AUTOMATED SLEEPER INSPECTION USING INTERNAL IMAGING TECHNIQUES

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KEYWORDS: Sleeper, Tie, X-Ray

ABSTRACT
Developing a comprehensive sleeper replacement program requires detailed condition data on each sleeper in a system to better prioritize where sleeper assets and labor resources are most needed. Recent applications of automated sleeper inspection technology have shown the ability to support the planning of full rail system sleeper programs with objective data. As demand for automated track inspection grows it is imperative to develop sub-surface defect recognition at track speed. Current sub-surface systems typically include ground penetrating radar (GPR), Ultrasonic, Acoustic, or Eddy Current inspection. These systems have various trade-offs such as stand-off distance, imaging resolution, inspection speed, and depth penetration.

Georgetown Rail Equipment (GREX) with the support of the University of Florida's (UF) nuclear engineering department in Gainesville has pioneered a revolutionary approach allowing for subsurface defect detection in sleepers at track speeds up to 20 mph (32 km/hr). The X-ray backscatter system is designed to inspect sleepers from a hi-rail platform collecting high resolution X-ray backscatter images, which can be evaluated by specialized image analysis software. This data is aligned with GREX's Aurora machine vision inspection data and location information to provide a more comprehensive condition of all sleepers inspected. As part of the development, two test tracks were constructed on campus at UF with timber, concrete, and composite sleepers of varying conditions, to determine the ability of X-ray backscatter to identify signatures of specific defects. Main track testing commenced in May 2014 in Texas with a goal of production rollout in March 2015. Recent mainline collections have been very successful and have identified subsurface defects in timber and composite sleepers that were not detectable by walking inspections.

INTRODUCTION

Sleepers perform three essential functions in track structure: to hold the rail securely to prescribed gauge and vertical position; to transmit the traffic loads to the ballast with diminished contact pressures; and to anchor the rail-tie structure against lateral and longitudinal movements (*1*). With the demands of heavier axle loads and increased tonnage, it is becoming more important to accurately assess the quality of sleepers without utilizing track time that could otherwise be used for revenue trains.

Conventional grading of timber sleepers is a labor intensive, subjective process utilizing significant resources and track time. While timber sleeper grading standards are well-defined, the application of the standards by individual sleeper inspectors can vary from one inspector to another. These inconsistencies in the application of North American Class 1 sleeper grading standards have led the industry to automated machine vision inspection technologies such as Aurora. With operating speeds in excess of 40 mph (64 km/hr) Aurora provides a more objective, safe, and efficient approach to timber sleeper grading. In addition, data can be stored and identified with accurate GPS positioning for historical trending, utilization in sleeper replacement planning services, and driving more accurate sleeper marking and set-out programs (**Error! Reference source not found.**).

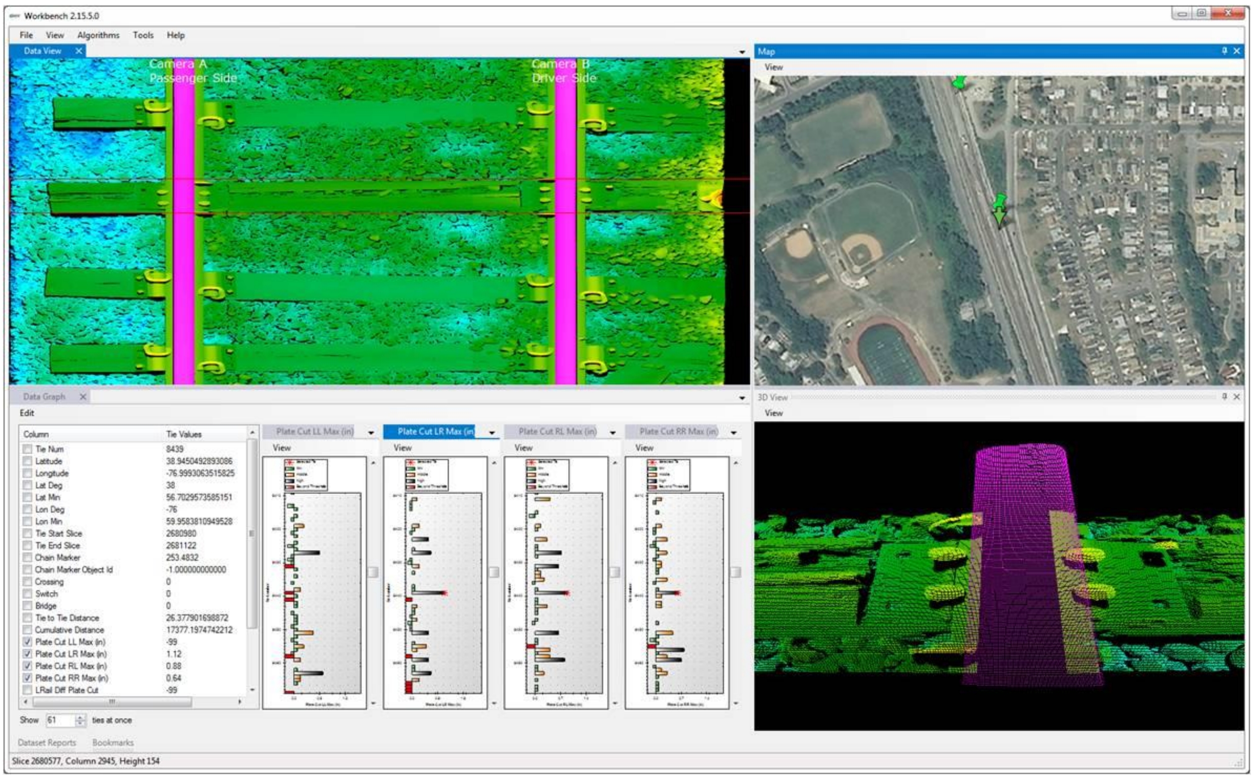

Figure 1: Aurora sleeper grading and planning system. Top Left is a 2-dimensional overview of track bed. Top Right is a map overview of sleeper locations based on GPS and Milepost coordinates. Bottom Left is individual measurements for a series of sleepers. Bottom Right is a 3-dimensional view of the rail and plate region of the track.

Traditional grading techniques involve human sleeper inspectors visually grading the sleeper surface and kicking the sleeper to determine if it is hollow or not. The reliability of this technique for grading purposes is questionable. Results can vary based on which part of the sleeper was struck, surface accessibility, and type of sleeper material (timber species, etc.). See **Error! Reference source not found.** for an example of a sleeper with a localized subsurface flaw.

Figure 2: A Subsurface Defect is shown in proximity to a spike hole

Understanding the importance of subsurface defect detection to sleeper inspection, GREX endeavored to create a subsurface flaw detection system that can be partnered with the surface imaging capabilities of Aurora. Research began in 2012 utilizing internal imaging solutions that were applied in the aerospace industry for airplane and shuttle inspection. The initial research produced desirable results but less than desirable track speeds, and therefore an operational model not suited for the railroad environment. Since January 2013 GREX has partnered with the Nuclear Engineering Department at the University of Florida in Gainesville to develop a novel approach that would allow for increased speed. The goal is for this system to be fully integrated with the Aurora surface scan, thus providing an "all encompassing" sleeper inspection methodology.

TECHNOLOGY SELECTION AND PROJECT PARAMETERS

The following criteria were considered when selecting an appropriate technology for sub-surface flaw detection:

1. Resolution comparable to, if not better than, Aurora's resolution. The current Aurora pixel size in the lateral direction (across track) is 0.04 in (1 mm) or 0.02 in (0.5 mm) depending on the lens used during the track scan. The sub-surface imaging system should have a pixel spacing similar to the Aurora system, enabling data from the two systems to be aligned easily as well as correlation of relevant information from each system to more effectively grade sleepers. This constraint eliminated solutions that included ground penetrating radar (GPR).
2. Higher Speed; a minimum of 10 mph (16 km/hr) collection speed, with desire for faster speeds. Aurora's theoretical top speed is 45 mph (72 km/hr) but in practice is typically 30 mph (49 km/hr) on a hi-rail truck platform. It was important to achieve a data collection speed for the sub-surface inspection similar to the current operational parameters of the Aurora surface inspection system.
3. American Railway Engineering and Maintenance–of-Way Association (AREMA) Plate C Compliance for rigid components; a minimum of 14 in (35.56 cm) vertical standoff distance.

The current Aurora scanning platform is AREMA Plate C compliant. As with the speed requirement it was determined that remaining Plate C compliant was an operational parameter that could not be compromised. This constraint was a very limiting factor in terms of technology selection. In the case of Acoustic Sensors the standoff distance would limit the ability to activate the sleepers at typical track speed, which is 30 mph [45 ft/s] (48 km/hr [13 m/s]), roughly 28 sleepers per second. In the case of Ultrasonic Detection it was understood by the authors that at the time of this document there was not any solution with the appropriate standoff distance.

4. Depth of Penetration; a typical timber sleeper is about 7 in (17.8 cm) deep, so to be conservative a minimum of 8 in (20.3 cm) sub-surface imaging capability was desired to reach the full depth of most sleeper. Therefore, shallow surface detection techniques, such as Eddy Current Inspection, did not apply.
5. Safety; Georgetown Rail Equipment has an unwavering focus on track safety as a service provider. The final parameter of the project was that the new imaging system must be able to safely operate within all rules and regulations of the U.S. Department of Transportation Federal Railroad Administration (FRA), railroad customers, State, and Federal Agencies. In addition any new mechanical designs needed to implement the safety of the system must comply with Parameters 1-4 above.

DESCRIPTION OF SCATTER X-RAY IMAGING

Based on the established criteria, Scatter X-Ray Imaging (SXI) held promise as a technological solution. SXI is different from typical Transmission X-Ray Imaging used in common medical and industrial applications. Transmission Images are made by the interaction of 4 components, shown in **Error! Reference source not found.**.

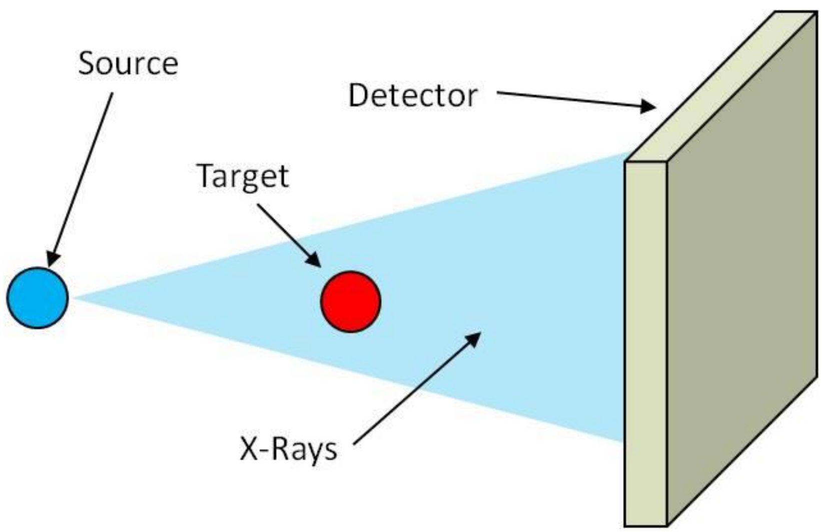

Figure 3: Typical Transmission Radiography Components

1. The Source which can be either a radioactive substance or an electron accelerator which emits electromagnetic radiation. If the source is a radioactive substance such as Cobalt-60 then the radiation is referred to as Gamma Radiation, or Gamma Rays. If the source is an electron accelerator then the radiation is referred to as X-Rays. For safety reasons an electron accelerator (vacuum tube) was chosen for this application. Electron accelerators require power to the system, therefore if the power is switched off there are no radioactive emissions present. In other words, the system will not leave behind radioactive residue as it operates. For the remainder of

this document all Electromagnetic Radiation will be referred to as X-Rays since that is the particular radiation used for this application.

2. The Target is the object to be imaged. The Target is oriented such that it is in the path that will be traversed by the X-Rays. In Transmission Imaging it is placed between the Source and the Detector. For example in medical imaging the Target could be a fractured arm bone that is placed on top of a plate of radiographic film.
3. The X-Rays emit from the source and travel in the direction of the target. Materials have individual X-Ray absorption and scatter properties, and therefore the number of X-rays transmitting through different materials will vary. These differences create contrast in the image which can be used to distinguish regions where the target density has changed. By comparing the expected values for absorbed X-Rays with those found by the X-Ray system an “areal” density measurement can be computed which represents where breaks, cracks, or voided regions reside.
4. In typical Transmission Radiography the Detector is a device which creates a digital or analog image based on the flux, spatial distribution, or spectrum of X-Rays. The detector produces an image, which can be thought of as a "count" of how many electrons passed through the material and were absorbed by the detector. The result is a grayscale image that represents the different absorption properties of the Target.

The drawback to traditional Transmission Radiography for sleeper inspection is that it is not feasible to place a Detector under each target (sleepers) in field applications. To create an X-Ray image of the sleepers the Detector requires an orientation in a more favorable position, namely above the track structure. This is the concept behind SXI, as shown in **Error! Reference source not found.**.

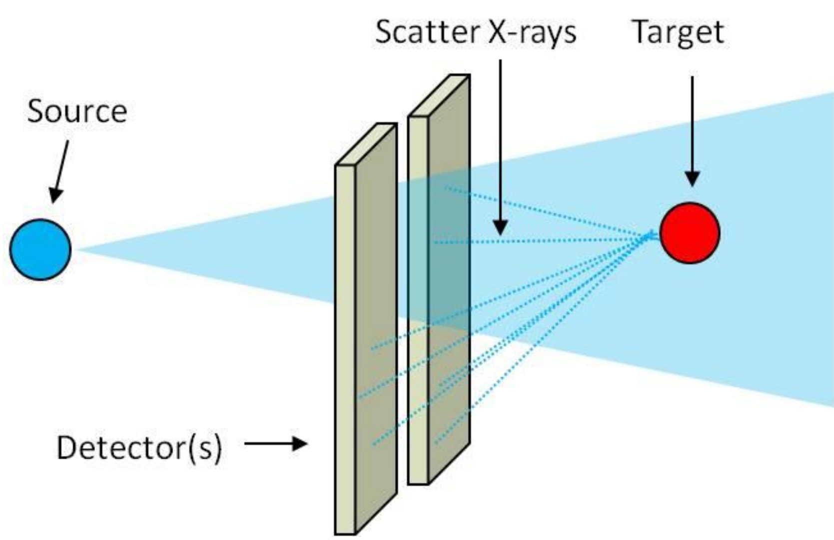

Figure 4: Typical SXI Radiography Components

In this orientation the X-Rays are detected via the scatter, or return signal, from the target. This approach allows the Detector and the Source to be positioned on the same side of the Target. For railroad inspection this means the X-Ray Tube and the Detectors are suspended above the sleepers in accordance with Plate C clearance.

RESEARCH FACILITIES

GREX partnered with the University of Florida in Gainesville to research the production and safety objectives associated with the project. Approximately 150 ft (46 m) of test track was constructed at the University of Florida consisting of:

- Timber sleepers in both new and deteriorated condition. Timber sleepers were pulled from mainline service and installed in test track varied in years of service. Some of these sleepers were installed in mainline track as recently as 2000. Sleepers were pulled from track in the Houston and Central Texas Areas and donated by the BNSF Railway.
- Concrete sleepers in both new and used condition donated by the Union Pacific Railroad
- Composite sleepers in new condition, donated by CSX Transportation and their supplier Axion
- Approximately 15 ft (4.6 m) of concrete slab. The slab has targets embedded at different depths from 3 in (7.6 cm) to 12 in (30.5 cm).
- Rail segments containing Rail Base Corrosion donated by Amtrak
- All track was installed on a one foot (30.5 cm) thick layer of ballast except for slab segment

Additionally, a hi-rail research cart (see **Error! Reference source not found.**) was designed and fabricated to provide the ability to test and verify various configurations of the X-ray components, and relevant system and safety design. Features of the research cart include:

- The ability to position the Source at heights ranging between 24 in (61 cm) and 84 in (213 cm) above the surface of the sleepers.
- The ability to move the Source laterally 30 in (76 cm) from the centerline of the track in either direction.
- The ability to rotate the Source laterally 30° from perpendicular to the track surface in either direction.
- The ability to tow behind an Aurora truck without interfering with Aurora's image acquisition. This allows system integration research without having to build an Aurora system on the research cart.

Figure 5: Research cart on the timber sleeper research track. The blue box in the center of the cart houses the Source.

RESULTS

X-ray data is collected as detector counts which are converted to multiple formats, such as a grayscale image, for processing and analysis. Sample images of X-Ray data are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. At the University of Florida Nuclear research facilities the scanning was performed at speeds of 1-2 mph (1.6-3.2 km/hr) due to the short length of test track. To maximize the X-ray shielding effect the rails provide, the project team designed the system to project the X-ray fan beam only inside the track gauge area on the sleepers.

Error! Reference source not found. shows X-ray images of a healthy timber sleeper that was never installed on track. The middle image is the grayscale representation of the X-Ray data. The sleeper is the bright white region running from top to bottom. The top image is the colored representation of the grayscale image. The bottom image is the average density profile of each column in the grayscale image along the longitudinal direction. In the density profile a healthy sleeper generally ranges from 900-1000 on gray scale values. Ballast is typically shown as black or dark gray in the grayscale image, black or red in the colored image, and an average density of 400-500 was observed.

Error! Reference source not found. shows three used timber sleepers that were pulled from Class 1 Railroad Main Line track, in various states of decay. Hollow or Low Density regions of the sleepers show up as gray or black in the grayscale image, blue or purple in the colored image, and as signal drops in the density profile.

Of particular interest was the leftmost sleeper in **Error! Reference source not found.**. The density profile ranged from 700 – 900, and showed a larger degree of variation in values across the sleeper. Also a significant void is visible near the top part of the image. However, the surface of the sleeper is in good condition (see **Error! Reference source not found.**). The crib ballast around the sleeper was removed and the 3 visible faces of the sleeper examined which showed no sign of internal defects. The voided region indicated in the X-Ray image is marked by the 2 cross-directional timber blocks. A destructive test was performed on this sleeper to verify the X-Ray results. The results are shown in **Error! Reference source not found.**.

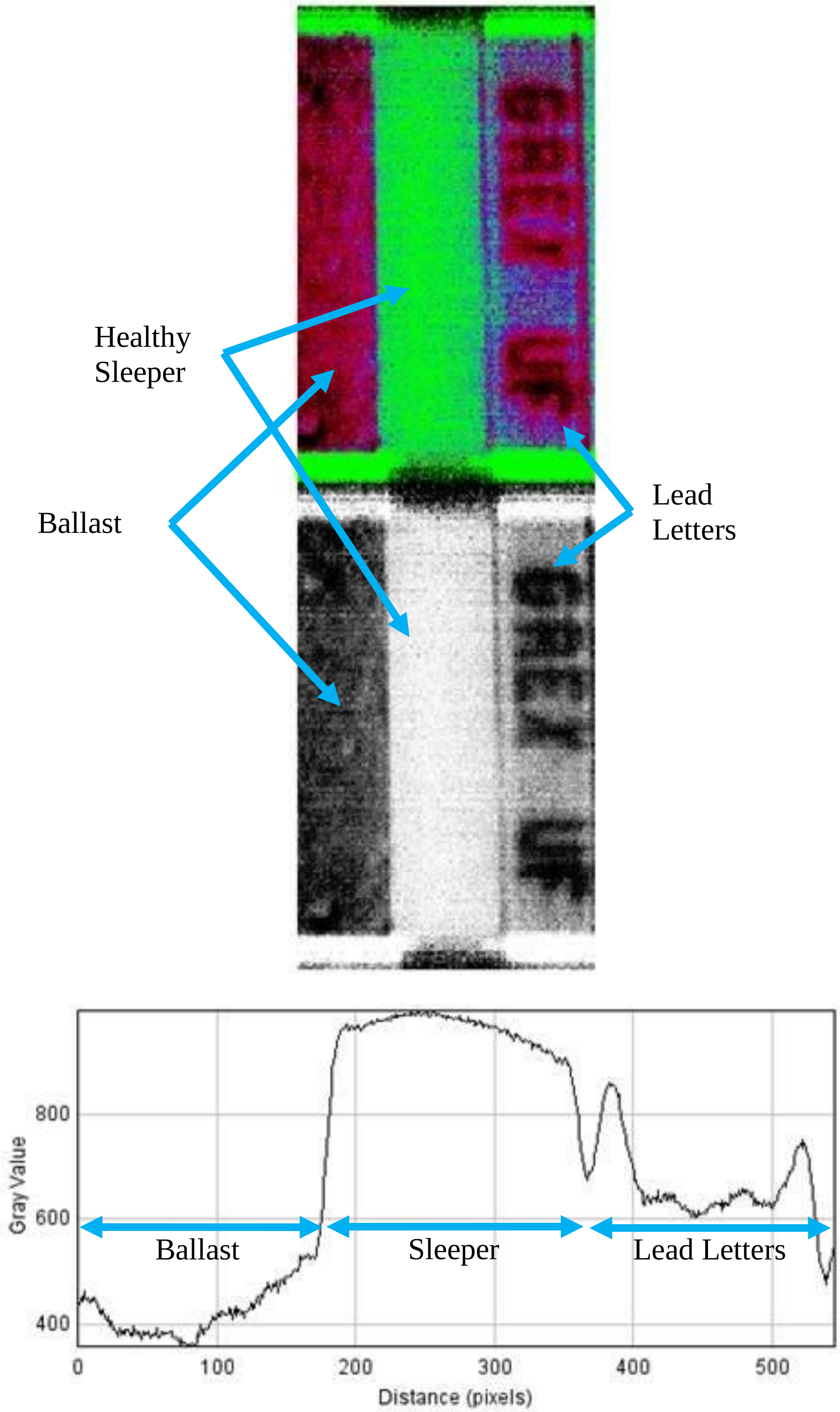

Figure 6: Various images of a healthy timber sleeper. Top: Colored Image. Center: Grayscale Image. Bottom: Average Density Profile in the longitudinal direction.

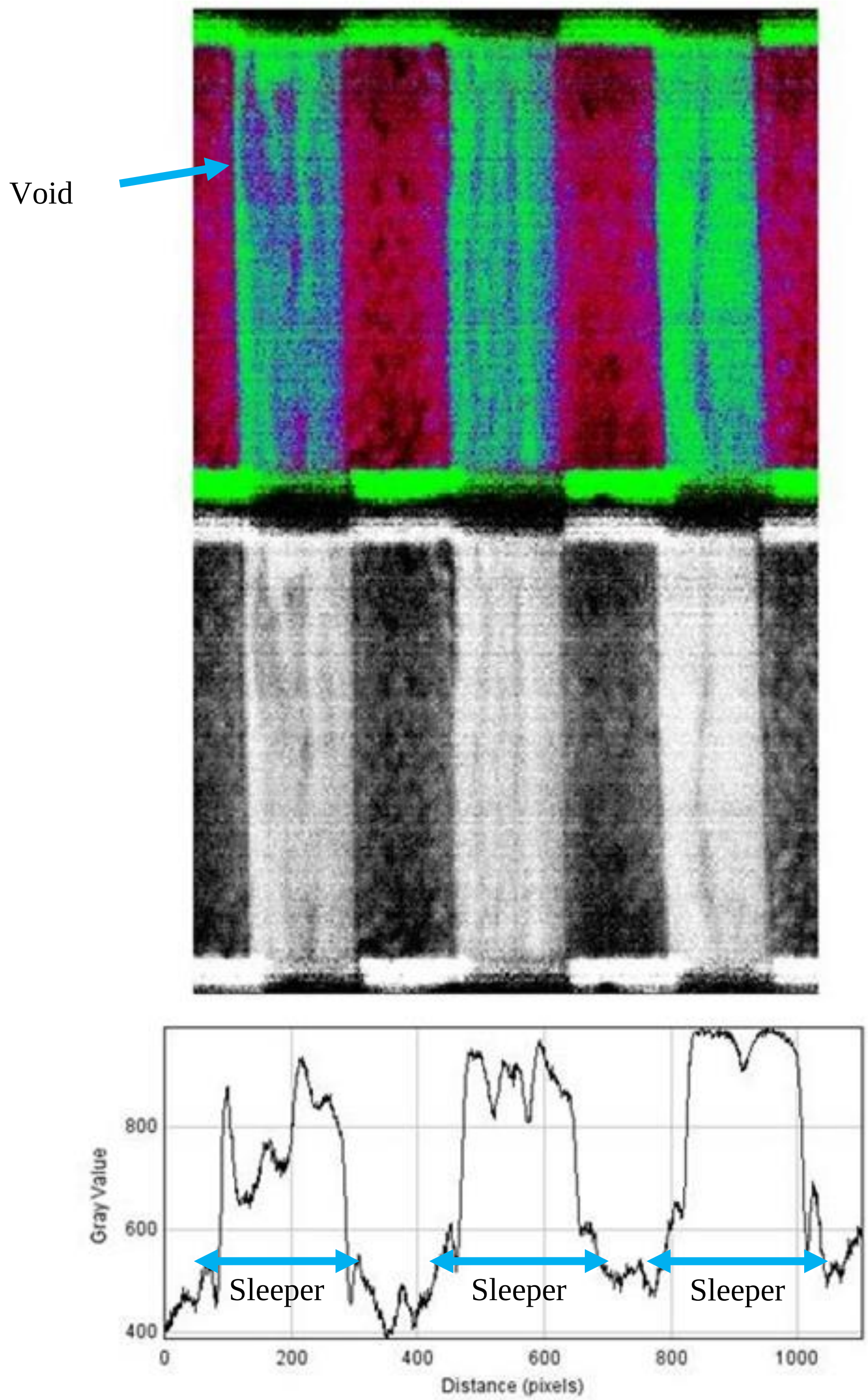

Figure 7: Various images of 3 used timber sleepers. Top: Colored image. Middle: Grayscale Image. Bottom: Average Density Profile in the longitudinal direction.

Figure 8: Sleeper surface before destructive examination. The void in the X-Ray image is between the two cross-member timber blocks.

Figure 9: Sleeper surface and subsurface after destructive examination. The void is readily apparent.

The next phase of the research called for the first application of the SXI technology on mainline Class 1 track in Southeastern Texas. It is with these early data collections that the process of developing a standard for assessing sleeper condition outside of the controlled research track was initiated. Figure 10 shows a section of track scanned in the Gulf coast Region of the United States, an area which is prone to internal rot and decay due to environmental conditions. Utilizing human inspector input, the Aurora surface grading system has proven the ability to use predictive modeling techniques on three-dimensional laser profile data to automate surface condition assessment. However, the challenge with SXI data is building a grading system based on internal qualities of the sleeper which inspectors cannot fully quantify.

In Figure 10 the track is running left to right across the screen. The bottom image is the grayscale display of the raw data. The top image is a color-coded grading scheme in which the order of health is indicated by color. Green represents the healthiest sleepers, then blue, yellow, and finally red for the sleepers that have been deemed a failure. Through modeling techniques and analysis, many metrics, including severity of internal loss, size of internal voids, and proximity to the plate or fastener, were combined into a single condition grade, represented graphically by a color.

For data collected on mainline track, internal condition was verified by drilling a hole into the subject sleeper and examining with visual means. Also, sleepers were marked for more in-depth destructive examination once removed from track by sleeper replacement crews.

For the final sleeper assessment, the combination of the surface and internal sleeper data streams will determine the overall grade to dictate whether or not it is a candidate for replacement.

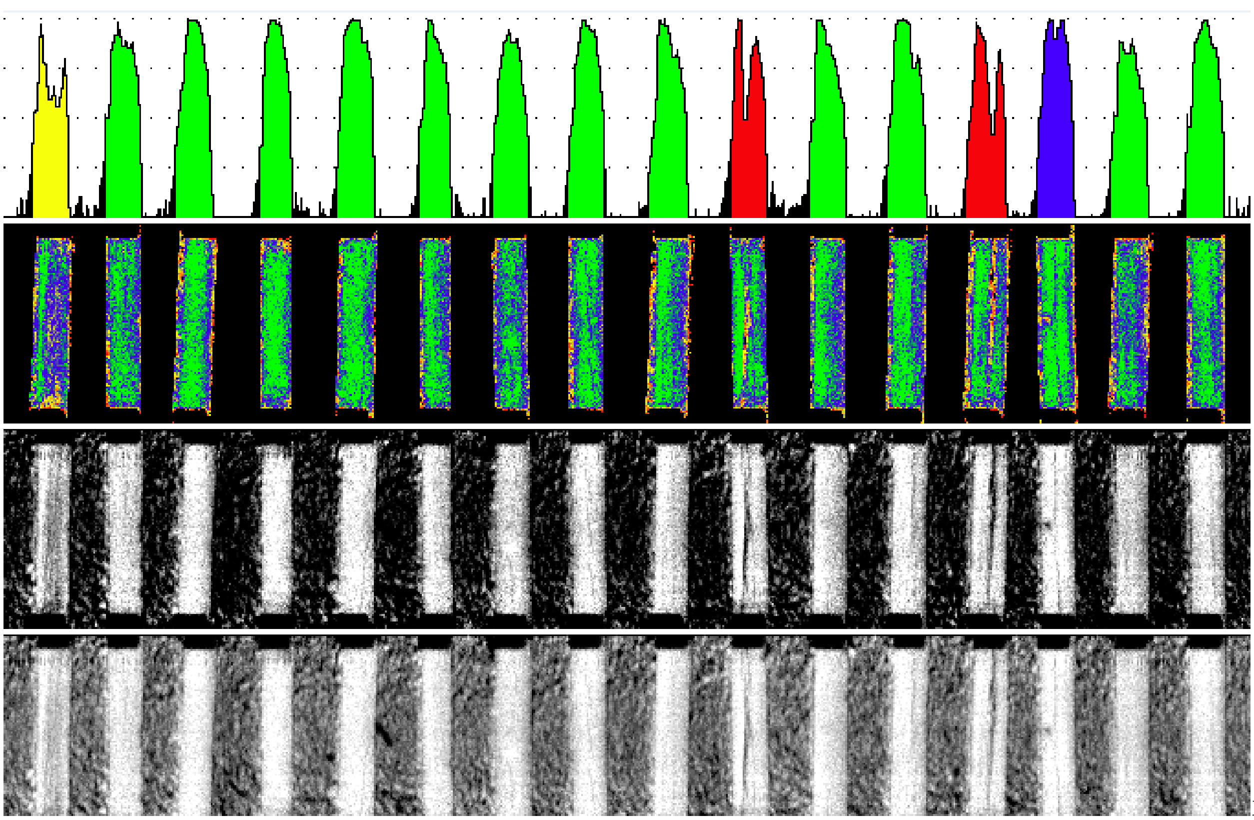

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Figure 100: 20 mph (32.2 km/hr) scan of sleepers in the U.S. Gulf coast region. Bottom Row: Grayscale Image. Second Row: High Contrast Image. Third row: Colored Image. Top Row: Profile Fitting

RADIATION SAFETY

Dose Rate

Industrial Radiography (IR) inspection is typically performed with a fixed Source position and a barricaded Restricted Area. The Restricted Area is the region around the Source in which access is controlled by the operator so that the public does not receive undue exposure (*2*). Regulations vary by state, but typically the dose rate for the public is not to exceed 2 millirem per hour (mrem/hr).

To inspect a railroad with high productivity requires that the source be moved continuously. In addition it is not practical to barricade a restricted area as the trucks scan an average of 43 miles (69 km) a day. For these reasons an approach was designed with state agencies to create a virtual barricade based on track fouling principles.

Fouling a track is defined as the placement of an individual or an item of equipment in such a proximity to a track that the individual or equipment could be struck by a moving train or on-track equipment, or in any case is within four feet of the field side of the near running rail (*3*).

This creates a virtual barrier of 4 ft (1.2 m) on either side of the track for the inspection system in which mobile radiation equipment can be operated. The radiation levels emitted from the system are not to exceed 2 mrem/hr at or beyond this 4 ft (1.2 m) zone. In order to achieve this requirement the system was designed such that the Primary X-Ray Beam was contained between the rails. The virtual barrier design constraint was coupled with AREMA Plate C Compliant radiation shielding to achieve the desired radiation levels.

Verification of the safety design was based on a grid of measurement points, shown in Figure 11. Each "x" in Figure 11**Error! Reference source not found.** indicates where 2 measurement readings were taken, one at 3 ft (0.9 m) above the height of the sleeper surface, one at 6 ft (1.8 m) above the height of the sleeper surface. The locations are spaced 4 ft (1.2 m) from each neighbor in all directions. Lateral and longitudinal symmetry was assumed for the distribution of the radiation field, thus the radiation levels were only tested in one quadrant. Measurements were taken while the cart was not moving. The recorded values are shown in the tables below and plotted in Figures 12 and 13.

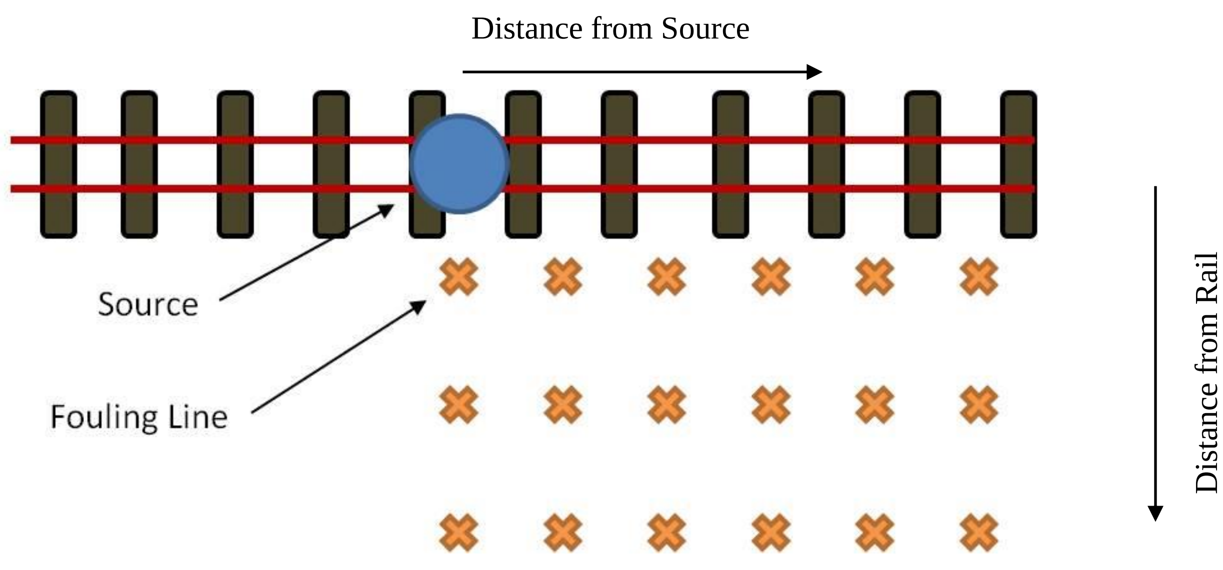

Figure 11: Measurement locations for radiation safety verification. The "x" locations are spaced 4 ft (1.2 m) from neighbor points on all sides.

TABLE 1: Radiation Exposure Levels 3 ft (0.9 m) above Railroad Sleeper Level

Distance From Rail, ft (m)	Distance from source, ft (m): 0 (0)	4 (1.2)	8 (2.4)	12 (3.7)	16 (4.9)	20 (6.1)
4 (1.2)	0.61	0.17	0.21	0.15	0.19	0.21
8 (2.4)	0.53	0.31	0.09	0.14	0.12	0.17
12 (3.7)	0.31	0.38	0.24	0.14	0.05	0.08

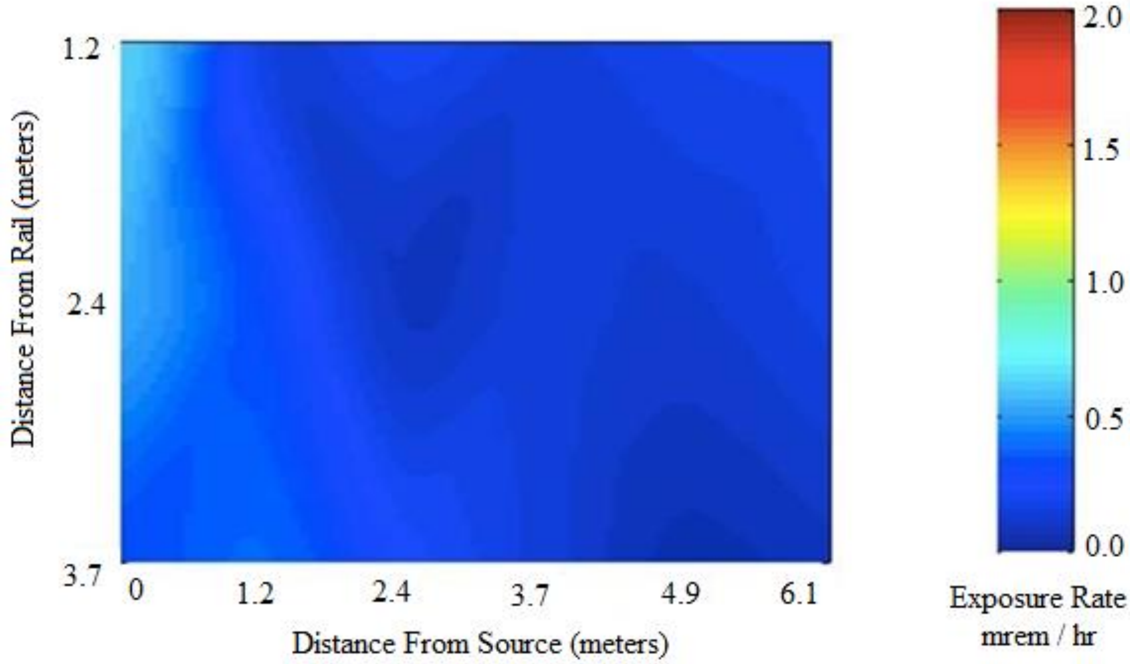

Figure 122: Plot of exposure rates 3 ft (0.9 m) above the surface of the sleeper.

TABLE 2: Radiation Exposure Levels 6 ft (1.8 m) above Railroad Sleeper Level

Distance From Rail, ft (m)	Distance from source, ft (m): 0 (0)	4 (1.2)	8 (2.4)	12 (3.7)	16 (4.9)	20 (6.1)
4 (1.2)	0.63	0.80	0.20	0.16	0.51	0.16
8 (2.4)	0.26	0.31	0.12	0.16	0.12	0.07
12 (3.7)	0.29	0.21	0.16	0.14	0.11	0.08

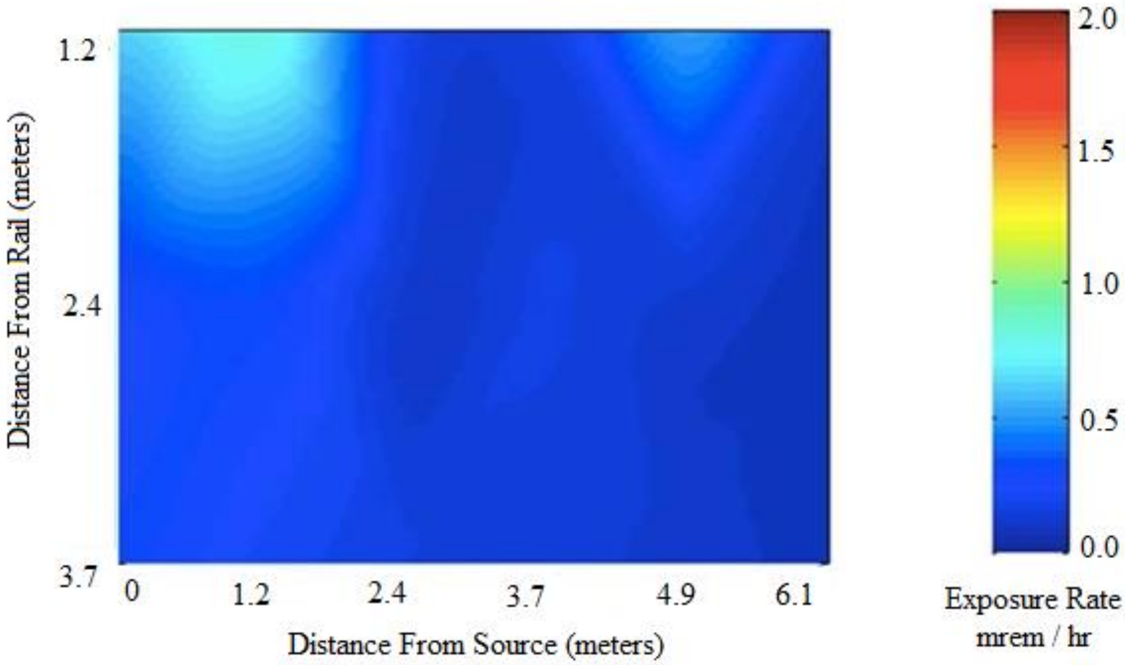

Figure 13: Plot of exposure rates 3 ft (0.9 m) above the surface of the sleeper.

Total Dose

Dose Rate as explained above applies to the instantaneous dose an individual is receiving at any given moment. As an additional safeguard the Total Dose individuals would receive from this system is monitored. It is a summation of the instantaneous Dose Rate over all moments of exposure and can be calculated as follows:

Total Dose $D_t = \sum_{i=1}^{n} R_i$

Where D_t is the Total Dose and each R_i is an instantaneous Dose Rate recording.

This is an important metric for this application as the Dose Rate scenario described above, which assumes a stationary vehicle, does not represent the normal interaction of the inspection system with the public. A more applicable scenario is a fixed human position beside the track and the inspection vehicle rolling by at speeds of 10-20 mph (16-32 km/hr). To test this scenario radiation safety monitors were fixed at the 4 ft (1.2 m) meter fouling line to record the total radiation received while the research cart moved by. The cart was positioned so that when the test began the monitor was beyond the reach of its radiation field. The cart was then moved past the monitor and stopped at a position such that the monitor was beyond the reach of its radiation field. The results of this test, as well as Total Dose measurements from other sources are shown in Table 3 below.

TABLE 3: Comparable Total Dose Measurements from Various Sources

Source of Radiation	Dose (mR)
Annual Background (Boston) (*6*)	300
Annual Background (Denver) (*6)*	600
TSA Backscatter Screening (*4*)	0.005
Flight (*5*)	2-5
CT, Head (*3*)	200
CT, Whole Body (*3*)	1000
Chest X-Ray (*3*)	10
Dental X-Ray (*3*)	1
Nuclear Medicine (PET) (*3*)	1,410
GREX Research Cart 1 mph (1.6 km/hr)	0.03
GREX Research Cart 10 mph (16 km/hr) estimated	0.003

CONCLUSION

The success of future track inspection technologies will depend on the ability to perform at high speeds, objectively report exceptions, and maintain a safe working environment. Track speed is of critical importance as higher tonnage and / or high-speed commuter lines increase the opportunity cost associated with down time for inspection and repair. Utilizing a non-contact inspection method such as SXI removes speed limitations associated with physically contacting the inspection target. The upper bound for the rate of inspection can be raised with improvements in detector design and electronic development.

In addition to improved inspection speed, railroads that adopt SXI systems will be able to store raw data in digital format for automated processing and storage. Historical trending of sub-surface structure decomposition can be analyzed and end-of-life dates can be calculated with unprecedented accuracy.

With all new technologies many viable applications exist beyond the initial development intentions. Although the research has been focused on timber sleeper inspection, SXI has a range of potential applications. Of particular interest in the next research phase is the detection of internal defects in concrete structures such as slab track and concrete sleeper, detection of rail base corrosion, and advanced imaging techniques such as 3D reconstruction. GREX is excited for the opportunity to explore these new frontiers and develop practical solutions that enhance railroad safety and efficiency.

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