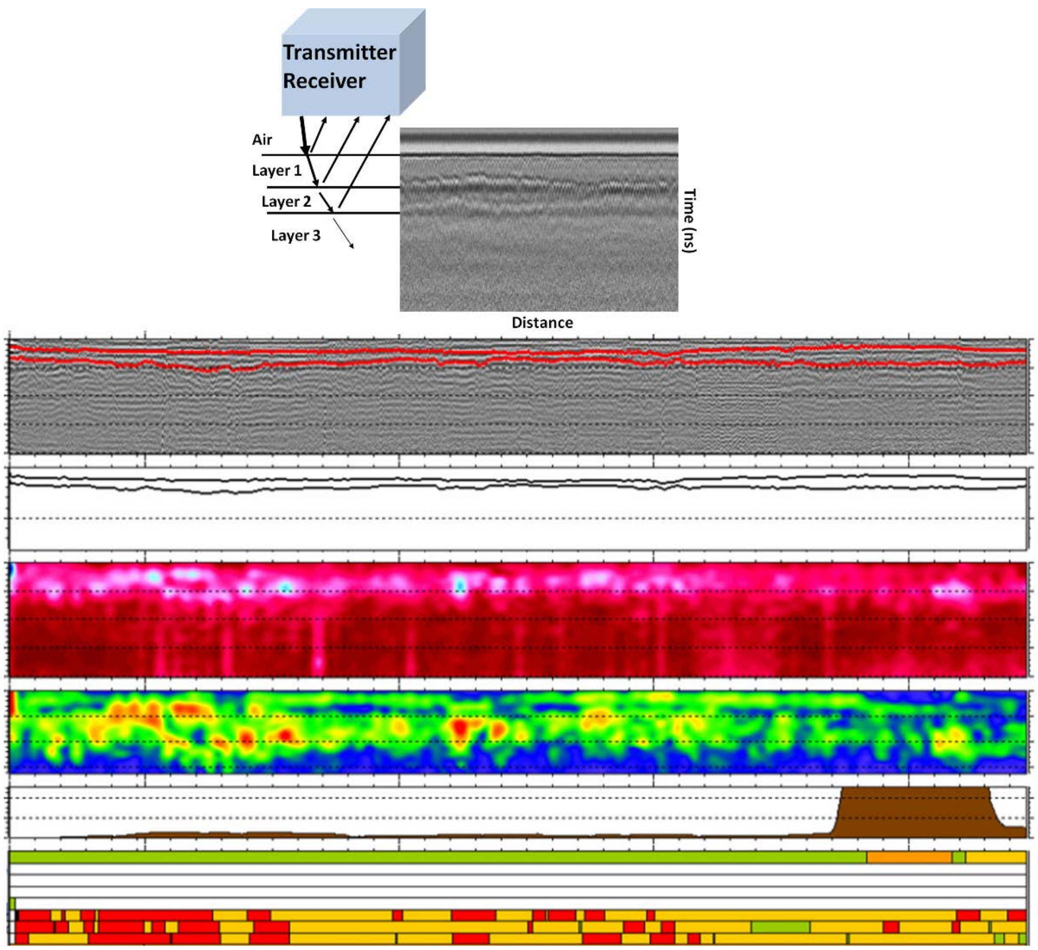
U.S. Department of
Transportation

**Federal Railroad
Administration**

Ground Penetrating Radar Technology Evaluation on the High Tonnage Loop: Phase 1

Office of Research,
Development
and Technology
Washington, DC 20590



DOT/FRA/ORD-17/18

Final Report
September 2017

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13. ABSTRACT (Maximum 200 words) This report describes and documents the results of an evaluation of ground penetrating radar (GPR) technologies performed by Transportation Technology Center, Inc. on the High Tonnage Loop at the Transportation Technology Center in Pueblo, CO. A number of GPR systems, representing most of the current North American service providers, participated in the evaluation. The focus of the evaluation was ballast condition assessment, specifically ballast fouling, layer depth, and moisture content.			
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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

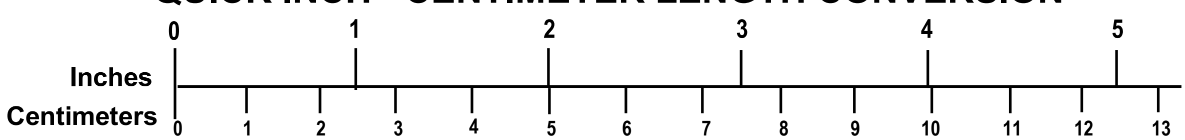
VOLUME (APPROXIMATE)

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)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

This report describes and documents the results of an evaluation that the Transportation Technology Center, Inc. (TTCI) conducted from 2010 to 2011 of ground penetrating radar (GPR) technologies on the High Tonnage Loop (HTL) at the Transportation Technology Center (TTC) in Pueblo, CO. This work was carried out as part of Federal Railroad Administration (FRA) Task Order 248, "Ground Penetrating Radar Evaluation and Implementation," with additional funding provided by the Association of American Railroads (AAR) Improved Track Substructure Strategic Research Initiative.

Six GPR systems, labeled 1 through 6, were evaluated at TTC's Facility for Accelerated Service Testing (FAST), and represented most of the current North American service providers. The focus of the evaluation was ballast condition assessment, specifically ballast fouling, layer depth, and moisture content. The following is a brief description of each system:

- System 1: 2-GHz and 400-MHz antennas and ballast fouling determined by signal scattering analysis.
- System 2: 1-GHz antennas and ballast fouling determined by signal dielectric dispersion analysis.
- System 3: 400-MHz antennas and ballast fouling determined by signal dielectric dispersion analysis.
- System 4: 400-MHz antennas from a second antenna manufacturer and ballast fouling determined by signal dielectric dispersion analysis.
- System 5: stepped frequency continuous wave (SFCW) antenna from antenna manufacturer 3 operating between 150 MHz and 2.5 GHz, and ballast fouling determined by signal dielectric dispersion analysis.
- System 6: 400-MHz and 900-MHz antennas from antenna manufacturer 2 and ballast fouling determined by signal propagation analysis.

Numeric fouling data was provided by systems 1–5 for both ballast shoulders, and by systems 1, 3, 4, 5, and 6 for the track center. Numeric layer data was provided by all systems for the track center and shoulders, in which this report will go more into detail.

1. Introduction

This report describes and documents the results of an evaluation of ground penetrating radar (GPR) technologies that TTCI performed on the HTL at TTC in Pueblo, CO. The work was carried out as part of FRA Task Order 248, "Ground Penetrating Radar Evaluation and Implementation," with additional funding provided by the AAR Improved Track Substructure Strategic Research Initiative.

The objective this study was to enhance the use of GPR as a railroad track substructure inspection technique through the following tasks:

- Evaluation of commercial GPR systems at FAST to establish the state-of-the-art for track inspection.
- Development of guidelines for GPR implementation by railroads.
- Identification of ongoing research needs.

The evaluation approach was primarily a comparison of the ballast fouling and layer depth outputs of the different systems for HTL Sections 25, 7, 3, and 33. Each system provided ballast fouling and layer depth data in digital formats. However, the fouling categorization was not consistent between systems. To compare the fouling results, TTCI, with assistance from the U.S. Department of Transportation's Volpe National Transportation Systems Center, brought the various fouling data to a common baseline with 4 being clean, 3 being moderately clean, 2 being moderately fouled, and 1 being highly fouled.

A number of GPR systems participated in the evaluation at FAST, representing most of the current North American service providers. The focus of the evaluation of this study was ballast condition assessment, specifically ballast fouling, layer depth, and moisture content.

1.1 GPR Background

GPR is a nondestructive geophysical technique that is widely used to identify and visualize subsurface structural and material conditions. The basic technique is well documented in GPR literature and involves the transmission of radio frequency electromagnetic energy into the ground or other physical medium by a transmitting antenna. A portion of the transmitted energy is reflected by contrasts in material dielectric permittivity and electrical conductivity that occur at material interfaces such as changes in soil layers, ground water surfaces, or manmade objects.

The amplitude and return time of signal reflections are captured by a receiver antenna as the transmitted wave penetrates the medium, while the antennas move along the surface. The recorded data is processed to produce an image (radargram) of the subsurface profile, as shown in Figure 1, where the wave reflections are shown as functions of the wave travel time. The wave travel time is converted to penetration depth based on the wave velocity.

Wave velocity (V) in a nonconductive material is determined by the dielectric permittivity of the material it is passing through and is calculated as [1]:

$$V = c/\varepsilon^{0.5} \qquad (1)$$

Where c is the speed of light in free space (11.8 in/nanosecond) and ε is the material dielectric constant (the ratio of a material dielectric permittivity to the permittivity of air, which is 1).

According to Milsom and Eriksen [2], the signal reflection strength depends on the incidence wave angle, the size and surface condition of the initial interface discontinuity, and the amplitude reflection coefficient (RC), which for low conductivity, nonmagnetic material can be calculated from the wave velocity change at the interface as:

$$RC = (V_1 - V_2) / (V_2 + V_1) \qquad (2)$$

Where V_1 and V_2 are the wave velocities in the host and target materials respectively.

Dielectric constants for various geological materials can be found in the GPR literature [2, 3, 4]. Most dry materials have ε values of less than 10, whereas, the ε value for water is 80. Therefore, a change in moisture content at an interface can have a significant effect on the wave velocity and reflection.

Attenuation of the transmitted wave is also governed by material conductivity. Increasing conductivity increases the attenuation, thereby reducing the wave penetration depth. Conductivity and attenuation values for geological materials can be found in the same references as the dielectric constants.

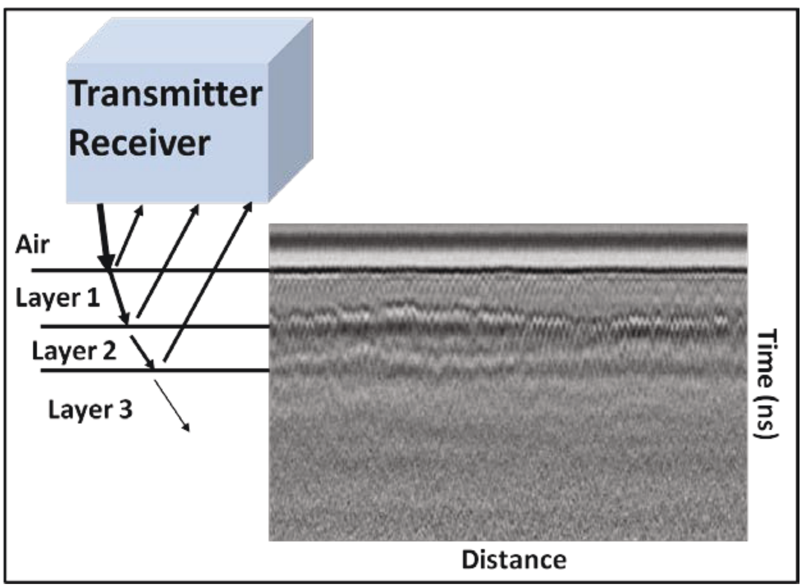


Figure 1. Typical GPR Radargram Showing Distinct Layer Interface Reflections

1.2 Track Application of GPR

The potential of GPR as a track substructure inspection tool has been recognized for some time; however, its use by North American railroads has been limited, until recently. The technology has, however, matured to the point that commercial systems providing track inspection services are available. These systems have data processing, interpretation, and visualization packages that have been developed specifically for track substructure analysis and reporting. The packages also incorporate ancillary information such as track geometry data, track asset information, video mapping, ballast section profiling, and other information/data sets.

GPR inspection of the track substructure is usually focused on the ballast layer condition in terms of fouling and layer thickness and possibly moisture retention. Ballast assessment can be a challenge for GPR, however, because the layer material is not particularly homogenous and variable dielectric and possibly conductive properties may exist. Moisture content within the layer may also vary, which can affect interpretation of the GPR data.

Issues surrounding GPR determination of ballast thickness and fouling are briefly discussed in the following two subsections.

1.2.1 Ballast Thickness

Layer thickness (D) is calculated from the two-way travel time of the wave (t) as [1]:

$$D = Vt/2 = ct/2\varepsilon^{0.5} \qquad (3)$$

From equation 3, the precision of the thickness calculation is clearly depicted as the dependent on the dielectric constant ε value is used. In Figure 2, the calculated layer thickness is plotted against a range of ballast material dielectric constants for wave travel times of 5, 15, and 30 nanoseconds (ns). The increasing ε values in Figure 2 represent increased fouling and/or moisture in the ballast.

Figure 2 indicates that the longer the time travel (i.e., increasing layer thickness), the more sensitive the thickness calculation is to the ε value. For travel times of 15 ns or less, the use of ε values between 4 and 7 that may be considered typical of many ballast conditions should produce reasonably accurate and consistent layer thickness data. However, for deep ballast layers, such as ballast pockets or locations where the track has been raised on ballast, a substantial amount ε becomes more critical.

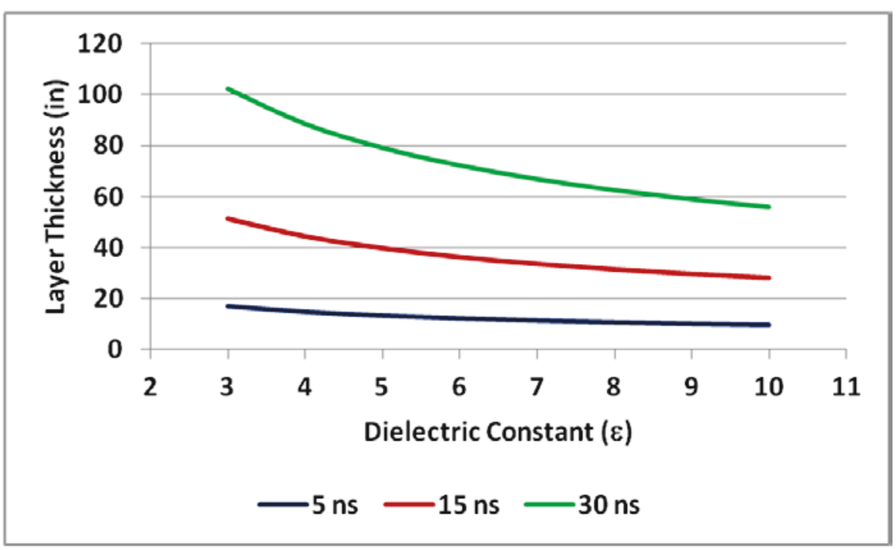


Figure 2. Sensitivity of the Thickness Calculation to Travel Time and Material Dielectric Constants

1.2.2 Ballast Fouling

Ballast is a uniformly graded course aggregate having multifaceted angular shapes and air voids between the aggregate particles. Fouling occurs as the voids gradually fill up with fine-grain size material generated by fracturing and abrasion of the particles under traffic, as well as material intrusion from outside the track and, in some cases, from the subgrade.

The distribution of fouling is not uniform within the ballast layer, but tends to increase with depth below the tie bottoms. Ballast above the tie bottoms, in the cribs and shoulders, is usually much less fouled than the ballast beneath the ties, and ballast at the bottom of the layer is usually the most fouled.

Given the amount of resources that railroads devote to ballast maintenance and renewals, the detrimental effect that fouled ballast can have on overall track performance, and the inability to quickly and efficiently measure fouling by other methods, assessment of the fouling condition is arguably the most important application of GPR for track inspection, but is also the most difficult.

The nonhomogeneous nature of the ballast layer and the top-to-bottom fouling variation makes the layer interface reflection of the GPR signal an impractical method for fouling determination [5]. Methods that have been developed to quantify ballast fouling include signal scattering analysis and dielectric dispersion analysis. Both methods were used in the evaluation at FAST and are briefly described here.

1.2.2.1 Scattering

Scattering of the GPR signal occurs when objects (causes of scattering) having perimeter sizes the same or larger than the incident wavelength are encountered. The higher the GPR wave frequency (i.e., shorter wavelength), the smaller the scatter dimensions that are needed to produce the scattering response. The air voids between particles in clean ballast act as scatterers for high frequency signals and the typical ballast void dimensions of 1/2 in (inch) to slightly more than 1 in (11 millimeters (mm) to 29 mm) [6] result in scattering of the 2-GHz frequency [5]. The degree of scattering is reduced as the void spaces are filled with smaller particle size material [7].

Scattering response provides a method for GPR to distinguish clean from fouled ballast, provided the transmitted wave frequency and ballast void spaces are dimensionally compatible.

One other point to make about scattering analysis is that, according to Zhang, et al., it is not reliant on ballast dielectric properties; it is therefore, not sensitive to ballast moisture content and is largely independent of variations in the subgrade material [8].

1.2.2.2 Dielectric Dispersion

Dielectric dispersion involves conversion of the time domain GPR reflection amplitude data to a frequency domain spectrum using Fourier analysis, as Figure 3 shows [9]. According to Silvast, et al., increasing amounts of fines and absorbed water in the ballast layer cause an increase in the dielectric dispersion (increasing permittivity) that is evident as a reduction in the frequency content of the signal compared with clean ballast [10]. In Figure 4, the frequency spectrums of clean and fouled ballast recorded with a 400-MHz antenna are overlaid to show the reduced frequency content, or reduced area under the curve, of the fouled ballast.

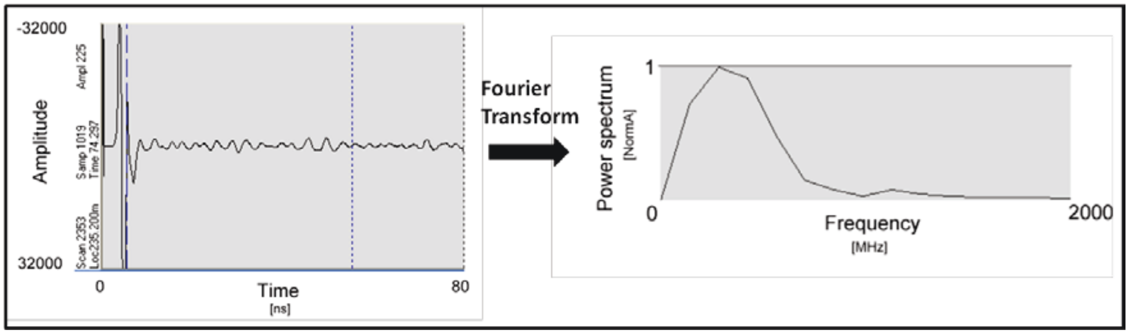


Figure 3. GPR Data Conversion for Dispersion Analysis [9]

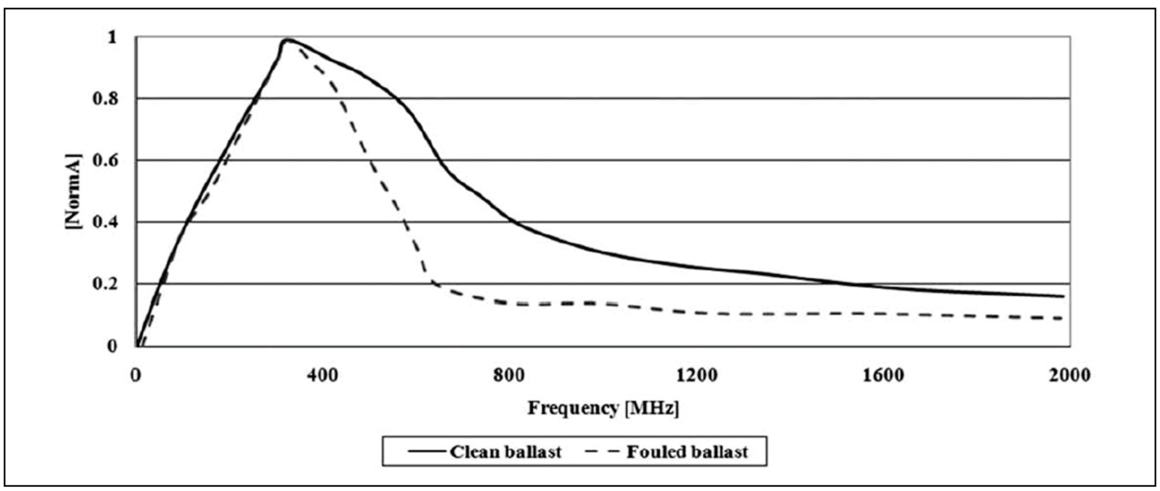


Figure 4. Fouled and Clean Ballast Frequency Data from 400-MHz Antenna [9]

1.2.2.3 Calibration

Both scattering and dielectric dispersion analysis provide methods through which clean ballast with significant interparticle void spaces can be distinguished from fouled ballast with reduced or nonexistent voids spaces. However, calibration of the GPR signal response to known fouling conditions, as derived from sieve analysis of relevant ballast samples, is required for either method to accurately quantify the fouling condition. The effect of moisture on the dielectric dispersion method should also be considered in the calibration process.

2. Evaluation Description

Evaluation of the GPR systems was performed on the HTL at FAST between mid-November and early December 2010. The objective, as previously stated, was to evaluate commercial GPR systems to establish the state-of-the-art for track inspection. Invitations to participate were sent to known service providers in North America and Europe, and the response was positive. Six systems participated with five systems providing final data packages. Descriptions of the evaluation process and participating systems are included in the following subsections.

2.1 Description of the High Tonnage Loop

The HTL is a 2.7-mile loop used for heavy axle load testing since 1988. As Figure 5 shows, the HTL is divided into test sections that include a variety of track configurations. Sections 25, 8, 7, 3, 33, and 29 were included in the evaluation and are described as follows:

- Section 25 is a 6-degree curve with a nominal 5 in of superelevation with primarily wood ties and some concrete and plastic composite ties.
- Sections 7 and 8 are a 5-degree curve and transition curve, respectively, with wood ties.
- Section 3 is a 5-degree curve that is approximately one-half concrete ties and one-half wood ties.
- Sections 33 and 29 are both tangent zones with a combination of wood and concrete ties.

Ballast is not cleaned or replaced as a regular maintenance activity around the HTL, but is added periodically as more of a spot maintenance approach. Therefore, the existing ballast has been in place for a number of years at most locations, with the exception of Section 3, where much of the ballast was removed and cleaned or renewed entirely in 2009.

The HTL subgrade is highly uniform and has been classified as predominately a silty sand soil conforming to the Unified Soil Classification System designation of SM. The exception to the subgrade condition is Section 29 where the subgrade was modified by the excavation of a 12-foot-wide by 5-foot-deep trench that was backfilled with a high-plasticity clay (buckshot clay) installed wet of optimum (moisture content above that for optimum soil density) in 1991. The clay is capped by a 6-inch layer of subballast and an 8-inch layer of hot mix asphalt (HMA).

HTL track conditions were essentially identical for the various system surveys. There was no precipitation recorded by the TTC weather station or train traffic on the HTL during the inspection period of November 12 through December 6, 2010.

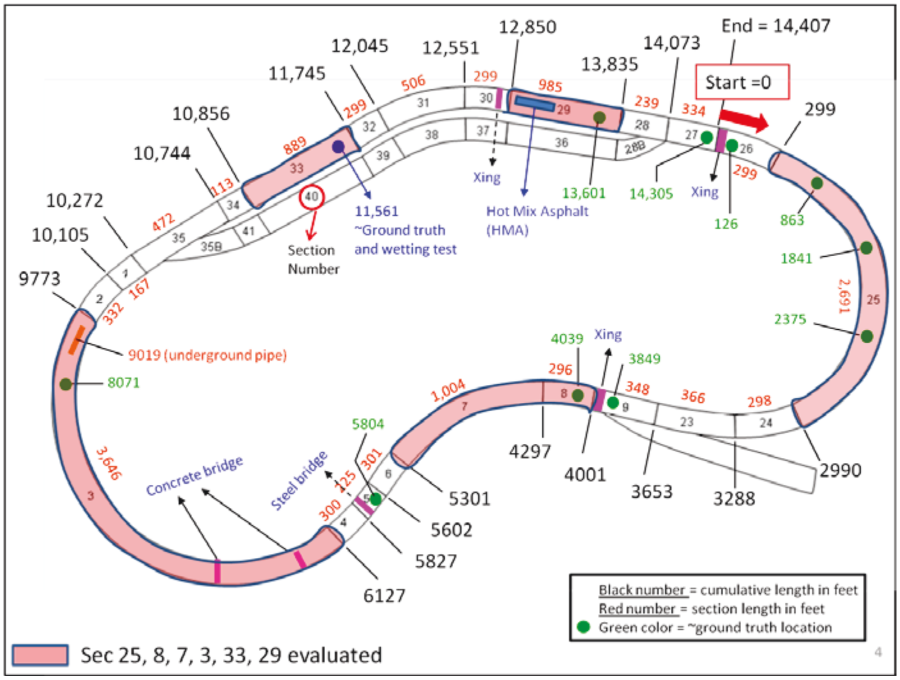


Figure 5. HTL Layout

2.2 GPR Systems

Providers of commercial GPR systems typically team together to provide the service:

- An engineering group that provides and operates the hi-rail vehicle on which the GPR antennas are installed, plus the hardware required to mount other inspection-related equipment such as GPS antennas and video cameras. GPR systems are currently installed exclusively on hi-rail vehicles in North America, but can also be mounted on track geometry or maintenance vehicles.
- A hardware supplier that provides the GPR antenna/receiver and other equipment such as the signal pulse generator, signal conditioning, and data collection systems. GPR providers may own or lease part or all of the hardware.
- A geophysics group that performs the processing, interpretation, and analysis of the data. The geophysics group usually has developed and owns the interpretation and analysis software that may be available as a stand-alone product separate from the inspection service.

Table 1 generically describes the systems participating in the evaluation and producing final results. The mix of antenna types, antenna manufacturers, engineering, and geophysics providers included:

- 400-MHz, 900-MHz, 1-GHz, and 2-GHz time-domain pulsed antennas from two different manufacturers.
- SFCW frequency-domain antenna from a third manufacturer with 31 transmitter-receiver dipoles spaced approximately 4 in apart. The SFCW system transmits a sine wave of constant amplitude and stepwise frequency variation, as Figure 6 shows. The waveform is

specified by determining a start frequency (fmin), a stop frequency (fmax), a frequency step (Δf), and a dwell time (Td). The start frequency was 150 MHz, and the stop frequency was 2.5 GHz. Data from three of the SFCW dipole antennas was analyzed [9].

- Two engineering teams supplying hi-rail vehicles, antenna mounting hardware and ancillary equipment such as wheel distance measuring encoders, video recorders, and GPS capability.
- Three geophysics groups who interpreted, analyzed, and reported the data.

Table 1. GPR Systems Description

System	Antenna Description	Fouling Analysis
1	Time-domain pulsed radar, ground coupled 400 MHz used for layer depth mapping and air coupled 2 GHz used for ballast fouling	Scattering
2	Time-domain pulsed radar, 1 GHz, air coupled	Dielectric dispersion/ frequency spectrum
3	Time-domain pulsed radar, 400-MHz antenna manufacturer 1, ground coupled	Dielectric dispersion/ frequency spectrum
4	Time-domain pulsed radar, 400-MHz antenna manufacturer 2, ground coupled	Dielectric dispersion/ frequency spectrum
5	SFCW radar manufacturer 3, 150-MHz to 2.5-GHz frequency range, air coupled	Dielectric dispersion/ frequency spectrum
6	Time-domain pulsed radar, 400-MHz and 900-MHz antenna manufacturer 2, ground coupled	GPR propagation analysis of 400-MHz signal

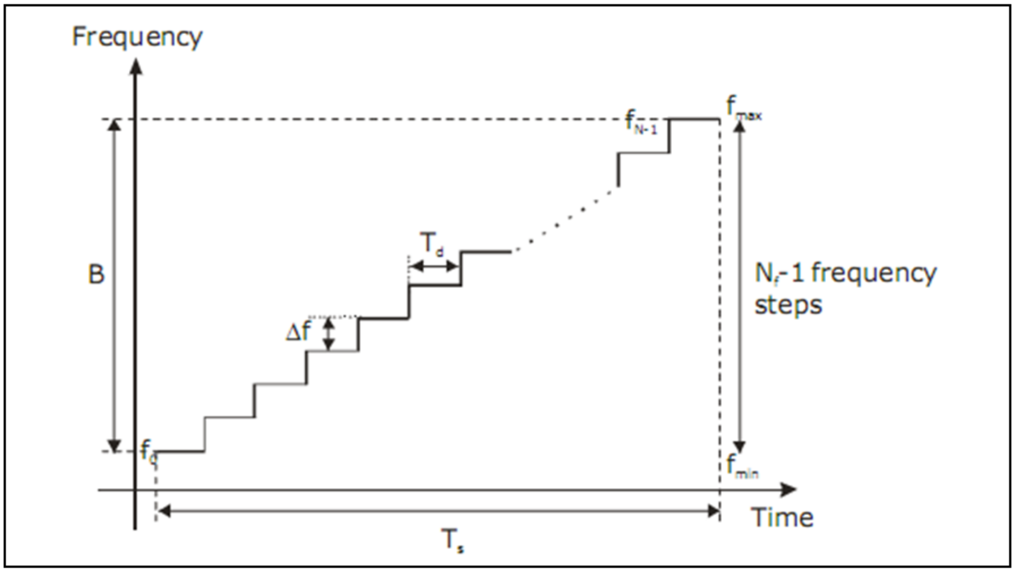


Figure 6. System 5—SFCW Waveform [9]

2.3 Inspection Procedure

All systems began and ended their surveys at the road crossing in Section 27, marked as 0 feet (ft) in Figure 5. All systems inspected the track center and both ballast shoulders just outside the tie ends, as Figure 7 shows. In some cases, only two antennas were available, and it was necessary to move the antenna from one shoulder to the other and make additional passes. Operating speeds were typical hi-rail speeds from 20 miles per hour (mph) to 25 mph.

All final reporting systems located the antennas 1 and 2 ft above the ballast surface. The sixth system mounted the antenna on a type of sled that was dragged along the ballast surface.

Figure 7. Pulsed Antenna Positioning for Track Center and Shoulder Survey

2.4 System Outputs

Each of the six systems produced a set of results in its standard output format along with a report describing the system and giving details concerning the data analysis and output. Table 2 summarizes the outputs provided in addition to the processed radargrams for System 1, Table 3 summarizes the outputs for systems 2–5, and Table 4 summarizes the output for System 6. A set of digital data for ballast fouling and layer depth was also provided for all systems. Examples of the different system outputs are included in Figures 8, 9, and 10.

Table 2. Summary of System 1 Output Data [7]

Ballast Layer Depth	Ballast Fouling	Moisture	Other
Depth based on a dielectric of 4.5 Primary and secondary layers identified relative to top of tie Track-bed indices: • Layer amplitude exceedence (LAE) – gives indication of water and/or wet clay/silt at bottom of primary layer • Ballast thickness index – gives indication of primary layer <19.7 in • Layer roughness index – identifies irregular primary ballast depths	Average fouling over 16 to18 in depth classified as clean, moderately clean, moderately fouled, fouled, severely fouled and plotted as bars for center and shoulders Full ballast fouling matrix from the 2-GHz data plotted against depth to depth of 17 in for center and shoulders Statistical summary of fouling data Fouling output based on calibration performed using a specific railroad's ballast condition	Moisture is not a specific output but can be identified from the LAE output	Surface/subsurface features Ballast section profiling and volume calculation Video asset and mapping Track geometry not included Detailed section-by-section summary of track-bed structure features and conditions

Table 3. Summary of Systems 2, 3, 4, and 5 Output Data [9]

Ballast Layer Depth	Ballast Fouling	Moisture	Other
Distance plot of layer depth (inches) based on a dielectric value of 6 for interpreted ballast layer and 9 for subballast	GPR ballast fouling index (GBFI) classified as clean to highly fouled as four steps and plotted as bars for track center and shoulders (see Figure 10) GBFI classification plotted as a function of depth and plotted as plan view Statistical summary of fouling data GIS map of HTL with GBFI classification Fouling analysis was relative and not calibrated	Relative moisture as function of depth	Images from digital video saved every 150 ft Track geometry/roughness data Track asset database

Table 4. Summary of Systems 6 Output Data [11]

Ballast Layer Depth	Ballast Fouling	Moisture	Other
Distance plot of layer depth (meters) Undulation of ballast layer shown in color coded bar chart Numeric layer depth data	Ballast fouling classified as clean to highly fouled over 100-foot segment and plotted as color-coded bar chart Ballast fouling color band for each 100-foot segment given for the central antenna Fouling analysis was relative and not calibrated	Relative moisture within ballast layer and at bottom of ballast layer shown in color-coded bar chart averaged more than 100 feet	Video footage of the survey

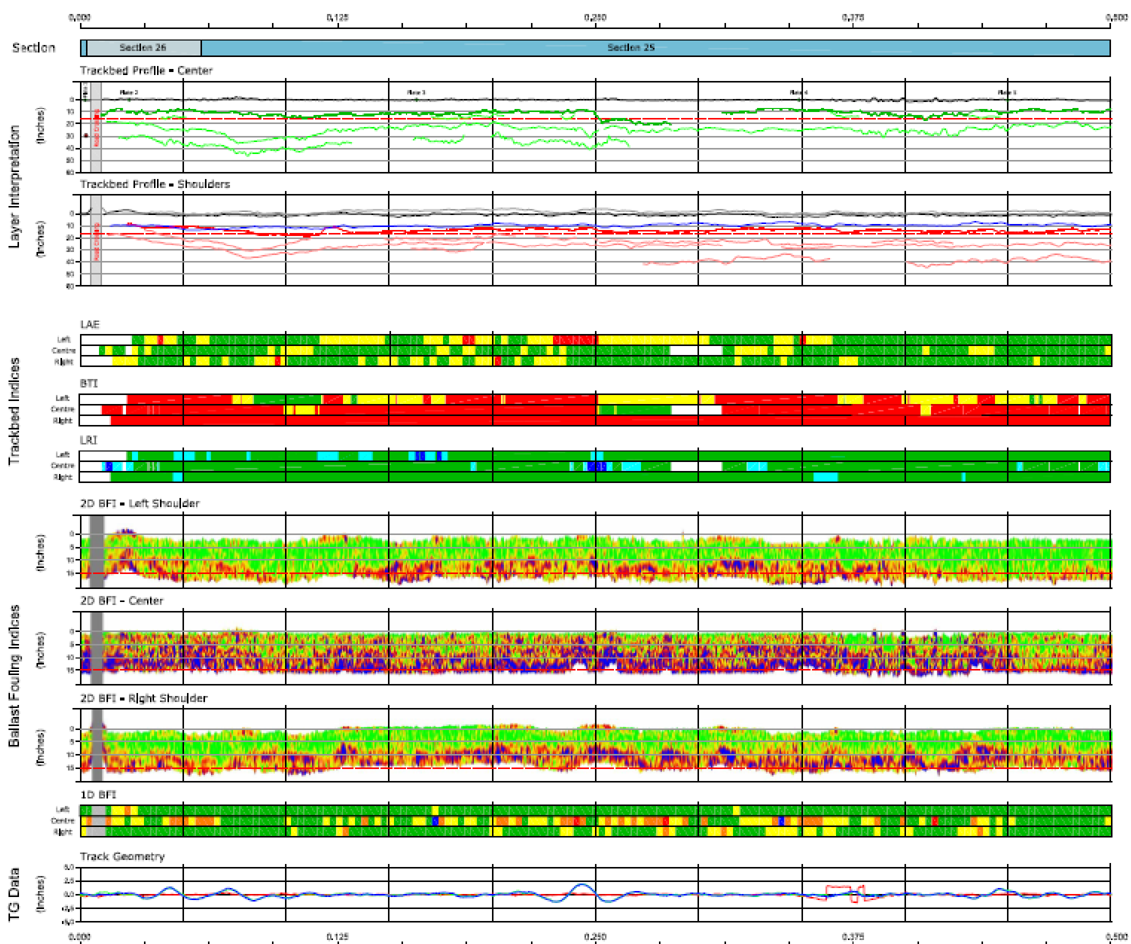


Figure 8. System 1 Layer and Fouling Data Output for Section 25

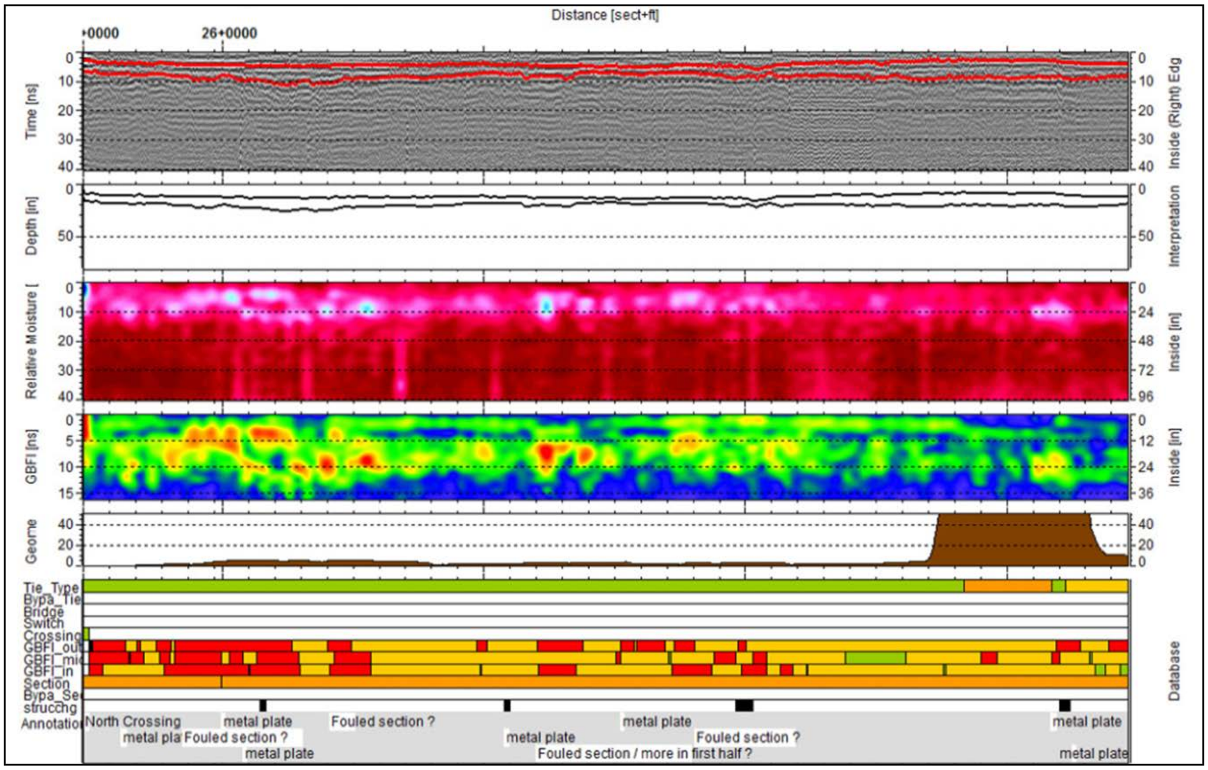


Figure 9. System 3 Output for Section 25—Similar Formats for Systems 2, 4, and 5

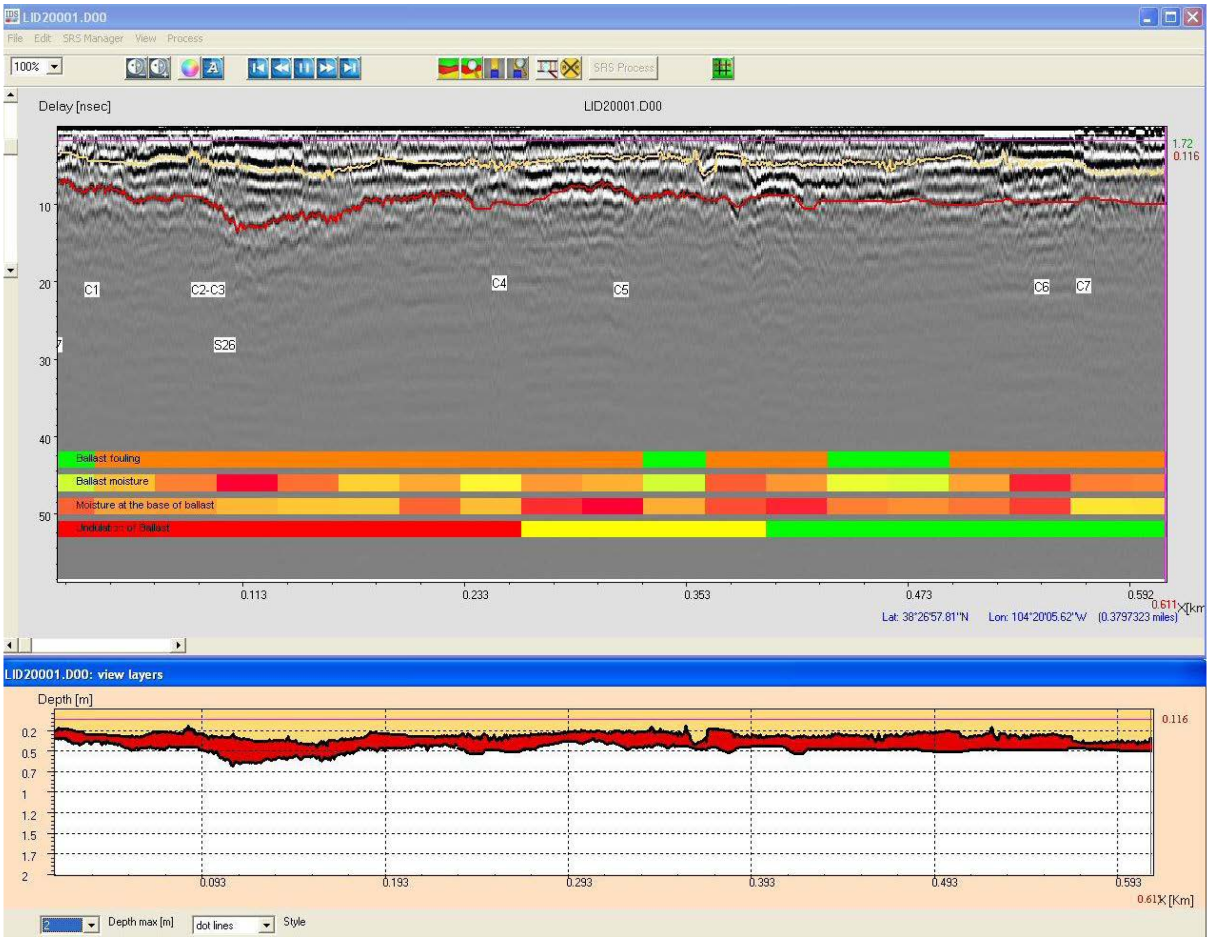


Figure 10. System 6 Output for Section 25

3. Evaluation Results

The evaluation approach was primarily a comparison of the ballast fouling and layer depth outputs of the different systems for the relevant HTL Sections 25, 8, 7, 3, 33, and 29.

A number of ballast samples were also taken from trenches at various locations in the sections and sieve analysis performed to define the particle size distribution of the sample. At the start of the project, it was assumed that comparison of the GPR data to these ground-truth locations would be the principal basis of the evaluation. However, less emphasis was eventually placed on this approach as the limitations of comparing discrete ballast samples to the GPR data in terms of where the sample was taken and relating a limited amount of ground-truth data to the overall survey became apparent.

There was also the tendency to place too much emphasis on the percentage of fines in the sample, which is a very exact number, and the fouling index (FI) values produced by the GPR systems, particularly systems 2–5, for which the fouling indexes were relative and not based on calibration. TTCI decided that ground-truth comparisons would be most applicable when the ballast was very clean or very fouled.

3.1 Ballast Fouling Evaluation

The first task in the fouling evaluation was to normalize the numeric fouling data provided by the various systems to a common baseline both in terms of the fouling category, or number, and distance. For example, the digital fouling data provided for systems 2–5 represented fouling on a scale of 0 to 60, with 60 being the highest level of fouling, and the distance in 8.2-foot (2.5-meter) increments (Figure 11).

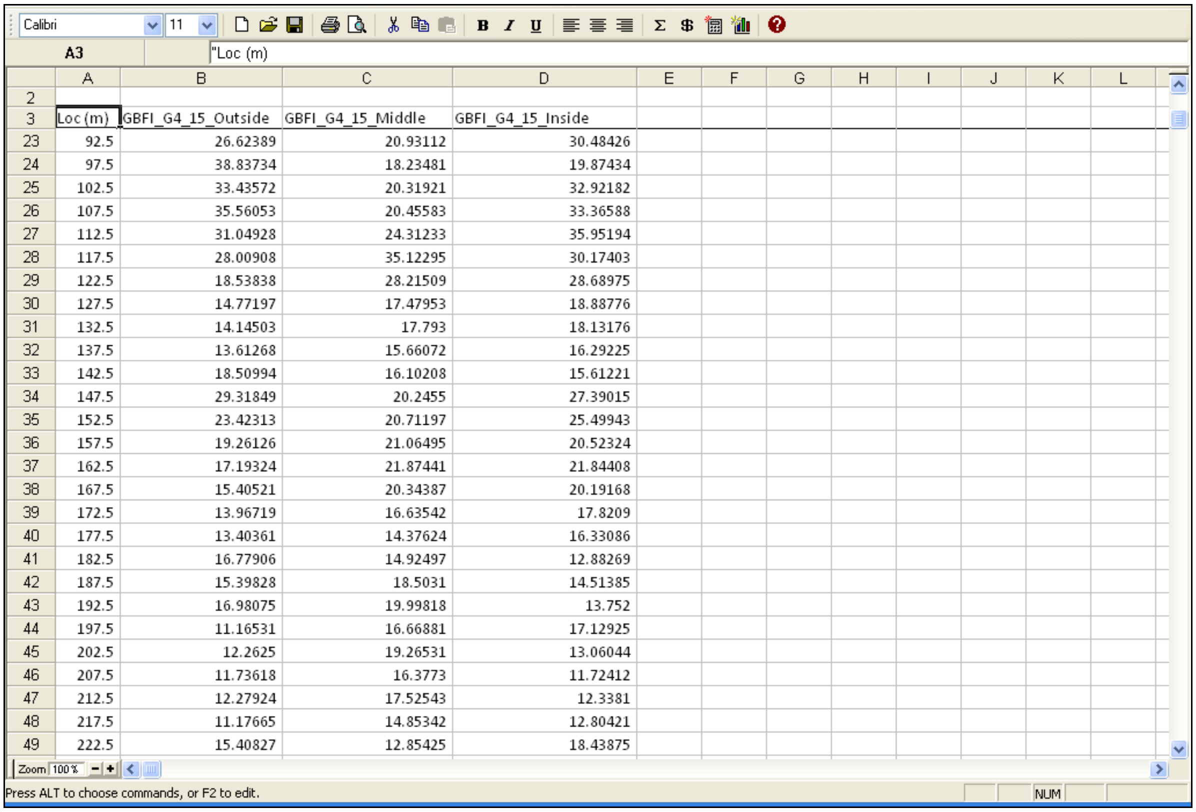
Fouling data from System 1 was identified based on a fouling classification of 1 to 5, with 1 being classified as severely fouled, 2 being fouled, 3 being moderately fouled, 4 being moderately clean, and 5 being clean. System 1 also correlated the fouling classification to FI values based on Selig's FI that was derived from a calibration performed using a specific railroad's ballast condition, and the distance was broken into 0.003-mile (15.84-feet) increments (Figure 12).

System 6 provided fouling data for the track center antenna in the format shown in Figure 13, where the fouling classification for a distance of more than 100 feet is presented as a color bar with red being fouled, orange being moderately fouled, yellow being moderately clean, and green being clean.

The different fouling values were brought to a TTCI generic categorization with 4 being clean, 3 being moderately clean, 2 being moderately fouled, and 1 being highly fouled using the following rationale:

- System 1 BF categories 1 and 2 were reclassified as TTCI generic category 1 and BF categories 3, 4, and 5 reclassified as TTCI generic categories 2, 3, and 4, respectively.
- Systems 2, 3, 4, and 5 GBFI values were reclassified to TTCI generic categories as GBFI 0–20 = generic category 4, GBFI 21–30 = generic category 3, GBFI 31–40 = generic category 2, and GBFI above 40 = generic category 1.

- System 6 data was reclassified to TTCI generic fouling categories with the green bar as category 4, yellow bar as category 3, orange bar as category 2, and red bar as category 1. Note that System 6 provided numeric fouling data from the track center only.



	A	B	C	D
3	Loc (m)	GBFI_G4_15_Outside	GBFI_G4_15_Middle	GBFI_G4_15_Inside
23	92.5	26.62389	20.93112	30.48426
24	97.5	38.83734	18.23481	19.87434
25	102.5	33.43572	20.31921	32.92182
26	107.5	35.56053	20.45583	33.36588
27	112.5	31.04928	24.31233	35.95194
28	117.5	28.00908	35.12295	30.17403
29	122.5	18.53838	28.21509	28.68975
30	127.5	14.77197	17.47953	18.88776
31	132.5	14.14503	17.793	18.13176
32	137.5	13.61268	15.66072	16.29225
33	142.5	18.50994	16.10208	15.61221
34	147.5	29.31849	20.2455	27.39015
35	152.5	23.42313	20.71197	25.49943
36	157.5	19.26126	21.06495	20.52324
37	162.5	17.19324	21.87441	21.84408
38	167.5	15.40521	20.34387	20.19168
39	172.5	13.96719	16.63542	17.8209
40	177.5	13.40361	14.37624	16.33086
41	182.5	16.77906	14.92497	12.88269
42	187.5	15.39828	18.5031	14.51385
43	192.5	16.98075	19.99818	13.752
44	197.5	11.16531	16.66881	17.12925
45	202.5	12.2625	19.26531	13.06044
46	207.5	11.73618	16.3773	11.72412
47	212.5	12.27924	17.52543	12.3381
48	217.5	11.17665	14.85342	12.80421
49	222.5	15.40827	12.85425	18.43875

Figure 11. Example of System 2, 3, 4, and 5 Numeric Fouling Data

FI Category	Description	FI range
5	Clean	<5
4	Moderately Clean	>5 to <10
3	Moderately Fouled	>10 to <25
2	Fouled	>25 to <30
1	Severely fouled	>30

Row	Route	Date	Section	Track	Mileage	Dec.Lat	Dec.Long	Left BFI Category	Left Fouling Index Value	Right BFI Category	Right Fouling Index Value	Centre (4') BFI Category	Centre (4') Fouling Index Value
40	HTL	12/6/2010	S 25	M1	0.064	38.453359	-104.33635	5	2	5	1	3	23
41	HTL	12/6/2010	S 25	M1	0.067	38.453342	-104.336298	5	1	5	0	4	5
42	HTL	12/6/2010	S 25	M1	0.070	38.453326	-104.336246	5	1	5	1	5	4
43	HTL	12/6/2010	S 25	M1	0.073	38.45331	-104.336194	5	1	5	2	5	5
44	HTL	12/6/2010	S 25	M1	0.076	38.453289	-104.336143	5	1	5	3	5	3
45	HTL	12/6/2010	S 25	M1	0.079	38.453271	-104.336089	5	1	5	2	5	3
46	HTL	12/6/2010	S 25	M1	0.082	38.45325	-104.336039	5	0	5	2	5	4
47	HTL	12/6/2010	S 25	M1	0.085	38.45323	-104.33599	5	0	5	2	5	4
48	HTL	12/6/2010	S 25	M1	0.089	38.45321	-104.33594	5	1	5	1	5	5
49	HTL	12/6/2010	S 25	M1	0.092	38.453188	-104.335888	5	0	5	2	5	4
50	HTL	12/6/2010	S 25	M1	0.095	38.453166	-104.33584	5	0	5	2	5	2
51	HTL	12/6/2010	S 25	M1	0.098	38.453142	-104.33579	5	1	5	1	5	3
52	HTL	12/6/2010	S 25	M1	0.101	38.453118	-104.335741	5	1	5	4	4	6
53	HTL	12/6/2010	S 25	M1	0.104	38.453092	-104.335694	5	1	4	8	5	3
54	HTL	12/6/2010	S 25	M1	0.107	38.453067	-104.335647	5	0	5	4	5	3
55	HTL	12/6/2010	S 25	M1	0.110	38.453041	-104.3356	5	1	5	3	5	2
56	HTL	12/6/2010	S 25	M1	0.113	38.453015	-104.335554	5	1	5	1	5	1
57	HTL	12/6/2010	S 25	M1	0.116	38.452989	-104.335509	5	1	5	1	5	4
58	HTL	12/6/2010	S 25	M1	0.120	38.452962	-104.335465	5	1	5	0	4	10
59	HTL	12/6/2010	S 25	M1	0.123	38.452932	-104.335422	5	1	5	1	5	4
60	HTL	12/6/2010	S 25	M1	0.126	38.452901	-104.335379	5	1	4	6	4	6
61	HTL	12/6/2010	S 25	M1	0.129	38.452872	-104.335334	5	1	3	12	5	3
62	HTL	12/6/2010	S 25	M1	0.132	38.452843	-104.335293	5	1	5	4	4	7
63	HTL	12/6/2010	S 25	M1	0.135	38.452811	-104.335252	5	2	5	2	5	4
64	HTL	12/6/2010	S 25	M1	0.138	38.45278	-104.335212	5	1	5	2	3	12
65	HTL	12/6/2010	S 25	M1	0.141	38.452748	-104.335172	5	0	5	1	5	5
66	HTL	12/6/2010	S 25	M1	0.144	38.452716	-104.335132	5	0	5	2	4	7
67	HTL	12/6/2010	S 25	M1	0.148	38.452682	-104.335094	5	1	5	1	5	3
68	HTL	12/6/2010	S 25	M1	0.151	38.452648	-104.335055	5	2	5	2	4	6
69	HTL	12/6/2010	S 25	M1	0.154	38.452614	-104.335019	5	5	5	2	5	3

Press ALT to choose commands, or F2 to edit.

Figure 12. Example of System 1 Numeric Fouling Data

Sections	From survey start		From section start					Ballast characteristics			
	X1[miles]	X2[miles]	X1[miles]	X2[miles]	Depth of Ballast bottom (inches)	Depth of clean ballast bottom (inches)	Depth of intermediate layer (inches)	Moisture at the base of ballast	Ballast moisture	Ballast fouling	Undulation of Ballast
S27	0.020	0.041	0.018	0.038	16.3	11.7	NA				
	0.041	0.061	0.038	0.059	18.3	10.7	NA				
S26	0.061	0.082	0.001	0.021	20.7	13.5	NA				
	0.082	0.102	0.021	0.042	23.9	15.0	NA				
	0.102	0.123	0.042	0.062	22.1	14.5	NA				
	0.123	0.143	0.062	0.083	18.7	11.7	NA				
	0.143	0.164	0.083	0.103	18.0	13.1	NA				
	0.164	0.184	0.103	0.124	16.6	12.1	NA				
	0.184	0.205	0.124	0.144	15.2	9.8	NA				
	0.205	0.225	0.144	0.165	18.0	10.7	NA				
	0.225	0.246	0.165	0.185	18.3	16.3	NA				
	0.246	0.266	0.185	0.206	17.6	12.1	NA				
	0.266	0.287	0.206	0.226	17.6	13.1	NA				
	0.287	0.307	0.226	0.247	17.3	13.1	NA				
	0.307	0.328	0.247	0.267	18.3	10.7	NA				
	0.328	0.348	0.267	0.288	19.3	13.5	NA				
	0.348	0.369	0.288	0.308	19.3	12.1	NA				
	0.369	0.389	0.308	0.329	19.3	15.4	NA				
	0.389	0.410	0.329	0.349	18.3	15.9	NA				
	0.410	0.430	0.349	0.370	18.6	15.4	NA				
	0.430	0.451	0.370	0.390	18.3	13.1	NA				
	0.451	0.471	0.390	0.411	16.3	11.7	NA				
	0.471	0.492	0.411	0.431	15.9	13.5	NA				
	0.492	0.512	0.431	0.452	20.1	9.8	NA				
	0.512	0.533	0.452	0.472	20.4	8.9	NA				
	0.533	0.553	0.472	0.493	20.1	14.0	NA				
	0.553	0.574	0.493	0.513	27.0	11.2	NA				
S25	0.574	0.594	0.017	0.037	22.6	21.1	NA				
	0.594	0.615	0.037	0.058	21.9	21.1	NA				
S24	0.615	0.635	0.006	0.026	25.9	27.4	NA				
	0.635	0.656	0.026	0.047	23.6	22.0	NA				
	0.656	0.676	0.047	0.067	25.2	22.0	NA				
	0.676	0.697	0.067	0.088	24.9	20.2	NA				
	0.697	0.717	0.088	0.108	18.6	17.5	NA				
	0.717	0.738	0.108	0.129	21.9	17.5	NA				
	0.738	0.758	0.129	0.149	22.2	16.6	NA				
S23	0.758	0.779	0.026	0.046	21.6	17.0	NA				
S9	0.779	0.799	0.035	0.055	24.3	17.0	16.7				
S8	0.799	0.820	0.011	0.031	24.9	16.1	21.9				
	0.820	0.840	0.031	0.052	25.9	16.1	21.9				

Figure 13. Example of System 6 Fouling Data

3.1.1 Fouling Distribution

The fouling comparison presented in Figure 14 is a statistical distribution of the TTC generic track center fouling categories for each system over HTL Sections 25, 8, 7, 3, 33, and 29 for a total distance of 9,511 feet. Similar distributions are presented for the ballast shoulder data in Figures 15 and 16. Results of the fouling analysis are summarized as follows:

- Track center fouling:
  - System 2 track center fouling data was not submitted because of noise issues.
  - Systems 1, 3, 4, and 5 all showed 6 percent or less of the track center being highly fouled. Differences between these systems were found in the interpretation of clean, moderately clean, and moderately fouled conditions. Systems 3 and 4 both interpreted more than 90 percent of the track as being clean, less than 2 percent as being moderately fouled or fouled, and the remaining 7–11 percent as being moderately clean. System 1 showed approximately 67 percent of the track as clean, 20 percent as moderately clean, and 13 percent as moderately or highly fouled. System 5 indicated roughly the same moderately fouled and highly fouled percentages as system 1, but showed a much higher percentage of moderately fouled ballast (49 percent) and lower percentage of clean ballast (34 percent) than systems 1, 3, and 4. In Figure 17, the track center clean ballast categories 3 (moderately clean) and 4 (clean) are combined to create a single clean ballast category; the fouled ballast categories 1 (highly fouled) and 2 (moderately fouled) are combined to create a fouled ballast category. Viewing the results as simply clean or fouled, the comparison in Figure 17 indicates that systems 3 and 4 results were identical, and systems 1 and 5 were similar for track center fouling.
  - Figures 14 and 17 clearly show that the results from system 6 were substantially different from other systems. System 6 interpreted the HTL ballast condition as being primarily fouled as opposed to the primarily clean interpretation of the other systems.
- Ballast shoulder fouling:
  - System 6 shoulder fouling data was not submitted in a numeric format and is not included.
  - System 5 indicated the highest percentage of fouled ballast and lowest percentage of clean ballast for both shoulders. System 5 also showed the most variability between fouling categories, as shown in Figure 18 where the fouling categories for both shoulders are plotted against distance for each system.
  - The combined clean and fouled ballast categories in Figures 19 and 20 shoulders saw the shoulder ballast as having a lower percentage of clean ballast compared with systems 1, 3, and 4.

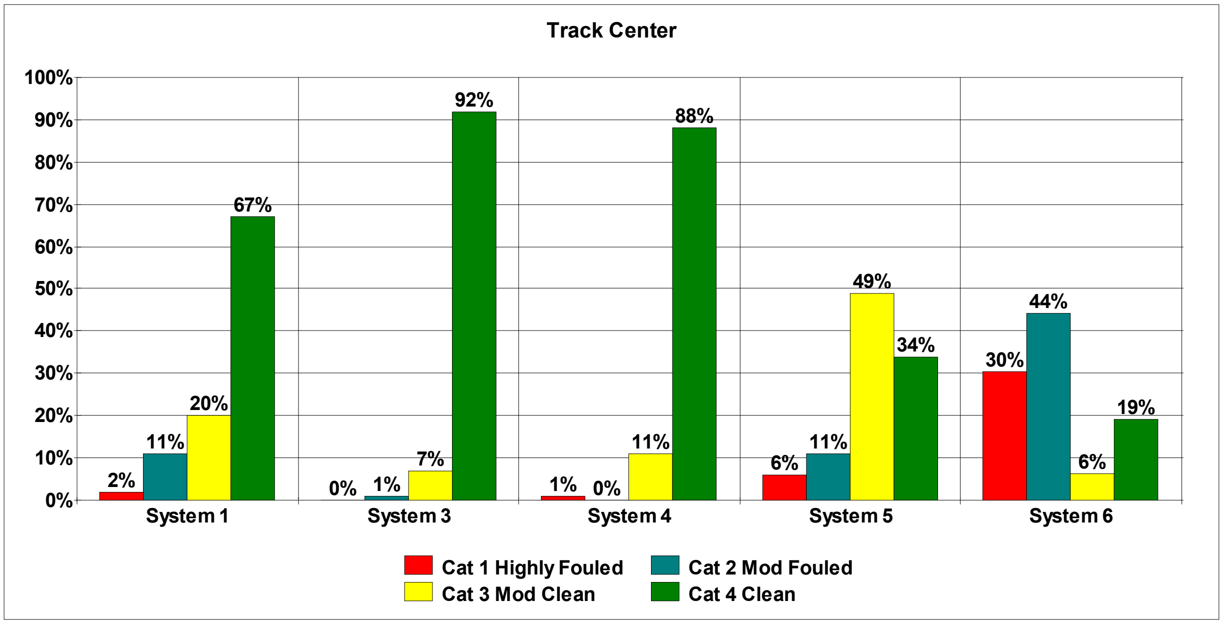


Figure 14. Distribution of Track Center Ballast Fouling Categories for HTL Sections 25, 8, 7, 3, 33, and 29

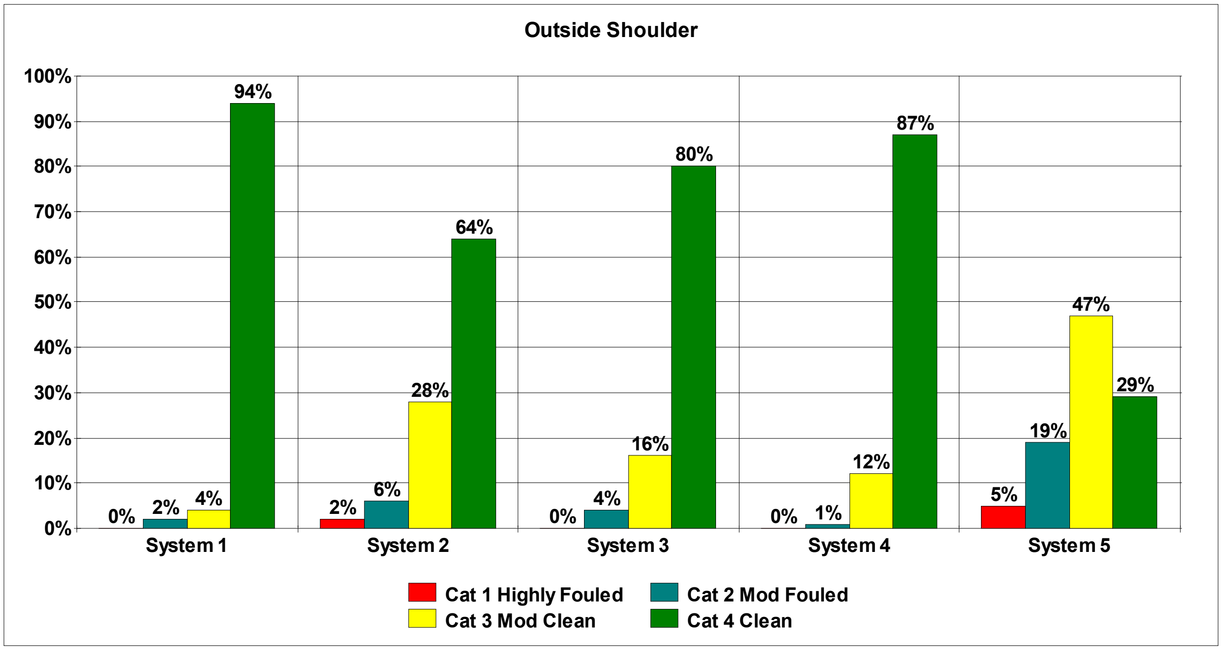


Figure 15. Distribution of Outside Shoulder Ballast Fouling Categories for HTL Sections 25, 8, 7, 3, 33, and 29

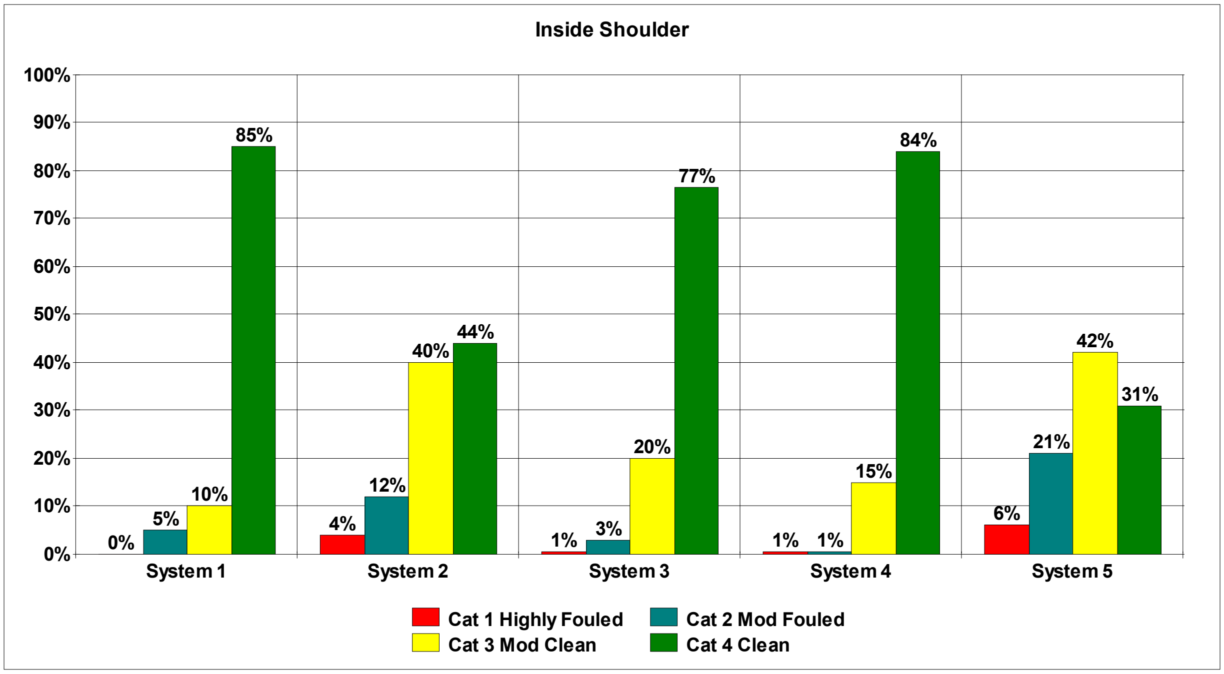


Figure 16. Distribution of Inside Shoulder Ballast Fouling Categories for HTL Sections 25, 8, 7, 3, 33, and 29

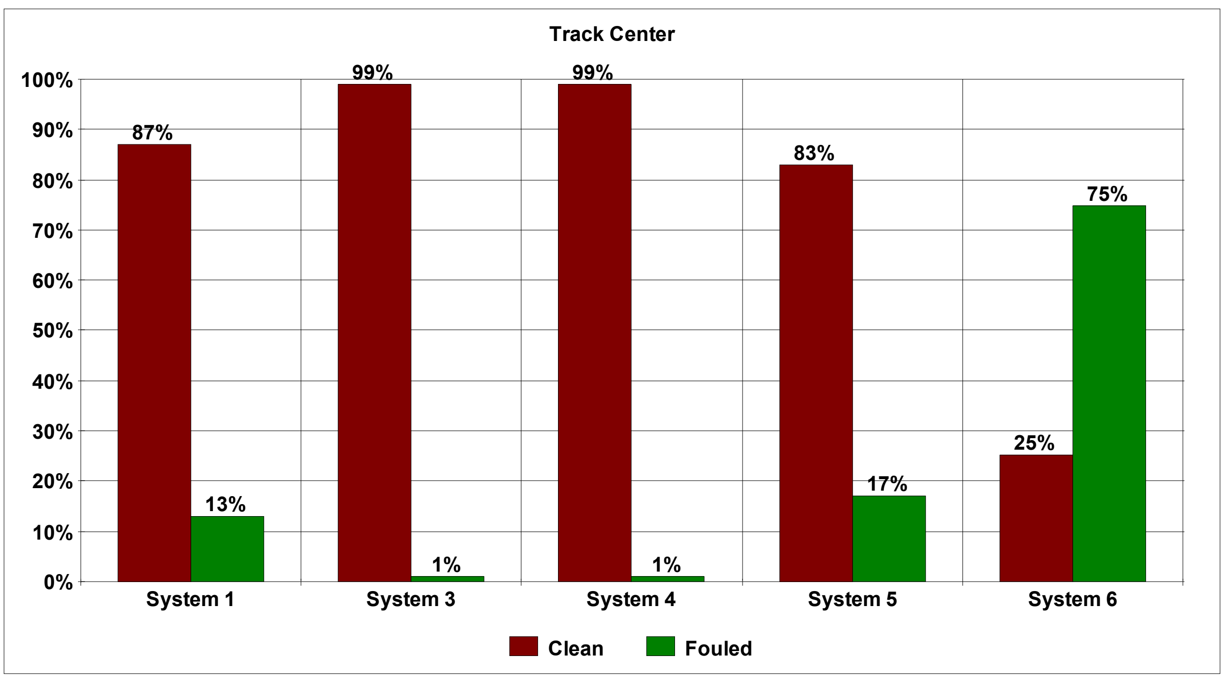


Figure 17. Comparison of Track Center Clean/Moderately Clean and Fouled/Moderately Fouled Interpretation

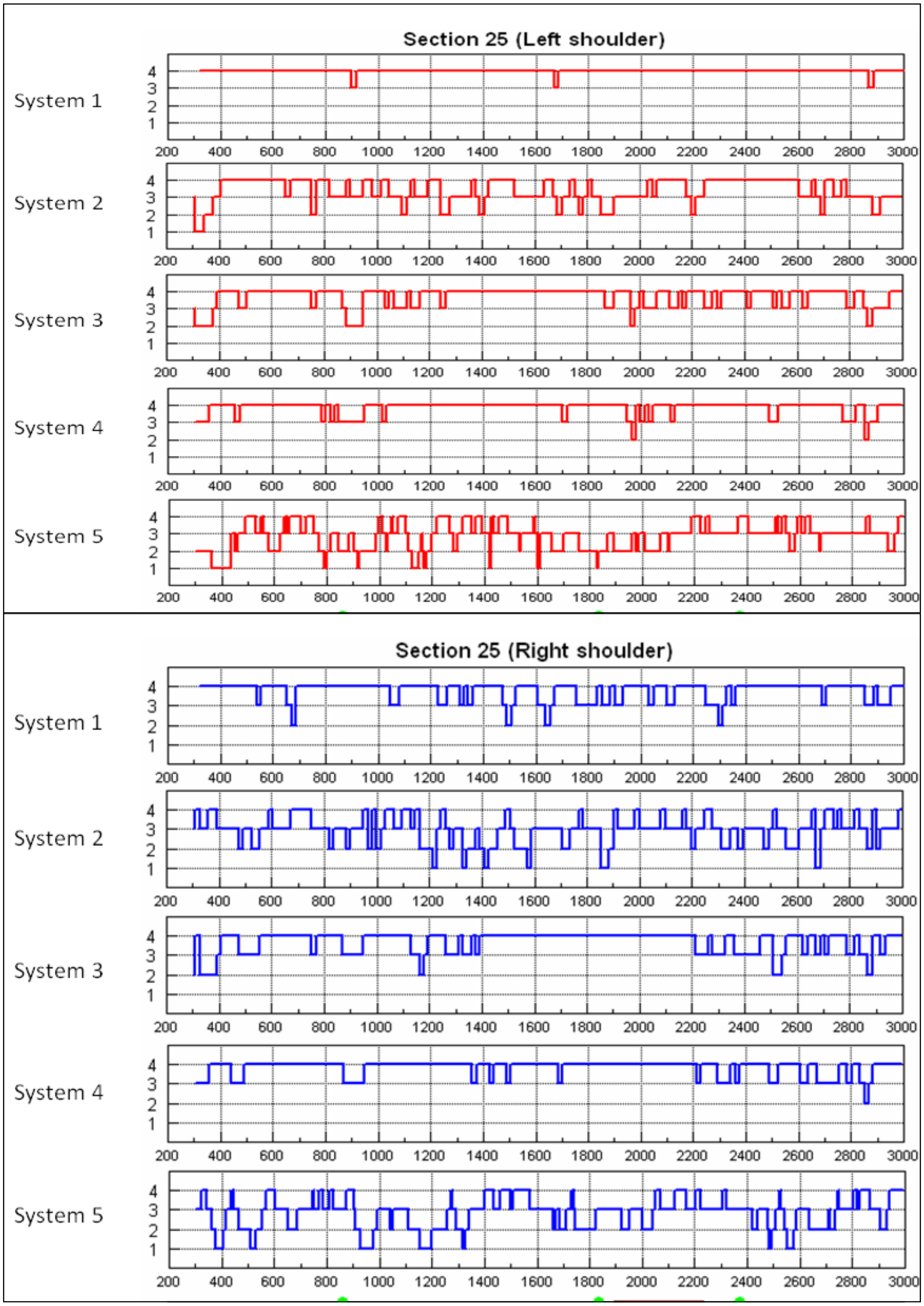


Figure 18. Fouling Categories for Both Shoulders Plotted Against Distance

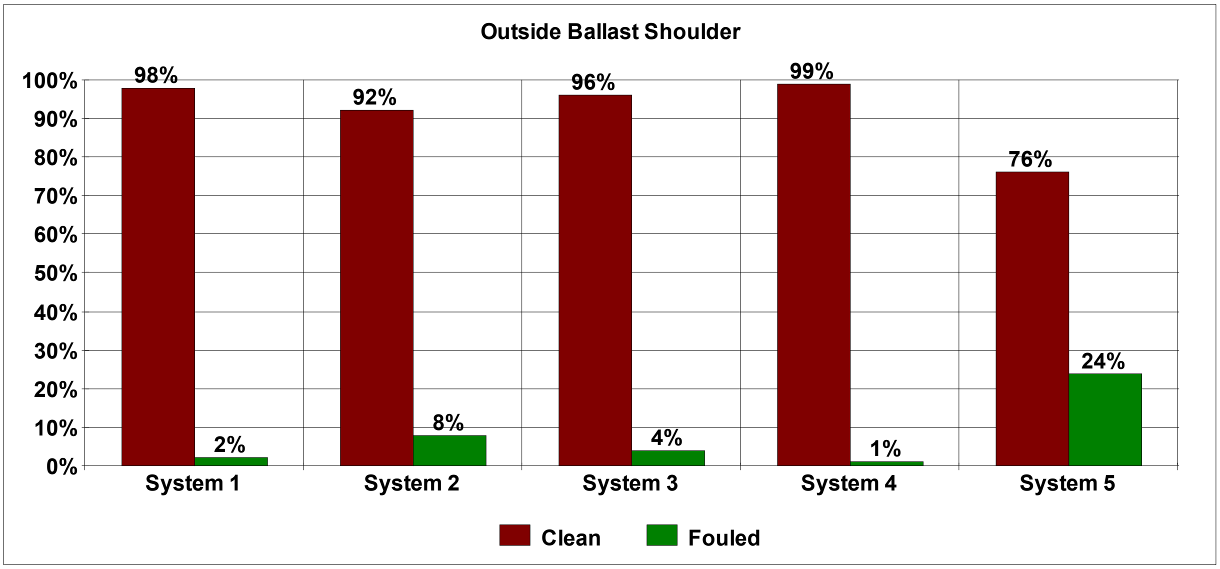


Figure 19. Comparison of Outside Ballast Shoulder Clean/Moderately Clean and Fouled/Moderately Fouled Interpretation

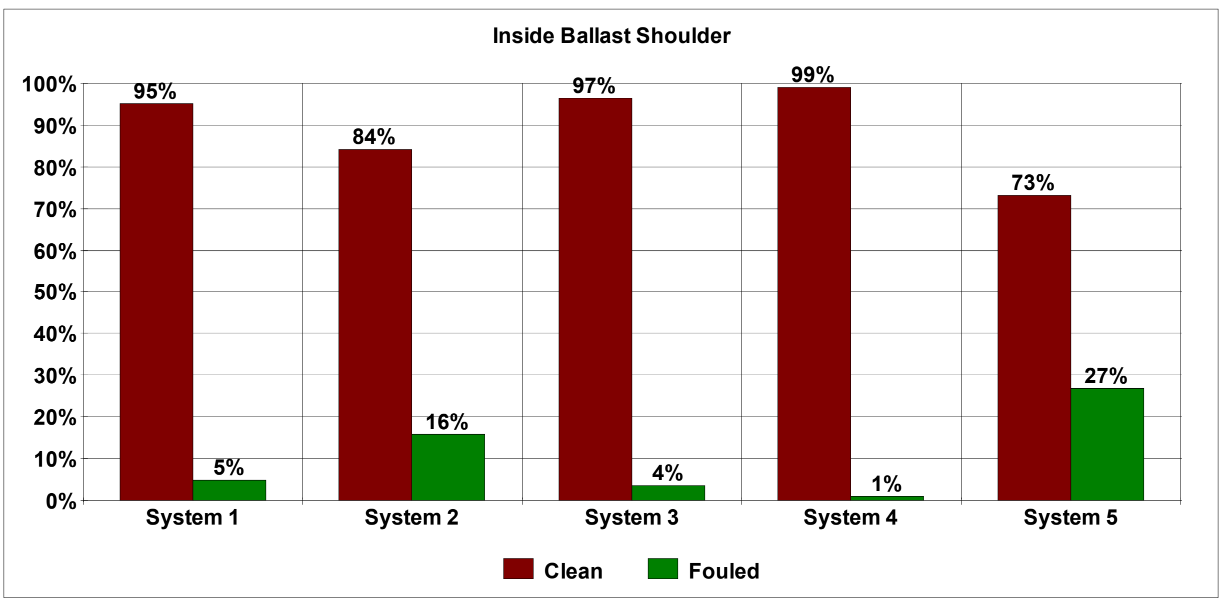


Figure 20. Comparison of Inside Ballast Shoulder Clean/Moderately Clean and Fouled/Moderately Fouled Interpretation

3.1.2 Ground-Truth Comparisons

Trenches were dug and ballast samples taken at eleven HTL locations immediately after the surveys were performed in late 2010. Additional ballast samples were taken without trenching at four locations in Section 25 during the summer of 2011. Sieve analysis was performed on all the samples to determine the particle size distribution or gradation of the sample.

Unfortunately, the earlier samples do not accurately represent the ballast layer as seen by GPR as most of the ballast was taken from beneath the ties to the subgrade surface rather than from the top of the ballast layer to a depth of approximately 20 in.

The subsequent Section 25 data is the most useful for this evaluation because the samples were taken in the top 20 in of the ballast at the outside shoulder and track center. Ballast samples were taken at tie numbers 200, 500, 700, and 1200 in Section 25. Figure 21 shows the gradation curves for the samples.

In Figure 21, the track center ballast sample particle size distribution, or gradation (red curve), and the outside shoulder sample gradation (green curve) are plotted along with the American Railway and Maintenance-of-Way Association (AREMA) Recommended Ballast Gradations 24 and 4 for mainline track [12]. All the data in Figure 18 lies within the AREMA 4 and 24 boundaries, indicating a low level of fouling at these locations.

Data in Figure 21 is summarized as follows:

- The track center ballast gradations at ties 200 and 1200 and the all the outside shoulder gradations are within the AREMA standards for clean ballast.
- The track center gradations at ties 500 and 700 are close to the outer AREMA 24 ballast limit and could be interpreted as being clean or moderately clean.

In Figures 22–26, the HTL generic track center fouling data from Section 25 is plotted as a function of distance for systems 1, 3, 4, 5, and 6 respectively. The ballast sampling locations at tie numbers 200, 500, 700, and 1200 are also shown. In summary, systems 1, 3, and 4 were consistent with the sampling results, showing the ballast as clean or moderately clean. System 5 was also in agreement, with the exception of tie 200 where it reported the ballast as being moderately fouled. There was no agreement between the sampling results and the System 6 fouling data in Figure 21, with all four locations being classified as moderately fouled.

The gradation data in Figure 21 is compared with the normalized fouling data for the outside shoulder of Section 25 in Figure 27. Systems 1–4 indicate clean ballast at the four sample locations, which is in agreement with the samples. System 5, however, shows a more fouled condition, which does not agree as closely as the other systems.

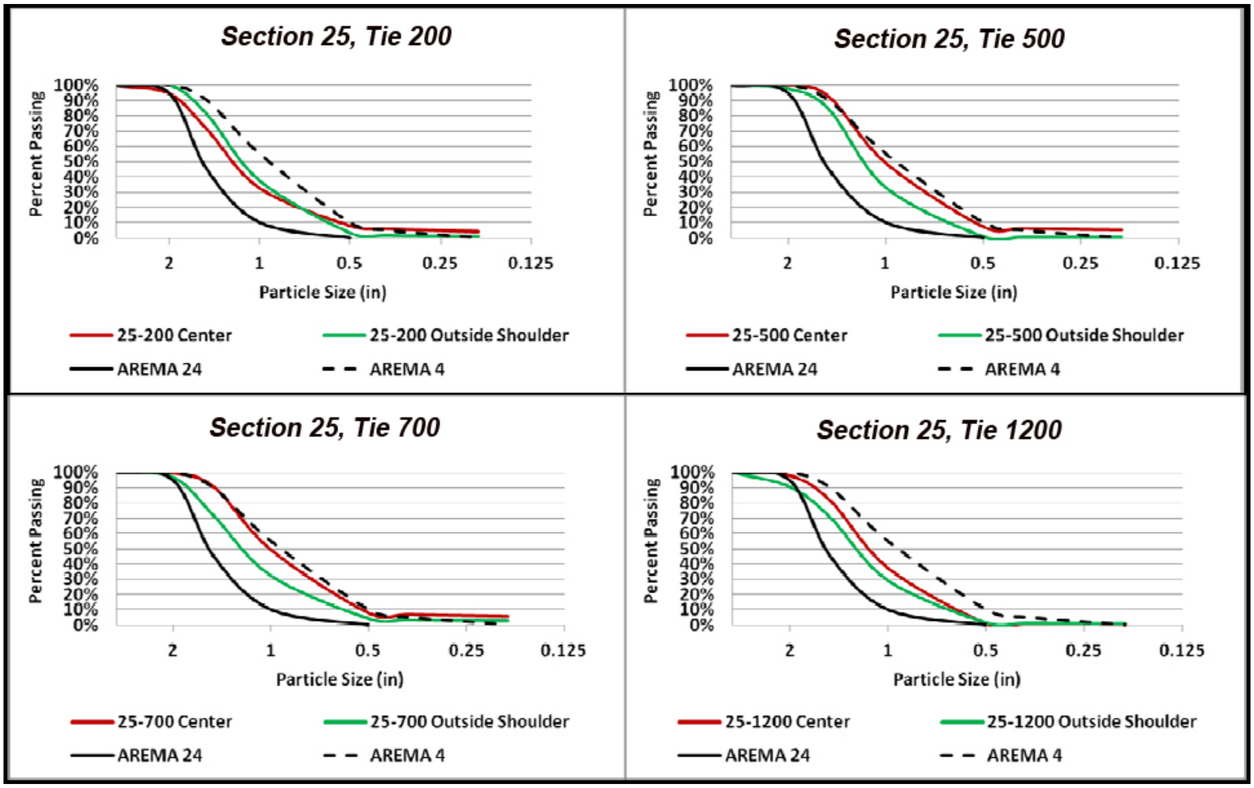


Figure 21. Section 25 Ballast Sample Gradations

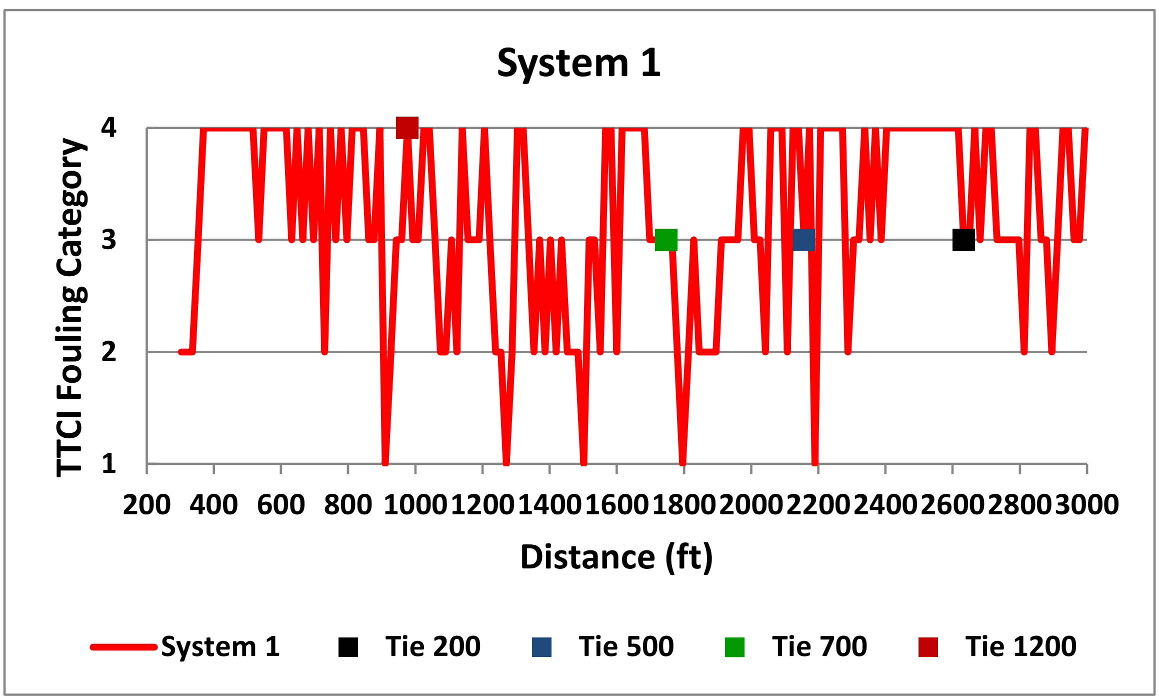


Figure 22. System 1 Track Center Fouling Data for Section 25 with Sampling Locations Indicated

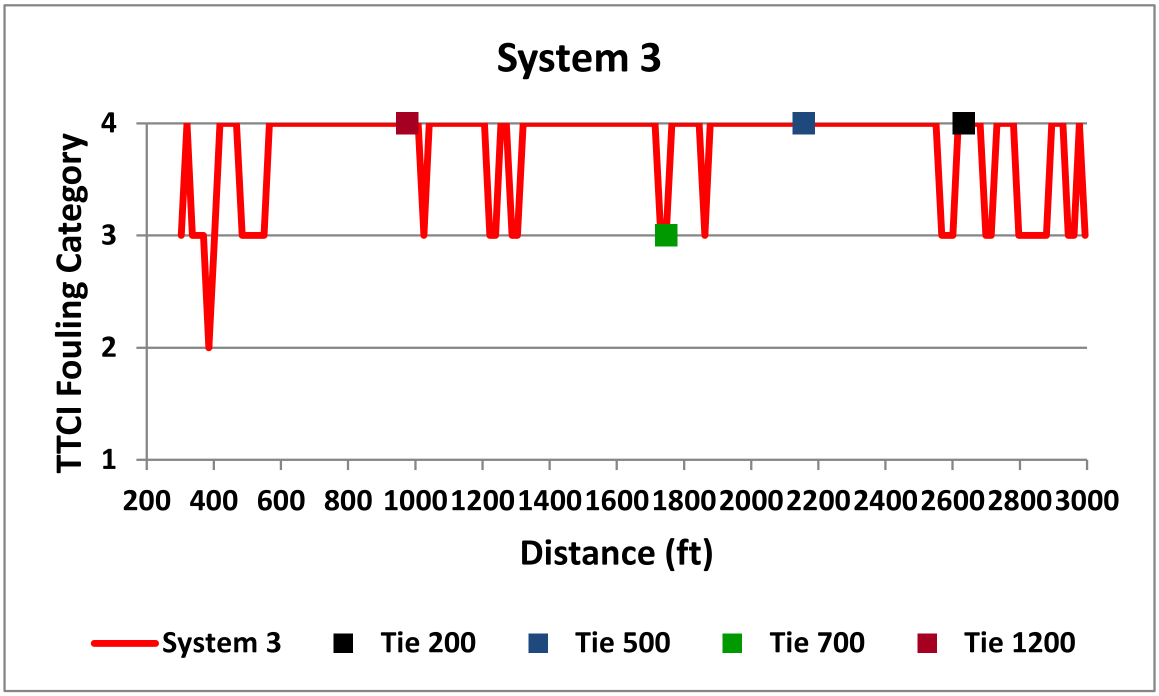


Figure 23. System 3 Track Center Fouling Data for Section 25 with Sampling Locations Indicated

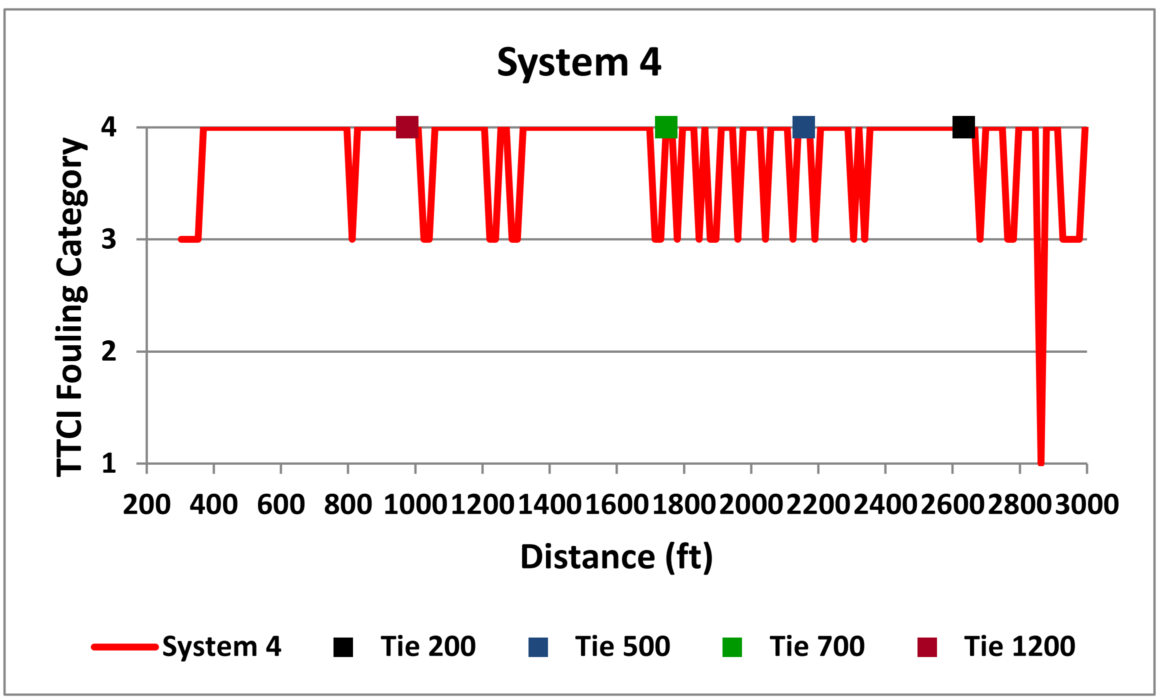


Figure 24. System 4 Track Center Fouling Data for Section 25 with Sampling Locations Indicated

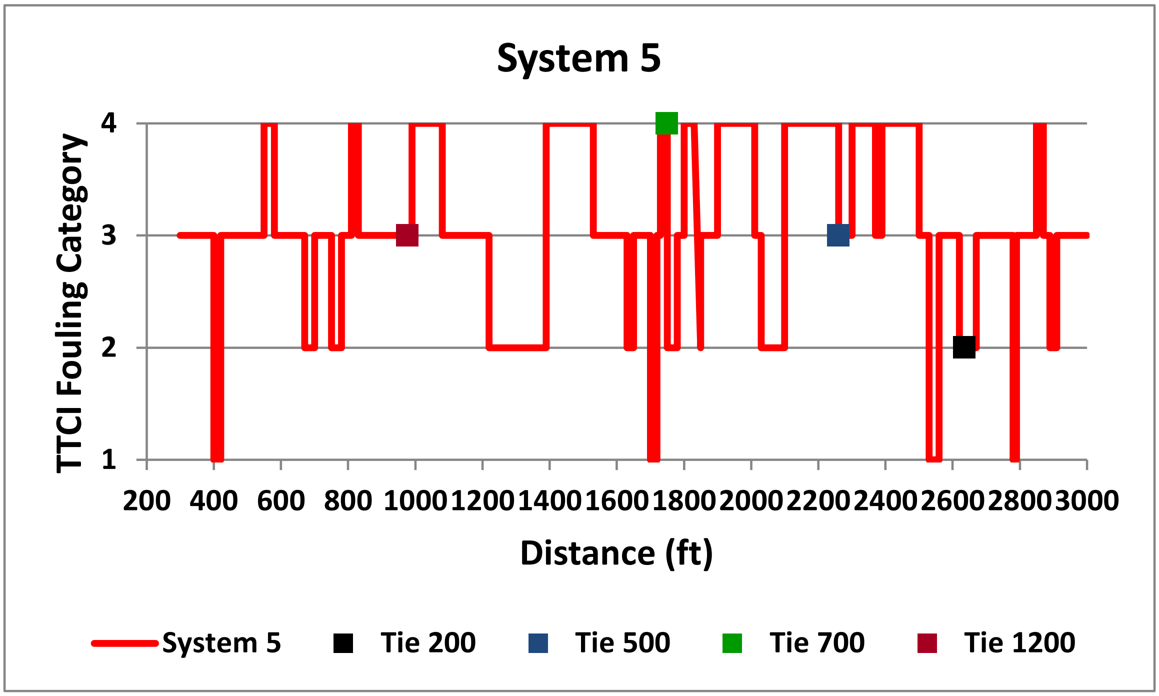


Figure 25. System 5 Track Center Fouling Data for Section 25 with Sampling Locations Indicated

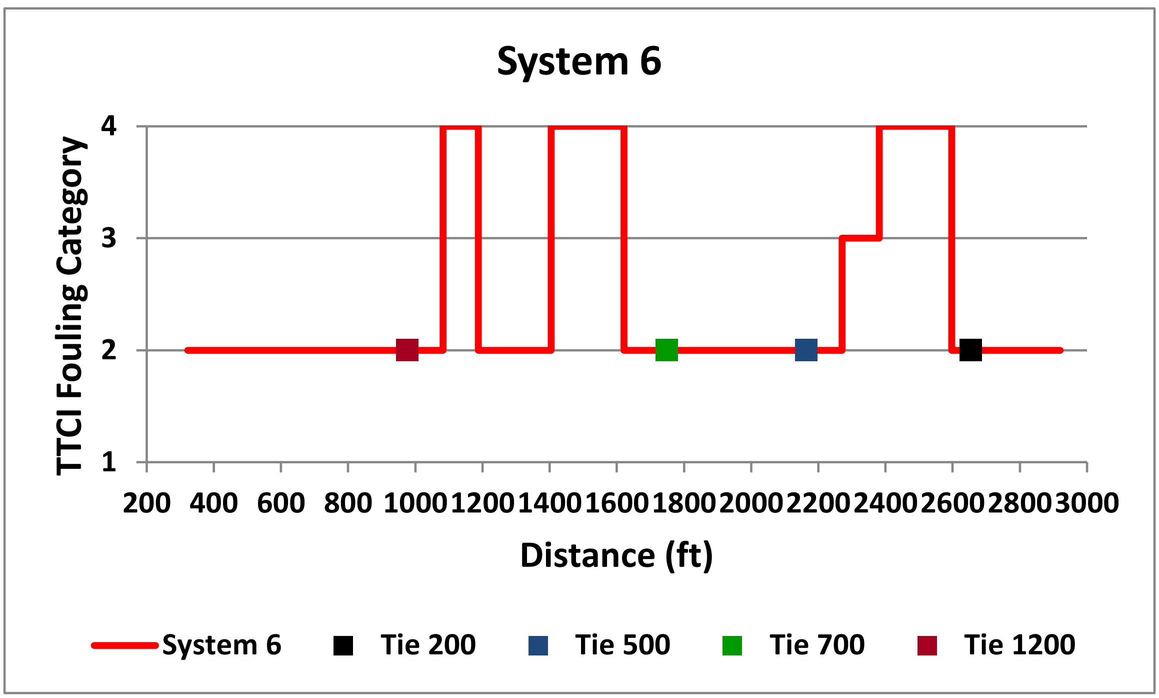


Figure 26. System 6 Track Center Fouling Data for Section 25 with Sampling Locations Indicated

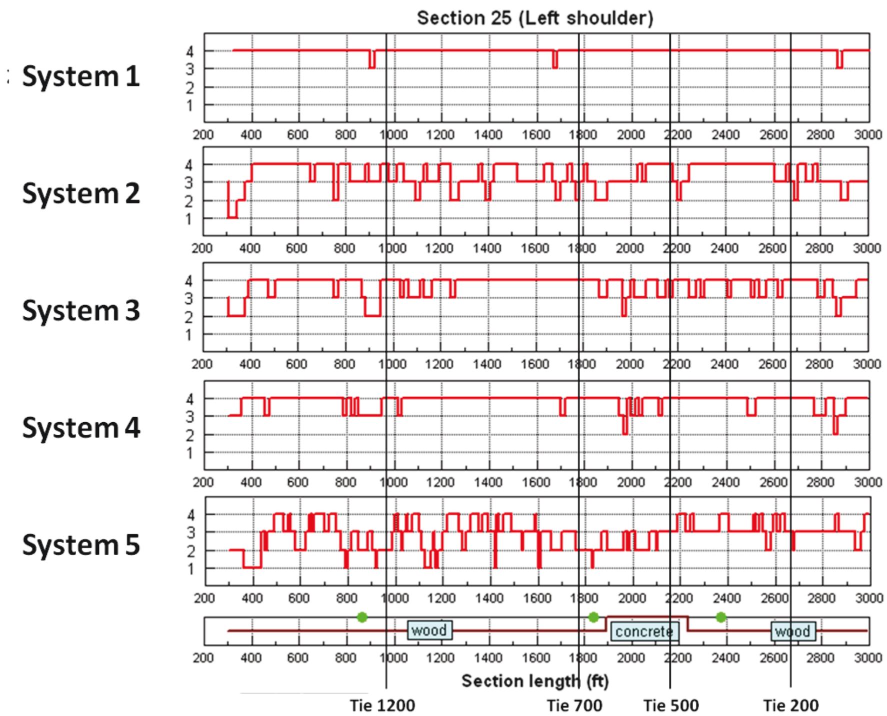


Figure 27. Fouling Data for the Outside Shoulder of Section 25 with Sampling Locations Indicated

3.1.3 Section 3 Anomaly

The largest discrepancy between the GPR fouling output and the actual ballast condition occurred in Section 3 at a location with relatively new ballast that had been in place for about 18 months. The sample gradation shown in Figure 28 indicates that the ballast is clean and the track center and outside shoulder gradation curves overlay the AREMA 24 recommended gradation very well. GPR systems 2–5 all saw the ballast at this location as being clean; however, system 1 indicated a highly fouled condition, as Figure 28 shows. The system 1 geophysics provider performed a full investigation of the apparent inconsistent output and determined the cause to be a higher measured percentage of small and flat/elongated ballast particles at the location.

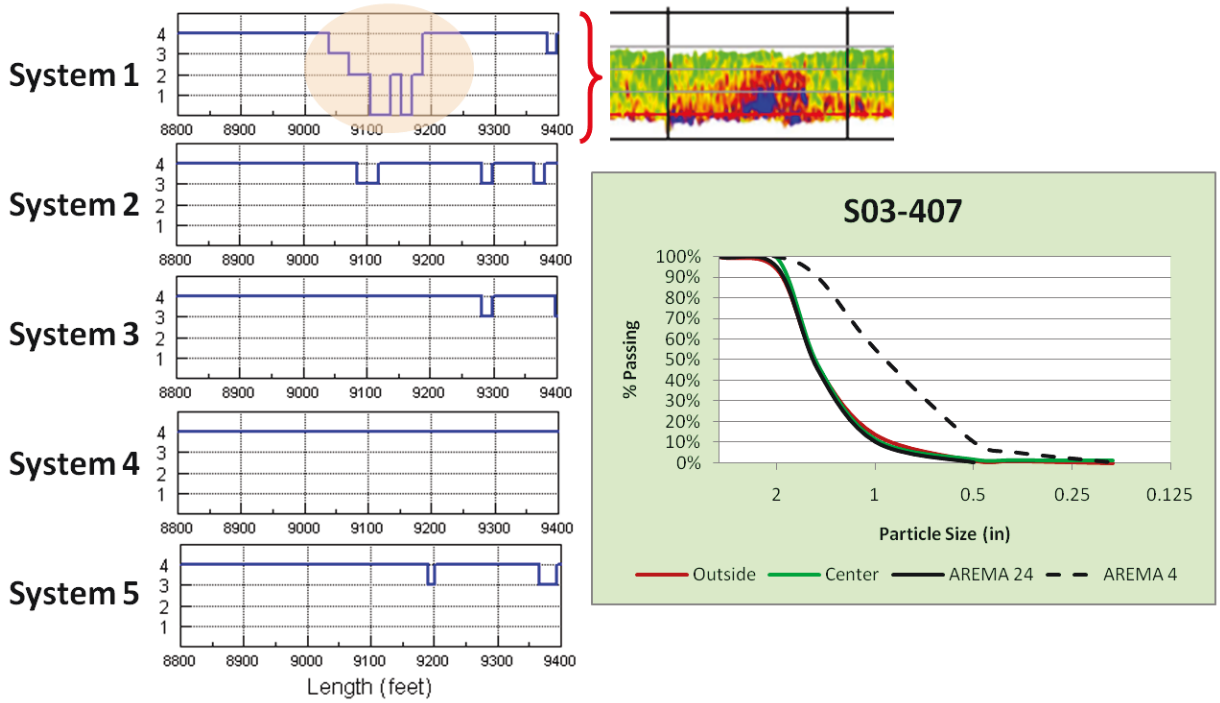


Figure 28. Anomalous Output from System 1 in Section 3

3.1.4 Tie Type Effect

The presence of ties and the incompatibility of the GPR signal with ties is one of the issues that can complicate track surveys. HTL Section 3 is approximately one-half concrete ties (1,419 ft) and one-half wood ties (1,667 ft) with recently screened or new ballast throughout. This condition was used to evaluate the effect, if any, of tie type on the track center fouling data. This analysis was performed, in part, because of the failure of System 2 to produce track center data, possibly due to noise from the ties.

The normalized track center fouling distributions for systems 1, 3, 4, and 5 in Section 3 are broken down into the concrete and wood tie segments of the section in Figure 29. The data in Figure 29 does not show a change in the distributions due to tie type difference for any of the systems. It does show the approximate 20-percent difference in clean ballast between System 1 and systems 3 and 4 that was noted earlier in the report.

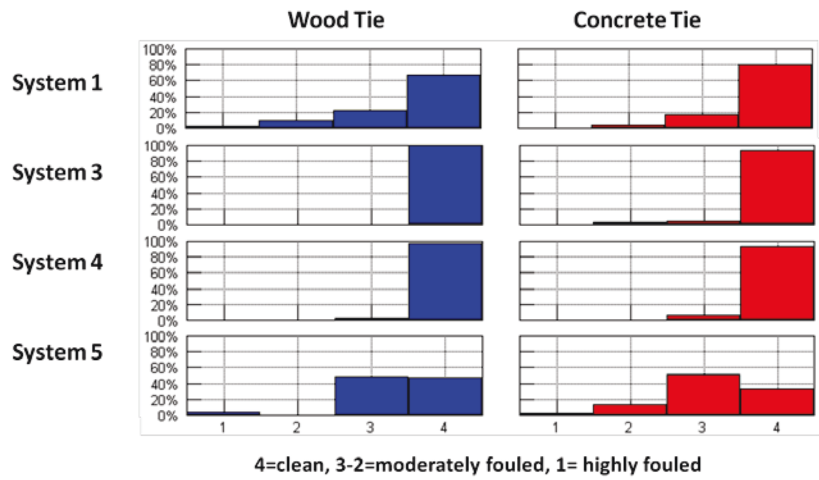


Figure 29. Comparison of Normalized Fouling Data Distributions for Wood and Concrete Ties in Section 3

3.2 Ballast Layer Thickness

Figures 30, 31, 32, and 33 show distance plots of the outside (left) shoulder and track center primary ballast layer depths from all systems for Sections 25, 7, 3, and 33, respectively. These sections have roughly equivalent ballast types and conditions and primary ballast depths of 10 to 15 in.

Primary ballast layer results are summarized as follows:

- Section 25: All systems gave results that were generally within 6 in of one another with one exception: System 6 gave a track center depth of 18–24 in between section footage 2,000–2,400, compared with depths of 9–12 in from the other systems.
- Section 7: Similar results were produced by all systems with the following exception: systems 2, 3, 4, and 5 indicated a reduced track center depth in the last 100 ft of the section from roughly 20 to 12 in, whereas system 1 saw no change in depth at the same location, and System 6 who saw an increase in depth from approximately 9 to 24 in.
- Section 3: The basic layer thickness longitudinal profile was similar for all systems, but with variations in depth of 6–12 in between the systems. The largest discrepancy occurred at approximately section footage 3,200 ft, where System 5 indicated an increase in the track center and outside shoulder ballast depths of approximately 12 inches. Systems 1 and 6 also showed an increase in depth. However, systems 2, 3, and 4 all showed a decrease in depth at the same location. Spot checks of the ballast depths in Section 3 indicated that 18–20 in is typical.
- Section 33: All systems showed consistent results for the first half of the section. However, at roughly section footage 450, systems 1, 2, 3, and 4 all indicated a decrease in depth of approximately 6 to 9 in that was not seen by systems 5 and 6. A second discrepancy is at section footage 680 where system 1 shows an increase in thickness from 12 to 24 in that is not seen by systems 2, 3, or 4.

An example of the secondary layer interpretation is provided in Figure 34, where the Section 25 track center data for all systems is plotted against distance. The basic longitudinal profile is the same for all systems, although System 6 does show the thickness as approximately 6 in less than the others for the first 1,800 ft of the section. The largest discrepancy is the intermittent multiple layer indications from System 1, highlighted in Figure 34 by showing only the System 1 data points. The multiple layer indications were found in other HTL sections and were discussed in the System 1 summary report as possibly being caused by moisture and/or material variations or by track-bed repairs.

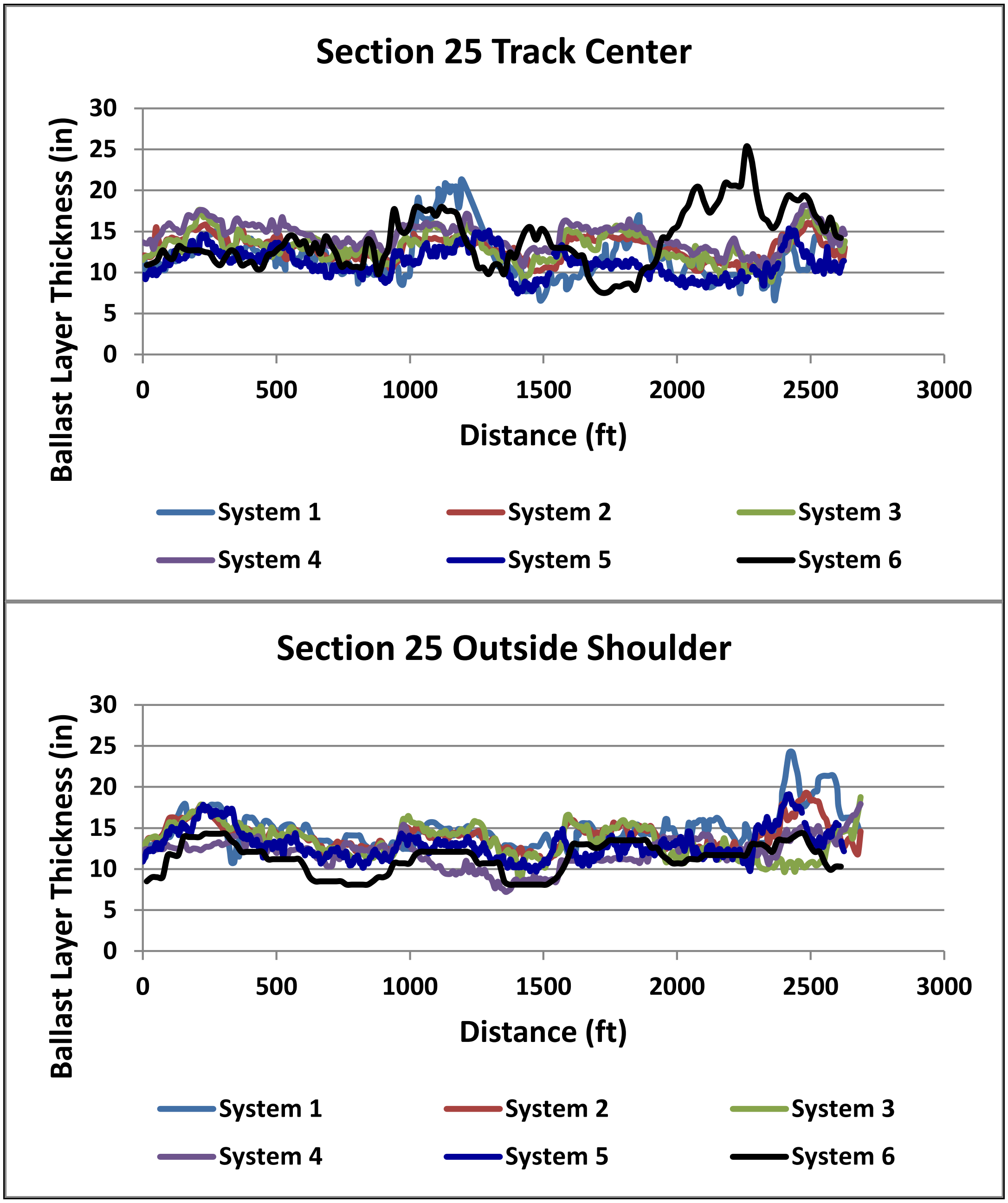


Figure 30. Section 25 Primary Ballast Layer Thickness Comparison

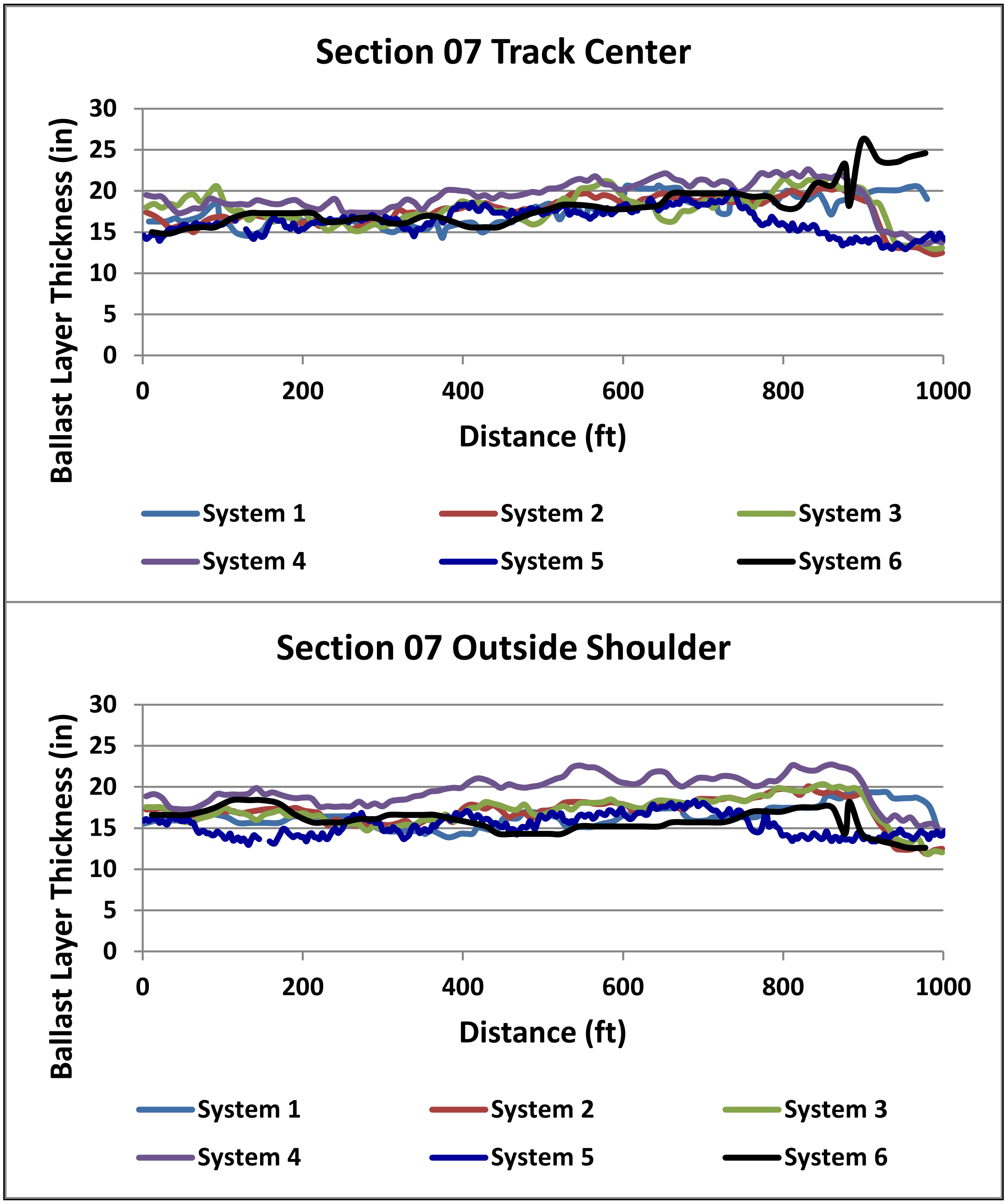


Figure 31. Section 7 Primary Ballast Layer Thickness Comparison

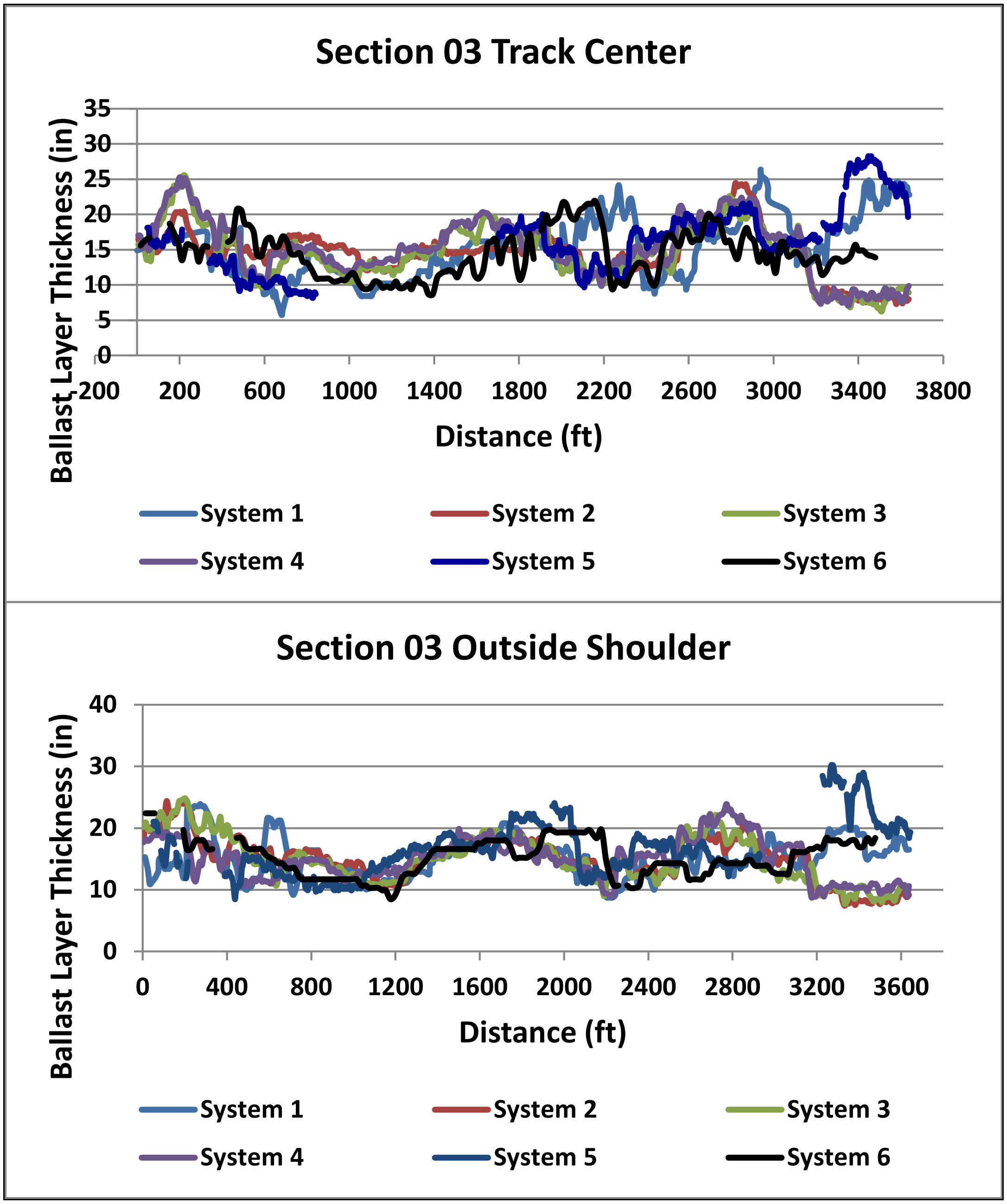


Figure 32. Section 3 Primary Ballast Layer Thickness Comparison

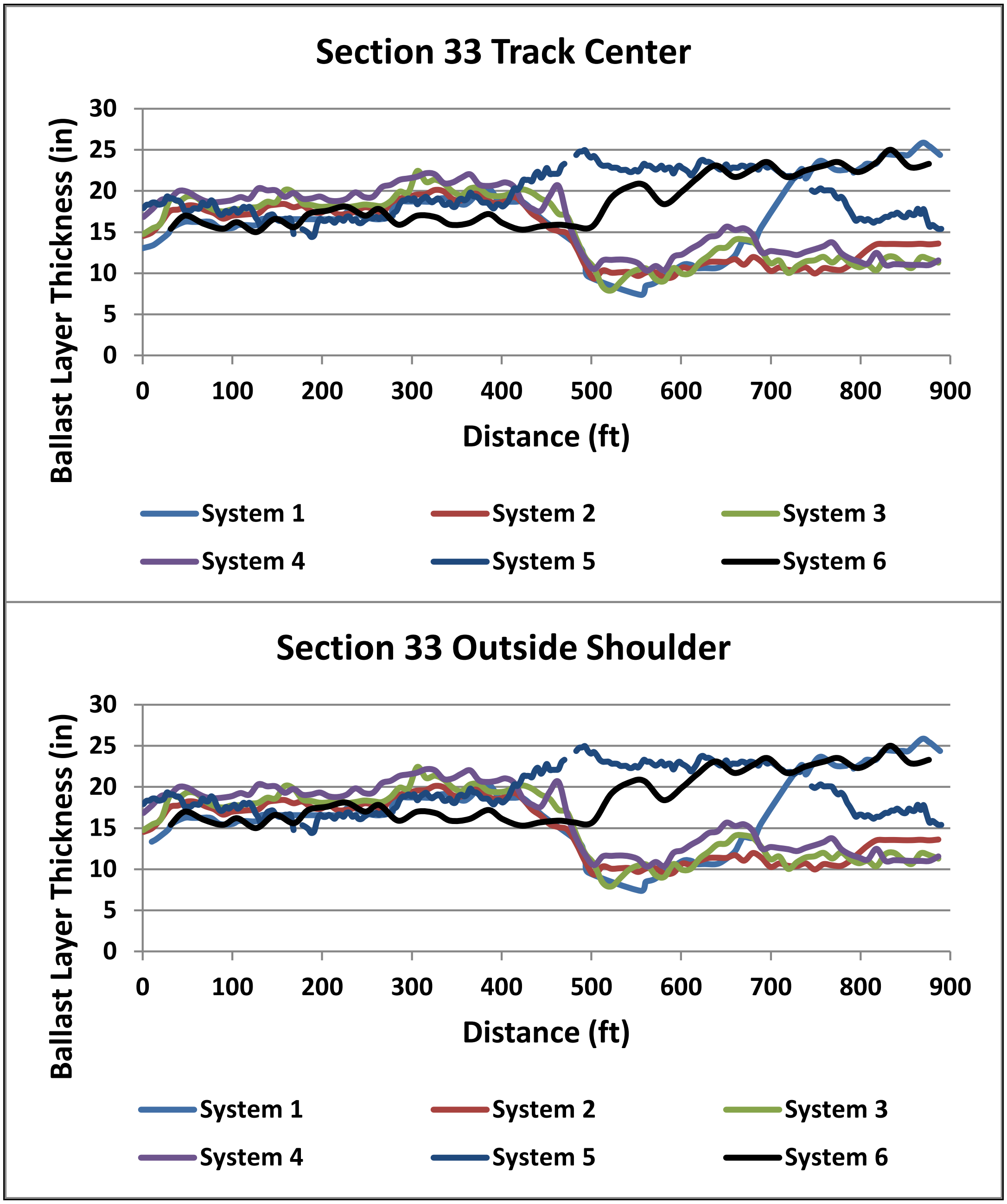


Figure 33. Section 33 Primary Ballast Layer Thickness Comparison

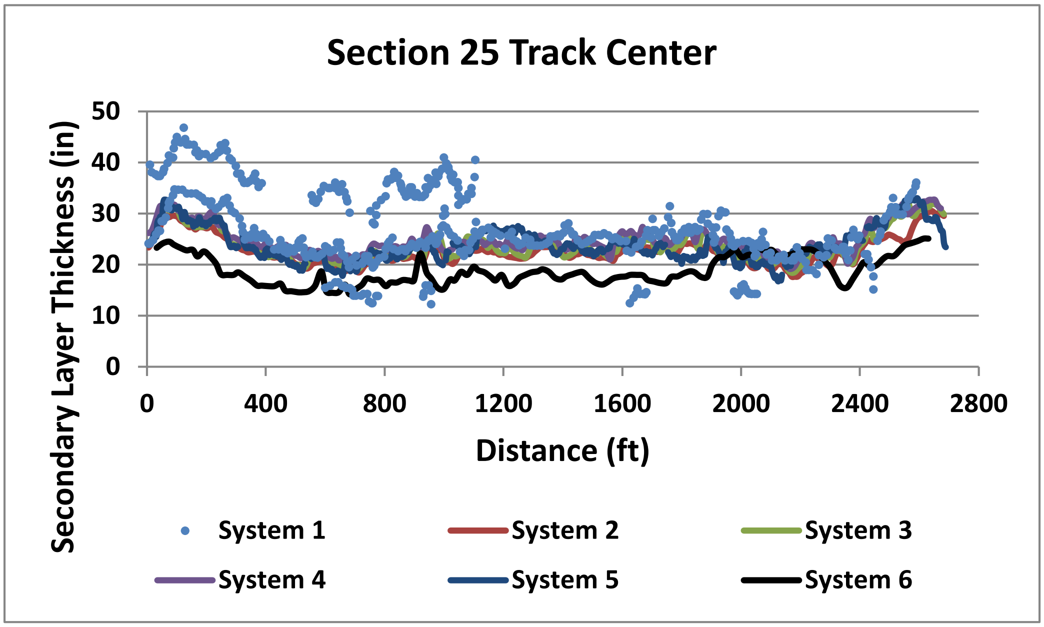


Figure 34. Secondary Ballast Layer Interpretation for Section 25 Track Center

3.3 Ballast Moisture Test

All systems were involved in a moisture condition test performed in Section 33. A survey was taken before and after water was artificially added to the track over a distance of approximately 50 ft using a fire truck. All the systems were able to distinguish the increase in moisture and to determine by a change in the moisture profile with depth that the water was draining.

The results confirm the well-established ability of GPR to sense relative changes in moisture. However, the outputs of systems 2–5 also showed a strong correlation between relative moisture level and relative ballast fouling, which is not surprising given the strong effect of water on the GPR signal response. Therefore, the ability of GPR to determine absolute moisture content in the ballast layer was not confirmed by this evaluation. Evaluations did, however, show that high moisture content occurring where water is trapped at the bottom of ballast pockets is readily visible to GPR as a strong interface reflection.

3.4 Preliminary Conclusions

- Six systems were included in the evaluation:
  - System 1 using 400-MHz pulsed antennas for layer interpretation and 2-GHz pulsed antennas for fouling inspection and scattering fouling analysis.
  - System 2 using 1-GHz pulsed antennas and dielectric dispersion analysis for fouling.
  - System 3 using 400-MHz pulsed antennas from antenna manufacturer 1 and dielectric dispersion for fouling analysis.
  - System 4 using 400-MHz pulsed antennas from antenna manufacturer 2 and dielectric dispersion for fouling analysis.

- System 5 using SFCW wave antenna from antenna manufacturer 3 and dielectric dispersion for fouling analysis.
- System 6 using pulsed 400-MHz antennas from antenna manufacturer 2 (same antennas as used by system 4), 900-MHz antennas from manufacturer, and signal propagation analysis for fouling and layer thickness interpretation.

- All systems except System 6 showed a low percentage (<6 percent) of the track as highly fouled. System 6 results indicated that 30 percent of the track center was highly fouled, and 44 percent was moderately fouled.
- Gradation analysis of ballast samples taken at four locations within HTL Section 25 was in general agreement with the fouling data from all systems except System 6. The samples taken at four locations within the section all produced gradation curves conforming to AREMA 4 and 24 standards for new ballast, indicating the ballast at the locations was clean. Fouling data produced by systems 1, 2, 3, 4, and 5 all showed the ballast as clean or moderately clean, which is considered as being in agreement with the degradation results. System 6, however, showed the ballast as being moderately fouled at all the sampling locations.
- Although all systems except System 6 indicated the ballast was primarily clean or moderately clean, as opposed to being moderately or highly fouled, there were notable inconsistencies between systems 1–5, including:
  - Systems 1 and 5 showed considerably more fouling and more fouling variation in the track center than systems 3 and 4. Systems 1 and 5 both showed the center as being 11 percent moderately fouled compared with less than 1 percent for systems 3 and 4. Systems 1 and 5 also showed a higher percentage of moderately clean ballast (20 and 49 percent, respectively) than systems 3 and 4.
  - System 1 showed similar percentages of clean and moderately clean shoulder ballast, as well as the tendency for the inside shoulder to have less clean ballast than the outside. Systems 2 and 5 showed higher percentages of moderately clean and moderately fouled ballast compared with the other systems. System 2 also showed less fouling on the outside shoulder.
- Systems 1–5 comparative fouling results are summarized as follows:
  - Track center: Systems 3 and 4 indicated, respectively, that 92 and 88 percent of the track center ballast was clean, whereas system 1 showed 67 percent and system 5 showed 34 percent as clean. System 1 reported 13 percent and system 5 reported 17 percent of the track center as moderately or highly fouled, compared with only 1 percent from systems 3 and 4. Systems 1 and 5 also showed a higher percentage of moderately clean ballast (20 and 49 percent, respectively) than systems 3 and 4. In summary, systems 1 and 5 showed significantly more variation in the track center fouling condition than systems 3 and 4. System 2 did not submit track center fouling data.
  - Ballast shoulders: System 5 showed the highest amount of moderate to highly fouled conditions—24 percent of the outside shoulder and 27 percent of the inside shoulder—compared with systems 1–4 that were at 16 percent or less. Other than the

system 5 fouling discrepancy, the other notable difference between systems was in the interpretation of moderately clean as opposed to clean ballast. System 1 saw both shoulders as having a lower percentage of moderately clean and higher percentage of clean ballast compared with the others, although systems 1 and 4 results for the inside shoulder were very similar.

- System 6 did not submit shoulder fouling data in a digital format.
- The 2-GHz/scattering analysis system did show a highly fouled condition at a clean ballast location that was not seen by the dielectric dispersion frequency analysis systems. Subsequent analysis by the supplier indicated that high percentages of flat and elongated ballast particles were the probable cause of the highly fouled interpretation.
- All the systems produced similar ballast layer longitudinal profiles although variances of 6–9-in in the reported primary layer thickness values were common. There were two significant discrepancies in the layer interpretations. The first discrepancy was at the end of Section 3 where systems 1, 5, and 6 indicated an increase or no change in the track center and outside shoulder ballast depths while systems 2, 3, and 4 all showed a substantial decrease in depth. Spot checks of the ballast depths did not support the reported reduced thickness. The second discrepancy occurred in the center of Section 33 where systems 1, 2, 3, and 4 all indicated a decrease in depth of approximately 6–9 in that was not seen by systems 5 and 6. An additional discrepancy was noted near the end of the section where system 1 shows an increase in thickness from 12 to 24 in that was not seen by systems 2, 3, or 4.
- All systems were able to distinguish a change in ballast moisture after water was added to the track in Section 33. The systems were also sensitive to changes in the moisture profile with depth.

4. GPR Implementation Guidelines for Track Surveys

The following general guidelines are presented based on the evaluation results at FAST.

4.1 Antenna Frequency and Fouling Analysis Methods

There are two methods that have been developed and are currently in use by commercial systems to determine ballast fouling: (1) signal scattering and (2) dielectric dispersion frequency analysis. Both methods distinguish clean ballast from fouled, but with different approaches. The scattering method requires the signal wavelength to be approximately the same size as the perimeters of air voids in clean ballast, and the 2-GHz wavelength is theoretically optimal. The wavelengths of lower frequency signals are too long and, therefore, not scattered by the voids.

The dispersion method converts the recorded time domain data to the frequency domain and generates a frequency spectrum. Clean ballast has less dielectric dispersion and a wider spectrum with higher frequency components than fouled ballast. However, in addition to fines, dielectric dispersion is also influenced by moisture, and the method cannot readily differentiate between moisture and fines. In many cases, this limitation is not critical, because there usually is a correlation between increased fouling and increased moisture being retained by the fouling. However, erroneous fouling results may be generated if the GPR survey is conducted when the ballast is abnormally wet (fouling is overstated) or dry (fouling is understated).

The application of the dispersion method to the 1-GHz data proved to be unsuccessful during the evaluation at FAST for the track center survey; therefore, it is unclear how appropriate this method is for frequencies higher than 400 MHz. The dispersion method was also used on the SFCW antenna data that was statistically different from the various pulsed antenna data. Both the scattering (System 1) and dispersion methods (systems 3 and 4) produced similar results in terms of the percentage of moderately fouled to fouled ballast on the shoulders. The primary differences between these systems were: (1) the percentages of clean and moderately clean ballast reported on the shoulders and (2) the percentages of moderately fouled ballast in the track center.

In summary, the ballast fouling method used by the GPR provider will dictate the choice of antenna frequency. The scattering method, which is not reliant on dielectric properties, should not be used with frequencies less than 2 GHz. Dielectric dispersion, which is sensitive to dielectric variations, particularly moisture variations, has been developed for use with 400-MHz antennas. Finally, the 2-GHz signal penetration is limited to approximately 30 in depending on the material. Deeper penetration, which is usually desired for adequate track substructure layer interpretation, requires lower antenna frequencies, of which 400 MHz is common.

4.2 Calibration

Both the scattering and dispersion fouling analysis methods require calibration to ballast sample sieve analysis data to quantify the GPR data in terms of fouling percentages of an FI. Calibration, specifically to the ballast on the HTL, was not done as part of the evaluation at FAST, although the output from System 1 was based on a ballast calibration performed using a specific railroad's ballast condition.

Calibration issues include what FI should be used, how many samples are necessary, how often they should be taken, and what procedure should be used to take the samples.

The FI that is most commonly referred to is the Selig FI that adds the material passing a No. 4 sieve to the fines passing a No. 200 sieve. The Selig FI is well documented regarding its relationship with ballast permeability and generalized ballast performance [6]. However, it double-counts the fines passing the No. 200 sieve as the same material also passing the No. 4 sieve. Therefore, calibration of the GPR results to the Selig FI would appear to be difficult.

A simpler approach would be to base the FI on a percentage of material passing a single-sieve size. An FI being used by a Class I railroad is the percentage of material passing the 3/4-inch sieve. With this approach, 25 to 35 percent passing the 3/4 sieve is set as an undercutting maintenance limit, and 50 percent is considered the ballast life limit. A similar approach could be used to calibrate the fouled and highly fouled thresholds of the GPR data.

Ballast sampling frequency can be defined based on local conditions and material variability. The sampling procedure, however, is important. The sample should duplicate as much as possible the same ballast seen by the radar. Ideally, a sample would be a column of material approximately 8-in in diameter taken at the appropriate inspection depth at the tie ends and track center.

4.3 Data Handling

All the systems evaluated at FAST produced a set of results within 24 hours of the inspection as one of the key evaluation criteria. The 24-hour turnaround results were, in most cases, consistent with the final interpretation of results that were received several weeks later indicating the current capabilities for rapid submission of results. However, as currently deployed via hi-rail vehicles, a GPR survey will collect data at speeds of roughly 15 to 20 mph, or faster if deployed on track geometry vehicles. It is therefore possible for the inspection to generate tens, if not hundreds, of miles of data in 24 hours, which may be more data than can be processed and analyzed in a short amount of time. Therefore, the railroad should have an understanding with the supplier as to data processing times and, if necessary, prioritize the track segments it wants analyzed. The processing and analysis time will certainly decrease in the future as the algorithms become more sophisticated and the process becomes more automated.

5. References

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Abbreviations and Acronyms

AAR	Association of American Railroads
AREMA	American Railway and Maintenance-of-Way Association
FRA	Federal Railroad Administration
FI	Fouling Index
FAST	Facility for Accelerated Service Testing
GPR	Ground Penetrating Radar
GBFI	GPR Ballast Fouling Index
HMA	Hot Mix Asphalt
HTL	High Tonnage Loop
IDS	Ingegneria dei Sistemi
LAE	Layer Amplitude Exceedence
RC	Reflection Coefficient
SFCW	Stepped Frequency Continuous Wave
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.