TRACK QUALITY FROM THE GROUND UP

James Hyslip\textsuperscript{1}, Steven Chrismer\textsuperscript{2}, Michael LaValley\textsuperscript{1}, Jonathan Wnek\textsuperscript{2}

\textsuperscript{1}HyGround Engineering, Williamsburg, Massachusetts, USA
\textsuperscript{2}Amtrak, Philadelphia, Pennsylvania, USA

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ABSTRACT

This paper presents the approach taken by Amtrak to address track substructure needs. As part of this ongoing track quality improvement program, Amtrak has been pursuing root-cause diagnostics of roadbed and ballast problems. This work is focused not only on Amtrak’s high-speed, joint-use Northeast Corridor between Washington and Boston but also on Amtrak’s regional lines.

Amtrak’s approach includes track geometry trending and analysis, ground penetrating radar, detailed aerial lidar surveying, and the use of robust databases and innovative visualization tools. Amtrak is also pursuing more durable surfacing and lining maintenance, transition improvement, and understanding the issues related to critical speed.

This paper presents the latest developments in these areas along with a discussion of track maintenance and capital improvements being planned and implemented to improve safety, reliability and cost efficiency of the United States’ premier passenger network.

Keywords: ballast, track maintenance, ground penetrating radar, drainage, subgrade
1.0 INTRODUCTION

The condition of Amtrak’s fixed infrastructure has a direct influence on revenue generation (1). Therefore infrastructure improvements resulting in ride quality improvements and minimum service delays allow Amtrak to compete with other modes of transportation and ensure customer satisfaction. The challenges to maintain track quality stem from a combination of high speeds and loading conditions from joint-use with heavy axle load freight traffic. Deteriorating substructure condition (ballast, subballast, subgrade, drainage) results in rough track geometry, variation in track stiffness and premature deterioration of track components. Deterioration of the substructure is commonly due to progressive settlement which is exacerbated by such things as poor drainage and excessive fouling levels in the ballast.

A significant part of Amtrak’s track maintenance budget is allocated, either directly or indirectly, to address track substructure performance issues. Direct costs include tamping, ballast cleaning, ballast renewal and ditching, as well as remediation of discrete chronic problem locations. Indirect costs are associated with the deleterious effects of poorly-performing substructure on superstructure components, such as ties, rails and fastening, and to a lesser extent, the rolling stock.

Amtrak’s ongoing track quality improvement program includes pursuing root-cause diagnostics of their roadbed and ballast problems, focusing not only on the Northeast Corridor between Boston, MA and Washington, DC, but also on Amtrak’s regional lines, e.g., Springfield, Harrisburg, Michigan and Empire Lines.
The goal of Amtrak’s track quality improvement program is to provide the following:

- Overall smoother track for a given level-of-service.
- Increased availability of track by minimizing maintenance interference and slow orders.
- Reduced rate of track deterioration.
- Reduced maintenance and capital costs by virtue of: focusing resources to when and where they are most effective, and; addressing the root-cause of the underlying problem rather than continuing to treat only the symptoms.
- Ability to address poorly-performing substructure issues on a network-based level where budgets are available for a systematic and economy-of-scale approach.

2.0 ADDRESSING TRACK SUBSTRUCTURE NEEDS

The approach to addressing substructure needs on Amtrak includes investigation and determination of the root-cause of poor track performance and then prescribing specific maintenance or capital improvement work. Tools in the root-cause analysis include: review of background information, track geometry analysis, topographic and asset mapping, field reconnaissance, ground penetrating radar (GPR), geotechnical testing and instrumentation, analysis and modeling. In areas where slope instability is a problem, additional tools have been used such as test borings and geotechnical instrumentation in order to develop solutions.

The following subsections discuss the key tools that Amtrak has been using in its track quality improvement program.
2.1 Aerial Lidar and Imagery Survey

Amtrak has used aerial lidar and imagery surveys on its property since 1997. Amtrak has employed the FliMap® LiDAR (Light Detection And Ranging) corridor mapping system, which provides high accuracy asset location information as well as ground points from which accurate digital terrain models (DTM) are developed. The DTM provides key information for root-cause analysis and drainage improvement designs. In order to integrate the lidar data with other information (e.g., GPR and track geometry data) the lidar data is reconfigured into a matrix configuration for ease in further manipulation and filtering, as well as use in databases and linear asset management systems.

2.2 Track Geometry Analysis

The fundamental indicator of track condition is track geometry, and in most cases, the condition defining the need for track quality improvement is poorly-performing track geometry. Track geometry data from Track Geometry Measurement Vehicles (TGMV) provide an objective indication of the roughness of track, and is useful in distinguishing the sections of track with different performance. Analyzing vertical profile geometry patterns provides useful information on the substructure condition of the track. Track geometry patterns, in particular vertical profile (surface) patterns, are influenced by such things as variable ballast fouling, changing drainage condition and variable subgrade stiffness.

Amtrak performs frequent track geometry surveys of the Northeast Corridor, and uses the geometry data for roughness indication, performance monitoring, and as a quantifier of track deterioration. An optimal estimation technique based on Kalman filtering is used by Amtrak to accurately align the track geometry data on a foot-by-foot
basis (2). The absolute location accuracy and the relative survey-to-survey alignment accuracy are very high. Amtrak uses Running Roughness (3), band-pass filtering (4) and fractal analysis (5) to meaningfully quantify track geometry data.

Figure 1 shows precisely aligned vertical profile track geometry MCO data (top plot) along with the corresponding Running Roughness of the same data (bottom plot).

Once the data is precisely aligned to itself and to track features, trending is used to provide meaningful predictions of track degradation and maintenance planning. Quantifying track geometry data and developing the trends of values over time from survey to survey can help predict the future condition of the track. Maintenance and/or remedial measures, including the allocation of capital resources, can then be planned based on these predictions. Also, comparing quantified geometry data for different sections of track can be used to rank the track sections for maintenance prioritization. Figure 2 shows a trend plot for a section of track with increasing rate of deterioration and corresponding shortening surfacing cycles.
Amtrak also uses a pseudo-3D representation of track geometry performance for viewing of geometry performance over time, as shown in Figure 3. In Figure 3, the x-axis is distance, the y-axis is time and the track geometry roughness is represented by color with hot colors (orange, red) indicating higher roughness than cool colors (blue, green).

Figure 3: Multiple aligned track geometry survey results (vertical profile data). Bottom plot shows location (double circle) with accelerating deterioration.
2.3 Ground Penetrating Radar

Ground Penetrating Radar (GPR) is being used by Amtrak to provide continuous measurement of the condition of track substructure layers at fast measurement speeds and providing information for maintenance and rehabilitation decision making. Figure 4 shows examples of GPR surveys both on-track and on right-of-way where new track is to be built.

Figure 4: GSSI 400 MHz 3-channel GPR antenna setup installed on back and front of hyrail vehicle (left photo). GPR system used to investigate right of way for new track (right photo).

Ground Penetrating Radar (GPR) is being used on Amtrak lines to provide continuous measurement of layer thickness and configuration (lateral and longitudinal variation) of individual substructure layers, moisture content and water holding tendencies of the substructure, and the fouling condition of the ballast. Amtrak is using GPR to map the lateral and longitudinal variation of ballast and subgrade layers and thereby provide information on subgrade deformation conditions.

Most of the GPR surveys on Amtrak are performed with GSSI SIR-20 control units and three 400 MHz GSSI antennas. Amtrak has also deployed 3d-Radar GPR equipment. The use of 400 MHz antennas enables to achieve information to a maximum depth of 6 to 8 feet. The 400 MHz antenna is able to collect good data even though the NEC is electrified track territory and is located primarily in an urban environment with a
large amount of ambient background electromagnetic noise. The antennas are deployed at the track centerline and at the end of ties to provide three longitudinal survey lines for each track.

2.4 Integrated Databases & Visualization Tools

A key aspect of root-cause analysis of substructure issues is the integration of the disparate track condition data and presenting the information in an intuitive and useful way. Amtrak’s approach to managing track quality is to integrate together as much information as is available in order to get the fullest picture of the track and right-of-way conditions. An integrated database and easy-to-use graphical user interface (GUI) system allows for understanding of complex interaction between condition and structural performance (1). A database and viewer system are key to interrelating disparate data (e.g. topography, geometry data, GPR) in order to develop a clear and accurate picture of the factors affecting track performance. The use of integrated software is very important since the combined evaluation of several different measurements is a key to success in finding root-causes to existing problems and predicting future problems. Amtrak uses Railway Doctor™ software from Roadscanners Oy (6) for integrating GPR, geometry data, video and mapping, maintenance input and topography from digital terrain models.

Figure 5 shows integrated GPR data, topography from aerial lidar, historic track geometry performance and track assets. Figure 5 is a screen-grab from the Railway Doctor software.
Figure 5: An example view from the Railway Doctor user-interface with actual data. GPR-derived information on ballast fouling condition and substructure moisture for 4-track right-of-way is shown integrated with topography from aerial lidar data, historic track geometry (5 years of data) and track assets.
2.5 Geotechnical Investigations

The investigation into root cause occasionally requires such things as test borings, cross-trenches, dynamic cone penetration (DCP) tests, and geotechnical instrumentation, along with laboratory soils tests. Test borings (see Figure 6) have been used at individual sites on Amtrak to determine track foundation conditions, particularly at embankment locations, and for procuring samples for laboratory testing.

![Image of test drilling on Amtrak right-of-way](image)

Figure 6: Various examples of test drilling on Amtrak right-of-way.

Amtrak uses geotechnical monitoring instruments to provide information on the nature and location of problems in the substructure, in particular, the subsurface movement within embankments (7). In particular, Amtrak employs various types of geotechnical instrumentation, including: soil extensometers, multi-depth deflectometers
(MDD), slope inclinometers, soil pressure cells, in-ground accelerometers, strain gages and ground water piezometers.

2.6 Engineering Analysis

Technical evaluation and analysis of the collected field and laboratory information is a requisite part of the track quality improvement work. Analysis is often needed to determine the cause of the problem and select appropriate solutions. The engineering analysis that is needed includes such tasks as assessing drainage requirements, evaluating adequacy of granular layer thickness to protect the subgrade, slope stability analysis, evaluating suitability of subballast to provide drainage, determining support characteristics of subgrade, and determining type and source of ballast fouling.

3.0 TRACK QUALITY IMPROVEMENT

The following sections resent a few examples of ongoing initiatives by Amtrak to improve track quality. Once the root-cause of substructure related problems is determined, then appropriate steps can be taken to mitigate the problems and thereby enhance track quality.

3.1 Higher Quality and More Durable Track

Track that was originally laid out using classic shapes of tangents, spirals and curves becomes distorted over the years due to traffic and maintenance. Very often the amount of distortion from the original design can become so large that it may not be possible to return to original design conditions without prohibitively large lateral track throws. One way to reduce the amount of required lateral track throw to correct alignment is to use
improved geometry correcting methods. Amtrak has been pursuing improved surfacing and alignment correction using TGCS (Track Geometry Control System, 8) which is a commercially available tamper control software that was found by Network Rail in the UK to produce track quality that is comparable to high speed systems in Europe while requiring relatively small track throws.

Europe obtains high standards of geometry by bringing the track back to a design alignment using fixed wayside monuments as references, which are very costly to establish. However, the only fixed references TGCS requires are the locations of curve points along the track as indicated by painted ties which can be established at far less cost and manpower than the much more numerous wayside monuments.

The alignment error from Amtrak’s geometry car space curve data is being monitored for curves that were tamped using the conventional smoothing approach, and for other curves tamped using TGCS. The change in alignment error following tamping is quantified by processing alignment space curve data with filters that determine the amount of error for a range of wavelengths. For example, the amplitude of the filtered waveforms in Figure 7 show the amount of alignment error through Curve 387 that exists over a wavelength range of 70 m to 140 m (mid-point of 105 m or 340 feet).
The amplitude is variable because the amount of alignment error is not constant through the curve. More importantly note that the alignment error amplitude for the right and left rail after tamping is only slightly diminished with conventional smoothing tamping.

Figure 8 shows the result of using TGCS on nearby Curve 388 which has very similar characteristics to Curve 387, including nearly identical initial (“before tamping”) alignment roughness.
Figure 8: Alignment error before and after surfacing Curve 388 using TGCS.

Note that in contrast with conventional smoothing tamping, the amplitude of alignment error after tamping with TGCS is less than half the “before” for the curve as a whole. Because of results like these Amtrak is installing TGCS on a second tamper and ride quality is expected to improve as a more track is tamped using TGCS.

3.2 Substructure Improvement

Amtrak’s substructure improvement work includes drainage improvement and reinforcement. Rough geometry often coincides with longitudinal and lateral variation of subgrade surface. The subgrade surface can have considerable variation due to deformation in the form of excessive plastic deformation (ballast pocket) and progressive shear failure (subgrade squeeze). Excessive plastic deformation is the result of greater load-induced settlement of the subgrade surface directly under individual rails or under the entire track. Progressive shear failure, or subgrade squeeze, occurs in predominantly fine-grained subgrade due to repeated over stressing and gradual shear failure and
remolding of the subgrade soil near the surface. Both of these phenomena result in depressions under the track that result in water holding depressions, which can subsequently lead to further softening and deformation of the subgrade.

![Figure 9: Right-of-way cross-section showing lateral undulation of subgrade surface.](image)

Treatments for this condition include internal drainage along the right-of-way road and reducing stress to the subgrade. Improving the internal drainage of the track substructure can be done with cross-drains, along with longitudinal collectors as needed, as illustrated in Figure 10. External drainage of water away from the track is achieved by ensuring adequate drainage away from track through track shoulder and any right-of-way access road to a proper ditch or embankment slope.

![Figure 10: Improvement of internal drainage.](image)

Stress reduction to the subgrade can be achieved by increasing the granular layer thickness (determined through granular layer thickness design) and/or by reinforcing the granular...
layer through the use of geogrid reinforcement, as illustrated in Figure 11. The geogrid reinforcement provides tensile strength to the granular layers thereby increasing the stiffness of the granular layer which results in lower vertical stresses transmitted below the reinforced layer. The reinforced layer also take up some of the load induced shear stresses that are not then transferred through this layer to the layer below.

![Figure 11: Geogrid reinforcement to reduce stress to subgrade.](image)

### 3.3 Ballast Cleaning

Amtrak is developing a long-term ballast cleaning program based on track geometry records and ground penetrating radar information. The ballast cleaning program includes ballast shoulder cleaning as well as both spot and production undercutting.

### 3.4 Transition Improvement

Amtrak is pursuing improvements in the design, maintenance and renewal of railroad track bridge transition. Amtrak is working with researchers from University of Illinois, Urbana-Champagne (UIUC) on a FRA-sponsored project to study bridge transitions. The transition research will develop ways to effectively arrest any settlement of the bridge approach and also provide stiffness compatibility between the bridge and bridge-
approach. Amtrak is focusing on solutions to transition problems that can be carried out with minimum impact on track availability.

3.5 Critical Speed

A “critical speed” track condition can occur when, at elevated speeds, the train induces a resonant vertical vibration in the track. This condition is more prevalent for the combined condition of high train speeds and very soft subgrade soils, where track vibration amplitude is significantly greater than the elastic deformation that occurs under static loading. The particular type of propagating wave that causes these large vibrations is known as the Rayleigh wave which travels along the ground surface and produces a strong vertical component of oscillation. Not only is the track downward deflection significantly increased at these speeds but track uplift is also introduced, amplifying the vibration further. (9)

Amtrak is developing a test section of track on the Northeast Corridor to measure vertical track vibrations in track that overlays a soft subgrade soil with high moisture content, where the Acela train speed approaches 150 mph. Although the condition is not unsafe, the test location is a good candidate to measure the velocity of the Rayleigh wave relative to the train speed and the resulting track vibration amplitude. Accelerometers and displacement transducers are being installed in the track and along the wayside to measure the track response as shown in Figure 12 at one of the stations. The test data will be used to validate a dynamic track model under development to predict the track response under higher speeds than 150 mph.
3.6 Embankments

The condition and behavior of railway fill embankments have a significant impact on overall railway corridor performance. Instability can cause problems ranging from chronic track geometry roughness to sudden service disruptions. Embankments often exhibit problems associated with improperly prepared foundations, poorly compacted fill and poor drainage. Instability is also exacerbated by relatively steep slopes due to right-of-way property limits, by decades of track surfacing that increases the height of fill and increases the weight of overburden, and in some instances this is combined with toe erosion.

Amtrak has found that instability of embankments made of loose granular fill is a problem along many of its corridors. The granular fill used for embankments can vary from natural sand with varying amount of fines (silt and clay) to man-made cinder and clinker mixture (bottom ash from steam locomotives).

Figure 12: Instrumentation placed along the track and right of way to measure track response under high speed loading
Figure 13 shows the subsurface cross-section for a location with slope instability. The location and rate of movement of the failure plane was determined by test borings and inclinometer instrumentation. Additionally, the role of ground water as a causal component was also determined by the use of ground water piezometers.

![Cross-section of embankment problem site.](image)

Figure 13: Cross-section of embankment problem site.

The Amtrak site depicted in Figure 14 was successfully repaired using a sheet-pile wall with soil anchors tie-backs, as shown in Figure 14.

![Sheet Pile retaining wall under construction.](image)

Figure 14: Sheet Pile retaining wall under construction.
4.0 CONCLUSION

In consideration of the profound ways in which the track substructure affects the overall track performance, Amtrak is taking a holistic view of the track system, and subsequently, emphasizes the functional relationship between the track substructure and the track’s overall health. Amtrak is instituting a track quality improvement program that is focusing on the root cause of bad track performance and utilizing new technology advances. In today’s high volume and heavy axle load environment, the root cause of bad track is increasingly becoming the deterioration of track substructure.
REFERENCES


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List of Figures

Figure 1: Aligned vertical profile MCO track geometry data (top plot) and corresponding Running Roughness, $R^2$, of same data (bottom plot).

Figure 2: Trending of the Running Roughness values for a deteriorating problem location.

Figure 3: Multiple aligned track geometry survey results (vertical profile data). Bottom plot shows location (double circle) with accelerating deterioration.

Figure 4: GSSI 400 MHz 3-channel GPR antenna setup installed on back and front of hyrail vehicle (left photo). GPR system used to investigate right of way for new track (right photo).

Figure 5: An example view from the Railway Doctor user-interface with actual data. GPR-derived information on ballast fouling condition and substructure moisture for 4-track right-of-way is shown integrated with topography from aerial lidar data, historic track geometry (5 years of data) and track assets.

Figure 6: Various examples of test drilling on Amtrak right-of-way.

Figure 7: Alignment error before and after surfacing Curve 387 using conventional smoothing tamping.

Figure 8: Alignment error before and after surfacing Curve 388 using TGCS.

Figure 9: Right-of-way cross-section showing lateral undulation of subgrade surface.

Figure 10: Improvement of internal drainage.

Figure 11: Geogrid reinforcement to reduce stress to subgrade.

Figure 12: Instrumentation placed along the track and right of way to measure track response under high speed loading

Figure 13: Cross-section of embankment problem site.

Figure 14: Sheet Pile retaining wall under construction.
Track Quality from the Ground Up

Jim Hyslip
Mike LaValley

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Jonathan Wnek

HyGround Engineering, LLC

AMTRAK®
Presentation Outline

- Background
- Root Cause Diagnostics
- Track Improvements
Problems

- Fouled Ballast
- Mudspots
- Ties
- Embankments
- Drainage
- Transitions
Root Cause Diagnostics

- Mapping
- Track Geometry
- Ground Penetrating Radar
- Geotechnical Instrumentation
- Analysis / Modeling
Mapping
Track Geometry

Measured

Aligned
Ground Penetrating Radar (GPR)

- Layers
- Moisture
- Fouling

2012 Annual Conference & Exposition
Case Studies: Case 2
Example Use of GPR for Ballast Undercutting Program
GPR Data Shows Higher Fouling As Darker Colors
Undercut When Ballast is Fouled AND Geometry is Rough

Ballast fouling intensity by color, Track 2, plan view

Ballast fouling intensity by index

Moisture in track, plan view

Track 1

Track 2

Present

Time

5 yrs Prior

Rough

Rough

Rough

Rough

Very Fouled

Clean

Very Fouled

Clean

Wet

Dry

MP 91

MP 92

MP 93

MP 94

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Finding Cyclic Geometry Error to Improve Ride Quality
Identifying Cyclic Error in Track Geometry Data

Left & Right Profile Space Curve Error (in.)

Track Footage

-1.5
-1
-0.5
0
0.5
1
-1.5
-1
-0.5
0
0.5
1
Left Rail Space Curve
Right Rail Space Curve
Identifying Cyclic Error in Track Geometry Data

Left & Right Profile Space Curve Error & Filtered Data (in.)

Track Footage

Left Rail Space Curve
Right Rail Space Curve
Left Rail Filtered
Right Rail Filtered
We can find cyclic error, but can we fix it?
Long Wavelength Cyclic Error Before & After Conventional Tamping

Space Curve Error (in.)

Distance (ft.)

Left Alignment SC Before
Right Alignment SC Before
Left Alignment SC After
Right Alignment SC After
Long Wavelength Cyclic Error
Before & After Tamping with TGCS

Space Curve Error (in.)

Distance (ft.)

-1
-0.5
0
0.5
1

Left Alignment SC Before
Right Alignment SC Before
Left Alignment SC After
Right Alignment SC After
Critical Speed
Critical Speed: The speed at which the train catches up to its own ground-borne wave

Ground deformation:
- at slow speed
- approaching Critical Speed
- at Critical Speed
Train Speed

Ledsgard site in Sweden
- Measured
- Simulated

Critical Speed
~ 235 km/hr
~ 146 mph

Vertical Displacement of track (mm)
- Upward
- Downward -5

Critical Speed

Train Speed (km/hr)
Critical Speed

- Ledsgard site in Sweden
  - Measured
  - Simulated

- Critical Speed
  - ~235 km/hr
  - ~146 mph

- Speed at Failure
  - ~200 km/hr
  - ~125 mph
Critical Speed

Ledsgard site in Sweden
- Measured
- Simulated

Critical Speed
~ 235 km/hr
~ 146 mph

Safe Condition at
~ 160 km/hr
~ 100 mph

Train Speed (km/hr)