Evaluation of Ground Penetrating Radar Technologies
for Assessing Track Substructure Conditions

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Abstract
Over the past few years, significant progress has been made using ground penetrating radar (GPR) technology to assess track substructure (ballast, subballast, and subgrade) conditions. Several GPR technologies developed in the United States and Europe have shown great potential as production inspection tools for testing ballast, subballast, and subgrade in an automatic and nondestructive manner. In 2009, under joint funding from the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA), Transportation Technology Center, Inc. (TTCI) started a project to objectively evaluate various GPR technologies for track substructure assessment, develop GPR implementation guidelines for North American railroads, and determine additional research needs for further improvements. This paper presents preliminary results and findings, as well as the path forward to achieve the final goals of the project.

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INTRODUCTION

Ballast, subballast, and subgrade form the foundation of the track and are often referred together as the track substructure. The condition of railroad track substructure has a profound influence on track performance. Poorly performing track substructure not only results in high rates of track geometry degradation, but also promotes higher rates of wear and failures of rail, ties, fasteners, and special trackwork.

North American railroads are placing increased demands on the track substructure with increased axle loads, traffic density, and train operating speeds. Accordingly, a significant part of North American Class 1 Railroads’ track maintenance budget is being allocated to cleaning and renewing ballast and correcting rough track geometry that is caused by the deformation in the track substructure under repeated train loading.

Many, if not most track substructure problems, are caused by conditions that tend to reduce the strength and stiffness of the track substructure, including:

- The inability of the track substructure to drain water from the track
- Fouled and deteriorated ballast conditions caused by ballast breakdown and/or infiltration from outside the track
- Over-stressed subgrades that are prone to deformation
- Non-uniform support conditions along the track

Although these conditions are well known as being problematic, their extent and severity are difficult to determine by visual inspection of the track surface and are, therefore, often unknown. Increased knowledge of the track substructure condition through enhanced inspection and testing techniques that measure the track substructure state continuously and
nondestructively will enable railroads to better prioritize their track maintenance programs and determine root causes of localized track substructure problems.

There are basically two onboard and nondestructive inspection techniques that are applicable to track substructure condition assessment: continuous vertical track modulus/stiffness testing and GPR testing (1-7). Track modulus/stiffness testing characterizes the capacity of the track substructure to support the track as an aggregate system, but cannot differentiate the condition of individual components. GPR, on the other hand, is capable of determining component conditions, such as the degree of ballast fouling, water trapped in the ballast or subballast layers, ballast and subballast layer thicknesses, and shape of the subgrade surface along and across the track (ballast pockets).

In 2009, TTCI started a project to evaluate the capability of available GPR technologies to determine track substructure conditions, and subsequently, develop guidelines for the implementation of GPR by North American member railroads. Known ballast and subgrade conditions at the Facility for Accelerated Service Testing (FAST) and in revenue service were used as test beds to evaluate GPR technologies. At FAST, track substructure conditions include test sections installed with various degrees of coal fouling and moisture conditions, as well as a soft subgrade test section containing various remedies. Revenue service test sites include a number of muddy ballast locations on the Norfolk Southern (NS) Railway, which have required excessive maintenance activities and are being investigated concerning their root causes and potential long-term remedies under a companion track substructure research project (8). This paper gives some preliminary test results of the current GPR evaluation project in process and discusses the path forward to achieve the final goals of the project.
RECENT DEVELOPMENT IN GPR TECHNOLOGIES

GPR is a well-established subsurface inspection technique used for a variety of applications, such as archaeology, mining, utilities, and roads. In the past few years, significant research and development has been conducted in North America and Europe for railroad applications of GPR. Figure 1 shows the basic principles of how GPR is used for railroad track testing. As illustrated, a GPR antenna consists of a transmitter and a receiver. The transmitter emits electromagnetic pulses into the track substructure and the receiver records reflected signals in terms of signal strength (magnitude) and return time. Reflections occur when the signal encounters a change in material conductivity and dielectric permittivity. Part of the signal is reflected at the interface, while the remaining signal continues to subsequent layers.

![Figure 1. GPR for Railroad Track Substructure Testing](image-url)
As Figure 1 shows, three GPR antennae are configured above the track center and both shoulders to capture track substructure conditions across the track. Figure 2 shows additional examples of GPR antenna configurations with hi-rail vehicle applications. Furthermore, GPR systems can be installed on track geometry inspection vehicles or on trains.

**Figure 2. Examples of GPR Antenna Configurations for Track Substructure Testing**

In general, the inspection depth and resolution are determined by the GPR signal frequency. Signals with lower frequencies can penetrate deeper into the track substructure, but give less resolution, i.e., the signal is less sensitive to changes of differences in the track substructure materials. Increased signal frequency allows better resolution but at reduced depth of penetration. Moreover, GPR signals with higher frequencies are often susceptible to interference from surrounding signal noises. For railroad track substructure testing, the proper GPR signal frequency range is considered to be between 400 MHz and 2 GHz for depths of 2-10 feet.

Recent developments in GPR technologies include advancements in both GPR hardware and software. In the United States and Europe, there are several GPR systems (antennae and associated signal processing and data acquisition systems) commercially available for railroad applications. Several software packages have been developed based on the recent development
of algorithms for analyzing GPR signals. The algorithms can be used to interpret GPR signals to determine the following track substructure condition and performance parameters (1-7):

- Ballast and subballast layer thicknesses
- Degree and depth of ballast fouling
- Water trapped in ballast and/or subballast
- Presence of ballast pockets (fluctuation of deformed subgrade surface along and across the track)

In Figure 3 are GPR test results taken at a NS location in 2009. As illustrated, the results included ballast and subballast layer thicknesses, moisture content in ballast and subballast (color coded), amount of ballast fouling (color coded with index number), and the correlation of GPR test results with track geometry roughness results. Figure 3 also shows that good correlation existed between rough track geometry and shallow ballast layer thickness, high moisture content (in blue color), and a high degree of ballast fouling (in red color and with an index number of 3) at two locations on the track.
Figure 3. GPR Results and Correlation with Track Geometry Results

Figure 4 shows another example of test results obtained by the University of Illinois at Urbana-Champaign under AAR’s Technical Scanning Program (9). As illustrated, GPR signals can be used to determine the degree of ballast fouling and presence of accumulated water in the ballast. These test results were obtained in a laboratory testing environment.

Figure 4. Ballast Fouling and Moisture Interpreted from GPR Signals (Ref. 9)
EVALUATION OF GPR TECHNOLOGIES

As various GPR systems have been developed and are commercially available for railroad applications, there is a need to evaluate the systems in terms of their capability, reliability, and accuracy. To implement GPR as a production track substructure inspection tool in North America, guidelines are needed in terms of the performance parameters to be measured, testing procedures, calibration methods to be employed, and methods for using GPR results to prioritize the out-of-face production track maintenance programs and determine root causes of localized track substructure problems. Further, an objective evaluation of the current state of the art in GPR technologies will provide the basis for determining additional research and development needs.

In 2009, a multiyear project was started to address these needs. TTCI is conducting the project under joint research funding from the AAR and FRA. The first major task of the project was to evaluate the performance of GPR systems over tracks with known track substructure conditions at FAST and in revenue service. The long-term goals of the project include evaluating the capability of GPR technologies to not only identify track substructure problem locations, but also classify and quantify various track substructure problems, thus providing actionable data and recommendations for correcting localized problems and planning track maintenance programs. Long-term project goals also include the development of a better understanding of the cost and benefits associated with using GPR for railroad applications.

Available GPR technologies will be evaluated under this project in order to make an unbiased assessment of how various technologies characterize subsurface features. Other details to be evaluated will include speed of testing, sampling frequency along the track, depth of
substructure layer investigation, calibration procedures, real-time display of test results, and post-test data analysis.

To achieve these objectives, TTCI plans to invite GPR researchers, developers, and service providers to participate in the project. In 2009, as a preliminary undertaking, two GPR teams (Roadscanners-HyGround and BBRI-Zetica) participated in the project, representing the latest advancement in both hardware and software of GPR technologies.

While much work remains to be done in this multiyear project, the following provides some preliminary findings based on the tests conducted by the two teams that participated in the project in 2009.

Figure 5 shows a comparison of GPR signals obtained by using two different types of GPR antennae over a section of the same track. This comparison was done in order to find out if the two GPR systems would provide similar results. As shown, similar GPR signal patterns were indeed detected, which provided a cross validation of each system in detecting track substructure conditions.

![Figure 5. Two Different GPR Systems Showing Similar GPR Scanning Signals](image)
Figure 6 shows the GPR signals that corresponded to a muddy ballast section at FAST. It was visually evident that the ballast was highly fouled and mud was pumping at this location. The GPR signals indicated variations of layer boundaries, probably as a result of fines and fouling materials having accumulated in the ballast. In other words, this example clearly shows the change in GPR signals that corresponded to the actual fouled ballast and mud spot.

![GPR Signal for Muddy Ballast at FAST](image)

Figure 6. GPR Signal for Muddy Ballast at FAST

Figures 5 and 6 show the GPR results in its traditional format, the so-called wiggling GPR signals along the track as a direct output from testing. Much has been done, however, to plot and display GPR results in a manner that better represents the track substructure performance and allows for easier interpretation of the raw data. For example, Figure 7 shows ballast fouling as measured along the track center and shoulders for part of the High Tonnage Loop at FAST. The data was processed to display the fouling in three categories: clean, moderately fouled, or highly fouled. Figure 7 also shows geographic information system (GIS)
data, i.e., tie types at different sections and track features such as curves and locations of special trackwork.

Figure 7. GPR Test Results Concerning Ballast Fouling at FAST

Figure 8 shows a similar ballast fouling representation for an NS revenue service location. Again, degree of ballast fouling was determined from GPR test results for the center and shoulders of the track and was plotted with other GIS information such as curves, road crossings, and visible mud pumping locations.
The GPR test results in Figures 7 and 8 were compared with ballast samples taken at the sites and preliminary results indicated good agreement between GPR test results and the field observations.

Preliminary tests have also compared how different track substructure parameter test results can be correlated with each other, as well as with results from other types of track measurements. In Figure 9, photographs of the track location and ballast surface conditions are overlaid with the ballast fouling and moisture content results from GPR testing. The location shown in Figure 9 has two tracks, one with mud spots and the other without mud spots. However, the GPR data shows similar moisture and highly fouled ballast conditions under both tracks. These results make sense because highly fouled ballast has very low permeability, and thus, poor drainage characteristics, leading to the accumulation of water in the ballast layer.
Furthermore, the results shown in Figure 9 indicate that muddy ballast does not always look muddy on the track surface. From the photographs, the track on the right hand side appeared to have a relatively clean ballast section, but the GPR data show it to be very similar in terms of ballast fouling and moisture to the track on the left where mud pumping was visible as indicated by the black rectangles on the bottom of the figure. The data in Figure 9 is a good example of how GPR data can be used to detect incipient problem locations that are not visually evident on the surface and before they become severe.

Figure 9. Correlation between Ballast Fouling and Moisture Content
SUMMARY AND CONCLUSIONS

Recently, significant progress has been made in the application of GPR technologies for track substructure inspection and condition assessment. Various GPR commercial systems that are rail specific have been developed both in terms of the measurement hardware and the data processing and analysis software.

In order to objectively evaluate the capabilities of the current systems and develop guidelines for implementing the GPR technologies by North American railroads, TTCI started a project in 2009 to work with GPR developers and service providers. This project is being conducted in conjunction with a companion track substructure research project to determine root causes and effective remedies for various track substructure problems under heavy axle load operations in North America. Preliminary tests were performed on known track substructure conditions at FAST and in revenue service with the results indicating that different GPR systems can indeed give similar results for the same track conditions. Results also indicate that current GPR technologies are capable of detecting several major track substructure performance and condition parameters such as ballast and subballast layer thicknesses, degree of ballast fouling, and presence of accumulated water in ballast and subballast. In addition, current technologies allow GPR test results to be displayed with other measurements such as track geometry and GIS data to facilitate cross correlations among various inspection results and track features.

TTCI is organizing and coordinating more testing of existing GPR technologies at FAST and in revenue service. A broad assessment of the current state-of-the-art of GPR for track substructure is anticipated to be completed in 2010. Afterward, the project will focus on developing guidelines for implementing GPR by North American Railroads and recommending
additional research and development needs to enhance and further improve GPR technologies for railroad applications.

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