRA track inspectors
- Non-FRA government researchers specializing in track inspection
- Representatives from one of the companies that manufacture the conventional TGMS and aTGMS vehicles
- A representative of BMWED

These interviews helped the Volpe team understand aspects of the inspection process that were not explored in detail during site visits, such as the role of FRA and labor unions. They also helped the Volpe team identify other relevant research to include in the literature review.

3.2 Model Development

The Volpe team used information gathered both from these discussions and the research literature to develop a set of models, beginning with a generalized model of the steps of the track inspection and maintenance processes. Section 4 provides a detailed description of this model, which provides a framework to discuss the activities required during both visual and automation-aided inspections.

The team then developed additional functional models in the course of performing a hazard analysis. The term *functional model* indicates that these models represent the functions or actions performed by people and technologies and the relationships between them. Section 5 describes these models.

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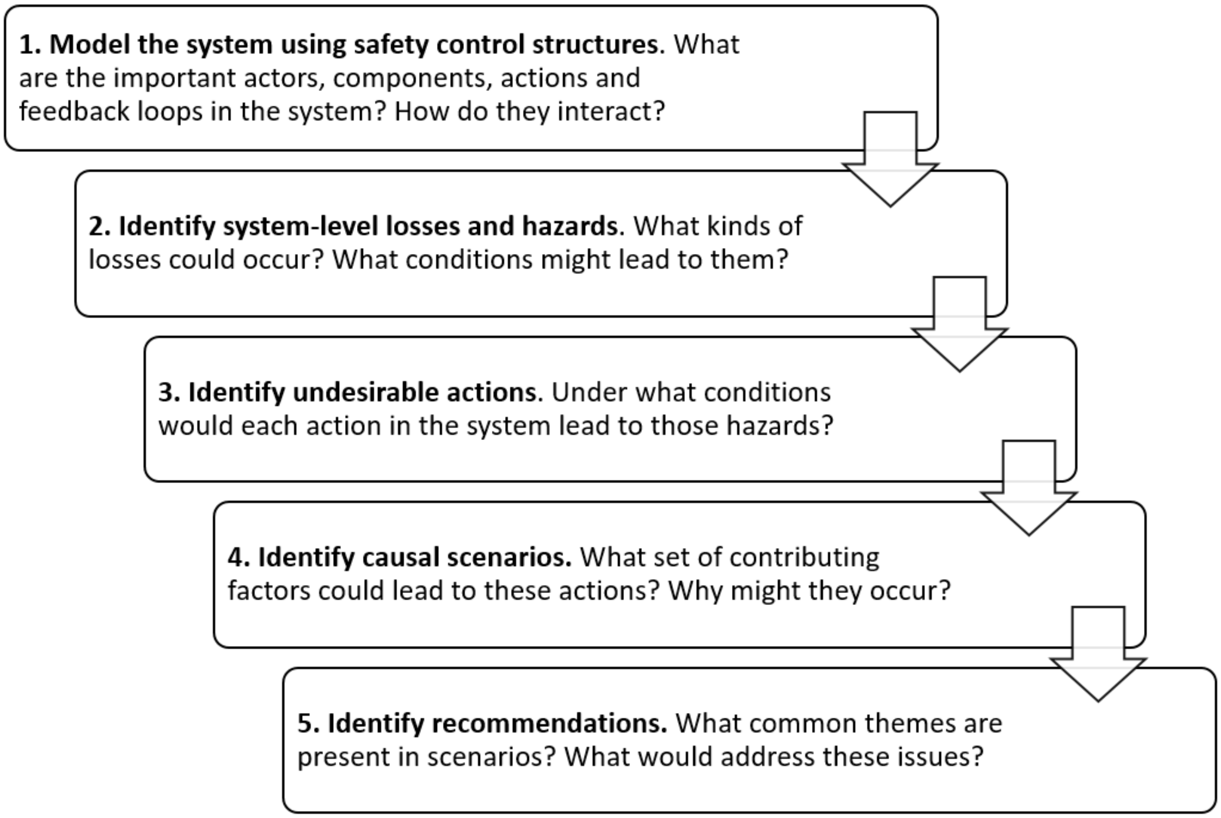
[4] Track inspectors are also qualified as maintenance foremen and can perform either inspection or maintenance work.

3.3 Systems-Theoretic Process Analysis

The team used STPA, a systems-based hazard analysis method (Leveson, 2011; Leveson & Thomas, STPA Handbook, 2018). The team chose STPA for this study because it was designed to examine complex sociotechnical systems, systems where both human and technological components can impact safety.

It uses a systems model of accidents, rather than a chain-of-events model, which allows analysts to examine accidents that result from multiple factors rather than a single point of failure. STPA includes human behavior as an integral part of the analysis and assumes human behavior is a product of its context, rather than modeling humans as a component with a probability of "failure." This approach gives a more realistic understanding of human error than traditional hazard analysis methods (Leveson, 2011; Leveson & Thomas, STPA Handbook, 2018). Figure 3 summarizes the steps of this analysis method, which the following sections describe in additional detail.



1. **Model the system using safety control structures.** What are the important actors, components, actions and feedback loops in the system? How do they interact?
2. **Identify system-level losses and hazards.** What kinds of losses could occur? What conditions might lead to them?
3. **Identify undesirable actions.** Under what conditions would each action in the system lead to those hazards?
4. **Identify causal scenarios.** What set of contributing factors could lead to these actions? Why might they occur?
5. **Identify recommendations.** What common themes are present in scenarios? What would address these issues?

Figure 3. Hazard analysis steps for STPA

3.3.1 Model the Sociotechnical System Using Safety Control Structures

The first step of STPA shown in Figure 3 is to develop "safety control structures," or functional models, for each sociotechnical system that analysts wish to consider. Using the team's general model of the inspection process and additional details from railroads, the Volpe team created functional models for three different sociotechnical systems:

1. Visual Inspection sociotechnical system

2. Conventional TGMS & Visual Inspection sociotechnical system
3. aTGMS & Visual Inspection sociotechnical system

Section 5 describes each of these safety control structure models in detail, including roles and responsibilities of each actor or component in the sociotechnical system and descriptions of each action taken.

3.3.2 Identify Sociotechnical System Losses and Hazards

The second step of STPA shown in Figure 3 is to identify losses and hazards relevant to the sociotechnical system. The Volpe team identified three accidents and three high-level hazards associated with track inspection, which are listed in Table 4.

Table 4. Sociotechnical system losses and hazards for track inspection.

Loss ID	Loss Description	Hazard ID	Hazard Description
Loss 1	An unsafe event (e.g., train derailment) related to track condition occurs *during operations*, resulting in death, injury, and/or property damage.	Hazard 1	Track issues are not addressed prior to use by operational crews and equipment.
Loss 2	An unsafe event occurs *during an inspection* (e.g., inspection equipment derailment; track inspector injury) resulting in death, injury, and/or property damage.	Hazard 2	Track inspectors or equipment/technology are exposed to danger during inspection (e.g., roadway worker protection issues or equipment safety issues).
Loss 3	The track inspection process results in an undue economic burden (e.g., high inspection costs or impacts to train service).	Hazard 3	Unnecessary costs or delays occur during inspection (e.g., inspection activities are carried out inefficiently).

Note that while undue economic burden may not meet the traditional definition of an accident, it is nonetheless a form of loss. Including losses that are financial is a means of preventing the hazard analysis from identifying solutions that are unrealistically costly.

The focus of this analysis was on Hazard 1: “Track issues are not addressed prior to use by operational crews and equipment.” This hazard encompasses a range of possible situations. For example, it may be that:

(1) Inspectors or technology do not detect an issue
(2) Inspectors or technology detect, but do not adequately report, an issue
(3) Inspectors or technology report an issue, but the railroad does not adequately address it

All these situations could lead to an unsafe event during operations (Loss 1).

3.3.3 Identify Undesirable Actions and Causal Scenarios

The third and fourth steps of STPA shown in Figure 3 identify undesirable actions and causal scenarios that explain how hazards may occur. In these steps, the Volpe team first used the safety control structure models to examine each action within the sociotechnical system and identified ways in which it could lead to a hazard. This led to a set of statements of "undesirable actions" that identify *what* actions railroads should attempt to prevent, but which do not describe *why* they might occur.

For example, the following are a few possible "undesirable actions" involving a track inspector:

- A track inspector does not identify a defect when a defect is present.
- A track inspector identifies a defect as less severe than it is.
- A track inspector identifies a defect where no issue exists.

The team also identified undesirable actions related to the use of automation. For example:

- aTGMS does not identify a defect when a defect is present.
- aTGMS identifies a defect as less severe than it is.
- aTGMS identifies a defect where no issue exists.

Using these statements, the team sought explanations for why each undesirable action might occur (e.g., what set of contributing factors may make those actions appear reasonable in context?). The researchers considered a wide range of systemic factors for these scenarios which included a combination of social, technical, and organizational influences. For example, the factors below may not lead to undesirable actions in isolation, but in combination could contribute to difficulties detecting defects:

- Environmental and technological factors such as poor weather or lack of tools, or inaccurate parameters for an automated inspection technology
- Individual factors such as experience level or fatigue
- Organizational factors such as scheduling, training practices, or production pressures

This list provides examples of a few types of factors the Volpe team considered. Using this method, the team developed a set of causal scenarios for each of the three sociotechnical systems examined in this hazard analysis to understand how hazards could occur.

3.3.4 Identify Recommendations

In the fifth and final step shown in Figure 3, the Volpe team reviewed the scenarios for commonalities and identified recommendations to address each potential contributing factor. For these recommendations, the team drew upon their collective human factors expertise, as well as the information gathered from railroads. Section 6 discusses some of the sociotechnical factors that the team identified, while Section 7 lists the recommendations by topic.

4. Modeling the Track Inspection and Maintenance Process

To capture the track inspection and maintenance process at a high-level, the Volpe team developed the model depicted in Figure 4 based on the literature review and data collected from the three railroads on how they conduct track inspection and maintenance practices. This model is general enough to reflect both visual and automation-aided track inspection processes, and provides a framework to discuss the role of humans and technology in this process.

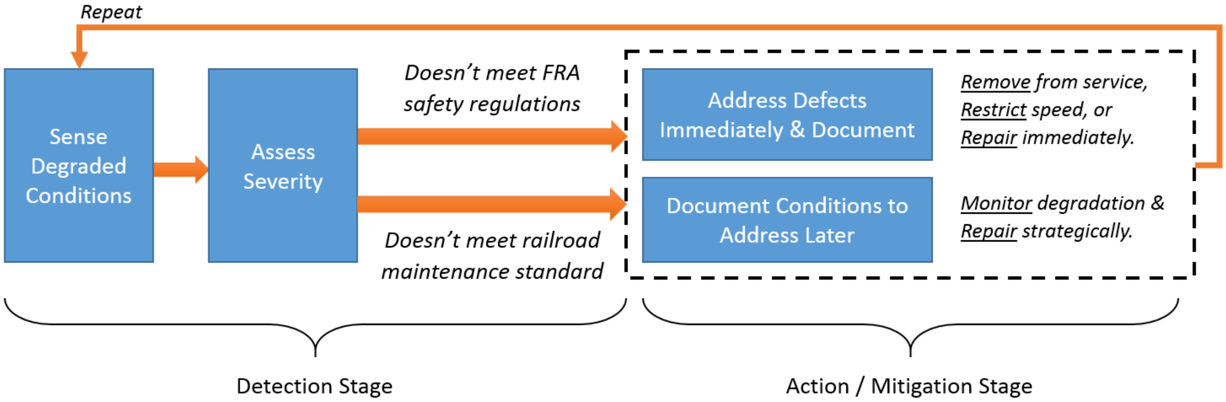


Figure 4. Generalized model of the track inspection and maintenance process

The model is divided into two stages:

1. Detecting and assessing degraded track conditions
2. Taking action to address the track conditions

The action stage goes beyond just the action the inspector takes to include any repairs and/or replacements made to track components.

The team included this stage because, despite the study's goal to focus on detection and assessment, inspection and mitigation of track degradation are both critical parts of the track lifecycle and are closely integrated processes. Inspectors may perform repairs at the time of an inspection, and repair activities are often followed by additional inspection to determine that the repairs were adequate.

4.1 Visual Inspection Process

This section discusses how the visual inspection process fits into the track inspection and maintenance process model depicted in Figure 4.

4.1.1 Sense Degraded Track Conditions

The term "visual inspection" refers to inspections that a human inspector performs either by walking the track or by hi-rail. However, such inspections are not exclusively visual. Inspectors use multiple senses to examine the track. An inspection by hi-rail vehicle involves using auditory cues (e.g., rattling noises) and kinesthetic or motion cues (e.g., bumps and vibrations) in addition to visual cues to detect track conditions and identify issues. A track inspector walking the track may use a hammer to bang the rail as a method for using auditory cues to monitoring the track. Therefore, the model uses the term "sense degraded track conditions" to reflect that the human inspector uses multiple sensory modalities to detect degraded track conditions during a visual inspection.

4.1.2 Assess Severity of Degraded Track Conditions

After detecting a degraded track condition, the inspector assesses its severity and decides what action is required. In other words, they determine whether the condition exceeds FRA safety standards, or only the railroad's maintenance standard.

In many cases, detecting a degraded condition and deciding its severity take place almost simultaneously (e.g., detecting a missing bolt). In other cases, the inspector may need time to determine if the degraded condition exceeds a threshold. The assessment process can be complex and is to open to interpretation. In some cases, different inspectors may arrive at different conclusions about track conditions. The inspectors that Volpe interviewed stated that if they are uncertain about an issue that is particularly challenging, they will request a second opinion from a colleague or supervisor. However, in cases of uncertainty they indicated that once a condition has been observed, it is better to be cautious and treat the condition as more severe than to ignore it.

4.1.3 Take Appropriate Action Based on Severity

Address Defects Immediately and Document

If a degraded track condition exceeds an FRA safety standard, the railroad must take immediate action to address the condition within the required timeframe. Track inspectors and their managers discussed three possible actions which they referred to as "the three R's:" repair, restrict, and remove. These are described below.

- **Repair**: The track inspector can immediately repair the degraded track condition. If the issue is something relatively straightforward and the inspector has the tools, parts, and time they need, they can repair the issue themselves. This may be easier in a hi-rail vehicle given the ability to carry additional tools and parts. If they lack the tools, parts, or time to make the repair, the issue will need to be fixed by a maintenance-of-way crew.
- **Restrict**: The railroad can restrict the track to a lower speed class until they can perform repairs.[5] Since tracks are classified by the speed at which trains and equipment can operate, lowering the track class reduces the speed at which trains and equipment can travel on the section of track. The outcome results in a temporary speed restriction that stays in place until the track is repaired. This process enables trains to operate over the track at a speed where the degraded condition does not pose safety issues and is no longer considered a defect.
- **Remove**: The track inspector can remove the track from service until a maintenance crew performs repairs. Removing track from service occurs when immediate repair is not possible and a speed restriction is not sufficient to meet FRA safety standards. Typically, this action takes place in the case of severe defects. Removing track from service is the

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[5] This applies to defects that are class-limiting; i.e., those that meet FRA requirements for a lower track class.

least preferred option, since it creates the greatest disruption to revenue service, compared to the other two options.

Regardless of which action the inspector takes, they must document the safety defect or track degradation and railroads must keep a record of the defect type, location, severity, and actions taken to address it. Inspectors use paper forms designed for reporting defects or computer-based methods such as a tablet or a computer. Once the inspector has completed the inspection, a supervisor will check over the log and sign off on it.

Document Maintenance Conditions to Address Later

If a track condition does not exceed FRA safety standards, but exceeds the railroad's own maintenance threshold, the railroad does not need to take immediate action. However, the inspector must still document these maintenance conditions so that they can be monitored, and a supervisor must review and sign off on the inspection log.

Railroads monitor changes over time so they can report when a degraded track condition is getting close to a threshold where action will be needed, or so that they can take action proactively, such as through large-scale capital planning and maintenance of safe, but degraded, areas.

4.1.4 Repeat the Inspection Process

As inspections are repeated over the same territory, inspectors can monitor known track conditions, revisit areas that have been recently repaired, or make mental note of conditions that remain below both railroad and FRA thresholds that may become degraded enough to document or take action in the near future. To monitor these changes, inspectors carry and refer back to logs from prior inspections. This continual monitoring of track condition increases the likelihood that changes in track conditions or defects are noted before they lead to an unsafe event.

4.2 Automation-Aided Inspection Process

This section discusses how the automation-aided inspection process fits into the track inspection and maintenance process model depicted in Figure 4.

4.2.1 Sense Degraded Track Conditions

As with the visual inspection process, the first step in the automation-aided track inspection process is sensing degraded track conditions. In this case, sensors can only sense degraded conditions for the specific types of issues they are designed to detect.

Just as with humans, technology-based sensors may sometimes miss detecting a degraded track condition or detect a condition that is not present (i.e., a false alarm). For instance, with one track geometry measurement technology that our team observed, false alarms occurred when running over a frog. The automated technology cannot distinguish between a frog and the rail. Just as with humans, technology has limitations in its ability to detect the conditions for which it was designed. Therefore, railroads need to be aware of the technology's limitations and verify information reported by the automated technology. In the case of the observed technology, a technician monitors the reported exceptions or anomalies and removes the erroneous exceptions reported when the vehicle moves over a frog.

4.2.2 Assess Severity of Degraded Track Conditions

Next, the automated technology must determine the severity of any degraded track conditions it identified. Does the degraded condition exceed FRA safety standards or the railroad's maintenance standards? Making the assessment is a joint human-computer process.

TGMS generates a list of degraded conditions, called "exceptions," and differentiates between safety defects (i.e., those that do not meet FRA regulations) and maintenance conditions that fall within FRA thresholds but exceed the railroad's maintenance standards. This assessment occurs for both staffed geometry cars (conventional TGMS) and unstaffed geometry cars (aTGMS); however, the two automated technologies review this information in different ways.

When using conventional TGMS, an onboard technician reviews these exceptions in real-time, taking out the exceptions that are known not to be legitimate concerns. The technician may see which conditions exceed FRA regulations as well as which ones exceed the railroad's maintenance standards.

Though some manufacturers and railroads refer to unstaffed track inspection technologies as "autonomous," this human review of the information to determine the severity of the defect, and to weed out non-defects/false alarms, is just as necessary as for a staffed system. This person serves the same role as the technician on a staffed geometry car except that the person is located elsewhere and the data review can happen at any time after the data is collected. The technology may filter out some of the known causes of false alarms before the list of exceptions is sent to be reviewed. At one railroad the Volpe team visited, an analyst reviewed exceptions from their aTGMS units the morning after the data was collected.

4.2.3 Take Appropriate Action Based on Severity

Address Defects Immediately and Document

If the railroad finds any FRA safety defects, they must still take action immediately[6] and the "three R's" (i.e., repair, restrict track speed, and remove track from service) still apply. On a conventional TGMS vehicle, someone on board will be responsible for notifying track inspectors or maintenance crews in the field that they need to verify the degraded condition, and/or notifying the dispatcher of the need to restrict or remove track. For issues detected using aTMGS, the person responsible for post-processing of data also contacts a track supervisor so that they can send track inspectors or maintenance crews to verify degraded conditions.

The railroad may be able to address some issues more quickly when using conventional TGMS vehicles compared to an aTGMS system. If a track supervisor rides the TGMS inspection vehicle, they can stop and verify whether or not the defect exceeds a threshold. Sometimes a MOW crew follows the staffed technology so that the crew can immediately attend to any defects. This reduces the need for restricting or removing track from service.

Both conventional TGMS and aTMGS create a record of any safety defects identified, much like the inspection logs that human inspectors create. Railroads can use these automated outputs to monitor track conditions over time, as well as to pass information to the inspectors who will be

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[6] Railroads may require track inspectors to verify the defect before taking action.

verifying the conditions. Railroads also document the actions taken to address degraded conditions and staff must sign off on completed repairs.

Document Maintenance Conditions to Address Later

Conventional TGMS and aTGMS will also create a record of conditions that do not exceed FRA standards, but that do exceed railroad maintenance thresholds. These can be used to proactively repair track conditions before they become safety defects.

To monitor track degradation over time, the systems also collect data on conditions that neither exceed FRA regulations, nor exceed railroad standards. Depending on the analysis tools used, railroads may use this type of data to inform large-scale capital planning and maintenance.

4.2.4 Repeat the Inspection Process

While automated inspections are not required to be performed at the same frequency as a visual inspection, railroads may use repeated inspections to monitor degradation over time, and in some cases, to verify that repairs were successful. Typically, aTMGS is able to collect more frequent data because it does not require the same resources (i.e., staff and track time) as conventional TGMS.

4.3 Summary of the Track Inspection and Maintenance Process

While visual and automation-aided inspections both follow the stages described in Figure 4, there are several differences between these two processes. Table 5 summarizes how each stage of the model is performed in each of the two approaches to inspection.

Table 5. Comparison of visual and automation-aided inspection processes by activity

Action	Visual Inspection	Automation-Aided Inspection
Sense Degraded Track Conditions	Uses human senses (primarily vision, but also hearing and motion cues) to detect degraded conditions. Can look for a wide range of conditions simultaneously (though some are more difficult to detect than others).	Uses sensors to take measurements and detect degraded track conditions. Typically designed to detect particular types of conditions (e.g., geometry only).
Assess Severity	Human inspectors must determine whether the condition exceeds an FRA regulated threshold (“defects”) or a railroad maintenance threshold (“maintenance conditions”).	A computer flags “exceptions” which the sensors indicate as a condition that may exceed an FRA-regulated threshold or railroad maintenance threshold. Human analysts, either onboard the inspection vehicle or elsewhere, review the data and can dismiss exceptions that appear to be false alarms.

Action	Visual Inspection	Automation-Aided Inspection
	Inspectors may resolve uncertainty by seeking a second opinion.	Inspectors are sent to verify the exceptions and classify them as defects or maintenance conditions.
Take Appropriate Actions Based on Severity	Defects must be addressed in one of three ways: repair the defect, restrict the track speed, or remove the track from service. Maintenance conditions do not require any particular action; however, the railroad may choose to address them proactively. Inspectors must keep a log of both defects and maintenance conditions.	Following verification, defects must be addressed in one of three ways: repair the defect, restrict the track speed, or remove the track from service. Maintenance conditions do not require any particular action; however, the railroad may choose to address them proactively. Output from automation-aided inspections must document both defects and maintenance conditions.
Repeat	Repeated inspections allow inspectors to monitor track condition on their territory, including making sure past issues have been adequately repaired and keeping an eye out for emerging issues.	Railroads may use repeated automation-aided inspections to quantitatively monitor degradation over time. Unstaffed ("autonomous") inspection technologies may be especially useful for track condition monitoring due to the volume of data they collect.

4.4 Building on this Conceptual Model

These different types of inspection, and the two variations of track geometry measurement technology, result in important differences in the hazards that may arise from the track inspection process, including how humans work with the technology. The following sections describe both visual and automation-aided inspection systems in greater detail, including the people, technology, and organizational processes involved, and present recommendations for strengthening railroads' inspection processes.

5. Comparison of Three Track Inspection Sociotechnical Systems

To perform a hazard analysis, the Volpe team needed a more detailed model of both visual and automation-aided inspection than that presented in Section 4. Furthermore, the team needed models that distinguished between the two types of automation-aided inspection selected for study: conventional TGMS and aTGMS. Therefore, to understand how these sociotechnical systems function and highlight differences between them, the Volpe team created a functional model, or "safety control structure model," of each sociotechnical system.

These safety control structure models are based on the interviews and observations that the Volpe team conducted at three passenger railroads, as well as relevant literature and interviews with subject matter experts. They show how the hazards examined in this study[7] are controlled within each sociotechnical system through a hierarchical structure consisting of:

- Actors (e.g., people, organizations, and/or technologies)
- Non-acting components (objects)
- Safety controls or actions, which constrain the behavior of actors and components lower in the hierarchy
- Communication or feedback channels, which convey information to actors higher in the hierarchy

These control and feedback relationships define the interactions between actors and other inspection process components that are required for the process to work effectively.[8]

The following sections present safety control structure models for each of the three sociotechnical systems that the Volpe team included in their hazard analysis:

1. Visual Inspection sociotechnical system
2. Conventional TGMS & Visual Inspection sociotechnical system
3. aTGMS & Visual Inspection sociotechnical system

To reflect current inspection practices and allow for the analysis of human-automation interactions, all three sociotechnical systems include a visual inspection component.

5.1 Visual Inspection Sociotechnical System

In this model, human inspectors are solely responsible for detecting degraded track conditions. Figure 5 depicts the actors (i.e., individuals, groups, and technologies) and non-acting

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[7] As discussed in Section 3.3.2, there are other hazards related to track inspection that can occur at the sociotechnical system level which are not within the scope of this study, such as injury to track workers.

[8] The models in this report do not represent any specific railroad, nor do they capture every detail of the inspection and repair/replacement process. In many cases, the Volpe team made assumptions or simplifications (e.g., grouping multiple actors together) to facilitate the hazard analysis. Appendix B has a list of assumptions for these systems.

components (i.e., track, inspection reports) involved in this process, as well as the key actions and feedback loops associated with each actor.[9]

The blue boxes in the figure represent actors in the sociotechnical system, while gray boxes represent non-acting components. Solid arrows represent actions, and dashed arrows represent feedback or coordination.

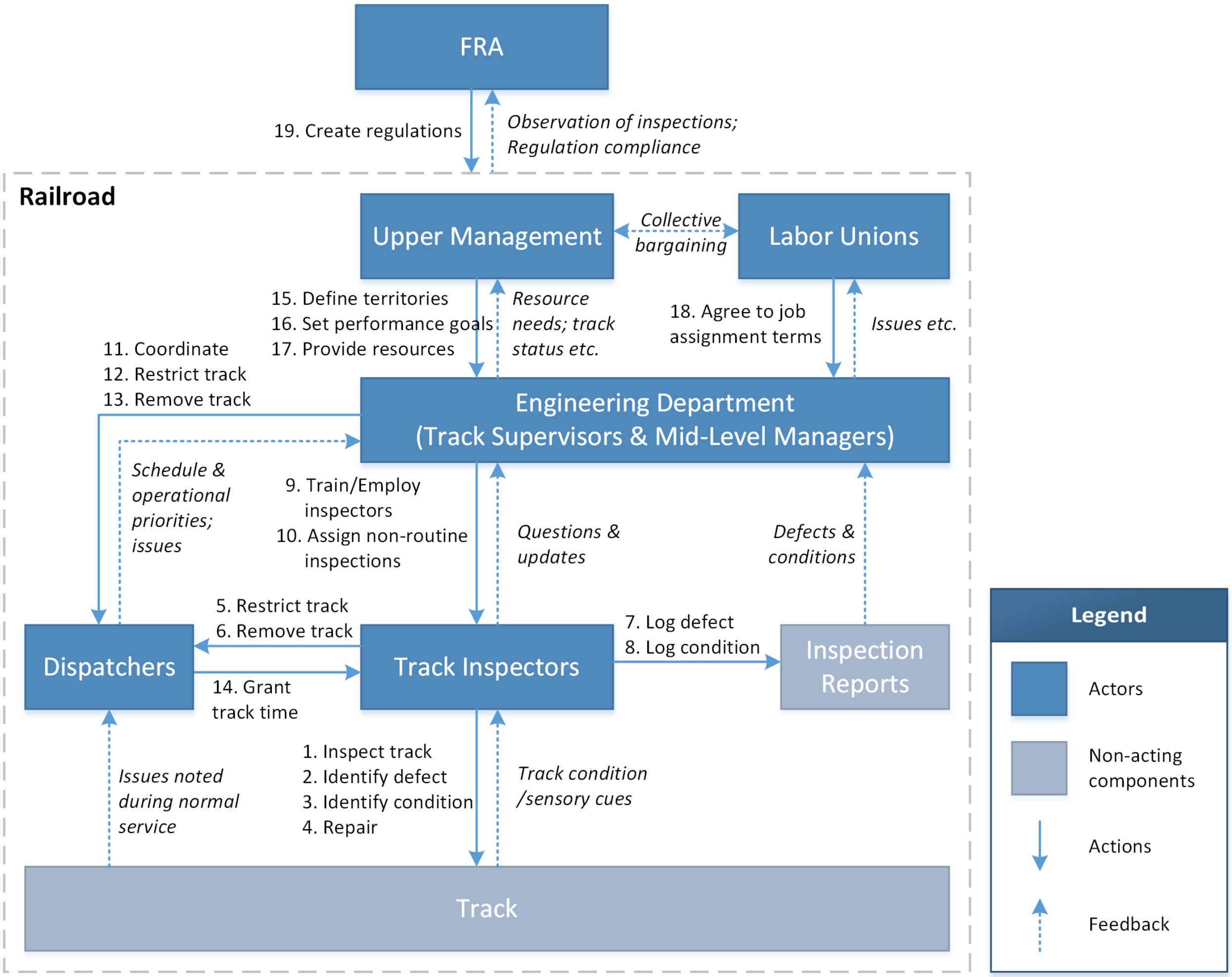

Figure 5. Model of a Visual Inspection sociotechnical system

The following sections describe the roles, responsibilities, and key actions for each actor or component in this Visual Inspection sociotechnical system. The numbering of these actions corresponds to the numbering in Figure 5.

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[9] In STPA, actors are typically referred to as "controllers" and non-acting components as "controlled processes" to denote the hierarchical relationships present in most sociotechnical systems. In such hierarchical relationships, higher level controllers "control" or constrain the behavior of lower-level system components through what are referred to as "control actions."

5.1.1 Track Inspectors

Track inspectors conduct visual inspections. They observe the track conditions using sensory cues, report to the track supervisor and managers within the engineering department with any questions or concerns, and coordinate with the dispatcher responsible for that territory to request time on the track. They also document the results of their inspections. They perform the following actions:

1. **Inspect the track**. Each track inspector is responsible for inspecting track in their assigned territory. Depending on the characteristics of the territory, they may do these inspections primarily on foot or via hi-rail vehicle.
2. **Identify defects**. Inspectors determine whether the track condition meets FRA safety standards.
3. **Identify maintenance conditions**. Inspectors determine whether the track condition meets the railroad's internal maintenance standards.
4. **Repair maintenance conditions and defects**. Inspectors may perform minor repairs. For more serious issues, they restrict track speed or remove track from service until a maintenance crew can perform the repairs.[10]
5. **Restrict the track speed**. For certain types of "class-limiting" defects, track inspectors place speed restrictions by calling the dispatcher to reduce the maximum permitted track speed for the section of track with the degraded track condition(s).
6. **Remove the track from service**. For severe defects, track inspectors can remove the track from service by calling the dispatcher.
7. **Log defects**. Inspectors log the defects they identify, and any actions they took to address them. They document the defects either on paper or using a designated IT system.
8. **Log maintenance conditions**. Inspectors typically log maintenance conditions as well as defects, though the railroad does not have the same degree of obligation to address them.

5.1.2 Engineering Department (Supervisors and Managers)

The engineering department's employees, including supervisors and managers, are responsible for supervising track inspectors and overseeing infrastructure and maintenance activities.[11]

This model groups several levels of employee together for simplicity and clarity; however, the research team recognizes that certain actions and decisions will be handled at the supervisor level, while others require manager involvement. Therefore, this report will occasionally make reference to supervisors or managers when referring to specific engineering department employees.

9. **Train and employ inspectors**. While a separate training department is typically responsible for training, the engineering department has a role in this process as they

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[10] As this analysis is focused on defect detection, rather than maintenance, maintenance activities are not depicted, except for minor repairs performed by track inspectors.

[11] Supervisors may be craft employees and belong to the same labor union as the track inspectors. Managers are not members of the labor union.

indicate their required staffing levels and provide support through on-the-job (OJT) training. Therefore, this analysis attributes these staffing processes to the engineering department for simplicity.

10. **Assign territory**. Some territory assignment activities happen outside the engineering department (e.g., through the job-bidding process). However, the engineering department is responsible for making sure all territories are covered and may make substitute assignments to cover absences.
11. **Assign non-routine inspections**. Non-routine inspections include special weather inspections as well as following up on issues reported by operations crews and other inspectors. It also covers arranging substitutions for track inspector absences.
12. **Coordinate with dispatchers**. Coordination with dispatchers allows the engineering department to inform the dispatchers of planned inspection and maintenance activities and manage track outages.
13. **Restrict track speed**. Occasionally, a member of the engineering department (e.g., a supervisor) may restrict track speed instead of a track inspector, such as if an inspector has trouble reaching the dispatcher.
14. **Remove track from service**. Like restricting track speed, the engineering department may sometimes contact the dispatcher to remove track from service.

5.1.3 Dispatchers

Dispatchers[12] oversee train movements and allocate track for maintenance. They grant track time to track inspectors and exchange information with train crews. The dispatchers work closely with train crews during day-to-day operations. While train crews have little direct involvement in track inspection, they may report issues to their dispatcher who will inform the engineering department. In the Visual Inspection sociotechnical model, the dispatcher performs the following actions:

15. **Grant track time to track inspectors**. Dispatchers inform track inspectors of how much time they have to complete their work on a particular track section.

5.1.4 Upper Management

Upper management refers to the railroad managers involved in allocating resources and setting performance goals. These resources and performance goals influence the engineering department's ability to perform inspection and maintenance activities. Upper management performs the following actions:

16. **Define the railroad's territories**. Territory size and complexity influences the workload of each track inspector.
17. **Set performance goals**. Performance goals provide targets and/or incentives for both safety and on-time performance.

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[12] Some railroads refer to dispatchers as rail traffic controllers.

18. **Provide resources for inspection activities**. Resources may include things like staffing, funding, equipment, etc. that influence the engineering department's ability to complete necessary inspections.

5.1.5 Labor Unions

In this model, labor unions include labor organizations such as BMWED that participate in the collective bargaining process with upper management.[13] This analysis includes one action for labor unions:

19. **Agree to terms for job assignment**. The terms that labor unions agree to during collective bargaining include job assignment, and influence the staffing practices of the engineering department.

5.1.6 FRA's Role in the Track Inspection Process

FRA influences the track inspection process through its role as the regulator. FRA sets safety standards for track conditions and monitors the railroads' compliance with these safety standards. Although FRA is also involved in inspection through educating railroads (e.g., assisting with and providing feedback on inspections) and sharing its technologies and resources, FRA's inspection activities are outside the scope of this analysis, which focuses on inspections within the railroad. The analysis team considered one action for FRA in this model:

20. **Create regulations (sets safety standards)**. These regulations address the required frequency of inspections and safety thresholds for many track conditions. These regulations shape decisions and behavior at all levels of the railroad.

5.1.7 Non-Acting Components

The track itself and the inspection reports that inspectors create are additional important components of the visual sociotechnical system.

Track refers to the railroad infrastructure that is controlled by dispatchers and maintained by the engineering department. Track inspectors gather condition information from the track, relying on sensory cues.

Inspection reports are paper or digital records created and maintained by track inspectors. They communicate information to the engineering department and to other inspectors and serve as an historical record for monitoring track conditions and repair history over time.

5.2 Conventional TGMS & Visual Inspection Sociotechnical System

The second sociotechnical system that the Volpe team considered includes both human inspectors and a conventional TGMS inspection vehicle, and is modeled in Figure 6. The following sections describe the roles, responsibilities, and key actions for each actor or component in this TGMS & Visual Inspection sociotechnical system. The numbering of these actions corresponds to the numbering in Figure 6.

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[13] Labor unions also represent employee interests in ways that are outside the scope of this analysis. In addition to addressing job assignments, the terms that labor unions agree to during collective bargaining address pay and employee working conditions.

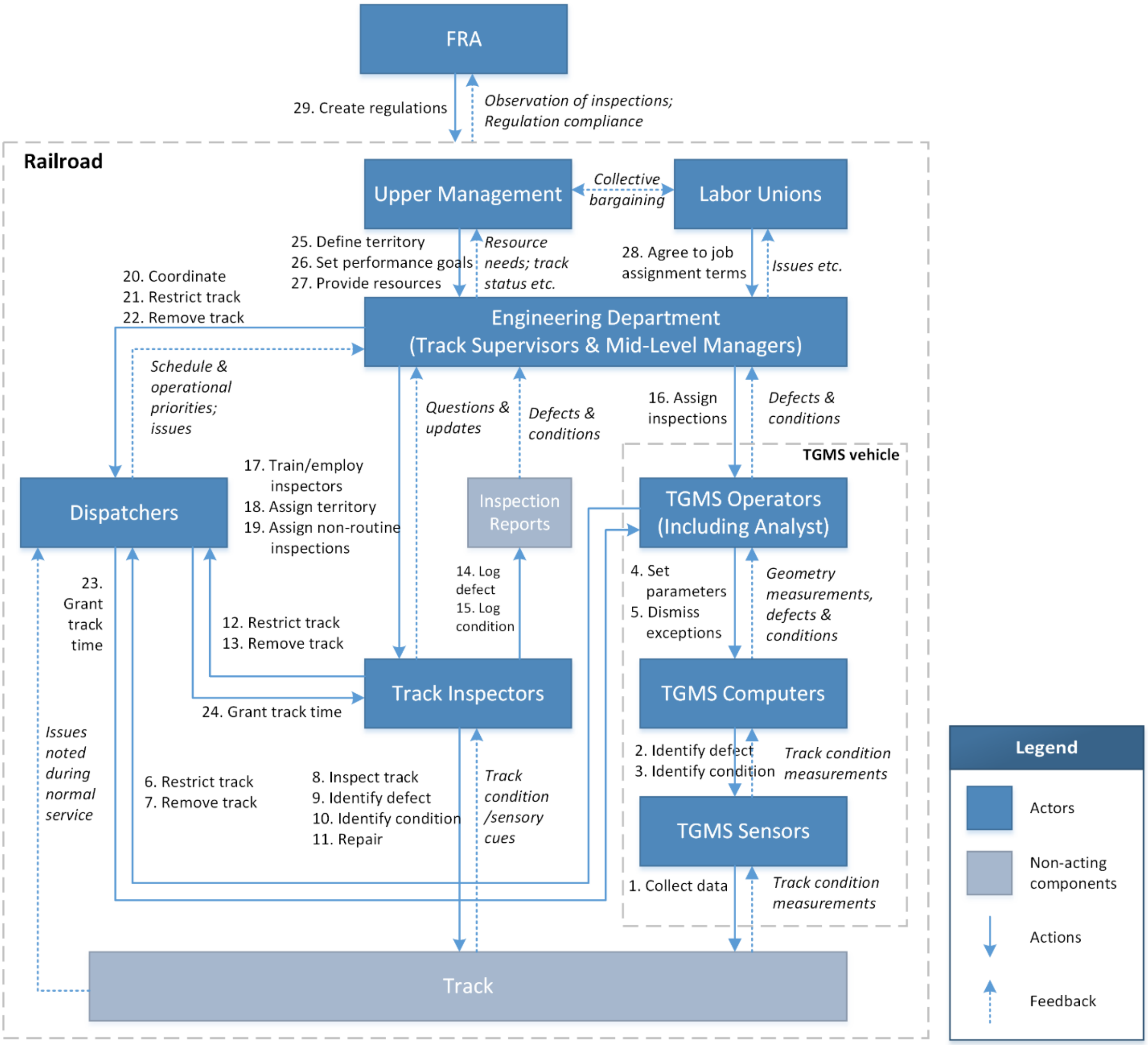

Figure 6. Model of a Conventional TGMS & Visual Inspection sociotechnical system

While the numbering differs from the previously-described Visual Inspection sociotechnical system, many of the control actions themselves are the same. In this section and Section 5.3, underlined text indicates actions that are new or changed from the visual sociotechnical system, as shown in Figure 7.

1. **<u>New Action</u>.** Underlined bold text indicates an action that is new or that has changed from the actions listed in the Visual Inspection sociotechnical system.

2. **Repeated Action.** Bold text without an underline is used to indicate an action that is unchanged from the Visual Inspection sociotechnical system.

Figure 7. Format example for actions repeated between sociotechnical systems

5.2.1 TGMS (Sensors & Computers)

The TGMS vehicle contains both sensors and computers. A locomotive or electric multiple unit (EMU) pulls the TGMS, but it is not operating in revenue service. The team onboard the TGMS vehicle includes TGMS operators and sometimes track supervisors or managers. A grey dotted line in Figure 6 indicates that the sensors, computers, and operators are all onboard the vehicle.

1. **Collect data (TGMS sensors)**. The TGMS uses sensors to take measurements of the track geometry. The TGMS computes then transforms the sensor data into information for the TGMS operator in the form of images and strip charts showing numeric measurements.
2. **Identify defects (TGMS computers)**.[14] When the TGMS computer identifies measurements that exceed the programmed thresholds, it flags them as defects.
3. **Identify conditions (TGMS computers)**. The TGMS computer may also flag maintenance conditions if the railroad has programmed thresholds stricter than FRA regulations.

5.2.2 TGMS Operators

TGMS operators include the onboard technicians and analysts involved in TGMS operations. They may be engineering department employees or contractors hired by the railroad. They are responsible for inputting parameters and monitoring the data output, as well as screening the data output and determining what actions are needed, including dismissing exceptions, contacting the engineering department, or reaching out to dispatchers. In some cases, track supervisors may ride onboard the TGMS vehicle; however the Volpe team does not consider these employees "operators" as they are not directly responsible for operating the TGMS and reviewing the output. Likewise, the Volpe team did not consider engineer and conductor(s) responsible for the movement of the geometry car "operators" as their actions are not directly related to the inspection process. The team considered the following TGMS operator actions:

4. **Set parameters**. The TGMS uses these parameters such as track class and location to determine appropriate thresholds. The operator also monitors the TGMS to verify that it applies preset and automatically detected parameters appropriately.
5. **Dismiss exceptions**. This is necessary in the case of false alarms such as inaccurate readings that occur when going over a frog.
6. **Restrict the track speed**. Often a member of the engineering department is onboard the TGMS vehicle, or otherwise available to restrict track speed when TGMS detects an exception. Occasionally, if this engineering department employee (e.g., a supervisor) is not available, the TGMS operator may restrict track speed instead.[15]

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[14] Discussion with subject matter experts revealed that TGMS marks both defects and conditions as "exceptions." The railroad only considers them "defects" once verified by an inspector. However, the Volpe team preserved this distinction in the analysis to indicate that railroads will ultimately class exceptions as either defect or condition.

[15] Railroads that the Volpe team spoke with indicated that they do not act on exceptions from TGMS until the exceptions have been verified. These actions may be more commonly performed by supervisors onboard the TGMS vehicle; however, the team assumed in some cases the TGMS operator could call the dispatcher. For additional information on the team's assumptions, see Appendix C.

7. **Remove the track from service**. Like restricting track speed, the TGMS operator may contact dispatchers to remove track from service if a member of the engineering department is not available to do so.

5.2.3 Track Inspectors

The control actions for the track inspector are largely the same as for the Visual Inspection sociotechnical system. However, in the Conventional TGMS & Visual Inspection sociotechnical system, their inspections may include verifying defects and conditions identified by the TGMS. In this sociotechnical system, inspectors perform the following actions:

8. **Inspect the track**. Each track inspector is responsible for inspecting track in their assigned territory. Depending on the characteristics of the territory, they may do these inspections primarily on foot or via hi-rail vehicle. When TGMS has detected an exception, the engineering department may assign inspectors to verify whether there is truly a defect or maintenance condition at that location.
9. **Identify defects**. Inspectors must determine whether the track condition meets FRA requirements. If it does not, inspectors must consider it a defect.
10. **Identify maintenance conditions**. Inspectors must also determine whether the track condition meets the railroad's internal maintenance standards. If it does not, the inspector must consider it a maintenance condition.
11. **Repair maintenance conditions and defects**. Typically, inspectors only perform relatively minor repairs; for more serious issues, they must restrict track speed or remove track from service until a maintenance crew can perform more complicated repairs.
12. **Restrict the track speed**. For certain types of "class-limiting" defect, track inspectors place speed restrictions by calling the dispatcher to reduce the maximum permitted track speed for the section of track with the degraded track condition(s).
13. **Remove the track from service**. For severe defects, track inspectors can remove the track from service by calling the dispatcher.
14. **Log defects**. Inspectors must log the defects they identify, and any actions they have taken to address them. They do this either on paper or using a designated IT system.
15. **Log maintenance conditions**. Inspectors typically log maintenance conditions as well as defects; though the railroad does not have the same degree of obligation to address them.

5.2.4 Engineering Department (Supervisors and Managers)

The engineering department is responsible for overseeing both automation-aided and visual inspections. In this sociotechnical system, they assign inspections to TGMS operators, and may assign verifications of TGMS data to track inspectors as one type of non-routine inspection. They may contact dispatchers on behalf of the TGMS operator when necessary to restrict track speed or remove track from service, and may coordinate with dispatchers for TGMS inspections. The engineering department performs the following actions in this sociotechnical system.

16. **Assign inspections to the TGMS operators**. The engineering department decides which territories to inspect using TGMS, including the order in which the territories are inspected and how frequently to inspect.

17. **Train and employ inspectors**. While a separate training department is typically responsible for training, the engineering department has a role in this process as they indicate their required staffing levels and provide input to the training process. Therefore, this analysis attributes these staffing processes to the engineering department for simplicity.
18. **Assign territory**. Some territory assignment activities happen outside the engineering department (e.g., through the job bidding process). However, the engineering department is responsible for making sure all territories are covered and may make substitute assignments to cover absences.
19. **Assign non-routine inspections**. Non-routine inspections include special weather inspections, arranging substitutions, and following up on issues reported by operations crews and other inspectors. When TGMS is in use, it also includes verifying exceptions identified by TGMS.
20. **Coordinate with dispatchers**. Coordination with dispatchers allows the engineering department to inform the dispatchers of planned inspection and maintenance activities and manage track outages. When TGMS is in use, the engineering department may coordinate with dispatchers to fit TGMS inspections into the schedule.
21. **Restrict track speed**. Occasionally, a member of the engineering department (e.g., a supervisor) may restrict track speed instead of a track inspector, such as if an inspector has trouble reaching the dispatcher. When TGMS is in use, the engineering department (e.g., a supervisor onboard the TGMS vehicle) may restrict track speed in response to information from the TGMS operator.[16]
22. **Remove track from service**. Like restricting track speed, the engineering department may sometimes contact dispatchers to remove track from service. When TGMS is in use, the engineering department (e.g., a supervisor onboard the TGMS vehicle) may remove track from service in response to information from the TGMS operator.

5.2.5 Dispatchers

Because conventional TGMS requires track time to operate, the dispatchers for this sociotechnical system must grant track time to TGMS operators as well as track inspectors. In the current sociotechnical system model, dispatchers perform the following actions related to the track inspection process:

23. **Grant track time to TGMS operators**. Because the conventional TGMS vehicle is pulled by a designated locomotive, it requires track time to perform inspections.
24. **Grant track time to track inspectors**. Dispatchers inform track inspectors of how much time they have to complete their work on a particular track section.

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[16] Railroads indicated that they currently require someone to verify the exceptions identified by TGMS before taking action on the track. The Volpe team assumed that this is sometimes done by members of the engineering department (i.e., supervisors). For additional information on the team's assumptions, see Appendix C.

5.2.6 Upper Management, Labor Unions, & FRA

The control actions for railroad management, labor unions, and FRA are the same as in the Visual Inspection sociotechnical system, though there may be differences in how these actions impact sociotechnical systems that use conventional TGMS. For example, upper management provides resources for both TGMS and visual inspection, and FRA regulations shape how railroads decide to use both visual inspection and TGMS. In this sociotechnical system, the team considered the following upper management actions related to track inspection:

25. **Define the railroad's territories (Upper Management)**. Territory size and complexity influences the workload of each track inspector.
26. **Set performance goals (Upper Management)**. Performance goals provide targets and/or incentives for both safety and on-time performance.
27. **Provide resources for inspection activities (Upper Management)**. Resources may include things like staffing, funding, equipment, etc. that influence the engineering department's ability to complete necessary inspections.
28. **Agree to terms for job assignment (Labor Unions)**. The terms that labor unions agree to during collective bargaining include job assignment, and influence the staffing practices of the engineering department.
29. **Create regulations (FRA)**. These regulations address the required frequency of inspections and safety thresholds for many track conditions. These regulations shape decisions and behavior at all levels of the railroad.

5.3 aTGMS & Visual Inspection Sociotechnical System

The third sociotechnical system that the Volpe team considered, depicted in Figure 8, includes both human inspectors and a locomotive-mounted aTGMS unit that collects geometry data during revenue service. The following sections describe the roles, responsibilities, and key actions for each actor or component in this aTGMS & Visual Inspection sociotechnical system. The numbering of these actions corresponds to the numbering in Figure 8.

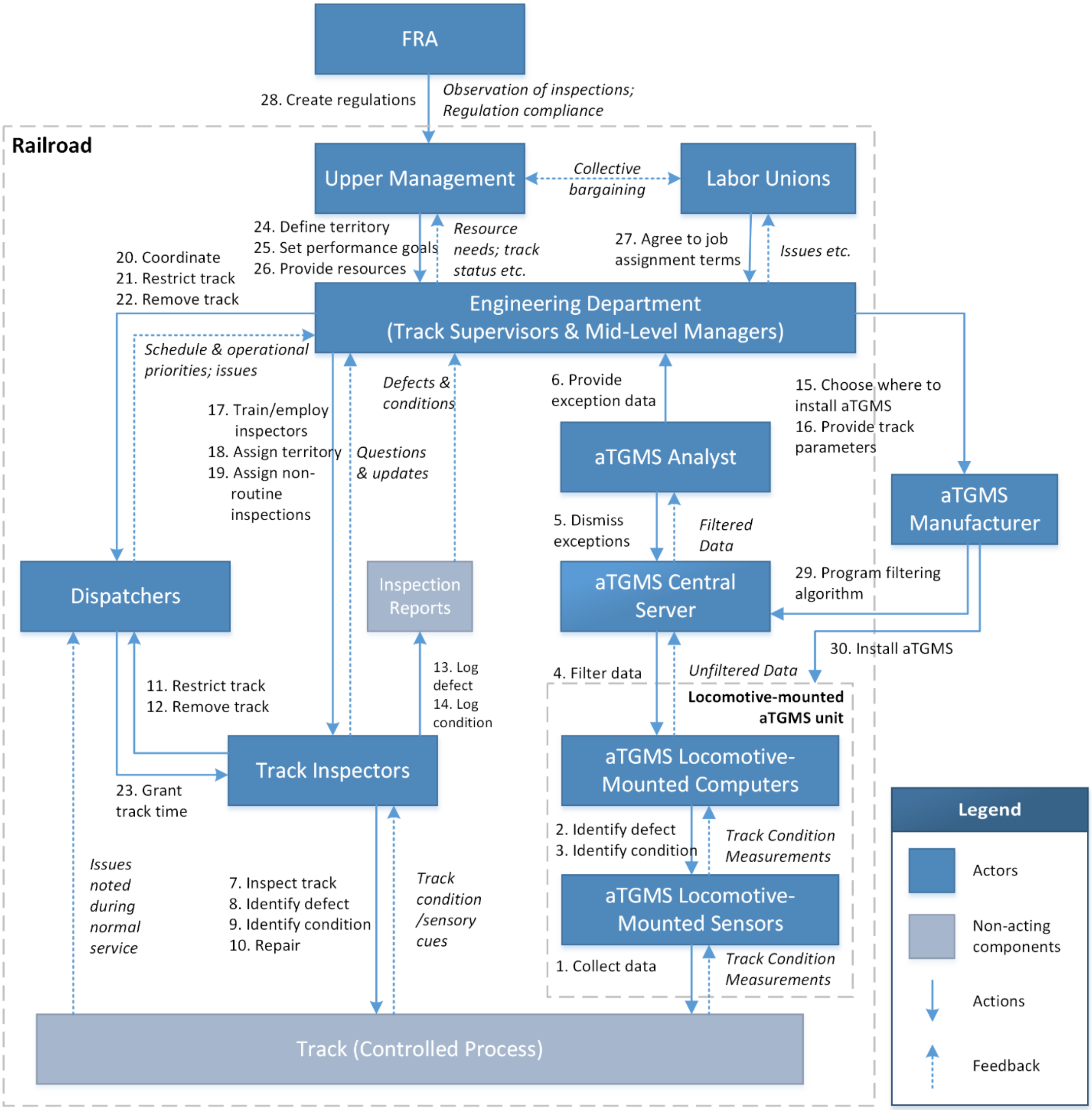

Figure 8. Model of an aTGMS & Visual Inspection sociotechnical system

Like in the Conventional TGMS & Visual Inspection sociotechnical system, many of the control actions are unchanged from the Visual Inspection sociotechnical system, though the numbering of these actions may differ. As shown in Figure 7, bold black text indicates control actions that are new or that contain changed information, while bold grey text indicates control actions that are unchanged from the Visual Inspection sociotechnical system.

5.3.1 Locomotive-Mounted aTGMS Unit (Sensors & Computers)

The aTGMS unit contains both sensors and computers. It is mounted to a locomotive or EMU operating in revenue service. It does not have any onboard staff. The aTGMS sends data to a central server where it can be viewed by an offsite analyst. A grey dotted line in Figure 8 indicates the components of the locomotive-mounted unit. The team considered the following actions:

1. **Collect data (aTGMS sensors)**. The aTGMS sensors collect measurements of the track geometry. The aTGMS computers will then process this data send it to the aTGMS analyst.
2. **Identify defects (aTGMS computers)**. When the aTGMS computers identify measurements that exceed the programmed thresholds, it sends these measurements to the central server.
3. **Identify conditions (aTGMS computers)**. The aTGMS computers may also flag maintenance conditions if the railroad has programmed thresholds stricter than FRA safety standards.

5.3.2 aTGMS Central Server

The aTGMS central server is responsible for storing data from the aTGMS locomotive-mounted unit so that the aTGMS analyst can access it.[17] It also uses algorithms to filter the data.

4. **Filter data**. The aTGMS server attempts to filter out false alarms and other data anomalies using the algorithms developed by the aTGMS manufacturer.

5.3.3 aTGMS Analyst

Much like a TGMS operator/analyst, the aTGMS is responsible for reviewing the data produced by aTGMS. However, the aTGMS analyst is not present while aTGMS collects data. The aTGMS analyst reviews the data at a later time. At one railroad the Volpe team visited, the aTGMS analyst received notifications when potential defects were flagged, and reviewed full track condition data the following day. The aTGMS analyst performs the following actions:

5. **Dismiss exceptions**. Much like a conventional TGMS operator, the aTGMS analyst may dismiss exceptions that appear to be false alarms.
6. **Provide exception data to the engineering department**. When aTGMS identifies a defect, the aTGMS analyst forwards that information to the engineering department so that they can send a track inspector to verify, restrict track speed, or remove track from service if necessary.

5.3.4 Track Inspectors

The control actions for the track inspector are largely the same as for the Visual Inspection sociotechnical system. However, in the aTGMS & Visual Inspection sociotechnical system, their inspections may include verifying defects and conditions identified by aTGMS. Inspectors in this sociotechnical system perform the following actions:

7. **Inspect the track**. Each track inspector inspects track in their assigned territory. Depending on the territory characteristics, they may do these inspections primarily on

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[17] Though this safety control structure model depicts the aTGMS server and aTGMS analyst within the railroad's organizational boundaries, in some cases, railroads may contract with vendors to store and analyze aTGMS data. The current analysis assumes that the aTGMS analyst is a railroad employee.

foot or via hi-rail vehicle. When aTGMS has detected an exception, the engineering department may assign inspectors to verify whether there is truly a defect or maintenance condition at that location.

8. **Identify defects**. Inspectors must determine whether the track condition meets FRA safety standards.
9. **Identify maintenance conditions**. Inspectors must also determine whether the track condition meets the railroad's internal maintenance standards.
10. **Repair maintenance conditions and defects**. Inspectors may perform minor repairs. For more serious issues, they restrict track speed or remove track from service until a maintenance crew can perform the repairs.
11. **Restrict the track speed**. For certain types of "class-limiting" defect, track inspectors place speed restrictions by calling the dispatcher to reduce the maximum permitted track speed for the section of track with the degraded track condition(s).
12. **Remove the track from service**. For severe defects, track inspectors can remove the track from service by calling the dispatcher.
13. **Log defects**. Inspectors must log the defects they identify, and any actions they have taken to address them. They document the track conditions on paper or using a designated IT system.
14. **Log maintenance conditions**. Inspectors typically log maintenance conditions as well as defects.

5.3.5 Engineering Department

The actions for the engineering department are very similar to the Visual Inspection sociotechnical system. Unlike TGMS, aTGMS does not require additional coordination with dispatchers. However, the engineering department may send inspectors to verify exceptions, and may restrict track speed or remove track from service, based on information received from aTGMS. They also choose where to install aTGMS and provide track parameters. In this sociotechnical system, the engineering department performs the following actions:

15. **Choose where to install aTGMS**. Because the aTGMS unit is locomotive-mounted, railroads that use multiple power types must choose the areas they would like the aTGMS to cover and install it on the appropriate locomotive.
16. **Provide track parameters for aTGMS**. The engineering department supplies track parameters because there is no onboard operator to adjust the parameters while the aTGMS operates. Therefore, track charts, track class, speed restrictions, etc. must be programmed when the aTGMS is installed and whenever changes are made.
17. **Train and employs inspectors**. While a separate training department is typically responsible for training, the engineering department has a role in this process as they indicate their required staffing levels and provide input to the training process. Therefore, this analysis attributes these staffing processes to the engineering department for simplicity.

18. **Assign territory**. Some territory assignment activities happen outside the engineering department (e.g., through the job bidding process). However, the engineering department is responsible for making sure all territories are covered and may make substitute assignments to cover absences.
19. **Assign non-routine inspections**. Non-routine inspections include performing special weather inspections, arranging substitutions, and following up on issues reported by operations crews and other inspectors. When aTGMS is in use, it also includes verifying exceptions identified by aTGMS.
20. **Coordinate with dispatchers**. Coordination with dispatchers allows the engineering department to inform the dispatchers of planned inspection and maintenance activities and manage track outages. (Note that aTGMS does not require any additional coordination beyond what is needed for visual inspection, as it does not require track time.)
21. **Restrict track speed**. Occasionally, a member of the engineering department (e.g., a supervisor) may restrict track speed instead of a track inspector, such as if an inspector has trouble reaching the dispatcher. When aTGMS is in use, the engineering department may restrict track speed in response to information from the aTGMS analyst.[18]
22. **Remove track from service**. Like restricting track speed, the engineering department may sometimes contact dispatchers to remove track from service. When aTGMS is in use, the engineering department may remove track from service in response to information from the aTGMS analyst.

5.3.6 *Dispatchers*

Because aTGMS does not require track time, the actions for dispatchers in the aTGMS & Visual Inspection sociotechnical system are the same as for the Visual Inspection sociotechnical system.

23. **Grant track time to track inspectors**. Dispatchers inform track inspectors how much time they have to complete their work on a particular track section.

5.3.7 *Upper Management, Labor Unions, & FRA*

The control actions for railroad management, labor unions, and FRA are the same as in the Visual Inspection sociotechnical system.

24. **Define the railroad's territories (Upper Management)**. Territory size and complexity influences the workload of each track inspector.
25. **Set performance goals (Upper Management)**. Performance goals provide targets and/or incentives for both safety and on-time performance.
26. **Provide resources for inspection activities (Upper Management)**. Resources may include things like staffing, funding, equipment, etc. that influence the engineering department's ability to complete necessary inspections.

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[18] Railroads indicated that they currently require someone to verify the exceptions identified by aTGMS before taking action on the track. The Volpe team assumed that this is sometimes done by members of the engineering department (i.e., supervisors). For additional information on the team's assumptions, see Appendix C.

27. **Agree to terms for job assignment (Labor Unions)**. The terms that labor unions agree to during collective bargaining include job assignment, and influence the staffing practices of the engineering department.
28. **Create regulations (FRA)**. These regulations address the required frequency of inspections and safety thresholds for many track conditions. These regulations shape decisions and behavior at all levels of the railroad.

5.3.8 aTGMS Manufacturer

The Volpe team's model for this sociotechnical system assumes that the aTGMS manufacturer is responsible for programming the algorithms used to filter data, as well as installing the aTGMS unit. The Volpe team depicted these actions for thoroughness, but did not examine them in detail, because these actions were outside of the railroad's control.

29. **Program the filtering algorithm**. The aTGMS manufacturer uses data provided by the railroad to set the parameters for the filtering algorithm. This algorithm identifies defects and maintenance conditions.
30. **Install the aTGMS unit**. The aTGMS manufacturer assists the railroad by installing the aTGMS unit on the designated locomotives.

6. Sociotechnical Factors Influencing Inspection

Safety science has migrated from models focusing on individual behavior to sociotechnical models that take into account the interactions between individuals, technology, and organizations. The current track inspection research adopted a sociotechnical framework by considering the organizational, technological, and individual factors within the railroad system that interact to produce hazards associated with track inspection.

Sociotechnical research asserts that the occurrence of hazards can only be understood by taking a systems perspective (Rasmussen, 1997; Leveson, 2011). In a systems perspective, safety is considered an emergent property of the sociotechnical system as a whole. Therefore, hazards (or, conversely, safety and efficiency) arise from the interactions of the parts (individuals, technology, and organization) within the sociotechnical system. This approach captures information that may be missed (i.e., the interactions between the parts) when using an approach that focuses on the individual parts of the sociotechnical system.

According to a systems perspective, hazards may not always be explained by the events immediately preceding them. Conditions within the sociotechnical system may combine and interact in unanticipated ways to produce hazards. When examining how hazards can arise during the track inspection process, it is important to also consider the sociotechnical factors, and interactions among them, that influence track inspection as a whole.

As shown in Figure 9, the factors that influence the track inspection process can be modeled as a series of hierarchical levels. The *Individual & Team* level consists of factors such as inspector experience and skill level, and teamwork and communication between inspectors and those with which they work. The *Tools and Technology* level includes factors such as automated track inspection technologies as well as less complex technologies such as hi-rail design, and job aids used by inspectors. The *Physical Environment & Technology* level includes factors such as weather and time of day as well as size and characteristics of the territory. *Railroad Organizational & Managerial Processes* are at the next level and include factors created or controlled by the railroad such as crew assignment and scheduling, inspector training, supervisory practices, and dispatcher management. At the highest level is *External Factors & Regulatory Activities*. This includes factors outside of the railroad that have some influence over it such as service demands, FRA regulations and enforcement activities, and collective bargaining agreements between unions and railroads.

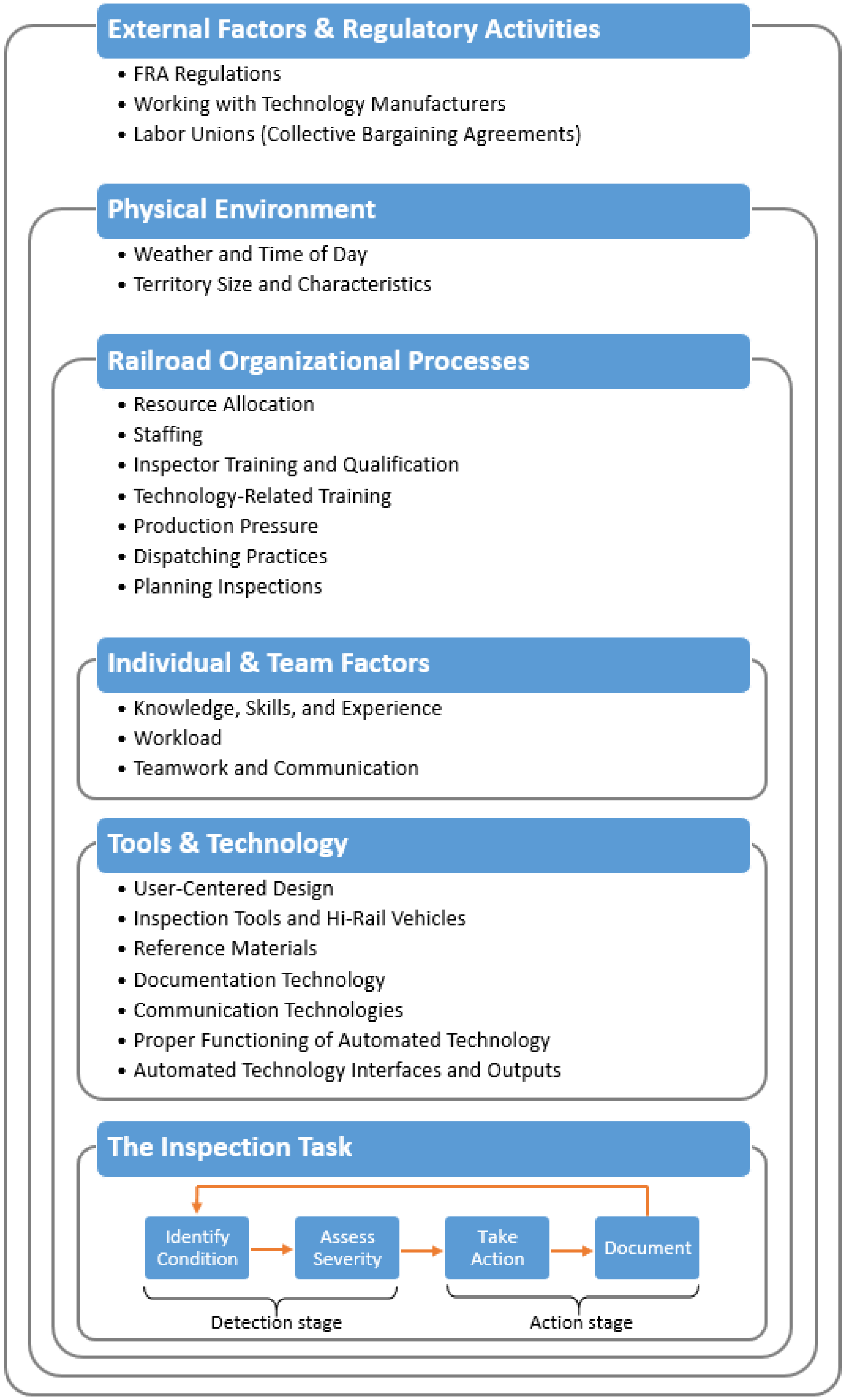

Figure 9. Sociotechnical factors influencing inspection: hierarchical view

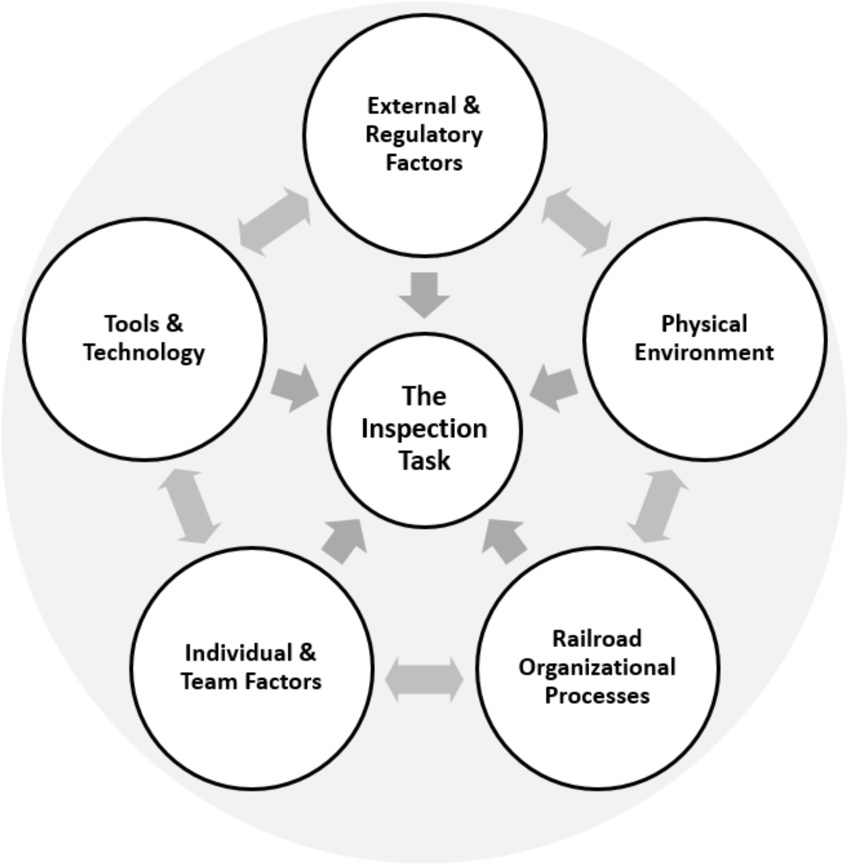

Figure 10. Sociotechnical factors influencing track inspection: inter-relational view

Figure 9 depicts how these levels layer on top of each other in a hierarchical manner, with each level exerting influence on the levels below it, and outlines some of the factors that will be discussed in the following sections. Although the team categorized each factor into one of the four levels, some could be placed in multiple levels due to the interactions between these categories, depicted in Figure 10.

Figure 10 illustrates why it would be incorrect to conceptualize accidents and unsafe events related to track conditions as resulting from a strictly linear progression of factors. There are many inter-relationships between factors at different levels. For example, organizational decisions influence which technologies are purchased and how frequently they are used, in addition to setting territory and schedules for inspectors, etc. All these elements interact with each other, and it can be through these interactions that hazardous conditions occur and potentially lead to accidents.

These figures are not meant to provide a comprehensive list of contributing factors, nor to quantify their potential contributions to accidents or hazards. The figures illustrate the breadth of factors that can influence a visual or automation-aided inspection based on the Volpe team's discussions with the three railroads and observations.

The following sections discuss some of these example factors in more detail. This discussion may be of particular interest to those readers that are unaccustomed to thinking about how sociotechnical factors can influence the track inspection sociotechnical system. Additionally, those readers that are less familiar with the track inspection process may find these examples illuminating because they are real-world examples provided during the team's site visits.

Readers will note that many of the same topics appear in Section 7. However, there is an important distinction between these sections:

- Section 6 is based on examples that the Volpe team heard during the interviews with railroad employees.
- Section 7 is based on the results of the team's hazard analysis. Therefore, it includes recommendations to address potential risks that the team identified, in addition to specific risks that railroad employees mentioned.

The current section can be seen as a foundation for understanding the team's recommendations, as it provides an overview of the type of factors that may impact safety at each level of the sociotechnical system. Additionally, because it is based directly on information from interviews, it may indicate topics that are of particular concern to railroads. However, this section is not intended to be an exhaustive list of risks.

6.1 Individual and Team Factors

Based on discussions with railroad employees, the Volpe Team identified many risk factors at the *Individual and Team* level of the sociotechnical system that could contribute to hazards. Individual factors include knowledge, skills, and experience. Team factors include teamwork, communications between team members, and complexities that may arise when some team members have competing priorities. (Section 7.2 and Section 7.3 include information on how to address these and additional potential risks in this area based on the team's hazard analysis.)

6.1.1 Knowledge, Skills, and Experience

Experience plays an important role in the ability of track inspectors to work safely, efficiently and effectively.

Skills gained through experience. The skills related to defect detection, time management, communication and repairs primarily come with experience. For example, more experienced inspectors described strategies for detecting defects even when the track was covered in snow, or strategies for obtaining track time for inspections or repairs, that less experienced inspectors might not know to employ.

Importance of territory-specific experience. Inspectors noted the importance of acquiring experience working in a particular territory. Understanding the areas within the territory that may be more prone to certain conditions or defects, understanding where within the territory they may be more likely or unlikely to receive track time, and having a sense for the history of repairs and conditions within the territory were all mentioned as important factors to consider when inspecting and repairing track.

Lack of experienced inspectors. At railroads that experienced large-scale retirements in recent years, supervisors lamented the lack of experienced employees working as track inspectors. The issue of less-experienced inspectors was also exacerbated at railroads that described issues with their collective bargaining agreements. Within track departments that allowed more frequent job bids and bumps, or which offered greater pay for other job types under the collective bargaining agreement, inspectors were less likely to stay on a job within a certain territory for enough time to become experienced, particularly with regard to the territory characteristics.

Managing inexperienced inspectors. Supervisors noted strategies for managing inexperienced inspectors, such as trying to pair experienced inspectors with inexperienced inspectors or rotating the jobs within their territory to get multiple sets of eyes on the tracks. Some supervisors noted that less experienced inspectors also tended to communicate with them more often for help determining whether or not a condition is present. They might also benefit from mentorship.

6.1.2 Teamwork and Communications

Teamwork and communication are important aspects of safe and effective track inspection. The track inspection process is comprised of several sets of "teams" which require effective communication both verbally and in written form. Teams can include:

- Track inspectors working together to inspect track
- Track inspectors working with dispatchers to obtain/restrict/remove track
- Track inspectors working with supervisors
- Track inspectors working with other engineering employees (e.g., Maintenance, Bridge & Building, Signal Department, etc.)
- Supervisors working with dispatchers
- TGMS operators, those running the train pulling TGMS, onboard supervisor (if present)

Some of the challenges in working as teams are summarized below.

Competing priorities. In some cases, team members' competing priorities make interactions within the team more complex. Dispatchers' priority is to keep trains moving on-time. Inspectors' priorities are to inspect track and ensure safe track conditions. Track supervisors' priorities involve planning and arranging maintenance in addition to inspections. As one railroad inspector commented, "The dispatchers care about trains. We care about track." While generally all employees the Volpe team spoke with understood the importance of working together to support the ultimate goals of safety and on-time performance, the team did hear examples where team members found it difficult to work with others effectively due to competing priorities. For example, across all railroads the team spoke with, at least some inspectors reported that getting track time can be challenging. A different type of competing priority was illustrated when one inspector reported receiving pressure from a supervisor to not report more track issues than the railroad could fix with existing resources.

Communication. There are several different railroad employees in different locations that need to work together in the track inspection and maintenance process. Many of them need to stay in communication with each other throughout the week or day as part of the standard workflow. For those in the field, daily communications may happen primarily through radio or phone.

Radio communications occur on a shared channel. This has some advantages in that if someone overhears a mistake, they can join the conversation to correct it. The phone may be used when longer communications are needed, and phone use is permitted as long as inspectors and other field staff are not on the track. Some railroad staff, such as track supervisors, may also utilize email in addition to phone calls.

For the inspection and maintenance process to function as intended, it is essential that these communications are both efficient and effective. However, in some cases there may be a tradeoff between these two things. This is apparent when it comes to redundancies in communications built into the track inspection and maintenance process. Redundancy may reduce efficiency, but it increases effectiveness by increasing the likelihood that critical information is received. For example, when an exception is found during an aTGMS run, a track supervisor may be notified by both a phone call and an email. Redundancies for critical or time-sensitive information can be helpful; however, redundant communications also contribute to additional workload for staff by increasing the number of calls and emails they need to attend to throughout the day.

6.2 Tools and Technology

Interviews with railroad employees revealed that tools and technology[19] are essential components of both the track inspection process as well as the process of recording information about track conditions. The Volpe team identified several issues at the *Tools and Technology* level of the sociotechnical system that can impact the track inspection process. Railroad employees discussed issues related to documentation technologies, hi-rail vehicles, and automated inspection technologies. (Section 7.4.1 includes how to address these and additional potential risks in this area based on the team's hazard analysis.)

6.2.1 Documentation Technology

Track inspectors discussed the documentation method as a factor that can create complexity. Inspectors shared challenges related to both paper forms and electronic forms (i.e., digital reporting software).

Paper forms. Railroads that use pen and paper noted challenges associated with this method including difficulty interpreting handwriting, the need for the inspector to re-write persistent conditions on every report and the need for supervisors to keep track of these persistent conditions (i.e., how long it has been on the report). Some employees the team spoke with discussed their desire to digitize these handwritten reports, and the difficulty in attaching visual documentation (photos) to the handwritten reports.

Digital report software. When designed properly, the use of a tablet or computer for digital report submission can help to mitigate the issues associated with pen and paper. However, poor design choices can lead to usability issues. Data submission forms that are error prone due to 'bugs' in the software, are sources of frustration among employees, particularly when bugs or poor usability cause the employee to spend significantly more time on the task. When inspectors need to log their handwritten notes onto a computer after a full shift inspecting track, the time required to do this extra task should be taken into account. Using handheld tablets to submit data during the inspection can help accelerate data submission; however, track inspectors also reported that when walking long distances along the track the requirement to carry extra tool like

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[19] Though all tools can be considered "technology," the authors refer to tools and technology separately here and in Section 7 to ensure that this section explicitly includes both the simple technologies used in measurement and repair (e.g., hammers), which researchers call "tools," as well as more sophisticated computer-based technologies.

a tablet may make the job more physically difficult, and durability and usability of such devices were among concerns that inspectors shared.[20]

6.2.2 Hi-Rail Vehicles

Certain inspection jobs require the use of the hi-rail vehicle because very large territory cannot be traversed on foot within the timeframe required by FRA regulations. The hi-rail vehicle allows inspectors to cover more track and has the added bonus of enabling them to bring tools and parts for basic repairs. Inspectors noted that hi-rail vehicles enabled them to use kinesthetic and auditory cues to search for certain track conditions. Despite these benefits of using a hi-rail vehicle, most said the best way to see track defects and conditions was by walking. This is for the reasons summarized below.

Vehicle speed. Hi-rail vehicles move at a faster speed than inspectors move on foot. Most inspectors said they go as slowly as they can in the hi-rail vehicle, which is still faster than walking. Although inspectors generally indicated that they can go slow enough to inspect effectively, they also noted that they prefer to walk certain areas when possible, such as curves, to get a closer look. (Track inspectors must also inspect switches on foot according to FRA regulations.)

Vehicle design. A second challenge to seeing defects from a hi-rail vehicle results from the design of the vehicle. The hi-rail vehicles at the railroads the team visited look like regular pick-up trucks. Inspectors noted that this current hi-rail vehicle design made it difficult to see out front because the vehicle hood blocked the view of the track. At one railroad, inspectors noted that the older hi-rail vehicles that they had previously worked with were more conducive to inspecting tracks, since those vehicles had windows lower down.

6.2.3 Automated Inspection Technology

Certain conditions must be met in order to maximize the accuracy and reliability of the automated inspection technology. For the geometry car, weather, speed of geometry car, calibration, and threshold inputs can affect the reliability of the data. For example, the Volpe team heard instances where the geometry car provided important data on track conditions, but due to an error with the Global Positioning System (GPS), the location coordinates were all incorrect. This outcome, resulted in wasted time and frustration for the track inspectors sent out to verify the locations of the previously identified track conditions. The following sections describe how some conditions impact the accuracy and reliability of the automation.

6.3 Physical Environment

Based on discussions with railroad employees, the Volpe team identified factors at the *Physical Environment* level of the sociotechnical system that could contribute to hazards. Inspectors noted issues related to aspects of physical environment that are constantly changing, such as the weather, as well as issues that do not change frequently, such as those related to territory characteristics. (Section 7.6 includes how to address these and additional potential risks in this area based on the team's hazard analysis.)

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[20] Software systems between railroads likely differ, but these are general observations based on the Volpe team's firsthand discussions with railroad employees using one such technology and the team's human factors knowledge.

6.3.1 Weather

Impacts on visual inspection. Weather is an important factor that can make scheduling inspections and repairs, as well as finding and repairing defects, difficult for the track inspector. Under certain weather conditions, the track inspector may need to alter their method of inspection. For example, during rainy conditions the inspector will likely inspect from the hi-rail rather than on foot. When more extreme weather occurs, inspectors may need to delay the inspection for their own safety, or because they will not be able to inspect effectively. For example, the hi-rail vehicle may not be able to operate when there is significant snow on the tracks. Snow and ice on the tracks also make it more difficult to detect and repair defects. Finally, when extreme weather occurs (e.g., extreme heat, floods, blizzards, etc.) the track inspector must schedule a non-routine inspection to look for degraded track conditions. Based on knowledge acquired through training or experience they search for conditions and defects that are more likely to occur based on these extreme events. Given the challenges around locating defects in certain types of weather conditions, it may be especially important to have skilled and experienced mentors impart expert strategies for detecting defects even during weather challenges to their less experienced peers.

Impacts on automated technology. In addition to inhibiting the human inspector, weather can also make it difficult for inspection technologies to inspect track. Because geometry cars rely on laser technology, they may be especially prone to weather disruptions. For example, if the track has enough snow accumulated on the rails, back drag from the train causes snow to get into the geometry car's sensors, which blocks the laser technology. This invalidates the data. The team also heard instances of too much sunlight, or glare, reflecting into the geometry car's sensors and affecting data collection. Finally, when track is flooded, the sensors on some technologies, such as track geometry car sensors, may become immersed in water and unable to function correctly.

6.3.2 Time of Day

For the most part, visual track inspections are scheduled during daylight hours. However, certain conditions (e.g., special occurrences or platform inspections on busy passenger railroads) require track inspections to occur at night under low/no light conditions. Track inspectors noted that though inspections can sometimes occur at night, the low light makes it difficult to visually inspect. Experienced inspectors said they were able to detect defects according to the 'feel' of the rails and how the track behaves when operating the hi-rail over it. Less experienced inspectors are less likely to pick up on these more subtle kinesthetic cues.

6.3.3 Territory Characteristics

Inspection jobs may also be physically challenging as a result of the size and characteristics of the territory.

Track complexity. Size and characteristics of the territory can both contribute to complexity of track inspection for the human track inspector. For example, the size of the territory may dictate the method of travel the track inspector uses: hi-rail or walking the track. Certain territories may be more complex to inspect, such as territory with many curves or interlockings. These areas require more time and attention to inspect than straight territory with fewer switches. The Volpe team also spoke with inspectors who inspect high-speed turnouts and crossovers, which are also known to be more complex in nature.

Ease of track access. Certain territories also add complexity to the inspection process because of their location and the amount of revenue service the track supports. For example, in one terminal, inspectors only had access to one track per day to keep trains moving. In other locations, territories contained very long blocks, making it more difficult to obtain track time because dispatchers did not want to remove long stretches of track from service. Additionally, tracks with little or no sidings also made it difficult for inspectors to inspect quickly using the hi-rail vehicle because they had less opportunity to get off the track when dispatchers needed to take the track back for train service.

6.4 Railroad Organizational Processes

Based on discussions with railroad employees, the Volpe team identified factors at the *Railroad Organizational Process* level of the sociotechnical system that could contribute to hazards. The employees described challenges related to inspector training for visual inspection and around the understanding of automated technologies. Challenges related to supervisory practices and dispatch practices can create challenges for inspectors in some cases. (Section 7.5 includes how to address potential risks in this area based on the team's hazard analysis.)

6.4.1 Inspector Training

The specifics of track inspector training vary by railroad. However, inspectors and supervisors from railroads the Volpe team spoke with identified several common limitations to the training process, such as the need for longer and more effective training for track inspectors. The factors that the Volpe team heard across the railroads visited are described below.

Trainer experience level. Finding experienced trainers poses a challenge to some railroads. Some inspectors noted that their trainers had very little experience themselves. As a result, valuable experience-based lessons, anecdotes and strategies may not be passed on to new hires.

Variability in on-the-job training. The quality of OJT is highly dependent on the mentor to which an inspector is assigned. Given that there is a lack of structure associated with the OJT mentoring process, there is variability in the effectiveness of the training provided by mentors on the practical skills needed to perform the job of the track inspector/foreman. In addition, similar to instructors, mentors may themselves lack experience. Mentors are often not given any training on mentoring skills, and may lack motivation to serve as an effective mentor. This can result in poor mentoring and/or an inability to pass down important inspection skills and strategies.

Insufficient automated-inspection training. Inspector training does not provide any training and experience related to understanding the automated inspection tools or their output.[21]

Inspectors told us that their training did not include any information on how the automated technology collects data. Many inspectors thought this would be useful to them, suggesting that if they were taught more about how data was collected they could better verify issues, or better determine why they are unable to verify issues. For example, understanding that the geometry

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[21] Several employees mentioned that because inspector training is combined with foreman training, including this kind of information would be superfluous for the foremen who end up working as maintenance only employees. Some recommended add-on training specifically about the automated technology for inspectors only.

car measures gage under load is useful for understanding why they are sometimes unable to find the measurements reported by the geometry car when not inspecting under load.

Training also does not include guidance on interpreting automated technology output. Generally, inspectors and supervisors noted that this was not a problem. However, a track supervisor described some instances where having a better understanding of the output would be beneficial for track inspectors and supervisors, when doing their job. For example, there is a lot of data that can be ascertained by the strip chart but it is not intuitive to read. The strip chart, he said, contains track condition data that may not be found strictly in the defects report he receives, so a better understanding of it would help in interpreting track condition data that does not pertain to safety defects.

6.4.2 Supervisory Practices

There were significant differences in terms of supervisory oversight and practices among railroads the Volpe team worked with. The team heard many instances of seemingly exemplary track supervisors who worked very well with their track inspectors. The team also heard of several instances where supervisor pressures or practices may lead to hazards.

Pressure to complete inspections quickly. Supervisors may pressure inspectors to complete inspections quickly to keep trains moving. Inspectors noted that there could be repercussions when they did not acquiesce to these pressures, noting that supervisors might withhold overtime jobs or promotions. One inspector told us of an instance where he was told to pilot a piece of equipment, but to also count that time on the tracks as an inspection. The inspector said he did not necessarily feel comfortable with it because he did not feel it was a proper inspection. However, he knew from experience that if he refused there would be repercussions from the supervisor.

Pressure to report fewer conditions. The Volpe team also heard about pressures on the track inspector to "work within the confines of the repairs that can be done." If the inspector knows that it is not possible for all the conditions identified to be repaired, there may be pressure not to list them all on the report. This was primarily with regard to degraded conditions that did not meet the railroad's maintenance standards rather than those that exceeded the FRA safety standards. Some supervisors indicated that they preferred inspectors to select and prioritize which maintenance-level conditions to report, because it is more difficult for supervisors to track and prioritize issues if there are too many included on the inspection report. One possible reason for this type of supervisor pressure was that the supervisors struggled with a documentation and information management system that did not work for them.

6.4.3 Dispatching Practices

Railroads are under pressure to move trains according to their schedule. Removing track from service for inspections and maintenance makes the dispatcher's job of keeping trains running smoothly and on-time more difficult. The degree to which track inspectors reported difficulty obtaining track time from dispatchers varied among railroads, and this may be more of an issue in passenger rail operations given their often tight schedules and the density of trains on the tracks.

In some instances, track inspectors reported that they had very little issue obtaining track time for inspections, since these might be pre-scheduled and/or the inspector has some flexibility in when and where to inspect. Other times, particularly for non-routine inspections and maintenance, inspectors reported difficulty obtaining track time, noting that they might wait several hours for a portion of track or receive track only to have it taken away soon after.

Several factors that contribute to the likelihood of obtaining track time are summarized below.

Experience and skill level. Experienced dispatchers have “expert strategies” they employ that allow them to be creative about how they give track time, and track inspectors have similar “expert strategies” regarding where they choose to work. For example, one experienced inspector takes note of what is going on with the adjacent territory to his and schedules his inspections or repairs accordingly. If track 1 on the adjacent block is being taken out of service, he might request that his track 1 be removed from service as well, since the dispatcher is more likely to give that track to him than track 2, which would make it difficult for the dispatcher to route trains across the adjacent blocks. Then he plans his inspections and repairs for that track during that time.

Relationship with the dispatcher. Some track inspectors noted that developing a good working relationship with the dispatcher and understanding the dispatchers schedule helps. For example, some track inspectors try to get to know their territory’s train schedule, and may call the dispatcher to request time only when they know the dispatcher has time to spare.

Another example illustrates the importance of developing a trusting relationship between track inspector and dispatcher. In this example, the dispatcher knew that if the track inspector asked for 15 minutes of track time, the inspector would not exceed that time. This helped the dispatcher feel more confident giving track time when windows were tight.

Territory characteristics. The Volpe team heard several examples of characteristics of territory that make it more difficult, or unlikely, that a dispatcher will give track time. Territory with frequent trains traversing can be difficult to obtain track time for scheduling reasons. Territory with only one station platform, on just one track in territory with multiple tracks, can be difficult to obtain track time on for similar reasons. Territory that contains long blocks may also be difficult to obtain time on because dispatchers might be hesitant to take them out of service. Territories with long blocks more often require the use of a hi-rail vehicle, so if the territory has no sidings or grade crossings that allow the hi-rail vehicle to quickly get off the track, the dispatcher is less likely to give track time unless there is an opening in the train schedule.

Type of inspection or maintenance activity. Many track inspectors noted that for routine, scheduled inspections they were often able to get track time. However, for non-routine, unscheduled inspections, for example, after an unstaffed geometry car went through, or after extreme weather events, it might be harder to obtain track time since it was more likely to interfere with the train schedule. Obtaining track time for unscheduled maintenance was also difficult. Track inspectors and supervisors at all railroads the Volpe team spoke with recalled instances where they were unable to obtain track time until they threatened to take the entire track out of service to complete a required inspection.

6.5 External and Regulatory Factors

Based on discussions with railroad employees, the Volpe team identified factors at the *External and Regulatory* level of the sociotechnical system that could contribute to hazards. Many factors at this level were beyond the scope of the study and so will only be mentioned briefly However, given the inter-relationships between factors at different sociotechnical levels (see Figure 9), the team heard about several topics at this level as factors worth discussing. In particular, this section discusses revenue service demands, and FRA regulations.

6.5.1 Revenue Service Demands

Revenue service demands, (i.e., the need to keep trains moving according to schedule) was an underlying theme addressed in all the research focus groups. The role of the track inspector is to detect degraded track conditions, and secondarily to repair them when possible. The ability of track inspectors to perform these tasks is impacted by an understanding that first and foremost, the railroad wants to keep trains, and the people or goods onboard, moving. In passenger operations in particular, service demands (i.e., pressure to adhere to train schedules), results in limited windows of track availability in which to perform inspections and maintenance work.

Unstaffed, or “fully automated” track inspection technologies can alleviate some of these pressures, because they operate on revenue trains without disrupting train schedules. However, railroad employees the Volpe team spoke with stated that challenges related to service demands were still felt when it comes to getting track conditions repaired.

6.5.2 Other External and Regulatory Factors

Sections 5.1.5 and 5.1.6 summarize the roles that labor unions and FRA play in the track inspection process. Labor unions interact with the track inspection process through collective bargaining agreements, which may impact job assignments and staffing practices for inspections. FRA creates regulations and safety standards that address the required frequency of inspections and safety thresholds for many track conditions. While detailed examination of either of these sets of factors is beyond the scope of this report, it is important to understand that both collective bargaining agreements and FRA regulations are part of the sociotechnical context in which inspection occurs.

7. Recommendations

Section 6 discusses sociotechnical factors related to the track inspection process and provides numerous examples of issues and concerns that railroaders mentioned during the Volpe team's data collection. However, the purpose of a hazard analysis is to understand and address potential risks, not just existing known risks. Therefore, in addition to the issues in the previous section, the Volpe team also identified areas where additional risks—not mentioned during data collection—could occur.

The team drew on their analysis of the three track inspection sociotechnical systems (i.e., a system using visual inspection only, a system using both visual inspection and conventional TGMS, and a system using both visual inspection and aTGMS) to systematically identify factors that may lead to undesirable actions (i.e., actions that could lead to a hazard).

Some of these potential risk factors align with things the team heard from railroads, while some are more hypothetical in nature. The inclusion of these factors in this report does not mean that they are currently a problem. Rather, it indicates an area where issues may arise. The recommendations offer ways to mitigate these possibilities.

The team did not quantify the likelihood of these factors. Some of the factors (particularly those in Section 6, which were mentioned by railroaders) may be more common than others. However, many of the factors discussed in this section may in fact be highly unlikely, particularly if railroads have already considered these risks and put practices in place to address them. Nonetheless, the Volpe team included recommendations to address any potential risks identified in their analysis. Railroads may then assess whether each risk applies to their railroad, whether they have met the recommendations of this section, and determine which changes, if any, they wish to implement. The task of prioritizing these recommendations is left to the individual railroad, as it is highly dependent on the existing mitigations and processes the railroad has in place, the resources available, and the particular challenges the railroad has encountered.

7.1 How to Use This Section

This section is organized using the same socio-technical framework as Section 6. As noted in that section, these categories are closely interrelated and influence one another in many ways (see Figure 10). Due to these interrelationships, the team's recommendations are often related to others across levels of the sociotechnical model. Therefore, readers may find it helpful to browse all the recommended sections.

The recommendations in this section include both general recommendations and those that are specific to automation-aided sociotechnical systems. Since all three sociotechnical systems examined in this research include visual inspection, recommendations related to visual inspection are considered "general."

Readers of this section may recognize some of these recommendations as a part of what their railroad already does. For example, the Volpe team identified a wide range of topics that could be addressed through training, and it is likely that railroads already include many of these topics in their training courses. That is a good thing. It means that railroads have already found ways to address potential risks.

However, the team urges railroads to consider each recommendation carefully, even if it seems basic. In some cases, railroads may believe they have done enough to address a risk, when in fact their mitigation strategies were not as successful as intended:

- Employees may not consistently follow procedures, particularly if they are not reinforced or there are perceived problems with the procedures themselves (e.g., inefficiency).
- Covering a lesson in training may not be sufficient if employees are not able to apply it hands on, or if too much time passes before the employee needs it in the real world.
- Issues related to basic competencies can be difficult to identify because employees, particularly new employees, may be reluctant to reveal that they are struggling.
- Employees may get used to a safety issue if they are exposed to it regularly in a phenomenon known as risk normalization.

The Volpe team suggests using these recommendations as a starting point for railroads to evaluate their current practices and verify that these recommendations are met, where possible.

The Volpe team expects railroad managers to exercise their judgement when determining which recommendations to apply to their own railroads and where to spend their limited funding. Some recommendations may not be relevant to all railroads and contexts. Other recommendations are more general, and require each railroad to interpret how to address them.

Many of these recommendations can be addressed in more than one way. For example, risks are often addressed through:

- Standardized procedures
- Training
- Designing technological systems to reduce or eliminate risk

In some cases, the Volpe team suggests a particular approach to an issue, e.g., “establish a procedure to…” However, in most cases, the team leaves it to the railroad domain experts to determine which approach is the best fit for that railroad. Keep in mind that in general, solving a problem through design (when possible), is preferable over addressing it through training or procedural methods.

While some of the team’s recommendations may seem obvious or require little action, the team encourages railroads to consider the intent behind each recommendation and reflect on ways to address the underlying issue. Even if a railroad initially appears to have implemented the recommendation, they may find additional ways to reduce risks.

Furthermore, with domain expertise may come better ideas. If a railroader identifies an alternative to one of the Volpe recommendations, the team urges the railroad to pursue whichever is stronger.

7.2 The Inspection Task

Some of the Volpe team’s recommendations are best categorized as related to the inspection process, including what happens after defects and maintenance conditions are found. As previously discussed in Section 4 when a defect is found, one of three types of actions must be taken on the track. The inspector can:

1. Restrict the track speed to a lower track speed where the issue is not considered at safety-defect levels
2. Remove the track from service
3. Repair the track

If the inspector cannot make an easy repair then the inspector restricts or, as a last resort, removes the track from service, and leaves repairs to a maintenance-of-way crew.

The following recommendations address potential risks associated with the track inspection process. These recommendations apply to all sociotechnical systems, since all three included visual inspection.

7.2.1 Identifying Defects and Maintenance Conditions

During visual inspections, track inspectors need certain resources to detect defects and maintenance conditions, including tools and technology, training, and information such as defect location. If they do not have these resources, they may be unable to detect the defect or maintenance condition. For railroads that use conventional TGMS or aTGMS, inspectors performing verifications may need similar resources and information, such as the exception location.

The following recommendations apply to all sociotechnical systems and address potential risks associated with identifying defects and maintenance conditions:

- **Provide the necessary tools and training for inspectors to detect defects and maintenance conditions**. Some defects and maintenance conditions may be easier to detect than others; while others require different types of tools to detect. Inspectors need to have thorough training on all types of defects; what tools to use; and how to use them. It is especially important to provide OJT around the various tools an inspector might need for those with little tool experience.
- **Make sure inspectors have all the information they need to verify a track defect or maintenance condition**. If an inspector needs to verify an exception identified by an automated technology, or check out an issue flagged by another type of inspector (e.g., during a C&S inspection), the manager/supervisor assigning the track inspector will need to provide all necessary information, including location. Inspectors may also want to double check the location information to make sure they understand where to find the potential defect.
- **Caution inspectors about the role expectations can play on their inspection**. If an inspector has low expectations of detecting defects, they are more likely to dismiss issues that the railroad should address. This may be particularly problematic if inspectors place too much faith in automated technologies detecting defects. In some cases, railroads may want to send a different inspector or supervisor to review the territory with “fresh eyes” to reduce the tendency for expectations to influence detection.
- **Plan how to handle defects that inspectors cannot detect**. Some conditions are only visible under load, and therefore may not be detectable when an inspector tries to look for them. Consider how to handle these issues: for example, railroads may use TGMS or

other technologies, or have inspectors recheck after some time has passed to see if the condition has worsened and is now detectable.

7.2.2 Assessing Severity of Track Conditions and Defects

Severity assessment is one potential source of risk in the track inspection process. If a track inspector underestimates the severity of an issue or feels too uncertain to make a difficult decision, the railroad will not be able to properly address the track condition or defect.

The following recommendations apply to all sociotechnical systems and address potential risks associated with assessing the severity of track conditions and defects:

- **Encourage inspectors to be conservative when assessing potential defects that are borderline cases or particularly challenging**. When inspectors are uncertain about a potential defect, such as when measurements are on the borderline of a safety issue, supervisors may wish to encourage them to take the more conservative approach and act on the defect. This may include restricting track speed or removing track from service. However, this cannot be substituted for strong inspection skills. If an inspector defaults to labeling things as “defects” too often (i.e., in instances that are not actually borderline or particularly challenging cases to determine) then false alarm rates will become too high. Supervisors may want to work with inspectors that seem to be frequently generating false alarms (i.e., recording things as defects that are not) to provide guidance or identify the need for additional training.
- **Establish guidelines for how to handle disagreements or uncertainty regarding defect severity**. If an inspector is uncertain whether something is severe enough to be a defect, or if, upon seeking a second opinion, two employees disagree about the severity of a defect, railroads may wish to establish guidelines for how to resolve these issues. For example, if one employee is relatively inexperienced, it may be best to defer to the more experienced employee’s assessment. Or, if both are experienced inspectors, it may be safest to defaulting to the more conservative opinion (i.e., the one that considers the defect more severe).
- **Have someone other than a direct supervisor that inspectors can reach out to for guidance**. A mentor or other experienced adviser can help inspectors if their regular supervisor is unavailable, or if they do not want to speak to their supervisor about a particular issue (e.g., due to embarrassment or a bad relationship with that supervisor). Having multiple people to reach out to helps reduce the risk that an inspector could need guidance and feel like there is no one to ask.

7.2.3 Restricting Track Speed or Removing Track from Service

Restricting track speed and removing track from service are important actions that railroads can use to reduce the safety risks associated with degraded track conditions. The Volpe team noted that delays to these actions, or ambiguity in how to perform them, could pose a safety concern. During automation-aided inspections, railroad employees perform these same actions (i.e., restricting track speed or removing track from service) in response to issues found by conventional TGMS or aTGMS.

The following recommendations apply to all sociotechnical systems and address potential risks associated with restricting track speed or removing track from service:

- **Contact the dispatcher immediately when a restriction or removal from service is needed**. This applies to anyone that may need to restrict track speed or remove track from service, including inspectors, supervisors, and TGMS operators. Even if the operator thinks no more trains will be operating on it before it is repaired, or that dispatcher will be upset, etc.
- **Once a defect is found, do not allow trains to pass prior to restricting track speed or removing the track from service**. Regardless of the train schedule, it is important that the inspector or person who identified the defect takes action.
- **When there are multiple people that could take action on the track, adhere to a standard procedure dictating who has that responsibility**. If any deviation to that procedure is expected or needed, reinforce the need for staff to communicate with each other and confirm who will be calling.
- **Make sure that any employees who may be responsible for restricting track speed are familiar with the CFR requirements for each track class**. For newer employees, or those who do not handle speed restrictions often, reference materials may be useful for this (see Section 7.4.3).

The following additional recommendations address potential risks associated with restricting track speed or removing track from service, and apply to the Conventional TGMS & Visual sociotechnical system:

- **Teach TGMS operators when and how to restrict track speed and remove a track from service**. Even though a TGMS operator would typically be working with the track supervisor to see that defects are verified and then addressed, the TGMS operator should know how to take action on track in the event this is occasionally needed (e.g., if the supervisor cannot be reached).[22]

Note that aTGMS analysts do not restrict track speed or remove track from service, but they may reach out to supervisors to have defects verified, and the supervisor or track inspector may then call in a restriction. Communications between aTGMS analysts and supervisors are discussed in Section 7.3.3.

7.2.4 Repairing Track Conditions and Defects

For the most part, considerations around heavy maintenance activity (e.g., conducted by maintenance-of-way-crews) was beyond the scope of the current project. However, at all three railroads the team visited, inspectors discussed how they may engage in light maintenance activities during the course of their inspections. The degree to which inspectors engage in maintenance activities depends on many factors, such as if they have the necessary tools with

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[22] Railroads that the Volpe team spoke with indicated that they do not act on exceptions from TGMS until the exceptions have been verified. These actions may be more commonly performed by supervisors onboard the TGMS vehicle; however, the team assumed in some cases the TGMS operator could call the dispatcher. For additional information on the team's assumptions, see Appendix C.

them and if they anticipate having sufficient time available to complete the inspection after taking time for the repair.

The following recommendations apply to all sociotechnical systems and address potential risks associated with repairing track conditions and defects:

- **Help inspectors assess when they have time to make repairs themselves**. If inspectors do not have a good understanding of how long certain repairs may take to complete, they might find that a repair takes much longer than anticipated, even if there are no problems during the repair process. An unexpected loss of time may make it more difficult for the inspector to complete the inspection activities planned for that day. Therefore, make sure inspectors know how long various repairs take to complete so they can more accurately assess whether they have time to make a given repair. This may be accomplished by training or by having reference material that an inspector can use to pull up typical repair times.
- **Teach inspectors to only perform repairs they feel confident making**. Railroads may wish to instruct inspectors only to undertake repairs they are confident they can complete correctly and efficiently, and for which they are certain they have all the necessary tools and parts available. This will reduce the chance that an inspector starts a repair and then cannot finish it or it becomes unexpectedly time consuming.
- **Reduce pressure on inspectors to perform repairs**. Discourage inspectors from performing repairs that might compromise the quality of the inspection. For example, if an inspector has concerns about finishing the inspection before the track is taken back or about getting to a new section of track in the timeframe needed, it may be preferable to save the repair for a maintenance crew. Consider hiring more maintenance crews, if needed, to relieve pressure on inspectors to address repairs. If the railroad needs inspectors to make substantial repairs, consider if the inspector's territory size allows for this. (See Section 7.6.2 for recommendations related to territory size and characteristics).
- **Establish procedures for handling unexpectedly time-consuming repairs**. In some cases, repairs may take longer than expected. To avoid these repairs having a negative impact on inspection, encourage inspectors to communicate with their supervisor and dispatcher about these challenges and identify ways to complete the inspection effectively. For example, inspectors may be able to come back later to finish the inspection, rather than rushing to finish within the originally allotted time.
- **Notify dispatchers of defects, even if repairs will be made before the inspector gives back the track**. This will ensure that the dispatcher is aware of the defect and knows who to contact before trains pass over the track if repairs take longer than anticipated.
- **Always confirm that repairs have been completed before removing speed restrictions and/or allowing trains to operate over the track**. Issues could arise during repairs (e.g., not having a necessary part or tool) that make them impossible to complete as planned. While inspectors or repair crews would likely communicate these issues to their supervisor and/or dispatcher, it is still best not to assume a repair has been made just because it has been assigned.

In automation-aided inspections, it is less common for railroads to perform repairs during a conventional TGMS or aTGMS inspection. During conventional TGMS inspections, railroads may have repair crews available on the same routes that TGMS is inspecting so that these crews can quickly follow up and address any defects. However, since the employees performing these activities are dedicated maintenance crews, rather than inspectors or TGMS operators, these repairs are outside the scope of this study. In the case of aTGMS inspections, the aTGMS collects data during regularly scheduled operations and analysts examine the data later. Therefore, aTGMS can inform regular maintenance activities, but railroads do not perform dedicated repairs during aTGMS operations.

7.2.5 Keeping Track of Inspection Activities

Keeping track of all the inspections needed and when they are due may be challenging at times. Different track classes have different requirements for how frequently they must be inspected. Exceptions generated by automated inspection technologies or noticed by other types of inspectors add to the inspection workload, as do any other inspection-needs generated by weather events or other incidents that could damage track. Furthermore, if one or more people that were keeping an eye on what was needed are unexpectedly out (e.g., sudden illness), it might be challenging to quickly figure out what was left to be done and when it was due. Therefore, the team considered risks related to these challenges.

The following recommendations apply to all sociotechnical systems and address risks associated with keeping track of inspection activities:

- **Establish an information management system for keeping track of inspection needs**. An information management system may be either paper-based or electronic, and can help inspectors keep track of how much time they have available to perform various inspection activities to meet regulatory requirements. This system would include information such as:
    - When each territory or section of the territory was last inspected
    - When the full territory was last traversed
    - When the next inspection is due
    - Who completed or will complete each inspection
- **Establish an information management system for keeping track of issues that require verification or follow-up**. This may be the same as the system for keeping track of inspection needs, or separate. It could also be integrated with the inspector's system for logging defects. Regardless of how this tracking is accomplished, tracking verification needs right away reduces any risk of forgetting due to a moment of distraction or periods of especially high workload. Inspectors may wish to document information including:
    - Who assigned the verification
    - Who will perform the verification
    - Location of the potential defect
    - Description of the potential defect
    - When must verification be completed

  - When verification was completed
  - What actions were taken

- **Teach inspectors to use tracking systems or informal memory aids during their inspections**. During inspections, inspectors may need to keep track of multiple pieces of information simultaneously, including potential defects to verify and actions they intend to take—particularly if they are not yet at the correct location or are waiting on communications from a supervisor or dispatcher. They also need to keep track of RWP limits and information. To make sure that inspectors do not forget to take a required action (e.g., communicating a speed restriction), they may find it helpful to use memory aids. This could be a formal tracking system, like information entered in a paper or digital inspection log, or an informal strategy like a well-placed reminder note or writing on a windshield with a dry erase marker.
- **Teach other employees (e.g., dispatchers, supervisors, technology operators/analysts) to use memory aids as needed**. This may be helpful when workload is high and/or there are interruptions and could apply to any staff intending to take action on a track.

The following additional recommendations apply to the Conventional TGMS & Visual sociotechnical system and address potential risks related to keeping track of inspection activities:

- **Have a system for keeping track of TGMS inspections**. This system can be used to track Federally-required TGMS inspections, as well as any additional TGMS inspections the railroad performs. If the railroad uses TGMS to inspect particular territories where they suspect geometry defects, this system can be used to prioritize such inspections. Railroads may wish to integrate this with whatever system they use to keep track of visual inspections.
- **Make records of TGMS inspections readily available**. Supervisors and other managers may want to double check what track has already been done and when, either as part of planning for future inspections or for maintenance planning.

7.2.6 Logging Defects and Maintenance Conditions

An inherent part of the track inspection process is documenting the defects and maintenance conditions found. Railroads may use paper or digital methods for this purpose. Recommendations related to the documentation systems themselves can be found in Section 7.4.4, whereas the current section focuses on inspector knowledge and activities related to logging.

The following recommendations apply to all sociotechnical systems and address risks associated with logging defects and maintenance conditions:

- **Give inspectors context for how the railroad uses inspection logs and maintenance condition information**. Inspectors may find it helpful to understand the impact of maintenance condition logging on the railroad's overall maintenance planning. Without this understanding, it is possible some inspectors may log these with less detail or consistency, especially when particularly busy. During training, railroads can explain how they monitor maintenance conditions over time so they can fix those conditions before they become safety defects.

- **Emphasize the importance of logging defects, even if they are repaired on the spot**. Make sure inspectors are aware of the importance of logging defects, even if the inspector has already repaired them. Inspectors may find it helpful to understand how railroads use defect information for future maintenance planning and defect-prevention efforts.
- **Encourage inspectors to log defects and actions taken as soon as possible**. The sooner inspectors log defects and actions, the more information they will be able to provide because their memory will still be fresh. Additionally, keeping logs updated during inspection will allow inspectors to have a record to refer to if they are interrupted.
- **Include all relevant information in inspection logs, including how to find defect locations**. Inspectors may communicate location information using GPS, but in other cases may describe the location using mile markers, landmarks, or marking the location with paint. A clear location description is important regardless of the way it is indicated.
- **Double check entries before submitting them**. By double checking logs before submitting them, inspectors can correct any mistakes (e.g., typos or number transpositions) or fill in incomplete information while they still remember it.

For additional recommendations that address logging methods, see Section 7.4.4.

7.3 Individual and Team Factors

This section discusses recommendations related to factors at the individual and team level. These include experience, workload, as well as teamwork and communication.

7.3.1 Knowledge, Skills, and Experience

Many considerations related to the knowledge, skills, and experience needed for visual inspection were previously discussed in Section 7.2 since they are strongly tied with the inspection task itself. This section discusses additional, technology-related recommendations related to knowledge, skills, and experience.

Inspector Knowledge Related to Technology

The following recommendations apply to all sociotechnical systems and address potential risks associated with inspector knowledge related to technology.

- **Teach inspectors the capabilities and limitations of automated inspection technologies used on their territory**. It may help inspectors to have a solid understanding of what the automated technology can detect well, what it cannot detect well, as well as under what conditions the output may not be accurate or reliable, if any. This could help inspectors better understand situations in which they and the technology have different assessments. Additionally, knowing the limitations of inspection technologies may help the staff stay particularly vigilant about things that conventional TGMS or aTGMS may miss. Remind all track staff not to assume that the technology is infallible, and to expect that they will sometimes come up with different results than the technology.

- **Teach field personnel to understand and use any automated inspection output they receive**. Inspectors may see output from the automated technology when they are assigned to verify an exception. For example, inspectors may receive aTGMS output that includes a strip chart with information about the possible defect. Inspectors may not be able to make good use of such output unless they are shown how to use it.

Knowledge Related to Working with Automated Inspection Output

Recommendations related to potential risks around training for TGMS operators and/or aTGMS analysts, as stated:

- **Provide anyone monitoring or analyzing automated inspection output with thorough training and documentation**. In some cases, additional staff may need to fill in for the aTGMS analyst in some capacity, so it is important to verify that they have the same, necessary training that the primary analyst has. For example, there may be a designated backup to the aTGMS analyst that also is cc'd on emails coming from the central server about 2-class drops that need to be verified. If this backup person might need to act on this information, they need to be trained on how to understand aTGMS output. Clearly document procedures for reviewing aTGMS output so that staff filling in, or replacing an analyst who leaves the railroad, can perform the job to the same standard.
- **Help TGMS operators and aTGMS analysts gain territory familiarity**. Implement strategies to increase operators' and analysts' territory knowledge, such as allowing them to ride along during hi-rail inspections. This will help them develop sufficient knowledge of all the territories for which they may have to review exceptions, especially if familiarity with the territory is needed to understand output for certain locations.
- **Train TGMS operators and aTGMS analysts to recognize data collection issues and encourage them to share their strategies for catching errors**. Certain anomalies in the data may reflect incorrect calibration and/or problems with sensors. Some of these may be known issues (e.g., false wide gage readings may be common when going over a frog), while others may not be well understood. Encourage operators and analysts to look for these indicators and share strategies as they identify them so they can be included in future training.
- **Consider what training and guidance is needed related to identifying false alarms**. TGMS operators and aTGMS analysts need to be able to recognize false alarms wherever possible so field staff time is not wasted. There may be some cases where this is straightforward (e.g., the TGMS operator knows that a frog at a given location causes a false exception reading every time). However, there may be times when making false alarm assessments becomes complicated or dismissing them correctly may be complicated if the false alarms occur right around the same time as other legitimate exceptions. Consider guidance and best practices around false alarm assessment and dismissal practices.

7.3.2 Workload

Inspectors, supervisors, TGMS operators, aTGMS analysts, and dispatchers can all be negatively impacted by excessive workload. For inspectors, workload depends largely on factors like territory size and complexity, inspection method (i.e., on foot or by hi-rail), and number of inspection tasks they must perform (e.g., identifying defects, logging, performing repairs, etc.). For supervisors, workload may depend on how many inspectors they supervise. For dispatchers, TGMS operators, and aTGMS analysts' workload may depend on how many screens or sources of information they must monitor simultaneously, as well as on the communication demands associated with their work.

Workload for those involved in inspections (e.g., inspectors and those reviewing automated inspection data) is, to a large extent, determined by factors such as territory size (see Section 7.6.2) and staffing (see Section 7.5.2). However, this section covers additional considerations specific to workload.

The following recommendations apply to all sociotechnical systems and address potential risks associated with employees' workload:

- **Identify possible indicators that workload is too high**. For each employee, railroads may want to consider what the signs would be if workload was unmanageable. For example, a railroad may decide to reconsider territory sizes if inspectors regularly report that they struggle to get enough track time on a particular territory, or if inspectors struggle to complete inspections on time. Railroads may also identify indicators for dispatchers and TGMS operators (e.g., if an inspector reports that they could not reach a dispatcher within a certain timeframe, or inspectors find a certain number of defects, or a TGMS operator takes longer than some number of minutes to report a defect to the engineering department). Once railroads have identified meaningful indicators, they can more successfully monitor over the years for signs that the workload needs to be adjusted.
- **Minimize situations that require multitasking, particularly when a less critical task would limit an employee's ability to perform a more critical one**. Competing demands for employees' attention can make it more difficult to perform key aspects of their work. Railroads can reduce multitasking demands by either eliminating or delaying less-critical tasks, or finding ways to make tasks easier. For example, railroads can lessen the requirement for inspectors to multitask by encouraging them to defer repairs to a dedicated maintenance crew as needed, or providing a well-designed logging software that makes logging less time-consuming. Similarly, dispatchers may be able to delay certain communications that they know are less time-sensitive.
- **Encourage TGMS employees to reduce conversations during periods of high workload**. For employees like TGMS operators, communication is an essential part of the job, but, like all multitasking, it may interfere with other tasks. If TGMS operators must enter important information like programming track class or location information when approaching a track change, consider encouraging employees to hold off on other communications so they can give full attention to the task at hand.
- **Consider multiple strategies when striving to reduce workload**. Because inspectors' workload is a result of multiple factors (e.g., territory size and complexity, inspection method, inspection time, track condition, number of repairs, etc.) there are many factors for railroads to consider when assessing workload and striving to reduce it. Some possible strategies for reducing workload include:
    - Reducing territory size or splitting up territories

  - Changing inspection method from on foot to hi-rail (i.e., if this will still meet the needs of the inspection)
  - Adjusting train schedules to provide additional inspection time
  - Adding another inspector who can help inspect track more quickly and conduct exception verifications

However, the best way of reducing workload may be different depending on the railroad. Therefore, the Volpe team recommends seeking the inspectors' input to learn which solutions they would consider most helpful.

7.3.3 Teamwork and Communication

Communications Between Inspectors and Supervisors

Supervisors communicate with inspectors when they need to assign someone to verify a potential defect, or to help inspectors resolve concerns. Risks associated with these communications may include misunderstandings about what the inspector needs to do, and could lead to tasks being left incomplete.

The following recommendations apply to all sociotechnical systems and address potential risks associated with communications between inspectors and supervisors:

- **Repeat back information to reduce the likelihood of miscommunications**. While giving assignments (e.g., potential defects to verify), supervisors may misspeak or inspectors may mishear information. Railroads may wish to encourage inspectors to repeat these assignments to help catch both types of errors.
- **Communicate instructions as part of a dialogue whenever possible**. For example, if supervisors send instructions by email or paper forms only, they cannot be certain that inspectors received and understood the information. Consider using phone calls, radio, or face-to-face communication when giving instructions so that inspectors and other employees can confirm that they have received them and ask any follow-up questions. When using emails or paper forms, consider notifying the recipient to expect such communications, and/or following up to confirm that they were received.
- **Encourage inspectors to communicate when their assignment or instructions feel unclear**. In addition to completing standard inspections for their territory, inspectors may receive instructions from their supervisor to verify exceptions, perform special inspections (e.g., following severe weather), or fill in for other employees. Encourage inspectors to ask questions or double check their instructions if they have any questions or concerns. If supervisors answer inspectors' questions and share the reasoning behind any instructions or changes, it will increase the likelihood that the supervisor and/or inspector will catch any possible oversights, mistakes, miscommunications, or misunderstandings.
- **Encourage inspectors to communicate when they need help prioritizing tasks**. For example, if an inspector is assigned to conduct a special inspection (e.g., due to a weather-related event) but also has little time left to complete a routine inspection for another part of the territory, this is important for the inspector to discuss with their

supervisor. The supervisor may be able direct the inspector as to how to prioritize or may have an alternative solution (e.g., assigning additional staff resources to this work).

- **Encourage inspectors to communicate when they need help getting track and time**. Sometimes dispatchers may be reluctant to grant track and time to inspectors and the inspector may need to request help from their supervisors. If this is a significant and ongoing issue, track supervisors need to know so they can talk with dispatcher supervisors about a solution (e.g., scheduling track outages for inspections further in advance).

Communications Between Inspectors and Dispatchers

Inspectors often need to communicate with dispatchers to request track and time, place speed restrictions, or remove track from service. Misunderstandings or delays to these communications could pose a safety issue. Railroads can encourage and strengthen communication and coordination between dispatchers and inspectors to help reduce risks. Additional strategies for dispatchers can be found in Section 7.5.6.

The following recommendations apply to all sociotechnical systems and address potential risks associated with communications between inspectors and dispatchers:

- **Develop coordination between inspectors, supervisors, and dispatchers about how to fit inspections into the schedule**. Dispatchers, supervisors, and inspectors can work together to fit both routine and non-routine (special) inspections into the train schedule, as needed. Dispatchers may be able to provide insight into the best times and ways to approach dispatchers, good and bad times to fit inspections into the schedule, and communication strategies that make dispatchers' jobs easier. In some cases, scheduling outages for inspections in advance may reduce communication burdens and challenges around getting enough track time for inspection.
- **Teach inspectors to communicate the degree of urgency when requesting track and time (if not scheduled in advance)**. Dispatchers may be better able to prioritize track usage if they understand the degree of urgency behind an inspector's request. Encourage inspectors to be clear about their needs when asking for track and time. For example, if the inspector has only 1 day left to meet regulatory inspection requirements, or has reason to suspect problems on that area of track (e.g., due to recent weather conditions), dispatchers may be able to grant more time or allow more flexibility than if the need were less urgent.
- **Consider protocols for repeating back information when taking actions on the track**. While communicating speed restrictions or removing track from service, it is possible that inspectors could misspeak or dispatchers could mishear information. If dispatchers repeat back the location and restriction information, this may help catch these types of errors. This recommendation also applies to communication between dispatchers and anyone taking action on track (e.g., supervisors or TGMS operators).
- **Include context when communicating speed restrictions or taking track out of service**. It is possible that someone taking action on a track (e.g., inspector, supervisor, TGMS operator) may make a mistake in what is needed. If dispatchers understand the

context for a speed restriction or track removal, (e.g., the type and severity of the defect), they are more likely to notice if the action being taken may not appropriate.

- **Establish protocols for how to proceed if the dispatcher is not responding**. If an inspector or other employee is unable to reach the dispatcher by radio or phone to take the action on a defect (e.g., restricting track speed or removing track from service), this could pose a risk for trains scheduled to operate over the track. Railroads may wish to establish protocols for how to handle these situations. For example, inspectors could write the issue down so they do not forget, then try again in 5 minutes or reach out to another dispatcher.

Communications Related to Automation-aided Inspection

The following recommendations apply only to the Conventional TGMS & Visual Inspection sociotechnical system and address potential risks associated with teamwork and communications:

- **Verify that TGMS operators understand inspection assignment correctly**. The TGMS operator (or other staff scheduling the inspection) can verify that the instructions were received and understood by confirming the location to be inspected so that any miscommunications can be flagged and corrected.
- **Verify track information entered into TGMS**. Consider having the TGMS operator that enters track class information say both the name of the track being inspected and the track class whenever starting a new inspection or switching track. The other operator can then acknowledge the correct information and repeat it back to confirm verification of the correct information.
- **State out loud when there is a TGMS exception that requires immediate action**. If the TGMS operator in charge of reviewing exceptions calls out defects that require action, this ensures that everyone in the TGMS car is aware of the situation. This reduces the possibility that any sort of distraction or high workload period for the TGMS operator would result in a major delay to acting on the exception information.
- **Provide information regarding TGMS-generated exceptions to the track supervisor as soon as possible**. In many cases the track supervisor is riding in the TGMS car and will learn of any exceptions right away. However, in cases where the supervisor is not onboard, the supervisor needs to be alerted as soon as possible so that an inspector can be sent to verify the exception as soon as possible.
- **Provide TGMS operators with key information relevant to their inspection**. Make sure that anyone filling in for the usual TGMS operator is notified of key information regarding past inspections on that line or is given the most recent logs to skim.
- **Consider any communication needed between train operating crew and TGMS operators**. In some cases, such as with less experienced TGMS operators or TGMS operators who work solo (with no co-operator), it may be helpful for the train operating crew and the TGMS operators communicate to make sure operators are aware of switches.

- **Support continued learning for TGMS operators**. If supervisors notice that the TGMS operator is consistently dismissing real exceptions either throughout the run or at specific locations, they may want to show this to the operator so that the operator can improve their skills in reviewing the data.
- **Support continued learning for inspectors**. If supervisors notice that the TGMS is consistently finding things that some of their inspectors do not, this input may be helpful in mentoring those employees. Supervisors can use this information to determine whether inspectors need additional guidance or refresher training on a particular topic.

The following recommendations apply to the aTGMS & Visual Inspection sociotechnical system only and address potential risks associated with teamwork and communications:

- **Have aTGMS analysts notify supervisors when aTGMS begins operating or is taken out of service**. Make sure that supervisors are aware of when aTGMS units installed on trains are working and when they are not (e.g., because they have broken or are undergoing routine maintenance).
- **Have aTGMS analysts notify track supervisors by both phone and email if aTGMS detects a serious exception**. The aTGMS analyst receives notifications for serious exceptions (i.e., two class drops) in real-time so that the railroad can take action on them immediately. To ensure receipt of this information, consider having analysts contact the supervisors about it through both phone and email. Additionally, this would allow the phone call to confirm knowledge of the exception and the email to contain more information about the exception.
- **Have supervisors notify the aTGMS analyst if inspectors are finding things that aTGMS is not**. In some cases, inspectors might detect geometry defects that aTGMS does not; for example, if aTGMS becomes miscalibrated or the algorithm or analyst inaccurately dismisses things that seem like false alarms. Analysts can consider what is happening and may use it to either refine their own analysis skills; or analysts may recommend having the aTGMS recalibrated or give feedback to the manufacturer to see if their detection algorithms can be improved.
- **Have supervisors verify that the aTGMS analyst sent the correct file (i.e., correct date and location)**. Given the amount of data aTGMS can collect and the number of potential files an aTGMS analyst may have to review, it may be possible for the aTGMS analyst to send the wrong file to track supervisors. Therefore, when supervisors receiving exception information from the aTGMS analyst may want to make a practice of quickly verifying that the inspection information on the output (e.g., date, inspection location, and track class) matches what is expected.

7.4 Tools and Technology

During both visual and automation-aided inspections, tools and technology play an important role in inspecting track, organizing information, and communicating with others. Many risks associated with tools and technology can be reduced through good design; however, some risks cannot be fully mitigated through design, and require training or procedures to address them.

This section presents some general recommendations related to technology design and training, followed by specific recommendations for various tools and technologies used in inspection.

7.4.1 User-Centered Design

In thinking about tools and technology, a major focus becomes the end-users, the people that work with the automated technology or its output. Tools and technologies should be designed with the end-user in mind so as to eliminate preventable errors and other challenges wherever it is possible to do so. Automated technology designs that do not do this set up inspectors, data analysts and other end-users for errors at times when they are most busy, time-crunched, and/or fatigued. The following recommendations apply to all sociotechnical systems and address potential risks associated with a lack of user-centered design.

There are many sources devoted to how to design a good human-machine interface. The recommendations below are consistent with good human-machine interface design in that they highlight several important considerations. However, railroads and technology manufacturers should consult other sources for more detailed guidance. For example, the Volpe team recommends resources such as those written by Shneiderman et al. (2016), or the series of documents published by the International Organization for Standardization (ISO) on ergonomics of human-system interaction (ISO 9241). While typically the burden of good design is on technology manufacturers (see Section 7.7.2), railroads nonetheless can benefit from an understanding of user-centered design. Railroads can use these recommendations as requirements when selecting manufacturers, or look for products that were designed with a user-centered approach when choosing between off-the-shelf tools and technologies. Previous work published by FRA provides guidance related to acquiring technological systems designed with a user-centered approach (Melnik, Roth, Multer, Safar, & Isaacs, 2018).

- **Gather and use input from end-users when designing any technological system's functionality and human-machine interface**. Whether a railroad is looking for an electronic defect logging system, advanced measurement tools, or automated inspection technologies, it is important to understand how employees will be using the system. Track inspectors, technology operators and analysts, and other end users can provide first-hand knowledge of the requirements associated with their work. By considering these requirements when designing or purchasing new tools and technologies, railroads can prioritize the features that will have the greatest impact.
- **Use established human-machine interface design standards or guidelines when developing technological systems**. Both industry-specific and more general design standards and guidelines can be helpful resources for system designers. Using such references will help create a system that meets basic expectations for usability and will go a long way towards ensuring that the system is perceived as user-friendly.
- **Reduce the chances of user error wherever possible through good design**. One of the benefits of a well-designed electronic system is that the interface can be designed to eliminate the ability to make certain preventable errors. Working with end-users to get input on the initial design and prototypes as well as following design guidance will go far towards identifying ways to prevent mistakes.
- **Conduct usability testing with end-users during the design process to enable design improvements**. It is important to get feedback during the design process so that any design problems can be modified before the system is finalized. This can be accomplished by using design mockups/low-fidelity prototypes to share design concepts with end-users before the design gets so far down the road that changes become very

costly. Often designers wait until a product is done to get end-user feedback and there is little that can be done to improve design flaws at that point in the process without spending a great deal of money to correct them.

- **When considering system design and requirements, remember that "end-users" include anyone that uses the system**. For example, if supervisors and maintenance crew staff use an electronic logging system, then they are end-users as well, not just inspectors. Likewise, inspectors may be considered "end-users" of automated inspection technologies if they use the data outputs of those technologies to inform their inspections.

7.4.2 Inspection Tools and Hi-Rail Vehicles

There are several tools that inspectors might have with them during an inspection. Some are used to conduct the inspection itself, such as a levelboard. Such tools used for inspection are always brought along. Others may be needed only when the inspector takes on a specific type of repair. The degree to which inspectors are expected to have tools available for possible repairs may also depend on whether they are conducting a visual inspection on foot or using a hi-rail. Those that conduct inspections in hi-rail vehicles have more access to tools for possible repairs since they can keep them on the truck.

The following general recommendations apply to all sociotechnical systems and address potential risks associated with inspection tools:

- **Provide thorough training on tools used for inspection, including how to access them**. Make sure inspectors are trained on how to use all tools they may be expected to use, and develop procedures for what to do if an inspector does not have the necessary tools for a particular task (e.g., make a note and return later via hi-rail).
- **Periodically take inventory to make sure the railroad has enough tools in good condition to meet current and upcoming needs**. Consider assigning someone to the job of checking existing tools periodically, making sure tools are calibrated and in good condition and getting them repaired or replaced, if needed.
- **Keep tools organized so that the most commonly used tools are easiest to access**. Good organization will provide greater efficiency when repairing and checking tools are all there and in good condition. This will also mean that the inspector does not have to waste time finding the right tools.
- **Have spare tools readily available in case a tool is lost or broken**. Make spare tools easy for inspectors to access so that they can continue their inspections with minimal interruption.

Additional recommendations related to inspecting on foot:

- **Consider having inspectors do less repairs during walking inspections than when using hi-rail**. Carrying multiple tools during inspections may be cumbersome and often may not be feasible. Therefore, consider minimizing expectations for repairs by inspectors that walk the track.
- **Determine whether there are better tools for walking inspections**. Railroads may wish to consider providing a better means to carry required tools (e.g., a tool belt), or purchasing tools that are better suited for walking inspections (e.g., lighter or more

compact versions of tools). If such products do not already exist, consider working with manufacturers to design them.

Additional recommendations related to inspecting via hi-rail:

- **Conduct inspections via hi-rail if it is expected that tools will be necessary**. For example, an inspector may consider using the hi-rail during a standard inspection if the inspector will also be verifying a possible defect (e.g., an exception identified by conventional TGMS or aTGMS) that would be fairly quick and straightforward to fix while there. However, do so only in cases where visual and hi-rail inspections are equally effective for the territory, and if the inspector is comfortable that they will be able to perform repairs without compromising their ability to perform their inspection.
- **Maintain a full set of tools an inspector may need in every hi-rail vehicle**. This includes returning all tools to the hi-rail after inspection and notifying the appropriate party if a tool has become lost, broken, or shows signs of breaking soon so that a new one can be obtained for the hi-rail.

Lastly, given that many territories cannot be covered in the required time frame without hi-rail vehicles, the team identified several potential risks around the possibility of not having enough hi-rails available to inspectors. The following recommendations address these possible risks:

- **Provide enough hi-rail vehicles that every inspector can easily access one when needed**. If it is necessary for inspectors to share the same vehicles (i.e., rather than having one assigned to each inspector for regular use), have a plan to effectively coordinate hi-rail use so that no inspections are delayed for want of a hi-rail vehicle.
- **Inspect hi-rail vehicles periodically to verify that they are in good condition**. Consider the frequency with which hi-rail vehicles need to be inspected to keep them in good working condition and minimize unexpected breakdowns.
- **Repair hi-rail vehicles as soon as possible**. Railroads may wish to make repairs proactively to minimize the likelihood of unexpected breakdowns. This is made feasible, in part, by having enough hi-rail vehicles that if one breaks the inspector can use an extra one while repairs are being made to the first.

7.4.3 Reference Materials

Given the large amount of information that inspectors must recall and use day-to-day, reference materials may be useful to supplement training and provide a quick resource. Reference materials may be especially valuable for inspectors who are newer to the job or uncertain about a particular situation, but do not want to seem inexperienced by contacting a supervisor.

TGMS operators may benefit from similar reference materials, particularly if they are contractors, rather than railroad employees. Contractors may not be as familiar with the territory they are inspecting, and might want to double check track class and speed restriction information for their location.

The following recommendations about reference materials apply to all sociotechnical systems:

- **Provide convenient reference materials for key information**. Reference materials may cover track classes and speed restrictions, appropriate restrictions for each defect, and other important information. They may also cover how to use trickier measurement tools, as well as inspection techniques and challenges. TGMS operators and aTGMS analysts may benefit from similar reference materials to those used by track inspectors, as well as manuals and other references for how to use the technology.

- **Make reference materials accessible in multiple formats**. Reference materials may take the form of a laminated card, printed booklet or manual, or an online resource, depending on the type of information they contain. Consider the appropriate format for each piece of information inspectors may need to reference, including how frequently it will be used and how much detail is needed.

Note that reference materials should be used as a supplement to the training employees receive, rather than a substitute.

7.4.4 Documentation Technology

Railroads may use slightly different tools to document and report conditions found on the track during inspections, as discussed below. Regardless of whether a railroad uses pen and paper or a digital logging method, it is important to make quick and accurate logging as easy as possible.

- **Consider which logging method best suits the railroad's needs**. Electronic methods can eliminate handwriting issues and make it easier to retrieve information from previous inspection reports. Paper-based logging, on the other hand, is affordable and familiar.
- **Design and assess logging tools for ease of use**. Regardless of whether inspectors use paper or electronic methods to log their inspections, they need to be able to log information quickly and accurately. Design logging systems with these needs in mind and test them with inspectors to make sure they are effective.
- **Use standardized forms and/or examples to make logging easier**. On paper, checkboxes and tables can be easier to fill out than open response fields. In electronic logging systems, certain fields can be pre-populated using data from prior reports. In either case, forms can provide examples so the inspector knows what type of information belongs in each field.

Paper-based Documentation of Track Issues

If defects and maintenance conditions are logged on paper, this gives the inspector some degree of freedom as to what he or she writes even with a standardized log form to fill in. However, inspectors are often under time constraints to complete inspections which puts pressure on inspectors to document issues quickly. In the case of paper logging, this could result in reports that are not fully clear to others because of handwriting issues, non-standardized shorthand, and/or missing information. Also, paper documentation may be inefficient in some ways. For example, inspectors may need to re-write persistent conditions (i.e., that are not severe enough to demand immediate maintenance) each time they inspect. Railroads may find it preferable to move from a paper logging system to a well-designed digital method.

If a paper logging system is used, the following recommendations, which apply to all sociotechnical systems, will help potential risks associated with paper-based logging:

- **Encourage legible handwriting**. When inspectors are required to write by hand, classroom and OJT can emphasize the importance of clear handwriting. This will help ensure that someone not familiar with an individual's handwriting can still read it.
- **Establish a shared method of abbreviations and shorthand**. Shorthand can be used to quickly indicate severity, changes over time and/or other types of critical information. If all track staff are taught the same methods (e.g., during training), this will help them log quickly and efficiently in a manner that everyone on the team can understand.
- **Clear up any issues as soon as possible after an inspection log is submitted**. Issues like missing information, illegible handwriting, or unclear descriptions may make inspection logs difficult to use and hinder the railroad's ability to address track conditions and defects. The supervisor who receives inspection logs may want to ask the inspector for clarification, if needed, before the inspector moves on to other tasks and forgets the details of the inspection.
- **Include all relevant information each time an issue is logged**. Maintenance issues that have not yet been addressed may require repeated logging over multiple inspections. Do not assume that someone looking at a given record will know about, nor be able to access, the previous paper reports when needed. Instead, report all critical information for anyone learning about the issue for the first time.

Electronic Documentation of Track Issues

Given the time pressure on inspectors to complete their inspections and logging quickly, data-logging systems must be reliable and efficient. An inspector cannot afford to be slowed down by a system that is not working properly or that makes data entry take longer than needed.

The following recommendations associated with electronic logging systems apply to all sociotechnical systems.

- **Assess the reliability of electronic logging systems**. An unreliable logging system may freeze or load pages slowly, require frequent rebooting, or present other issues. If a railroad determines that their system is not sufficiently reliable, they may wish to replace it or pursue upgrades to improve the system.
- **Seek staff input when designing or purchasing an electronic logging system**. By understanding the inspectors' needs and the challenges associated with logging inspection information, railroads can select or design a system that best meets those needs. Also consider input from supervisors and any other railroad employees that may need to utilize these systems.
- **Facilitate easy data entry wherever possible**. Electronic logging technology can facilitate data entry. For example, electronic logging may allow inspectors to attach images or GPS coordinates rather than providing a written description of a location. Additionally, in the case of maintenance conditions that are not a current priority for repair, inspectors continue to re-log much of the same information at each inspection. The ability to re-use some previously entered information (where appropriate) would save time and reduce the possibility of log entries becoming sloppy or incomplete when inspectors are in a hurry and entering information that could be redundant.

- **Allowing exceptions to be sorted on a variety of fields so that end-users can quickly locate the information they need**. Consult end-users at a variety of levels (e.g., managers, supervisors, and inspectors) on what fields they would like to be able to sort by. For example, sorting by location may be useful when making maintenance plans, while sorting by severity can help supervisors attend to more severe safety issues.
- **Design computer-based interfaces to minimize errors**. The best way to accomplish this is to adhere to recommendations made in Section 7.4.1 related to user-centered design. However, during the study the team identified examples of several specific needs related to minimizing errors and identified the following recommendations:
    - Provide error messages if the user performs an action that seems to be erroneous (e.g., leaving a field blank)
    - Allow users to correct or edit information they have entered, or undo changes
    - Enable data logs to save automatically when the system is exited to prevent losing data
    - Design software to check for likely data entry errors (e.g., values off by orders of magnitude)

Electronic Documentation of Automated Inspection Results

With conventional TGMS and aTGMS technologies, a file is generated that documents the entire inspection. The following additional recommendations related to electronic documentation of automation-aided inspections apply to sociotechnical systems that utilize conventional TGMS and aTGMS.

- **Include critical information, such as inspection date and location, as part of file names**. This way if the wrong file is sent to someone by accident, the mistake is more likely to be noticed before incorrect data is used. This may be particularly important for aTGMS files given that many may be generated if the aTGMS inspects during every train run.
- **Maintain a copy of the original record of exceptions generated by the automated technology**. This allows whoever is reviewing the exception data to refer back to the original information in case there is ever a need or desire to consult it.

Additionally, the following recommendation applies for sociotechnical systems using aTGMS:

- **File exception reports requiring immediate verification after they are addressed**. Keeping such reports filed separately once addressed will reduce the likelihood of mistaking them with reports not yet addressed.

7.4.5 Communication Technology

Communication is a critical part of the track inspection process—including communication between inspectors and their supervisors, and communication with dispatchers. The Volpe team noted that problems during track inspection could arise from inadequate communication technology.

The following recommendations apply to all sociotechnical systems and address potential risks related to communication technologies needed for track inspection:

- **Provide multiple methods of communication with dispatchers**. Having multiple methods of communication (e.g., both phone and radio) makes it more likely that employees will be able to reach the dispatcher to communicate time sensitive information. Even if the dispatcher uses one method as the primary method, having a secondary method is useful in case the primary communication channel is unavailable—due to technical issues or other communications.
- **Consider alternate communication methods**. Currently, most inspectors use primarily verbal communications by phone or radio. However, alternatives like digital or text-based communications may provide increased reliability or help reduce misunderstandings. For example, an advantage of text-based or digital written communication is that recipients can refer back to messages later. These technologies may be useful for communications between inspectors and dispatchers. Note that any railroad interested in implementing digital written communication methods should carefully consider how to do so in compliance with safety regulations around electronic device use.

As radios are one of the most common methods railroads used to communicate, the following additional recommendations address issues related to radio use:

- **Make sure radios are in good working order**. Track inspectors depend on their radios to communicate safety information. Therefore, it is important for radios to have sufficient battery life, receive a clear signal, and transmit reliably. Railroads may wish to assign someone to check the radios regularly and replace or repair any that are not in working order.
- **Make sure radios receive a signal throughout the railroad's territories**. Many railroad territories include tunnels and terminals which can limit radio signals. Test radios in these locations and consider whether to make any improvements to the communication infrastructure.
- **Use multiple radio channels to minimize crowding**. When many workers across multiple locations share the same radio channel, it can be difficult for workers to communicate clearly. Inspectors may incorrectly believe a communication is for them when it was intended for someone else; or communications may get "stepped on" (i.e., interrupted by another person's message). Railroads may wish to assess whether the number of radio channels they use is adequate for inspector's needs.

The following additional recommendations associated with communication technologies relate to conventional TGMS and/or aTGMS, as stated:

- **Consider transmission needs when designing and installing TGMS and aTGMS**. These automated technologies need to transmit from sensor to computer and design requirements need to take into account infrastructure conditions (e.g., make sure it works in tunnels/terminals etc.)
- **Have aTGMS output sent to the railroad in such a way that it can be accessed by multiple people**. Consider delivering information from the manufacturer or central server to more than one person or email account at the railroad. Even if one primary data analyst

is assigned to review aTGMS data, this would allow others to access the output in the event that the primary analyst is unavailable.

- **Have a backup plan for aTGMS communications in case of email issues or power outages**. The manufacturer that maintains the central server will need a backup plan to get data to the railroad quickly in the event of various technical issues such as the following:
    - If there are problems with the email server (e.g., the data could be uploaded to a secure site for the railroad to download from)
    - If the power goes out where the central server is located (e.g., can data also be sent to a second location as a backup)
- **Establish multiple communication channels between the technology manufacturer and the railroad**. Redundant communication channels provide a way to communicate when one channel fails. In planning backup communication channels, keep in mind that communication breakdowns could happen due to issues related to humans (e.g., someone being sick, or busy elsewhere and not currently reachable) as well as issues related to computer systems (e.g., the central server that sends summary reports of aTGMS data could go down, or the email system at the railroad could experience problems).

7.4.6 Proper Functioning of Automated Technology

To have meaningful data, the automated technologies collecting it must be functioning correctly and as intended. The following recommendations apply to both automation-aided sociotechnical systems and address potential risks related to ensuring the technology works as intended.

- **Test automated inspection technologies before implementing them**. Whether using conventional TGMS, aTGMS, or another automated inspection technology, testing can help the railroad determine that everything works as intended and resolve any issues with data collection, transmission, or analysis.
- **Develop a maintenance schedule for automated inspection technologies**. Implement scheduled timeframes for regular maintenance checks to check that conventional TGMS and aTGMS sensors are in working condition.
- **Be prepared to handle repairs if TGMS or aTGMS breaks down**. If a railroad does not have staff capable of performing significant repairs on conventional TGMS and/or aTGMS, they will need to establish relationships with the manufacturer or outside maintenance companies who can perform such repairs.
- **Maintain proper calibration of automated inspection technologies**. The manufacturer may provide instructions for how frequently the automated technology needs to be calibrated; or the railroad can assess calibration needs based on prior performance. Railroads can then make a plan for where, how, and when regular recalibration will occur.
- **Provide calibration information**. The TGMS or aTGMS computer should indicate to operators or analysts when last calibration was performed and when calibration is due so that they know whether the data is likely to be valid.

The following recommendations apply specifically to aTGMS:

- **Work with aTGMS manufacturers as needed during installation and/or relocation**. Especially for aTGMS, which railroads choose to install on locomotives, it may be necessary to work with manufacturers to make sure the automated technology is programmed with the correct parameters for the track it will be used on. If a railroad moves aTGMS, the railroad will need to update the parameters for the aTGMS (e.g., track class information), which may include notifying the manufacturer.
- **Establish plans for how to access aTGMS units for maintenance**. Because aTGMS units are installed on revenue service vehicles, it may be more difficult for railroads to get access to them for maintenance, and may require taking the whole locomotive out of service unless it is feasible to separate the aTGMS unit from the locomotive it was installed on while the aTGMS is under repair.

7.4.7 Automated Inspection Technology Interfaces and Outputs

When using TGMS, the human plays the role of entering key information that the automated technology references (e.g., track class), monitoring output, and making decisions regarding it.

The following recommendations apply to sociotechnical systems using conventional TGMS and/or aTGMS address potential risks associated with operators setting up for inspection run:

- **Provide the TGMS operator with accurate location information**. The TGMS operator needs to have access to accurate GPS information regarding the TGMS's location as well as to accurate maps of the territory for all areas inspected.
- **Clearly display the track class parameters used when flagging defects and maintenance conditions**. This will enable users to verify that the parameters were correct. Making this information visible to all TGMS operators (i.e., the operator that sets track class/threshold and enters location as well as for the operator that examines exceptions) will provide greater opportunity to catch any mistakes.
- **Check that automated inspection technologies are programmed with the desired thresholds**. To compare the collected data against FRA-regulated thresholds and railroad's internal maintenance standards, automated inspection technologies need to be programmed with the correct thresholds and track class information for the territories they will operate over. Enable railroad employees (e.g., TGMS operators, aTGMS analyst, or other members of the engineering department) to verify and change thresholds when needed.

Outputs Shown to TGMS Operators or aTGMS Analysts

The following recommendations apply to automation-aided sociotechnical systems, as described, and address potential risks associated with technology outputs that must be analyzed.

- **Provide the ability to review information**. The TGMS operator and aTGMS analyst need to be able to review information to assess if some of the exceptions flagged are false alarms. TGMS output may only be visible to the operator for a limited amount of time and so, in such cases, there needs to be a way for the operator to review information that might have been missed or that the operator would like to review at a different time.

- **Make large defects highly visible on the TGMS display**. Defects that require immediate action (e.g., defects that are severe enough to require track to be dropped two classes) should be highly salient in the output display. (This may be less critical for aTGMS data output because the central server emails the aTGMS analyst a separate notification as soon as a defect requiring a two-class drop is found and then the full file comes at whatever time it is always sent.)
- **Consider if automated inspection output can be used to help identify multiple issues below the maintenance threshold**. Even when issues are not severe enough to be defects, they may pose a safety risk when several are co-located in the same vicinity. Currently, conventional TGMS and aTGMS technologies cannot locate this type of problem area. This may be something that can be improved as automated detection software improves. Or perhaps some combination of flagging by the automated technology and increased training for TGMS operators or aTGMS analysts can help make such instances easier for staff to identify when reviewing automated inspection output.

Outputs Shown to Inspectors/Others

Although inspectors do not need to review automated inspection technology outputs to do their regular inspections, they may receive some amount of these outputs when assigned to do exception verification. The following recommendations apply to automation-aided sociotechnical systems, as described, and address potential risks associated with technology outputs shown to inspectors.

- **Make TGMS outputs/instructions to inspectors for verification easy to read and interpret**. Instructions should be clear and easy to understand; include GPS, landmarks and/or maps when possible. It should be easily interpreted by field personnel that may use it.
- **Have designated employee(s) able to format aTGMS exception information for field staff**. Preferably, railroads can get aTGMS output in a format that is easy for field staff to understand and use when verifying exceptions (see Section 7.7.2 on working with technology manufacturers). If this is not possible, designate one or more railroad staff members to become an expert in reviewing such information so that what is sent to staff in the field is clear and meets their needs. This person can also answer any questions regarding how to interpret the data.
- **Include names of person(s) reviewing data output**. During a TGMS inspection this would be the TGMS operators and the supervisor onboard (if present). When using aTGMS, this would be the data analyst. Doing this may become increasingly important if automated inspections become used much more frequently and it may not always be the same person reviewing data from a given territory each time.
- **Data logs should include track class used by the automated technology**. In the unlikely event that TGMS operators and/or aTGMS analyst do not catch an error caused by incorrect track class parameters, including parameters in the data logs, will make it possible for inspectors to identify that incorrect parameter information used when they follow up on any identified conditions or defects.

Design Suggestions to Reduce Possible Errors

In addition to the general, design-related recommendations made in Section 7.4.1, the team identified several additional recommendations that seek to reduce the potential risk of data errors and apply to the Conventional TGMS & Visual Inspection and aTGMS & Visual Inspection sociotechnical systems.

- **Design the software interface for TGMS/aTGMS to prevent common usability-related errors**. For example, when the operator or analyst selects a data point (e.g., to dismiss a false alarm), the software could highlight the selected item so that the user can see that they have selected the correct one. An "undo" feature can also help users correct errors easily if they make a mistake.
- **Design the software to notify operators or analysts of potential data collection issues or anomalies**. For example, if the speed drops below the required speed for data collection (if applicable), or the GPS signal is lost, the interface should clearly and immediately indicate this to the TGMS operator or aTGMS analyst, in case the situation can be remedied. The automated technology should also flag any portions of the data that may be inaccurate so that the operator or analyst knows not to base decisions on that data.
- **If algorithms are used to dismiss suspected data anomalies, make the original retrievable**. If algorithms identify data anomalies that suggest a possible interference with sensors (e.g., sunlight, leaves), these anomalies may be filtered out. However, in case of inaccuracies of the algorithm, the aTGMS analyst or TGMS operator should be able to retrieve the original data and examine the anomaly. The software should also allow filtering raw data through a different set of algorithms if a mistake is later discovered.
- **Make sure data transmission problems are visible**. Design track inspection technologies so that if the sensor is not collecting data (e.g., due to traveling below the speed needed for accurate data collection, sensor failure, or something interfering with sensor data collection), the automated technology shows that no data is being collected rather than simply showing that no defects are being found. Otherwise those reviewing automated inspection data output may have a false sense of the track condition.

7.5 Railroad Organizational Processes

Railroad managers make many decisions that influence track inspections; therefore, even though the current project was not focused on developing recommendations for upper management, some management-related recommendations emerged.

7.5.1 Resource Allocation

Railroad management determines how to allocate railroad resources to different departments and activities, including to the engineering department for inspection and maintenance. They also determine how new technologies are obtained and deployed.

Resource allocation is closely related to other organizational processes, including staffing, training, dispatching practices, supervisory practices, and production pressure (see Sections 7.5.2 through 7.5.7).

The following recommendations apply to all inspection sociotechnical systems and address potential risks associated with resource allocation.

- **Provide sufficient resources for training, including employee time**. Training employees is one of the main ways to address possible risks in the track inspection process. Therefore, it is important to allocate enough resources for employees to receive training that covers topics in sufficient depth, and allow time for employees to attend such training. This may include recurrent training, as well as training on new technologies, as needed, when the railroad procures them.
- **Assess financial incentives for job selection**. When determining pay for various railroad jobs, upper management may wish to assess whether there is sufficient financial incentive to become an inspector, or whether other positions are more highly incentivized. Allocating additional resources toward inspection and inspector pay may increase the likelihood of skilled workers staying in inspection roles.

The following recommendations apply to TGMS & Visual Inspection as well as aTGMS & Visual Inspection sociotechnical systems and address potential risks associated with resource allocation.

- **Allocate sufficient resources to the engineering department to promote effective coordination between visual and automation-aided inspections**. In addition to the resources required for the inspection task, the engineering department needs sufficient resources to promote effective coordination between humans and technology. This may include training employees on new technology and how to interpret outputs, as well as using visual and automation-aided inspections to inform one another.
- **Deploy new technologies according to where they would be most effective**. If a railroad does not possess enough aTGMS units to cover all territories, railroads would most likely choose to run any extra TGMS inspections or deploy aTGMS units according to areas most in need of regular geometry inspection and monitoring (e.g., high-traffic, prone to weather-related damage, or with characteristics like curvature that experience faster degradation).
- **Seek input from inspectors, supervisors, and technology operators / analysts when choosing where to deploy technology and resources**. Track inspectors, supervisors, and technology operators and analysts are likely to have insight regarding which areas are prone to defects that could benefit from new technologies (e.g., aTGMS) or additional resources. Therefore, management should work closely with engineering department employees to seek input when deciding where to deploy technologies and resources.
- **When possible, implement new technologies in ways that create flexibility**. When possible, aTGMS units should be installed such that they can be relocated to other territories if desired (e.g., not limited by locomotive power type differing across territories), or installed on locomotives of the type that is used most substantially by the railroad.

7.5.2 Staffing

The Volpe team identified several potential risks associated with staffing, including both inspector staffing and staffing of other employees (e.g., supervisors, dispatchers, and technology operators and analysts). If a railroad does not have enough staff available for both regular inspections and additional emergent demands, they will be challenged to meet regulatory and safety requirements. This will also place a much greater burden on their existing staff (see Section 7.3.2 on workload).

The following recommendations apply to all sociotechnical systems and address potential risks associated with staffing:

- **Assess staffing needs for inspectors and maintenance foremen**. To make sure the railroad trains enough inspectors, the engineering department should assess their staffing needs; considering territory sizes and workloads. Since inspectors are also qualified to work as maintenance foremen, it is important to have enough employees to fill both roles.
- **Use prior data to estimate training and staffing needs**. Railroads can collect data on how many inspectors they have trained in the past, how many stayed in inspection jobs, and how long they stayed in those jobs. Railroads can then use this data to identify how many inspectors they will need to train in the future to achieve the desired staffing levels.
- **Have additional employees who are qualified as inspectors available to fill in when needed**. Railroads may need to assign substitute inspectors to cover for absences, or may wish to assign additional inspectors to help manage workload in the case of unexpected issues (e.g., delayed inspections or additional inspections needed due to severe weather). If these substitute inspectors work other jobs like maintenance work or mentoring when not inspecting, it is important to have enough staff that assigning them to inspect does not have a negative impact on these other activities.
- **Provide additional support for inspectors that are not working their usual job**. When an inspector is not working their usual job (i.e., either a different territory or different role than usual) they may need additional support to make sure they are comfortable performing all aspects of the job. For example, if the substitute does not have strong relationships with the dispatcher, supervisors may be able to help them coordinate with the dispatcher when needed for track and time or to place restrictions. In other cases, railroads may be able to assign inspectors to work in pairs, with someone more experienced on the territory available to support a less-experienced inspector.
- **Include inspection-related tasks when assessing dispatcher workloads and determining dispatcher staffing needs**. In addition to overseeing train operations, dispatchers must be available to track inspectors, maintenance crews, and equipment operators who use the track. Railroads should make sure to hire and staff enough dispatchers that a dispatcher is always available to these employees within a reasonable time frame. This includes making sure that there is sufficient coverage during dispatchers’ breaks.
- **Assess the minimum amount of field experience needed for supervisors to be effective in their job**. Supervisors require a strong understanding of the inspection task to effectively oversee inspectors, weigh-in on defect decisions, and help inspectors resolve problems. Railroads may wish to establish a minimum experience requirement for supervisors to make sure that they have the necessary background.

The following recommendations apply only to the TGMS & Visual Inspection sociotechnical system and address potential risks associated with staffing:

- **Include coordination with the engineering department and TGMS operators when assessing dispatcher workloads and determining staffing needs**. TGMS inspections require track time and coordination with dispatchers. Railroads may have determined their staffing needs based on standard inspections and operations. However, finding space in the train schedule to accommodate TGMS inspections may take up additional workload for the dispatcher. Therefore railroads may wish to consider these needs when determining the number of dispatchers at any given time. For example, a railroad that uses TGMS quarterly could choose to have more dispatchers available during those inspections if they determined it was useful.

The following recommendations apply only to the aTGMS & Visual Inspection sociotechnical system and address potential risks associated with staffing:

- **Identify multiple employees capable of reviewing aTGMS data output**. If a single employee is responsible for reviewing aTGMS output, there is a risk that person could someday be unavailable, either temporarily (e.g., due to illness or vacation) or permanently (e.g., the person retires or leaves the railroad). Therefore, railroads may wish to hire multiple employees to fill the aTGMS analyst role, or train other employees to act as a backup if the aTGMS analyst is unavailable. A backup analyst may benefit from the regular opportunities to observe the primary analyst and/or perform data reviews under supervision to make sure they are prepared to perform these tasks in the future, as needed.
- **Establish plans for who to contact if the aTGMS analyst is not available**. For example, if an inspector has been sent to verify an exception that aTGMS located, but has questions about what to look for, the inspector may want to talk to the aTGMS analyst. If this person is not available, the inspector should be able to reach out to someone else who knows how to interpret aTGMS data.

7.5.3 Inspector Training and Qualification

The Volpe team identified several potential risks related to track inspector training. This section focuses on the training process and how to assess and strengthen it. (Recommendations related to specific topics to cover in training are primarily located in Section 7.2.)

Classroom Training

The following recommendations apply to all three sociotechnical systems and address potential risks related to inspector training:

- **Assess the qualifications and experience levels needed**. It is important for training instructors to have experience doing inspections. Railroads will need to determine how much is needed for them to be effective. Consider whether OJT trainers and mentors have sufficient expertise to be effective in their role.
- **Measure training effectiveness and use findings to strengthen future training**. This can be done using pre- and post-training knowledge tests for what is learned in the classroom. Assessments of OJT and other mentoring experience in the field may be helpful as well. Look for feedback about both the content and the length of classroom and OJT.

- **Keep the training curriculum and materials current**. Classroom trainers need to be up-to-date on any new information related to policies, equipment, etc. Consider setting a timeframe for regularly reviewing training materials for old information and updating them, as needed.
- **Solicit input from inspectors and track supervisors about how to strengthen classroom and OJT**. Supervisors, and experienced inspectors may have a good feel for where newer inspectors struggle and need more training time. However, experienced inspectors may have taken training long ago and no longer have a good feel for what is covered currently. Therefore, railroads looking for input may also want to consider checking with those that mentor newer inspectors. Newer inspectors themselves may also have input on where they are experiencing challenges and what they wish they had spent more time on in training. It would be helpful to have input regarding both classroom and OJT.
- **Protect the privacy of employees who ask questions or share areas of struggle**. Inspectors may be reluctant to ask questions or share areas where they struggle if they have concerns about their privacy. (For example, will they be seen as less competent if they do not understand what the new technology does?) It is important to avoid identifying employees when discussing the types of questions that employees are asking. If employees feel comfortable raising questions and being open about areas of struggle, they are more likely to do so. This allows the railroad to understand how training may be improved.

On-the-Job Training (OJT) and Mentoring

OJT and mentoring can play an important role in inspector training. The following recommendations apply to all sociotechnical systems and address potential risks related to OJT and mentoring:

- **Formalize and incentivize OJT and mentoring roles**. Make sure that new inspectors have opportunities to be partnered with or shadow experienced inspectors. Consider incentivizing the mentoring inspectors (e.g., mentor title and bump in pay while mentoring) to provide this additional support given that teaching the mentees during inspections increases their workload and may slow them down when they take the time to teach. Railroads may also participate in activities that allow inspectors to work together and share knowledge and best-practices across the industry.
- **Consider designating inspection mentors**. One approach is to have someone designated as a mentor available to work with newer inspectors and any other inspectors that might need some extra support, rather than limiting mentoring to OJT. This person could also be someone to reach out to for guidance if the inspector’s supervisor was unavailable when quick guidance is needed.
- **Use mentoring to help inspectors in areas where there may be little formal guidance**. For example, mentors may be able to help mentees learn strategies for working with dispatchers more smoothly, and how to prioritize their remaining track inspections when they have limited time. Railroads can help identify these types of challenges that may not receive formal training and urge mentors to provide support in these areas.

- **Consider providing recurrent OJT to make sure the inspectors' knowledge is thorough and current**. Incorporate actual current and emerging issues to make sure inspectors learn about these topics.
- **Provide OJT in a range of situations and environments**. Allow trainees to shadow inspectors in a range of situations (e.g., on hi-rail and on foot, in various weather conditions, at different times of day, and on different types of territory). If the primary way that inspectors learns real-world skills is OJT, they will need exposure to a wide range of situations and issues to do their jobs effectively and safely.
- **Avoid compromising the quality of inspections for the sake of training**. If an inspector needs to complete certain inspection activities within the required time frame, this takes priority over any special adjustments needed to train a mentee. For example, if an inspection requires using a hi-rail vehicle to be completed on time, the inspector should not do a walking inspection, even if there are things that a trainee could benefit from seeing up close. The decision on whether to stop the hi-rail to show the trainee specific issues can be made on a case-by-case basis when time permits, or the inspector can find another time to revisit these issues with the trainee. In addition to allowing the inspector to complete necessary work, this can benefit trainees who get to see how experienced inspectors handle working under time pressure.
- **Solicit strategies for effective and efficient coordination with dispatchers**. Encourage experienced inspectors to submit their expert strategies for efficient and effective coordination with dispatchers. Training instructors can incorporate the best of these strategies into their training programs.
- **Teach track condition logging strategies**. Include instruction on any logging strategies for maximum efficiency and clarity during OJT and when mentors, formal or informal, are working with less experienced instructors. Include any workarounds or tips that experienced inspectors commonly use to manage design issues with the logging system.

Inspector Qualification

Inspectors need to be qualified for the territory assigned to them for inspection. The following recommendations related to qualifying inspectors apply to all three of the sociotechnical systems studied:

- **Assess the inspector exam difficulty to determine if it is appropriate**. It should be challenging enough to confirm candidates have the required knowledge, but not so challenging that candidates with sufficient knowledge cannot pass. Make any changes needed to ensure that applicants that have learned the material taught in training have a good chance at passing the exam. Likewise, if a significant number of candidates pass the exam, but seem to struggle extensively during OJT, the exam may not be sufficiently challenging to reflect what inspectors need to know.
- **Consider rechecking qualifications and/or offering brief refresher training** before assigning inspectors to territory that they have not recently worked.
- **Verify track inspectors are qualified on the territory they are inspecting**. This may be straightforward when it comes to an inspector covering their own assigned territory. However, in the event someone needs to fill in or verify an issue elsewhere, it may not

always be obvious who is qualified to inspect in which locations. Supervisors need a way to easily look up information about which territory an inspector is familiar with to confirm whether or not an inspector is suitable to inspect a given territory in the event that there is uncertainty.

7.5.4 Technology-Related Training

When railroads acquire new technologies, providing training and support to the employees who will use them will promote effective job performance. This is true for both relatively simple technologies, like a defect logging software, as well as automated inspection technologies like either type of TGMS.

When technology is designed with a user-centered approach (i.e., with end-user input and adherence to established interface guidelines, and usability testing), it should be easier for employees to learn and use the technology (see Section 7.4.1). However, for technologies that are not as well designed, training and support become essential to help users understand the interface, cope with design issues, and avoid making errors. Employees who are less comfortable with technology may require more support.

- **Provide training support on defect-logging technologies**. Inspectors and other employees can benefit from training and ongoing support on any new technologies they are expected to use. Anticipate that additional financial resources will be needed for training in cases where end-users were not carefully considered in the interface design.
- **Training resources should be provided for any new automated-inspection technology procured by the railroad** so that the end-users know how to use it and the railroad training staff is not required to design training for an automated technology they might not yet know enough about. Railroad training departments can ensure that any TGMS operators at their railroads are trained using the manufacturer's training materials.
- **Keep track of the types of questions inspectors and other employees ask about new technologies, and use these to inform training and/or redesigns**. Whoever is receiving questions (e.g., a mentor, trainer, supervisor, technology analyst, etc.) should provide input to the training department so that such questions can be addressed in future trainings. They may also wish to share this information with the technology manufacturer in case there is an opportunity to address employee's concerns through updates or redesigns.
- **Consider identifying and sharing best practices across railroads in terms of technology-related training for track inspectors**. If multiple railroads use the same technologies, or encountering similar challenges, they may be able to share best practices for improving the inspectors' understanding of new technologies. This practice may be particularly helpful if the manufacturer has not provided the railroad with any training courses or materials and railroads are left to develop their own.

The following additional recommendations apply to the Conventional TGMS & Visual Inspection as well as aTGMS & Visual Inspection sociotechnical systems and address potential risks associated with technology-related training:

- **Train employees about differences between the new technologies being implemented and other similar/related technologies the railroad uses**. In addition to technical changes, new technologies can create differences in responsibility. Both immediate users of the technology (such as operators and analysts) as well as users of its output (such as inspectors) should be made aware of any key differences.

- **Use mentoring to train new TGMS operators and aTGMS analysts**. Work with new analysts in a mentoring-style with real-world examples to help them learn.
- **Seek input from inspectors to identify training topics regarding automated inspection technology**. Though inspectors are not the primary users of automated inspection technology, they may be required to use information from automated inspection reports to verify potential defects. Railroads may wish to ask inspectors what they do and do not understand about automated inspection technology, and what types of information would help them use automated inspection data more effectively. For example, inspectors may benefit from being able to interpret a strip chart to understand the geometry characteristics of a longer segment of track, rather than simply being assigned to verify a single potential defect.
- **Leverage existing training resources, when possible**. Consider if there are any resources (e.g., online or in person training modules, reference materials, etc.) used to train aTGMS analysts or TGMS operators that can be leveraged to teach inspectors. Using these existing resources will reduce the financial burden on the engineering department. Inspector trainers and supervisors may also find that they can gather things from the manufacturer's training, if available, that would be helpful to pass on to inspectors so they can understand how the automated technology works.
- **Collaborate with technology manufacturers, operators, and analysts when developing technology-related training for inspectors**. Both manufacturers and railroad employees working with the technology may have valuable input on what types of information inspectors would benefit from knowing about the new technology, and how to communicate that to inspectors.

7.5.5 Production Pressure

Railroads must manage two somewhat conflicting pressures. There is pressure to move people and/or goods as quickly and efficiently as possible. If a railroad cannot do this, customers will be unhappy and may turn elsewhere for their transportation needs. At the same time, there is pressure to maintain a high level of safety. Both goals are of fundamental importance to the railroad; however, these two goals may conflict sometimes in day-to-day practice.

The following recommendations apply to all three sociotechnical systems and address potential risks related to production pressure:

- **Establish a culture that prioritizes safety, even if it sometimes interferes with on-time performance**. Despite knowing that safety is a priority, railroad employees will naturally feel the competing pressures of on-time performance with safety measures that sometimes impact on-time performance. Establishing and supporting a strong safety culture will help reduce tensions that inspectors may feel while doing their job (e.g., if inspectors report more maintenance issues than a supervisor feels able to address, or inspections require track time at a time that is inconvenient for the dispatcher).

- **Encourage inspectors to report maintenance conditions even if it will be difficult to address them all**. In some cases, supervisors may find it difficult to address the maintenance conditions inspectors report if there are many, or more than expected. If inspectors feel that they are being discouraged from reporting, there could be negative impacts:
    - Incomplete reports will be much less useful to management when trying to monitor track changes over time and do longer-term planning for repairs.
    - The railroad may underestimate the need for maintenance crew employees if they base their staffing needs on the number of conditions reported.
    - Inspectors may feel pressure to perform certain repairs even when they cut into the time needed to do a thorough inspection.
- **Teach inspectors strategies to resolve conflicts related to production pressure**. Encourage inspectors to share concerns about production pressure with their supervisors so that supervisors can help resolve conflicts. For example, if an inspector has a conflict with a dispatcher, (e.g., the dispatcher is resistant to giving track and time because of previous interactions where the inspector had to take track out of service) the supervisor can help the inspector communicate with the dispatchers or management as needed to find a solution. Consider providing non-supervisory supports, like mentors, who can help inspectors navigate conflicts and feel confident in pushing back if someone has asked them to take an action that they feel will compromise safety. While such situations may be rare, it is important for inspectors to have the tools to address them.

Other recommendations also related to production pressure are included in Section 7.3.3, as well as in Section 7.5.6.

7.5.6 Dispatching Practices

Dispatchers play an important role in the track inspection process. Working with dispatchers is essential for getting time to inspect track (in visual and conventional TGMS inspections) as well as for taking actions on track, such as reducing track speed, removing track from service, and fixing track.

This section addresses recommendations related to what the dispatcher should know or do, whereas the communication recommendations in Section 7.3.3 reference what others should know or do when working with dispatchers.

The following recommendations apply to the visual inspection as well as Conventional TGMS & Visual Inspection sociotechnical systems and address potential risks associated with dispatching practices:

- **Support dispatchers' understanding of the track inspection and maintenance process**. Educate train dispatchers and their managers to understand the importance of safety-related activities and restrictions that may slow on-time performance (i.e., visual and conventional TGMS inspection activities, as well as resulting actions on the track, such as removing/restricting track, and repairing track); Train dispatchers need to understand possible impacts if degraded track is handled improperly.

- **Support inspection staff's understanding of dispatcher processes**. There may be times when inspectors can act in a way that is less likely to disrupt traffic or which makes things easier for dispatchers. For example, if there's a reason to believe it is an unusually challenging day that will not permit routine inspection to be done without causing major headaches then inspectors can reschedule the routine inspection.
- **Provide dispatchers with a realistic understanding of how much time it takes to inspect track**. Dispatchers may better support giving inspectors enough time to do the job if they have a realistic understanding of how much time it takes to inspect on their territory. This issue may also be resolved by scheduling track outages further in advance, so that dispatchers do not need to make moment-to-moment decisions about how much time to grant inspectors; though this may not be possible in all circumstances.
- **Teach dispatchers to coordinate with inspectors when granting or making changes to track and time**. Communicate clearly to inspector how much time the inspector can expect to receive, and avoid making sudden changes whenever possible. Changes to track and time, such as taking track back early, can have a negative impact on inspections because inspectors may make decisions (e.g., whether to stop and make certain repairs) based on the amount of time they expect to receive. Sudden changes to track and time may make it difficult to complete inspection activities. Therefore, before taking back track, dispatchers may want to consider:
    - Giving as much advanced notice as possible
    - Finding out the status of the inspection (e.g., can it be completed in a shortened amount of time?)
    - Advising the inspector on when they anticipate providing additional time.
- **Consider encouraging dispatchers to double-check with inspectors about track concerns**. When taking back track from inspectors, dispatchers may wish to check with the inspector about whether the inspector needed to take any actions on that track, or expects to need the track in the near future. While it is ultimately the inspector's responsibility to communicate any necessary actions, dispatchers can add a layer of protection by asking questions if they suspect an inspector may have forgotten something, or if a communication was unclear. Proactive communication can also help the dispatcher with planning. For example, if the inspection was not complete, the dispatcher may want to know when the inspector is available to return to complete their work.

Conventional TGMS inspections require substantial coordination and planning, much more so than for a visual inspection. It requires that:

- The TGMS is attached to a train that is already set up in the correct location on the track
- A crew is secured to run the train
- Trained staff are scheduled to operate the TGMS

The time needed to do this extra coordination should also make it possible for dispatchers to have substantial notice prior to inspections.

The following additional recommendations apply to the Conventional TGMS & Visual Inspection sociotechnical system and address potential risks associated with dispatching practices:

- **Coordinate with dispatchers in advance of conventional TGMS inspections**. Given that TGMS operators are scheduled in advance, it should be possible to give dispatchers plenty of notice to allocate track time. This coordination is particularly important for dispatchers on days/routes where non-routine issues arise.
- **Explain to dispatchers what a conventional TGMS inspection entails**. Unlike a walking or hi-rail inspection, TGMS can collect data at track speed. This knowledge may lessen the dispatchers' concerns about allowing a TGMS inspection to go ahead of regular train traffic.
- **Develop best practices for accommodating conventional TGMS inspections**. Because conventional TGMS requires track time to operate, dispatchers need to find ways to fit TGMS into the train schedule. When possible, prioritize these TGMS inspections for off-peak hours.

Because aTGMS does not require designated track time and does not have onboard staff, the Volpe team did not identify any specific recommendations related to dispatching practices for the aTGMS & Visual Inspection sociotechnical system.

7.5.7 Planning Inspections

The recommendations in the current section relate to planning that may occur with some inspections. It discusses recommendations related to inspection method and using conventional TGMS for special inspections.

Inspection Method

Often the visual inspection task is conducted in the same way (e.g., walking or hi-rail) during each inspection period. However, in some cases the method of conducting visual inspection may vary. It can be dependent on whether the inspection is part of the inspector's regular territory inspection or if the inspection is addressing a request for verification or another type of special inspection (e.g., ensuring the track is okay after a weather incident).

If the inspection methods are equally effective for finding degraded track conditions, then allow the inspector to use either walking visual inspection or hi-rail or a combination of the two as long as the inspection can be completed within the required time frame. However, if there is a particular reason why one inspection method is more effective for a given territory or purpose, railroads can promote the preferred method wherever possible.

Recommendations addressing potential risks related to planning inspections are as follows:

- **Consider whether the territory is of appropriate size and complexity to allow a walking inspection, if it is required**. If walking is the most effective means to inspect a given territory, railroads may wish to assess territory size and complexity to make sure the inspection can be completed within the required time frame. Where walking inspections are required, reinforce the need for dispatchers to find sufficient time to enable inspecting on-foot.

- **Use hi-rail when it is needed to complete the inspection within the required time period**. This applies for territories where hi-rail and walking inspections are equally effective, but for which a hi-rail inspection is necessary to complete the inspection within the time period.
- **Be flexible to accommodate inspections by the preferred method, when possible**. Unless there is a reason why a walking inspection is required (e.g., to inspect switches), or why a hi-rail is required (e.g., to bring particular tools), use flexibility in the inspection schedule to accommodate the desired inspection method(s). For example, some potential ways to create flexibility are rescheduling a walking inspection due to poor weather, or using a second inspector to bring tools via hi-rail so the first inspector can do a walking inspection.

Additional recommendations that related to inspection method may be found in Section 7.3.2, as well as Section 7.6.2, territory size and complexity.

Using Conventional TGMS for Non-routine (special) Inspections

Regulations only require TGMS to be used a few times a year. However, the Volpe team worked under the assumption that railroads may sometimes also assign additional TGMS inspections to certain territories (See Appendix C). The degree to which this happens is dependent on a railroad's budget and access to TGMS.

The following recommendations for TGMS address potential risks related to assigning additional TGMS inspections:

- **Consider information from inspectors when deciding where to send TGMS**. If the railroad bases TGMS use on expected territory degradation, they may wish to seek the inspector's input to determine where TGMS should inspect. This may include looking at inspection logs; in which case the railroad should use information on maintenance conditions as well as safety defects to assess needs, as maintenance conditions could worsen and using both provides a more complete picture of track condition.
- **Consider whether there are cases where visual inspection is more effective than TGMS**. Even if a railroad routinely uses TGMS to perform special inspections (e.g., to assess the track condition following severe weather), there may be cases where a visual inspection is more effective. For example, if an ice storm has knocked down a lot of trees, visual inspection is likely to be more effective because the anticipated defects are unrelated to track geometry. In other cases, visual inspection may be more effective or efficient because inspectors can perform minor repairs while examining the territory, as long as those repairs do not interfere with completing a thorough inspection. Visual inspections may be able to cover more territories quickly if the railroad has a limited number of conventional TGMS vehicles.

7.6 Physical Environment

The physical environment including weather, time of day or lighting conditions, and territory characteristics can create challenges for inspection. The recommendations in this section describe ways to reduce risks associated with weather and lighting, as well as those associated with territory size and characteristics.

7.6.1 Weather and Lighting Conditions

Weather and lighting conditions impact inspections in several ways. First, they can reduce visibility during inspection. This is particularly true for snow and ice that may cover the tracks completely, or low-lighting conditions in evening or overcast weather. Additionally, weather conditions like flooding or heat waves can contribute to the formation of defects; therefore, railroads may require additional inspections following such events. Lastly, weather can delay inspections, creating schedule-related challenges.[23]

Recommendations to address these potential risks related to weather and lighting are as follows:

- **Plan for seasonal weather issues**. In regions that experience snow and ice, planning ahead for snow and ice removal (e.g., identifying equipment and staffing needs) will help railroads mitigate the challenges associated with inspecting in snow and ice conditions.
- **Teach inspectors to use schedule flexibility in the event of poor weather**. Inspectors are typically given flexibility around which territory to inspect on a given day. This flexibility is particularly important during poor weather or lighting conditions, where, if inspectors have sufficient slack time in their schedules, they can work around weather-related delays. For example, if a weather issue seems fairly short term, inspectors may be able to return and finish the inspection later, rather than rushing to complete the inspection as planned; or, inspectors may be able to time their inspections for when conditions are better for detection.
- **Include weather-related issues and strategies in training**. Train strategies for detecting defects in poor weather and low light conditions, perhaps during on-the-job training or mentoring. When possible, teach inspectors to use alternate methods (e.g., auditory cues in addition to visual) to support detection.
- **Track inspection needs related to poor weather**. Poor weather may make it difficult to complete activities when planned, or may lead to new issues which inspectors need to inspect before the railroad uses the track again. A tracking system can help railroads prioritize their inspection needs and make sure these inspections are done as soon as possible after the weather clears. For example, this tracking system could be used when:
    - A defect cannot be verified due to unsafe weather conditions.
    - Bad weather (e.g., flood) makes it difficult or impossible to conduct an inspection.
    - Weather shuts down traffic on that track and inspection is required before the track is used again.
- **Provide sufficient lighting to identify defects if inspectors must work in low light**. There may be times when an inspector needs to check the track immediately, such as when a defect needs to be verified, and cannot wait until lighting conditions improve (e.g., verifying a defect in the evening that cannot wait until morning). Consider keeping

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[23] The authors are aware that there are also risks to track inspection staff during inclement weather and low light conditions. Track inspectors the team spoke with noted that they consider inspections during low/no light conditions to be less safe, likely because they were less likely to be seen by trains or equipment traversing the rails and/or increased potential for slips, trips, and falls. However, these risks are beyond the scope of the current project since it is focused on risks related to track condition.

portable, cordless floodlights on a hi-rail vehicle in addition to handheld flashlights to help with verifying defects in the case of low natural light.

Additionally, for railroads that use conventional TGMS or aTGMS the Volpe team identified these recommendations:

- **Design sensors to handle likely environmental conditions**. Identify situations that could damage sensors or reduce accuracy, and design to prevent these situations if possible. Otherwise, alert operators and analysts to these situations (i.e., through training and reference materials) so they can avoid them.
- **Identify conditions under which data becomes less accurate or reliable**. Railroads may wish to compare data across runs and seek input from technology operators and analysts to identify these conditions. For example, if conditions such as bright sunlight, or leaves blowing in front of sensors are known to affect data collection, TGMS operators or aTGMS analysts should be aware of these conditions.
- **Plan how to handle environmental conditions that interfere with sensors**. Identify situations that could interfere with or damage sensors and create policies to prevent them (e.g., stop if a branch is on tracks that might hit the sensor). While it may not be possible to avoid such conditions completely, being aware of them may help operators and analysts spot data anomalies or false alarms.

7.6.2 Territory Size and Characteristics

The CFR determines the frequency with which inspections must take place for track of a given track class, regardless of the size of the territory (49 CFR § 213.233(c)). Therefore, the size and characteristics of the territory have a significant impact on the inspector's workload and can create challenges to completing inspections effectively.

Recommendations to manage risks related to territory size and inspector workload are as follows:

- **Assess the inspectors' workload to determine whether territory sizes are manageable**. When assessing workload, railroads may consider factors including territory size, number of inspectors, ability to access the track for inspection, expectations for inspectors to perform maintenance, and the time needed for logging degraded track conditions. If there are certain territories where the inspector always struggles to finish on time, or territories where only the best inspectors can manage to do a thorough job, these may be signs that the workload is very high.
- **Establish a regular interval for reassessing territory sizes**. Railroads may have used the same territories for many years, despite changing demands on the infrastructure and workforce. There may also be certain territories that inspectors consider "harder" than others; such territories pose a risk for employees who bid on them but may not be as confident in their ability to handle them. Reassessing territory sizes will help keep workloads manageable so that inspectors can perform their tasks equally thoroughly, regardless of which territory they work.
- **Find ways to adjust workloads that may be too high**. Given the timeframe between inspections is regulated by FRA, railroads can adjust workload by decreasing the territory

size or adding additional inspectors. Other options may include changing inspection method (i.e., switching from on-foot to hi-rail, if feasible), or finding other ways to free up the inspector's time, like switching to an efficient digital logging system or reducing expectations for inspectors to perform repairs.

7.7 External and Regulatory Factors

External and Regulatory factors were not a primary focus of this report. However, some recommendations still emerged in this area, particularly related to technology manufacturers.

7.7.1 Working with Technology Manufacturers

Some of the design recommendations the Volpe team proposed regarding technology design (see Section 7.4.1) are outside the control of individual railroads. However, railroads nonetheless play a role in selecting and purchasing tools and technologies.

The following recommendations address ways that railroads can work with technology manufacturers to improve the design of tools and technology:

- **Consider giving feedback to technology manufacturers so they can further improve their algorithms**. The railroad may want to discuss with the manufacturer whether it would be helpful to receive information about defects that their technology did not locate, if any occur, and/or information about places where there are repeated false alarms at certain locations. If the manufacturer is able to use such information to improve their algorithms and reduce these issues in the future, it would benefit the railroad.
- **Ask that data output be formatted so it is easy for end-users to understand**. When contracting with aTGMS manufacturers, railroads may want to require that data output sent to them is in a format that is as easy as possible for the end-user to understand with minimal training. Consider different types of end-users, including office workers such as managers and data analysts that may need to look at all or most records, as well as field staff that may need to review detailed information on specific exceptions that require verification. It is possible that more than one type of user interface or report output could be needed.
- **Minimize the work required to prepare an exception report for field staff**. Ask the manufacturer to provide the ability to generate exception reports for field staff that meet field staff needs with minimal, if any, additional work by the analyst. The team learned that in some cases, the data cannot be used "as-is" by field personnel and so the railroad's data analyst needs to create specialized exception reports to make the information usable for field staff. This may involve adding in additional information (e.g., adding a map of the exception location), paring down information that is not relevant to that particular exception, and reformatting the remaining information. This will become increasingly important as use of automated inspection technologies grows and more exception reports are sent out.

7.7.2 Other External and Regulatory Factors

The team did not make recommendations related to FRA regulations, since this was outside of the project scope. However, FRA regulations clearly play a large role in inspection since the entire process is centered on looking for FRA-defined defects. Additionally, FRA inspectors may help to coach railroad inspectors in cases where defects were missed at the railroad level and that can have an impact on the railroad's inspection process as well.

Similarly, it is beyond the scope of this report to make specific recommendations for labor unions and railroads regarding collective bargaining agreements. While it is certain that collective bargaining impacts the inspection process in various ways, this was not the team's focus in this study.

8. Discussion

This section discusses the key findings of this project. First, it summarizes commonalities and major themes that arose in the recommendations in Section 7. Despite various differences in the three sociotechnical systems, the team identified several areas that are important to prioritize across all three.

Next, this section draws comparisons between the three types of inspection examined in this study and discusses strengths and weaknesses that the team noted during their observations and analysis. Lastly, this section presents thoughts on the future of humans and automation in track inspection, including the evolving role of inspectors and the importance of good design.

8.1 Commonalities among Inspection Sociotechnical Systems

Though there are some significant differences between the Visual Inspection, Conventional TGMS & Visual Inspection, and aTGMS & Visual Inspection sociotechnical systems (see Section 5), there are ultimately many similarities in how they function and the types of risks that can occur. The generalized model of the inspection process shown in Figure 4 captures many of these similarities. Each of the three sociotechnical systems encompasses a series of activities from sensing the track condition to assessing severity and taking action.

The major differences between these sociotechnical systems deal with:

- Who or what senses the defects (humans or technology)
- What types of defect they can detect (only geometry or multiple types)
- How sensitive they are (able to detect slight deviations from thresholds or not)
- When the information is considered (in real-time or after-the-fact)
- Where decision-making happens (at the inspection location or elsewhere)

Section 8.2 discusses how these differences impact the inspection process and lead to strengths and weaknesses of each sociotechnical system. However, given the number of commonalities between them (particularly because humans are still involved in verifying technology outputs), the Volpe team noted several themes that emerged as important across all three sociotechnical systems.

User-centered design of tools and technologies. From inspection tools and communication systems to computer-based software and automated inspection technologies, the tools and technologies that inspectors and other employees use play a significant role in the success of inspection and maintenance activities. While good design can make work easier, allowing workers to readily access information and accomplish their tasks efficiently, bad design can lead to delays or errors that compromise safety. Railroads can promote good design through their own internal activities (e.g., assessing employee's needs prior to purchasing any new technology) and through their interactions with manufacturers, either by seeking out technology designed with a user-centered approach or requiring such an approach during procurements.

Thorough classroom and hands-on training. In any sociotechnical system, training is one of the ways of preventing risks. By making sure employees know all the basic information necessary for their work, railroads can prevent what may seem like obvious mistakes. However, the Volpe team noted that going beyond classroom training and providing hands-on learning opportunities may be a valuable way to reinforce key skills, and teach informal strategies for things that are hard to teach in a classroom, like workload management, prioritization, and resolving conflicts. During the team's conversations with track inspectors, the inspectors spoke highly of OJT and mentoring programs that allowed them to develop strong defect detection skills and other necessary tools for the job. The Volpe team encourages railroads to embrace and strengthen these training approaches and continually assess what new skills and knowledge inspectors need to effectively and efficiently work with technologies.

Communication and coordination. One of the major themes that emerged during the team's hazard analysis was that effective communication and coordination is essential during track inspections. The requirement for communication and coordination is no less important during automation-aided inspections, which may require different types of coordination to effectively work in harmony with visual inspection processes. There are many opportunities for visual inspection to shape the use of automation; for example, inspectors can share their extensive knowledge of the territory and help railroads direct the use of TGMS. And similarly, automation-aided inspection can be extremely useful for informing visual inspections and verifications, particularly with more frequent data collected by aTGMS. However, effectively coordinating these activities requires strong communications. Likewise, during both visual and automation-aided inspections that require track time, communication between the engineering department and dispatchers is essential so that the two groups can establish a shared understanding of each other's priorities and resolve potential conflicts over track usage.

Managing production and resource pressures. Railroads are under a great deal of pressure to provide efficient service, maintain safety, and comply with regulations. Track inspection is essential to maintain safety, but can also pose challenges if inspectors or automated technologies reveal greater needs than the railroad is able to meet—or if the demands associated with those inspections interfere with the railroad's ability to meet service demands. As the gatekeepers for track usage, dispatchers handle the majority of these pressures, but management is ultimately responsible for setting the tone for the railroad's priorities and establishing a safety-oriented culture. At all levels of the organization, employees must feel supported in taking actions to promote safety, from inspectors who may find a greater number of defects than anticipated, to supervisors responsible for assigning maintenance and dispatchers who have to accommodate these needs in the train schedule.

8.2 Strengths and Weaknesses of Automation-Aided Inspection

While the primary purpose of this study was to examine potential risks associated with visual and automation-aided inspection methods and suggest ways to reduce those risks, the Volpe team noted some potential strengths and weaknesses associated with each sociotechnical system during data collection and analysis. This section describes the strengths and weaknesses that the team identified.

Note that because comparison was not the primary purpose of this study, these strengths and weaknesses should not be considered comprehensive. The team collected data at only three passenger railroads, and focused on two different variations of track geometry measurement systems. To provide a comprehensive comparison would require data from other railroad environments (including freight railroads), as well as other types of automated track inspection technologies. Therefore, the team's observations are limited to the context in which the team collected data and may not be representative of the industry at large.

8.2.1 Comparing Automation-Aided Inspections to Visual Inspection

The three railroads the team visited and the subject matter experts the team spoke with all indicated that both automated inspection technologies and inspectors have certain strengths.

Relative Strengths of Visual Inspections Compared to Automation-Aided Inspection

One of the strengths of visual inspection that railroads mentioned is that inspectors can look for multiple categories of track conditions. At the time of this report's writing, most automated inspection technologies can look for one category of track condition at a time, with some automated technologies incorporating multiple types of sensors to look for several categories of condition at a time. However, for some types of track conditions there are no inspection technologies available to date that can consistently locate them. For example, human inspectors can identify loose ballast, or notice a tree that may fall onto the track. So, visual inspection can cover a much broader range of issues.

Experts told the team that inspectors may also find things during visual inspections that are overlooked by current technology. This is consistent with findings that visual inspection may be more sensitive to maintenance conditions than TGMS (Al-Nazer, Raslear, Wilson, & Kidd, 2017). Automated technologies detect defects based on measurement thresholds, but in some cases, track conditions that are below threshold can still pose a safety issue, such as if multiple issues are co-located. Currently, railroads told the team that they rely on inspectors to identify these types of issues. Inspectors are also able to provide overall track quality assessments in ways that technology cannot.

Relative Strengths of Automation-Aided Inspections Compared to Visual Inspection

The strengths of automation-aided inspection that railroads mentioned were similar to those that the Volpe team found in the literature. Perhaps most frequently, the railroads commented on the fact that they appreciated the ability to collect objective measurements and compare them over time to monitor track degradation.

The railroads also mentioned that they rely on automation-aided inspections to find things that track inspectors cannot. Many automated inspection technologies have higher sensitivity than human inspectors when it comes to detecting defects that exceed regulatory thresholds by very small amounts. For example, on class 5 track and above, geometry standards are very strict, so it is difficult to identify the slight measurement differences that constitute defects visually. This is a case where TGMS is particularly useful. In other cases, automated technologies can detect conditions that are very difficult to detect during visual inspection, such as geometry defects that only appear under loaded conditions, or internal rail flaws.

Relative to visual inspection, automation-aided inspection has advantages in that it does not rely to the same extent on the capacity of human attention. During visual inspection, inspectors are expected to simultaneously monitor for 21 categories of defect (see Table 1) and may have difficulty inspecting thoroughly for all of them, particularly if their workload is too high or they do not have sufficient time to perform inspections. Inspectors' can also be biased during inspections, such as if a railroad places too much pressure on reducing false alarms.

Automated inspection technologies, while unable to detect the same breadth of defects as visual inspection, are highly sensitive to the particular conditions they are designed to detect and can take frequent, consistent measurements across large stretches of territory. This degree of consistency can help reduce the risks of attention decrements and detection biases. However, it does not completely eliminate biases, as humans are still responsible for programming the algorithms that the automation uses and for reviewing the data, and could be subject to similar expectation biases and organizational pressures as track inspectors.

The railroads the Volpe team spoke to indicated that, given the relative strengths and weaknesses of each inspection approach, they saw automation-aided inspections and visual inspections as complementary. While automation may excel at finding certain types of defects, railroad employees and subject matter experts emphasized that visual inspection (including human verification of potential defects identified by automation) remains an essential part of the inspection process.

8.2.2 Comparing Conventional TGMS and aTGMS

This section compares the strengths and weaknesses of the two automation-aided sociotechnical systems studied during the current project: a sociotechnical system using conventional TGMS to supplement visual inspections (Conventional TGMS & Visual Inspection), and a sociotechnical system using aTGMS to supplement visual inspections (aTGMS & Visual Inspection).

Relative Strengths of aTGMS Compared to TGMS

One of the primary reasons why automated inspection technologies like aTGMS are so attractive to railroads is that they do not require obtaining track and time. Since aTGMS is mounted on a revenue service train, it can gather data on a given line as frequently as the train runs and without interrupting revenue service.

This ability to gather data frequently allows for other benefits, such as supporting maintenance quality control. The railroads the team visited commented that automated track geometry data is useful as a check on repairs. They can review it to confirm when repairs are done and ensure they are correct. One employee stated "…we can use it for quality control. When we finish a track blitz, we can run it [aTGMS] to see how we did."

Another benefit of the frequent inspections possible with automated technologies like aTGMS is that having frequent data points allows analysis of how track issues change over time. This allows railroads to plan their maintenance more strategically—both in terms of how to efficiently tackle current maintenance needs and with regard to understanding rates at which certain issues begin to arise so as to plan for future maintenance needs.

Additionally, because aTGMS does not need to have a human analyst reviewing the data in real-time, there is more flexibility for the analyst. With conventional TGMS, the day and time of the inspection and the time allotted for the inspection may be constrained not only by track availability, but also by staff availability. That is, the conventional TGMS inspection can only occur when the TGMS operators, supervisor (if joining them) and train crew are all available. With aTGMS, analysis can happen whenever the analyst is available, without any additional staff required to operate the technology.

Relative Strengths of Conventional TGMS Compared to aTGMS

Even though aTGMS has some significant benefits, there are still some advantages to using conventional TGMS.

First, railroads that use conventional TGMS are already comfortable with how to manage the amount of data it generates. In contrast, one railroad that uses aTGMS noted that it can generate "extreme amounts of data" as a result of its continuous operation. While more data is generally a good thing, it can pose challenges for railroads that must find ways to store, analyze, and act on much more data than they are used to collecting with other inspection methods.

Conventional TGMS may also make it easier, in some ways, to analyze data because the analyst is present when the data is collected: in fact, the operator onboard can analyze the data in real-time. During the Volpe team's TGMS observations and conversations with inspectors, railroad employees indicated that one can often "feel" problems with the track when traveling over it on hi-rail or conventional TGMS. TGMS operators can also use out-the-window cues to reinforce their understanding of where the train was when certain exceptions were recorded because they are reviewing data in approximately real-time.

In comparison, with aTGMS the analyst who reviews the output is removed from the track environment, and typically reviewing data after data collection has been completed. Given that aTGMS analysts are removed from the track environment and unable to use out-the-window cues, it may be more difficult for aTGMS analysts to gain the same understanding of track characteristics and defects as TGMS operators.

Conventional TGMS may also have some advantages over aTGMS when it comes to quickly verifying exceptions and assigning repairs. At one railroad, the Volpe team observed that supervisors may ride along during conventional TGMS inspections. In such cases they can respond quickly to any exception that appears to be a safety defect by getting off the TGMS vehicle and verifying the measurement. Additionally, during the same inspection, a maintenance-of-way crew followed the TGMS vehicle so that they could address defects immediately, while the track was already out of service for the inspection. Both of these examples demonstrate the value of having track staff co-located with or near the automated inspection technology.

In comparison, with aTGMS the technology would send a notification to the aTGMS analyst, who would then review it. Once the analyst decides the exception is legitimate, the analyst sends it to the supervisor, who then assigns an inspector to verify the exception. The inspector must then travel to the defect location to determine whether maintenance is necessary; if so, the inspector will repair the condition or call their supervisor to assign a maintenance crew, who will also have to travel to the location. Therefore, it may take more time to address *individual issues* identified by aTGMS, even if the overall process of using aTGMS increases efficiency in other ways.

Lastly, conventional TGMS may be easier to access for repairs or calibration than aTGMS. Railroads do not use conventional TGMS vehicles for anything other than TGMS inspection, so there are no challenges to accessing them for maintenance or calibration. The aTGMS unit, on the other hand, is mounted to a locomotive in revenue service and therefore may be more difficult to gain access to once it is installed and in operation. Therefore, though both automated technologies may require occasional recalibration, railroads may need to plan further in advance for aTGMS calibration.

8.3 The Future of Humans and Automation in Track Inspection

Ultimately, the industry is moving toward greater use of automation in track inspection. The team spoke with some domain experts that expressed a desire to have a single vehicle with all the various technologies incorporated on it that can inspect a territory all at the same time. This is an appealing idea; however, there are some potential challenges that come to mind should such a multi-purpose system emerge. One technological challenge may be keeping many technologies or subsystems functional and calibrated. Some of the more human-centered challenges may be somewhat less apparent: the changing role of the inspector, the increased importance of user-centered technology design.

8.3.1 The Changing Role of Track Inspectors

At railroads that utilize automated technologies to supplement visual inspections, the inspector conducts the standard, mandated inspections but also serves in the role of examining exceptions found by the technology to either verify the exception is a defect or to determine that it was something else (e.g., a false alarm or a maintenance condition that has not yet become a defect).

As railroads increase the use of automated inspection technology, it is likely that the inspector role will change in one of two ways (regulations permitting):

1. The inspectors' role will be more heavily focused on verification, with inspectors acting as backup to automation.
2. Inspectors will still perform full inspections, but perhaps with a change in frequency or focus, and with more significant guidance from automation.

In a hypothetical future where automated technologies could search reliably for all 21 categories of defects (see Table 1), the railroads would still need humans for defect verification and that could become the more dominant role of inspectors in such a future. This seems somewhat straightforward at first when considering the role that inspectors play today with verification. However, the inspectors in today's railroad environments are able to verify so skillfully in part because they have so much practice inspecting. If that regular ongoing experience of inspecting were not there, even experienced inspectors would become somewhat deskilled and new inspectors may never develop enough skill to do the job adequately in the first place. If railroads expect to continue needing humans to verify exceptions, then they will have to take measures to help inspectors maintain their knowledge and skills. This might be possible though targeted efforts, such as some combination of regular continued refresher training and continuing to keep inspectors engaged in visual inspections.

Another possibility for a joint human-automation inspection process would be to maintain ongoing visual inspections (which also helps retain a skilled inspector workforce), but use automated inspection technology to help steer inspectors towards certain things. For example, in a hypothetical future (i.e., regulations permitting), railroads might receive automated guidance to help them prioritize which track to inspect based on automated assessments of track condition, rather than deciding what to inspect based on what is due next. A variation of this would be providing management and/or supervisors with more information from automated technologies that they could use to prioritize inspections.

8.3.2 The Importance of Good Design

Regardless of exactly how the joint human-automation track inspection process looks in the future, good design is important. This includes:

- Design of the automated technologies themselves
- Design of their output
- Design of the logging and tracking systems used by railroad staff

If more and more locomotive-mounted technologies are used where analysts review the data at a later time, this may become a lot of data for review and, because issues requiring immediate review and possible assignment for verification may come in at any time, it will be important that reviewing the data is as straightforward as possible. It will become increasingly important that data output is easy to understand, not only for analysts but also for supervisors and inspectors. At the railroad the Volpe team visited that utilized aTGMS, the analyst has to take the information provided by the automated technology and create a report to send out to supervisors and inspectors—something that was more tailored to their needs. In a hypothetical future where all tracks are inspected by many types of technologies on a near constant basis, having a staff member make tailored reports for other staff may not be the best use of railroad time or financial resources. Rather, the technology manufacturer should talk to their customers about the various categories of end-users and what their needs are and then design different types of output/reports for different end-user needs.

Additionally, with multiple types of output to review, it becomes increasingly important that it is as intuitive as possible. A number of inspectors the Volpe team spoke with indicated that they did not understand the aTGMS output as well as they would like to and that they thought it would be helpful for verification if they had received some training on how to interpret it. As more technologies are used and inspectors increasingly are asked to verify exceptions found by automated technologies, such training will become increasingly important not only because of the number of verifications the inspector may be asked to do, but also because of the potential for a wide variety of different types of graphs and interface designs.

9. Conclusion

As automation becomes increasingly prevalent in the railroads' track inspection process, researchers have attempted to understand the impacts of automation. The full impacts of automation cannot be observed by examining technologies in isolation. Automation is one aspect of a broader sociotechnical system that includes the railroads' technologies, processes, and people operating in coordination. Therefore, to thoroughly understand potential risks in the track inspection process, the present research adopted a sociotechnical framework to examine not only the technology itself, but also the context in which it operates. In this study that took place from February 10, 2018, to March 31, 2020, the Volpe team examined three track inspection sociotechnical systems which encompassed both human and technology components of track inspection. These three sociotechnical systems included:

- A Visual Inspection sociotechnical system
- A Conventional TGMS & Visual Inspection sociotechnical system
- An aTGMS & Visual Inspection sociotechnical system

The team chose to include sociotechnical systems with conventional TGMS and aTGMS to reflect both staffed and unstaffed (or "autonomous") ways of using track geometry measurement technology. Both these sociotechnical systems included visual inspection to reflect the way these technologies are currently used in conjunction with FRA-mandated visual inspections.

For each sociotechnical system, the team developed models of the inspection process that included human factors related to the task, individual and team, and organizational levels. The team then utilized a sociotechnical hazard analysis methodology, STPA, to identify potential risks associated with all three sociotechnical systems and develop recommendations to reduce these risks. Despite the differences between these sociotechnical systems, the team noted that there were many commonalities and areas where all three could benefit from the same recommendations.

The team's recommendations address potential risks at various stages of the track inspection process (i.e., detecting, assessing, and acting on defects) as well as different levels of the sociotechnical system (e.g., task, individual and team, organizational, tools and technology, physical environment, and external factors). Major themes that emerged from these recommendations include the need for strong user-centered design when incorporating new technologies, the value of hands-on training, the importance of communication and coordination, and a need to manage the impact of production and resource pressures on inspection and maintenance activities.

Railroads can use these recommendations to assess their practices and mitigate potential risks, thereby strengthening the safety of their current inspection process. Furthermore, while the team developed these recommendations to address potential risks associated with visual inspection and TGMS, railroads may use them as a baseline when assessing future inspection technologies.

For future work, researchers may consider turning their attention to freight railroads, to the repair and replacement part of the maintenance process, or to employee safety during inspection and maintenance, all of which were outside the scope of the current work. Additionally, it may be valuable to apply STPA to other, more novel inspection technologies to identify and mitigate potential risks while the automated technology is still developing and evolving. This would also allow researchers to examine how broadly the recommendations in this report can be applied to technologies beyond track geometry measurement systems.

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Appendix A.
Glossary of Terms

TERM	DEFINITION
Accident	An undesired and unplanned event that results in a loss (e.g., loss of human life or injury, property damage, etc.).
aTGMS	"Autonomous" Track Geometry Measurement System. A type of TGMS (an automated inspection technology) that is not staffed, and instead consists of sensors and computers mounted on a locomotive or freight car. This automated technology runs continuously and data is analyzed (typically after the fact) by employees not onboard the vehicle.
aTGMS analyst	The person responsible for examining aTGMS system output; in this analysis, it is assumed to be a railroad employee.
aTGMS & Visual Inspection sociotechnical system	An example of an "automation-aided" sociotechnical system in which unstaffed aTGMS units are used to collect data, in addition to visual inspection.
Automated technology; automated inspection technology	A technology which uses sensors to collect track condition data (rather than human senses) and uses computers to perform some interpretation or analysis of that data. May include some human analysis and decision making. Typically used in addition to visual inspection.
Automation-aided inspection	Track inspection that utilizes automated technologies, such as TGMS and aTGMS, to assist humans with the work of finding, making decisions about, and recording track defects and maintenance conditions.
Causal scenarios	Short stories that help us identify how and why undesirable actions may occur. Typically they are based on two or more causal factors.
Class-limiting defect	A track problem that exceeds thresholds or falls outside track-class based requirements set by an FRA regulation. This type of defect can be addressed by reducing track class (i.e., placing speed restrictions) so that the track no longer exceeds thresholds for the new, reduced track class.
Conventional TGMS	A type of TGMS that operates using staffed vehicles (often referred to as "geometry cars") equipped with sensors and computers. Railroads must schedule conventional TGMS inspections as they require track time and dedicated operators, as well as a locomotive and train crew to pull the geometry car. The operators are onboard and can analyze data in real time.

TERM	**DEFINITION**
Degraded track condition	An identified track problem that may or may not exceed an FRA regulated threshold. May be classified as either a safety defect or a maintenance condition.
Exception	A potential defect or maintenance condition identified by an automated inspection technology such as conventional TGMS or aTGMS.
Hazard	A system state or set of conditions that, together with a particular set of worst-case environmental conditions, will lead to an accident or loss.
Hazard analysis	The process of identifying hazards and their potential causal factors.
Maintenance condition	A track problem that does not exceed FRA regulation thresholds, but does exceed thresholds voluntarily set by the railroad.
Maintenance standard	Internal standards set by the railroad and used to hold track to stricter standards than FRA regulation. Typically based on FRA regulations for the next highest class of track.
Safety control structure model	A diagram used in STPA hazard analysis that depicts control and feedback relationships between the major components of a process (e.g., people and technologies) and shows the functional relationships between them that are required for the sociotechnical system to function safely.
Safety defect ("defect")	A track problem that exceeds thresholds or falls outside requirements set by an FRA regulation.
Safety issue	A track problem that poses safety concerns—including safety defects or problems comprised of multiple degraded track conditions below regulatory thresholds.
Sociotechnical system	A combined set of people, machines, and processes that share a common goal. For example, inspectors, TGMS vehicles, TGMS operator, data analysts, and supervisors are part of the sociotechnical system for track inspection.)
Staffed	Refers to automated inspection technologies with onboard staff. May also be referred to as "manned."
Systems perspective	A perspective which considers emergent properties of the sociotechnical system, such as safety, which result from interactions between people, technology, and processes.
TGMS	Track Geometry Measurement Systems: A category of automated inspection technology used to examine track geometry. Includes both conventional TGMS and aTGMS.

TERM	DEFINITION
Conventional TGMS & Visual Inspection sociotechnical system	An example of an “automation-aided” sociotechnical system in which a staffed TGMS is used to collect data in addition to visual inspection.
TGMS operator(s)	Onboard technicians and analysts involved in conventional TGMS operations. They are responsible for inputting parameters and monitoring the data output, as well as screening the data output and determining what actions are needed, including dismissing exceptions, contacting the engineering department, or reaching out to dispatchers. In some cases, members of the engineering department may ride onboard the TGMS vehicle, but the Volpe team did not consider these employees “operators.” Likewise, the Volpe team did not consider the engineer and conductor(s) responsible for the movement of the geometry car “operators” as their actions are not directly related to the inspection process.
Track safety standards	Regulations set forth in 49 CFR Part 213 regarding railroad track classes, allowable speeds, and track inspection and maintenance.
Undesirable actions	A statement that describes the context in which a particular action could lead to a hazard. (In STPA terminology, these are typically referred to as “unsafe control actions.”)
Unstaffed	Refers to automated inspection technologies without onboard staff. May also be referred to as “unmanned.”
Verification	The process of following up on potential track safety issues, either identified by an automated inspection technology or by other track users and inspectors (e.g., bridge and building inspectors).
Visual inspection	Inspections that a human inspector performs either while walking the track or riding in a hi-rail vehicle. These inspections are primarily visual, but not exclusively visual. Inspectors may also use auditory cues (e.g., rattling noises) and kinesthetic or motion cues (e.g., bumps and vibrations) in addition to visual cues to detect track conditions and identify issues.
Visual Inspection sociotechnical system	Inspection sociotechnical system in which visual inspection is the sole mode of inspection, and no automated inspection technologies are used to supplement the process.

Appendix B.
Sample Discussion Questions

This appendix provides a sample of the questions the Volpe team used to hold semi-structured discussions with track inspectors, supervisors, and managers. The actual questions the team asked, and order in which the team asked them, varied depending on the flow of the discussion and topics the railroad employees raised.

Questions for Track Inspectors

- Can you walk us through a typical ‘day in the life’ of a track inspection worker?
    - Where is your starting location?
    - Do you conduct any job briefings? With who?
    - When you inspect track do you work with another track inspector? Is it the same one every time? Do you work alone? Does it depend on the track location and/or use of technology?
    - Can you describe any paperwork and/or tools you bring with you for track inspection?
    - Do you have a subset of defects you look for, or do you inspect generally for any/all defects?
    - Who do you communicate with during a normal day? How do you communicate?
    - How much time (on average) is spent: (a) inspecting track (b) repairing track (c) communicating with others (d) paperwork (e) waiting for track time
    - When defects are detected, how are they documented?
    - Who do you report these defects to and how?
    - What happens when your shift is over but due to other circumstances (difficulty receiving track time, maintenance issues, weather, etc.) you have not completed your scheduled inspection? Overtime? Is a different inspector sent out?
- In your role as track inspector, how familiar are you with track inspection technologies? Do you interface/work with the inspection technologies and/or their direct output? If yes:
    - What is your role in automated track inspection?
    - How are defects communicated to you from the technology? When are they communicated (real time, later)? In what form are they communicated?
    - Are all defects found by the automated tool verified by a track inspector? A subset? None?
    - Do situations arise where the automated track inspection tool finds a defect but a track inspector conducts a manual inspection and determines it is not a defect? Can you give a recent example of this type of situation and explain why it might occur?
    - What are some challenges with using automated track inspection technologies? (false positives, missed detections, technology malfunction?)

  - Can you give recent examples?
  - How are these challenges being handled?
  - How are automated track inspection tool errors/malfunctions discovered/communicated, and to who? How often do these tools malfunction? How difficult are they to repair?
  - In your opinion, how could the use of automated track inspection technologies be improved?
- We'd like to understand the challenges associated with visual track inspection. Can you describe some of the challenges you have experienced to effectively inspecting track?
  - Are there strategies experienced track inspection workers use to deal with these challenges? Can you give specific examples?
- Which defects are hardest to visually detect (visually/physically challenging/most error prone)?
  - Can you explain why detecting these defects is challenging/error prone?
  - Can you give a recent example to illustrate your point?
  - Does technology exist that can detect these defects?
- What level of subjectivity is there to detecting defects?
  - Could a situation arise where one track inspector might classify something as a defect, where another track inspector would not? How are these situations handled?
- How do you document and communicate defects to your supervisors?
  - Do you provide verbal briefings or only the track inspection report?
  - What are some challenges, if any, to documenting and communicating defects?
  - Any recent examples?
- Do situations occur where track inspectors and track supervisors disagree on a defect? For example, an inspector thinks it is below the safety threshold but a supervisor does not? What happens if so?
- Given that some issues may be somewhat subjective, what pressures, if any, are there to delay reporting issues that may be above FRA's regulated thresholds but below what an inspector deems 'acceptable' in order to keep trains running?
- How has track inspection changed over the course of your career?
  - For example with the introduction/more widespread use of track inspection technologies?
  - What about with the introduction of Roadway Worker Protection? Has that changed the way you do your job?
- Can you describe the training that track inspection workers receive?

    - How much classroom/OJT? Is the training standardized or more ‘ad hoc’ depending on the mentor?
    - How much of training is focused on defect detection vs repairing defects?
    - How much training do you receive on using automated technology, if any?
- Do you feel your training adequately prepared you for locating/identifying track defects using manual/visual inspection?
- Do track inspection workers receive subsequent/refresher training?
- How do you think training could be improved?
- Are there any physical/environmental challenges that track inspection workers face?
    - What are some of the ways track inspection workers cope with these challenges? Expert strategies?
- Under certain situations or inspection job types track inspection workers might mostly use hi-rail or might mostly/only walk the track. Can you describe under which circumstances these occur and what the benefits and challenges of each might be?
- While along the right of way, can you describe how you communicate with dispatcher/supervisors? Radio? Cell?
    - How easy is it to reach dispatchers and/or supervisors?
- Do you feel you have adequate time to thoroughly inspect your territory’s track?
    - What are some of the challenges track inspectors face as it relates to scheduling track time?
    - What are some strategies you use when track time is difficult to obtain?
- What is a typical track inspection worker schedule?
    - Since track inspections primarily occur during daylight hours, are track inspection worker schedules based on a ‘normal’ workday? Is there shift work?
    - What happens if a track inspection worker’s shift ended but the track has not been fully inspected yet?
        - Do track inspectors receive overtime?
        - Are track inspection workers subject to hours of service?
    - Is fatigue an issue for track inspection workers?
- Are you responsible for determining which track you will inspect and when? What are some factors that need to be considered?
    - What about after special weather occurrences?
- When a track inspector finds a defect that can be fixed ‘then and there’ & they have the track time to do it, do they fix it?
    - Do they need to request permission/get approval?

  - Are they expected to fix it or is it at their discretion?
- Does it ever happen where you stop to fix a defect and, as a result, do not have time to inspect the remaining track? Is this something ‘experts’ are better able to manage?
- How much does your intimate knowledge of the territory and your expectations of where defects will be play a role in determining which areas to inspect more thoroughly?
  - How much does the data provided by technology (for example, the geo car) shape where/how you inspect?
- How many years’ experience would you estimate a track inspector has before they are considered “experts” at defect detection and are able to expect trouble spots?
  - How long does it take to obtain ‘expert’ skills? How much experience on a certain territory before you would consider them ‘experts’ in the territory?
- We have heard from others that a big part of the job is knowing the ‘feel’ of the railroad as you operate the hi-rail vehicle.
  - We understand there may be different configurations of hi-rail vehicles. Can you describe the configuration of the hi-rail vehicle you operate?
  - How helpful is it to operate the same hi-rail vehicle every day?
- At what speed do you typically operate the hi-rail vehicle? Does it depend on how many tracks (two vs. one), inspector’s experience level, trouble zones?

Questions for Supervisors

- Can you introduce yourselves and tell us a little about your railroad background, including how many years you’ve worked as a track inspection worker and which automated track inspection technologies you may have worked with, if any?
- In your role as track supervisor, how familiar are you with track inspection technologies? Do you interface/work with the inspection technologies and/or their output? We are primarily focused on the track geometry car. If yes:
  - What is your role in the track geometry car program?
  - How are defects communicated to you from the geo car? When are they communicated (real time, later)? Who communicates them? In what form are they communicated?
  - Are all defects found by the geo car verified by a track inspector? A subset? None?
  - Do situations arise where the geo car finds a defect but a track inspector conducts a manual inspection and determines it is not a defect? Can you give a recent example of this type of situation and explain why it might occur?
- What kind of training do you receive with regard to using the technology and analyzing output?
- Have track inspection processes changed with the expanded use of inspection technologies? Can you explain?

- What are some of the benefits to using the geo car, or automated track inspection technologies generally? (More/more reliable data, easier to project long term needs, etc.?)
- What are some challenges with using the geo car, or automated track inspection technologies generally? (False positives, missed detections, technology malfunction?)
    - Can you give recent examples?
    - How are these challenges being handled?
- Can you explain under which circumstances the geometry car might not work as desired and/or collect data?
- How are geo car errors/malfunctions discovered/communicated, and to who? How often do they malfunction? How difficult are they to repair?
- In your opinion, how could the use of geo cars, and automated track inspection technologies more generally, be improved?
- Can you briefly describe at a high level your responsibilities as they relate to visual track inspection?
    - How many track inspectors are you responsible for? How many miles of track are within your territory?
    - Are you satisfied with the time and resources you have to supervise the inspectors/track?
- Who is responsible for scheduling track inspection workers? Do track inspection workers decide on their own which sections of track they will inspect? What are some factors that need to be considered?
    - What about after special weather occurrences?
- Can you explain the hiring process for track inspectors—do incoming inspectors generally come from the railroad or off the street?
    - What about the job bidding process for track inspectors? How often do workers get 'bumped' / how difficult is it to keep a steady job?
    - Generally speaking do you find you have an adequate pool of employees for the job?
- Can you describe some of the challenges to effectively inspecting track?
        - *Prompts if necessary:*
    - Obtaining track time
        - What are some strategies you/inspectors use when track time is difficult to obtain?
    - Physical conditions—weather
    - Number of defects to look for
- Which defects are hardest to manually detect (visually/physically challenging/most error prone)?
    - Can you explain why detecting these defects is challenging/error prone?

  - Can you give a recent example to illustrate your point?
  - Does technology exist that can detect these defects?
- What are some challenges inexperienced track inspection workers face as it relates to manual defect detection?
  - Are there strategies experienced track inspection workers use to deal with these challenges? Can you give specific examples?
- How many years' experience would you estimate a track inspector has before they are considered "experts" at defect detection?
  - How long on a certain territory before you would consider them 'experts' in the territory?
- What level of subjectivity is there to detecting defects? Could a situation arise where one track inspector might classify something as a defect, where another track inspector or supervisor would not? How are these situations handled?
- How do track inspectors document and communicate defects to you?
  - Do you receive verbal briefings or only the track inspection report?
  - Any tools/job aids for this?
  - When inspectors need to call supervisors or dispatchers to communicate something immediately, how is this handled? Radio? Cell?
  - What are some challenges, if any, to documenting and communicating defects? Any recent examples?
- Do situations occur where track inspectors and track supervisors disagree on a defect? For example, an issue is above the FRA mandated safety threshold but an inspector thinks it's below the maintenance threshold but a supervisor does not? What happens if so?
- After track inspectors restrict or remove track from service, what is the process for planning repairs and bringing the track back into service? Are track inspectors/supervisors involved in this process?

Questions for Managers

- Can you tell us about your railroad's use of automated or autonomous track inspection technologies?
  - Specifically, we are interested in Track Geometry Cars. Can you discuss the various implementations and how/where they are used?
  - How often do you use the various implementations of Track Geometry Car? (The Volpe team heard that some of them run daily)
    - Who analyzes the output from the geo car?
    - What is the format? Is there any 'real-time' analysis or is it all done after the fact?

    - What are some of the pros/cons to ‘real-time’ analysis vs analysis done after the fact?
        - How do you handle the vast amount of data you receive from running geometry cars daily?
            - Are your geometry cars ‘automated’/‘unmanned’ or do they have an operator on board?
- What are some of the strengths to automated track inspection?
- From your perspective what are some of the challenges associated with track inspection using technology? (Finding qualified employees to analyze data? resource constraints? Reliability of technology—do they tend to break down often?)
- How have your railroad’s track inspection processes changed since implementing track geometry cars and other track inspection technologies?
- From your perspective what are some of the biggest challenges to visual track inspection? (Pool of workers, resource constraints, getting track time?)
- Do track inspection technologies alleviate some of these challenges?

Appendix C.
Working Assumptions

The process of writing undesirable control action statements and causal scenario factors required the Volpe team to make certain assumptions about the track inspection sociotechnical system. Below is a list of the team's assumptions about each sociotechnical system.

To do the analysis, the sociotechnical systems that the team examined needed to be very clearly defined. In some places the team was required to make assumptions about each sociotechnical system. These assumptions may not comprehensively explain the behavior of people and technologies in each sociotechnical system. However, they will help the reader understand the decisions the team made at certain points during the analysis.

Assumptions About Visual Inspection

- How it is done:
    - Visual inspection is not limited to the use of the eyes. Inspectors may also use other senses to locate defects.
    - Visual inspection may be conducted on foot or via hi-rail vehicle.
- Inspection schedule:
    - Generally, track inspectors use their discretion and experience to determine the section of their territory on which to conduct routine track inspections on a given day.
    - Often, but not always, these routine inspections are coordinated with the dispatchers ahead of time to schedule track outages.
    - "Non-routine" inspections, such as extra inspections due to severe weather, may require coordinating with dispatch without advanced notice.
- Inspection tools:
    - Track inspectors who conduct walking inspections do not carry many, if any, tools. Hi-rail vehicles are equipped with track inspection tools.
- Classification of defects/maintenance conditions:
    - If under pressure not to find "too many problems" inspectors could dismiss less severe defects and maintenance conditions that they think are "safe" to ignore. The team does not believe that this is a common practice; but documented the possibility so that it can be prevented.
- Communication with dispatcher
    - Inspectors and supervisors (part of the "engineering department" actor) are responsible for calling the dispatcher to obtain track, restrict track, and remove track from service. There are instances where both the inspectors and supervisors would call the dispatcher for the same issue; or where supervisors may step in to assist inspectors in communicating with the dispatcher.
- Restricting track speed/removing track from service:

    - Though dispatchers are unlikely to deliberately interfere with the track inspection process, it is possible that frustration with track restrictions could lead dispatchers to be less cooperative with track inspectors in the future. Therefore, inspectors may be cautious of placing restrictions that dispatchers may perceive as particularly difficult.

Assumptions About Conventional TGMS Inspection

- TGMS data collection:
    - At certain low speeds, TGMS data accuracy may be reduced. Interviews with railroads and track inspection subject matter experts suggested that while some TGMS vehicles can collect data at all speeds, others may only collect accurate data when going above a certain speed (20 mph). The team included scenarios regarding TGMS speed to be conservative.
    - TGMS may have issues collecting data in certain weather conditions: very sunny weather (when sun obstructs the sensor), flooded conditions (when water obstructs the sensor), and very snowy conditions (when snow obstructs the sensor).
- Operator sets parameters:
    - The TGMS operator must set track class if changing tracks; or check that it has adjusted appropriately if it is set automatically.
    - The TGMS operator must tell the TGMS where it is located (e.g., which track); or check that location is correct if adjusted automatically.
    - The TGMS operator that ensures correct track class and location information is different than the operator that dismisses exceptions. I.e., there are two operators with different jobs. (For the purpose of simplicity in data analysis the team sometimes referred to them as a singular operator.)
- TGMS interface:
    - At the time of this project, the conventional TGMS interface the team observed only allowed the operator to see full data logged from the last 10 minutes, including images of the track. Previous data was no longer accessible on the scrolling data log, but was saved elsewhere, on the cloud.
    - The team assumed TGMS does not flag when multiple issues exist that are individually below defect thresholds, but that, when combined, pose a risk to safety.
    - Exceptions are marked by highlighting the row in the spreadsheet. Different colors are used for a FRA-defect (e.g., red) vs something that is less critical and simply exceeds the railroad's own internal thresholds (e.g., yellow). Exceptions can be dismissed by removing the highlighting.
- Dismissing exceptions:
    - If under pressure not to find "too many problems," TGMS operators could dismiss less severe exceptions that they think are "safe" to ignore. The team does not believe that this is a common practice; but documented the possibility so that it can be prevented.

- Verifying exceptions and communication with the dispatcher:
    - The team assumed that railroads require someone (i.e., a track inspector or supervisor) to verify that an exception is a defect or maintenance condition before contacting the dispatcher to take action on the track.
    - In infrequent cases, a TGMS operator could be the actor who verifies an exception, and contacts the dispatcher to take action on the track (i.e., removes the track from service or restricts track speed), such as when a supervisor is not available.
    - The team noted that railroads could allow TGMS operators to contact the dispatcher to take action without verifying the exception first; however, this may not be practiced at all railroads. Whether or not this happens may depend on factors such as whether the TGMS operator is an employee of the railroad or a contractor performing the inspection.
- Assign TGMS inspection:
    - FRA regulates how often TGMS must inspect track for different track classes. The team assumed that:
        - Some railroads may use TGMS only to meet minimum mandated frequency regulations and inspect for FRA level defects.
        - Some railroads assign scheduled TGMS inspections more often than what is mandated according to the regulation (e.g., quarterly, though according to the regulation TGMS is only required to inspect twice per year).
        - Some railroads may assign TGMS inspection outside of regular schedules, e.g., as a result of degraded track condition.

Assumptions About aTGMS Inspection

- aTGMS installation:
    - Locomotives equipped with aTGMS are likely to run on the same line (i.e., are not moved across territories for the purpose of inspecting different lines).
    - aTGMS are installed on revenue trains and inspect whichever route the revenue train operates. The team heard examples of the engineering department/track inspectors asking dispatchers to send a revenue train with aTGMS a certain route—mostly in the terminal—if there is somewhere in particular they want inspected.
    - At the time of this work, railroads did not change entire routes of trains with aTGMS installed to collect data on other routes, however, the team assumed that they might in the future. Specifically railroads mentioned a desire to use aTGMS to check track for new repairs.
- aTGMS data filter:
    - aTGMS data filtering occurs on a central server, either in the ‘cloud’ or at the railroad. Data filtering does not occur on the aTGMS unit.
    - Railroads using aTGMS employ an aTGMS analyst whose role includes filtering/checking/cleaning aTGMS data. This may not be the case at every railroad

using aTGMS (i.e., it is at the railroad's discretion and the decision or need to employ such an analyst may be due to the type of contract and support they receive from the aTGMS supplier); however, in this analysis, the team assumed that a sociotechnical system using aTGMS includes an analyst employed by the railroad.

- Other track geometry technology:
    - Railroads utilizing aTGMS may also use conventional TGMS for their required TGMS geometry inspections.
- Data transmissions from central server:
    - A summary email is sent to the railroad once per day. It includes exceptions from the past 24 hours which exceed preset maintenance and safety limits as defined by the railroad. The email contains information the railroad needs to locate and identify defects.
    - For exceptions significant enough to warrant a two-class drop, an email is sent to the railroad in near real-time.
- Verifying exceptions and communication with the dispatcher:
    - The team assumed that railroads require someone (i.e., a track inspector or supervisor) to verify that an exception is a defect or maintenance condition before contacting the dispatcher to take action on the track.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
aTGMS	Autonomous Track Geometry Measurement System
BMWED	Brotherhood of Maintenance of Way Employes Division
CFR	Code of Federal Regulations
CBA	Collective Bargaining Agreement
EMU	Electric Multiple Unit
FRA	Federal Railroad Administration
GRMS	Gage Restraint Measurement System
GPS	Global Positioning System
GPR	Ground Penetrating Radar
IT	Information Technology
ISO	International Organization for Standardization
LIDAR	Light Detection Ranging
MOW	Maintenance-of-Way
OJT	On-the-Job Training
RWP	Roadway Worker Protection Act
STPA	Systems Theoretic Process Analysis
TGMS	Track Geometry Measurement System
VTI	Vehicle-track Interaction Systems
Volpe	Volpe National Transportation Systems Center