Use of Ballast Inspection Technology for the Prioritization, Planning and Management of Ballast Delivery and Placement

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Abstract

This paper presents the results of a study on the optimization of ballast placement planning, prioritization and management for railway ballast distribution. Specifically, this paper presents the requirements for and inputs necessary to more effectively manage the ballast placement process and take advantage of the new track inspection technologies that provide more accurate and reliable data about ballast condition and track profile. This is to include addressing such key issues as:

- Where and how much ballast should be placed; to include ballast at end of ties (shoulders), under ties, and in cribs.
- How much ballast should be placed; to include reference or required ballast profile based on vertical, lateral and longitudinal performance requirements

A key portion of this study was the introduction of new inspection technologies now available to more accurately define the ballast requirements. This includes such newly introduced inspection technologies as LIDAR for measurement of the ballast profile, Ground Penetrating Radar inspection for ballast depth deficiency, and other related inspection technologies. This in turn allows for more accurate ballast deficit analysis and calculation to include the reference or "ideal" profile used to determine the ballast deficit and the calculation of the difference between the current profile and this reference profile, which includes vertical load distribution and lateral and longitudinal restraint requirements. It also addressed the latest state-of-the-art delivery systems that allow for significantly more accurate placement of the correct amount of ballast.

Introduction

The ballast section is a key part of the track structure. It serves several essential functions including distribution of vertical load from the bottom of the tie to the top of the subgrade, providing lateral and longitudinal restraint for the tie and track superstructure (rail, ties, and fasteners), allows for correction of track geometry variations, facilitates drainage, provides damping for noise, vibration, and dynamic impact loads, etc. Thus for example, an adequate ballast section beneath the tie will reduce the level of vertical dynamic loading from the bottom of the tie the top of the subgrade, thus reducing the vertical degradation of the track structure and its geometry (surface or profile, cross-level, twist, warp, etc.). It will also serve to provide dynamic attenuation and damping of the wheel/rail loads, to include impact loading such as from wheel flats, engine burns or other discontinuities at the wheel/rail interface. Likewise, proper and adequate ballast shoulders and cribs provide lateral and longitudinal resistance to movement of the track superstructure, reducing the lateral degradation of the track geometry (alignment) and preventing buckling of the track in hot weather.

Conversely, an inadequate ballast section will result in high rates of track geometry degradation in the vertical and/or lateral directions, necessitating frequent track maintenance. It can also result in more catastrophic types of failures, such as a track buckle, which can end in a derailment of a passing train.

Traditionally, ballast section is inspected as part of the regular weekly or bi-weekly walking (or slow speed) track inspection activity where the inspector will note any locations with inadequate ballast sections. As such it is a subjective inspection process, where the inspector visually evaluates the condition of the ballast and any locations where the ballast section is inadequate. This subjective process usually results in the reporting of locations with significant deficiencies (e.g. missing or small shoulders, open cribs, etc.), but locations with less than obvious deficiencies are often overlooked.

Thus, ballast is an area where new technology is being employed to assist the traditional inspector and provide reliable measurements of conditions that can be used for maintenance planning and management. Technologies such as LIDAR (LIght Detection And Ranging, or Laser Imaging Detection And Ranging) use optical remote sensing technology that can measure the distance to or other properties of, targets by illuminating the target with laser light and analyzing the backscattered light. LIDAR technology has specifically been applied in the railroad industry in measuring and mapping the surface of the track, and in particular, the ballast profile of the track structure. Likewise technologies such as Ground Penetrating Radar (GPR) which uses radar pulses to image the subsurface of the track have been used to map the bottom of the ballast and top of the subgrade sections of the track structure.

This paper presents recent developments in the application of these new inspection technologies for inspection, mapping and analysis of the ballast section and determination of ballast needs along the right of way. It also introduces a new prioritization algorithm that allows railroads to determine the relative importance of any missing ballast sections, and to plan the ballast placement/replacement process as part of an overall track maintenance program.

Importance of Ballast Section

The ballast section refers to the upper layer of the track substructure upon which the superstructure (i.e. the rails and ties) is placed. Thus it is the zone located between the ties and the subgrade (Figure 1). It consists of strong, open-graded granular materials placed around and under the ties.

As noted previously, it serves several essential functions, including distribution of vertical load from the bottom of the tie to the top of the subgrade, providing lateral and longitudinal restraint for the tie and track superstructure (rail, ties, and fasteners), allowing for correction of track geometry variations, facilitating drainage, providing track resiliency and damping for control of noise, vibration, and dynamic impact loads, etc.

The principal parts of the ballast section are as follows (refer to Figure 2)

- Ballast cribs

        - The ballast located between the cross-ties extending from the top of the tie to the bottom of the tie and along its entire length (zone 2)
    - Ballast shoulders
        - The ballast located beyond the ends of the cross-ties extending from the top of the tie (or even above the top of the tie) to the bottom of the tie on either tie end (zones 1 and 3).
        - The ballast shoulders also extend at an angle (usually 2:1) from the end of the top of the shoulder down to the top of the subgrade.
        - Thus the ballast shoulder support zone would include the ballast below the bottom of the tie, extending at this 2:1 slope to the top of the subgrade (zones 5 and 6)
    - Ballast layer under the tie
        - This is the layer of ballast directly beneath the bottom of the tie extending to the subgrade (zone 4)
        - This layer (together with zones 5 and 6) could also include a sub-ballast layer which is an intermediate ballast type layer directly above the subgrade which can be made up of a lower quality (and small particle sized) material.

Each of these zones plays a key role in the overall performance of the track structure.

Thus for example, an adequate ballast section beneath the tie (zones 4 together with 5 and 6) will reduce the level of vertical dynamic loading from approximately 65 to 85 psi at the bottom of the tie to approximately 20 to 25 psi at the top of the subgrade. It will thus allow for the reduction of the significant level of loading, such as under heavy axle load 286,000 lb. cars, to a level that even a "weak" subgrade can support. In fact, increasing the depth of the ballast layer is one of the techniques used in track design to allow for the proper performance of track built on a "weak" subgrade material. Correspondingly, an inadequate depth of ballast can result in "overstressing" of the subgrade, particularly a weak or wet subgrade, with a corresponding increase in the rate of track surface degradation (e.g. surface/profile, cross-level, etc.). In addition, this ballast layer provides resiliency to the track structure, to allow for distribution of the wheel load along the track structure, over as much as 6 to 10 cross-ties, as well as damping of the vehicle dynamic behavior and associated wheel/rail loads for the control of dynamic impacts, noise and vibration.

Likewise, adequate shoulders will provide lateral restraint to the cross-ties and the track superstructure itself, resisting both short term and long term lateral movement of the track, and facilitating maintenance of the track alignment. This is particularly true for continuously welded rail (CWR) track, where inadequate ballast shoulders, and the associated inadequate lateral track resistance, can result in rapid loss of alignment or even buckling of the track structure [1]. Studies have shown that inadequate shoulders can result in a loss of overall track resistance on the order of 20 to 40% [2, 3, 4, and 5].

Similarly, full cribs will provide longitudinal resistance to the movement of the ties, to prevent tie skewing or movement along the track. Tests have shown that half-empty cribs can reduce tie longitudinal restraint by the order of 50% or more, as shown in Figure 3 [2]. This longitudinal restraint is of even more importance on grades, where full cribs (together with adequate longitudinal anchoring) will prevent creep of the rail or movement of the ties under traffic loading. In addition, the cribs also provide supplemental lateral resistance for the track, on the order of 15 to 50%[1] of the total lateral resistance [2, 3, 4, and 5].

[1] There is a strong interaction between the crib and base friction lateral resistance.[2]

Thus maintenance of an adequate ballast section, to include shoulders, cribs and ballast layer under the tie, is of real importance from both a maintenance and safety point of view.

Ballast Inspection Technologies

As noted in the introduction, technologies such as LIDAR are being applied in the railroad industry to measure and map the ballast profile. In response to an industry need to more accurately and efficiently calculate mainline ballast requirements, Georgetown Rail Equipment Company (GREX) created the BallastSaver system (Figure 4). BallastSaver is a LIDAR based track inspection system designed to scan the track at up to 20 mph and calculate ballast deficiencies in cubic feet along any desired length of contiguous track. The BallastSaver system is operated by the hi-rail truck driver, who has the ability during the run to mark sections of track as "No Dump Zones" where a ballast train should not be dropping ballast, such as a switch or crossing.

At the conclusion of the scan the BallastSaver analysis is run automatically, in which the appropriate tangent or curve ideal track profile is overlaid with the measured data to calculate the ballast deficiency volume along the track (Figure 5). The operator can also modify the analysis to include additional track lift if desired by the track engineer.

Once the BallastSaver analysis is complete, the operator uses a reviewer to verify the properties of the scan and the intended ballast dump plan. At this time the operator can review the LIDAR data in a 3-D representation along with an overhead map and camera images to validate location accuracy. The 3-D model includes a color-coded visualization of ballast deficiency, compared to the ideal track profile (Figure 6). The operator can make adjustments to the lift requirements and add or modify the boundaries of No Dump Zones.

The final reports from BallastSaver include: (1) a report specifying how many total cars of ballast are required per mile, (2) a survey on where to deliver ballast, and (3) images of the track from the still pictures taken with the camera. In addition, an output file is generated that serves as an automated input file for GREX's automated ballast delivery system, GateSync.

BallastSaver can be utilized as a stand-alone tool as part of a ballast delivery planning program or alternatively as a means to collect the necessary information to automate the ballast delivery using GREX's GateSync software on ballast trains.

Measurement of the depth of the ballast layer has always been a challenge. However, technologies such as Ground Penetrating Radar (GPR) allow for the mapping of the ballast section beneath the cross-tie, and the specific measurement of the depth of ballast to the top of the subgrade. GPR is a nondestructive inspection method that uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures. GPR can be used in a variety of media, including rock and soil. GPR uses high-frequency (usually polarized) radio waves and transmits into the ground. When the wave hits a boundary with different dielectric constants, the receiving antenna records variations in the reflected return signal. In the railroad application, good penetration is achieved in ballast materials such as granite and limestone. The change in material from ballast to soil represents a detectable boundary layer, as are locations where moisture is present. Clay-laden soils and soils with high electrical conductivity are also readily detectable.

Until recently GPR has been difficult to use; however, advances in analysis technology to analyze the GPR signal and convert the reflected images to depth data have allowed for the increased use of GPR in defining the depth of ballast, as illustrated in Figure 7, which shows a GPR test on a major Class 1 railroad where the bottom of ballast layer and top of subgrade are clearly defined.

Analysis of Ballast Inspection Data

The analysis of the LIDAR ballast profile output data is illustrated in Figure 8 where digitized LIDAR data is overlaid onto an idealized track structure representing the top of tie, the shoulders, and the shoulder slope. The LIDAR data represents the combined measurement points from two LIDAR units mounted on the inspection vehicle (also illustrated in Figure 5 in a more refined analysis output).

A LIDAR unit is a combined laser source and detector that rotates continuously to determine the distance to the nearest solid object by detecting its laser light reflection. A distance measurement is taken at regular angular intervals, such as every ½ degree as the unit rotates. To measure the track surface profile, each of the two LIDAR units rotates and measures the reflection of the laser to determine the distance from the laser source/detector, which produces two sets of data as polar coordinates with different reference origins. The two sets of data are then converted to Cartesian coordinates and translated to use common reference axes to produce a cross-sectional slice of the track profile. As the measurement truck travels along the track, the collection and storage of the LIDAR data is continuous, and so aggregating a series of consecutive cross-sections produces a three-dimensional track profile surface.

To ensure the correct longitudinal position of the measurement, a GPS unit is used to determine data location, and a wheel encoder is used to measure the distance traveled from the defined and marked starting point. Each measurement truck also captures periodic photos of the track as additional information when planning a ballast delivery.

The collection of data by the entire set of BallastSaver systems (LIDAR, GPS, wheel encoder, camera) is controlled by a central computer inside the cab of the truck and operated automatically by the driver. The driver can provide real time inputs such as demarcating a No Dump Zone where a ballast delivery train should not place ballast (such as a switch, crossing, or other special track feature). Often the LIDAR-measured datasets will include data points that need to be filtered out of the dataset. These include vegetation and the mounting hardware of the measurement vehicle. For this specific application where only the track surface and below should be included in the analysis, the data points representing the rail, fasteners, and tie plates should also be filtered out.

Once the true ballast profile has been determined (Figures 5 and 8) and overlaid onto a representation of the ideal ballast cross-section, calculation of missing ballast can be performed. It should be noted that the ideal ballast cross-section is defined by the user railroad and can differ from railroad to railroad as well as from track location to track location. For example, many railroads specify larger shoulders on curves than on tangent track; for example 18” shoulders on sharp curves vs. 12” on tangent. Likewise, CWR track will have a larger shoulder than jointed track; e.g. 12” vs. 6”.

The calculation of the missing profile ballast can be visualized in Figure 8, where the missing ballast is clearly seen as the gap between the idealized (desired) profile and the actual profile. Thus noting Figure 8, it can be seen that the left shoulder is missing ballast at the top of the shoulder, but further down the slope, the actual ballast profile extends beyond the idealized profile, indicating a surplus of ballast in this area[2]. On the right side, the gap is more pronounced and extends down the shoulder slope. In the crib, there is a non-uniform ballast section, with significantly more missing ballast on the right side of the crib.

Calculation of missing ballast below the bottom of the tie is likewise performed using an overlay of the GPR measured bottom of the ballast (top of subgrade) and the railroad defined idealized ballast depth (which again can vary as a function of location, particularly for areas of poor or weak subgrade material).

In order to facilitate the calculation of the missing ballast, six ballast zones are defined for any given cross-section of the ballast as follows (see Figure 2):

1. left shoulder
2. ballast crib
3. right shoulder
4. ballast under bottom of tie
5. ballast under left shoulder[3]
6. ballast under right shoulder

It should be noted that the cross-section at a cross-tie will differ from the cross-section between ties, in that zone 2, the crib zone, will have ballast between the ties but will be filled by the cross-tie itself at the tie location. This must be properly accounted for when calculating ballast volumes along the track.

Thus for each of the six zones, the difference between the idealized ballast section (as defined by the railroad for that track location) and the actual ballast section (as measured from the LIDAR based profile and GPR based depth of ballast) is calculated and then summed to get the missing ballast area for the defined cross-section.

Noting the inspection interval of the LIDAR unit along the track (which ranges from approximately 0.35” at 1 MPH to 7” at 20 MPH), the volume of missing ballast can be calculated by multiplying the ballast missing from each cross-section by the longitudinal inspection interval, and then summing up these volumes for the desired length of track (e.g. mile intervals).

[2] Surplus ballast, i.e. ballast that is outside the idealized profile boundary is not included in the missing ballast calculation.

[3] The top of zones 4, 5 and 6 are defined to be the bottom of the tie. Thus for a standard 7”x9”x8.5’ wood cross-tie, the top of zones 4, 5 and 6 are 7” below top of tie. This is because the lateral resistance of the shoulder (zones 2 and 3) are based on tests where the ballast shoulder resistance is calculated by testing the tie with and without ballast shoulders (above the bottom of tie). See references 2, 3 and 4.

Note the missing ballast volume must be adjusted to reflect the presence of the cross-ties as their actual spacing (nominally 9 inches wide every 19.5 inches).

Figure 10 shows overlays of several different simplified ballast cross-sections and illustrates how the missing ballast area will vary as a function of the actual profile.

The following table shows the corresponding missing ballast volumes for each of these profiles, prioritized by missing volume.

Ranking of Sections based on Volume deficiency (in cubic yards) per foot of track

1. Section 3 Green: 0.37 CY/FT
2. Section 2 Yellow: 0.29 CY/FT
3. Section 1 Red: 0.25 CY/FT
4. Section 4 Cyan: 0.20 CY/FT
5. Section 5 Magenta: 0.18 CY/FT

Development of Prioritization Index

As seen in the table above, the simplest method of prioritizing ballast replacement requirements is using the volume of missing ballast (in cubic yards) directly. Thus for example, if the volume of missing ballast per mile is calculated for a segment of track, the ballast delivery could be prioritized on a mile-by-mile basis based on missing ballast volume (in cubic yards or tons of ballast) or alternatively by number of carloads of ballast needed per mile. This is illustrated in Figure 11, which shows the number of carloads of missing ballast per mile for a 20 mile length of track. Thus in Figure 11, MP 404 requires the greatest volume of ballast, almost 8 carloads, followed by MP 405 and then MP 391, 396 and 400.

However, while it is essential to know the volume of missing ballast in order to plan and execute ballast replacement, prioritization of ballast needs should also account for any increased risks associated with missing ballast. Thus for example, locations with missing ballast shoulders in territory where there is a high risk of track buckling[4] or locations with inadequate depth of ballast and poor subgrade support conditions will have a higher need for a full ballast section than jointed rail territory or track built on a very strong and stable subgrade.

In order to account for actual need for ballast in critical areas, and to give these critical locations a higher priority for ballast addition, a ballast prioritization model was developed to complement and enhance the analysis of missing ballast volume.

The ballast prioritization model makes use of two sets of ballast prioritization factors.

The first set of factors are based on the cross-section of the ballast section, and the relative importance of the missing ballast for different portions of the cross-section, based on the cross-section zones as defined in Figure 2.

The second set of factors are based on the segment of track itself and the relative importance of that track segment, and the type of traffic that operates on that segment. Thus, for example, this second set of prioritization factors address such key operating parameters as the presence of

[4] For example CWR territory with significant variation in temperature between summer and winter and thus with a high risk of both buckles and pull-aparts

passenger trains, the presence of significant amounts of hazardous material, whether the segment is on a key route, or whether it is a very high tonnage route.

The first set of factors is used to weight each individual cross-section. The second set of factors is applied only at the route or segment level.

First addressing the first set of weighting factors, the cross-section factors, the modeling approach is to calculate a weighted area (volume) of missing ballast as follows:

$$\text{Weighted cross section } A_w = \sum_{i=1}^{6} a_i \times A_i$$

Where i represents the ballast zones 1 through 6 shown in Figure 2, and the weighting constants a_i are related to the functionality and importance functions of the missing ballast in each zone. Thus the a_i values are functions of such parameters as curvature, grade, axle load, temperature range, etc.

The weighting factors A_i in turn represent the cross-sectional area of missing ballast from each Zone (1 through 6), where the missing ballast is calculated as the difference between the idealized ballast area for each zone (as defined by the railroad's definition of shoulder width, slope, etc.[5]) and the actual measured area as illustrated in Figure 8 and defined previously. Thus, A_w represents the weighted "missing ballast" for a defined cross-section. And A_i (when a_i = 1) represents the unweighted "missing ballast" area.

Specifically, the weighting factors used for the weighting of the missing ballast in the track cross-section zones are based on the following parameters.

- Curvature
  - It has been noted previously that curves are susceptible to increased levels of lateral force and as such have a greater potential for loss of alignment in areas where there is inadequate lateral track resistance. This lateral resistance is primarily based on adequate shoulders (zones 1 and 3) and cribs (zone 2).
- Grade
  - On grades, there is an increased risk of longitudinal track movement that requires a good ballast interface section, particularly in the cribs (as seen in Figure 3). This longitudinal resistance is primarily based on full cribs (zone 2).
- High Buckle Risk Locations
  - CWR track in locations with large variation in ambient temperature as well as a very high maximum rail temperature are susceptible to increased levels of track buckling risk particularly in areas where there is inadequate lateral track resistance. This lateral resistance is primarily based on adequate shoulders (zones 1 and 3) and cribs (zone 2).
- Heavy Axle Loads
  - On heavy axle load track, there is an increased level of loading that must be dissipated through the ballast section or else the track will rapidly lose vertical track geometry

[5] This definition can vary from location to location such as for CWR territory or curves. Thus for example, a railroad may require 15 or 18" shoulder on curves but only 12" shoulders on tangent track.

integrity and develop surface or cross-level defects. This requires a good ballast section under the tie, particularly directly under the tie in zone 4.

- High Speed Track
  On high speed track, there is likewise an increased level of dynamic loading that must be dissipated through the ballast section or else the track will rapidly lose vertical track geometry integrity and develop surface or cross-level defects. This also requires a good ballast section under the tie, particularly directly under the tie in zone 4.
- Mud Spots or Soft Subgrade
  On track with soft subgrade or where there is a high moisture content, mud spots, etc., it is critical that there be sufficient depth of ballast to reduce the level of stress to that which is within the strength capabilities of the subgrade. If the depth of ballast is insufficient, the track will rapidly lose vertical track geometry integrity and develop surface or cross-level defects. This requires a full ballast section under the tie, particularly directly under the tie in zone 4.

Thus based on the above sensitivities, a set of weighting factors was developed, with a specific focus on zones 1, 2 and 3 for lateral resistance, zone 2 for longitudinal resistance and zone 4 for vertical track performance.

Using available engineering research the following weighting factors were developed:

Lateral Resistance/Buckle Risk
Using research on lateral resistance [2,3,4,5], and buckling risk [7] a set of lateral risk weighting factors was developed for zones 1, 2 and 3. Using the buckle risk parameters defined in the track buckling risk approach defined in [7], the calcuated increase in buckle risk for ”average” CWR track was calculated to be as follows:

Inadequate shoulders	1.08 to 1.15	
Inadequate cribs	1.08 to 1.15	
Grade	1.08 to 1.38	(1.18 medium severity)

It should be noted that in a similar manner, the lack of adequate cribs or shoulders in a curve will not only increase the risk of a track buckle (sun kink) it will also allow for an increasing rate of lateral misalignment growth, i.e. loss of alignment and associated growth of alignment defects. Likewsie for grades, inadequate cribs will result in an increase in longitdunal track movement.

Speed/Heavy Axle Load
Using the AREMA dynamic load formula [8] and speed/tonnage relationships from work unit and damage models [9] the calcuated increase in vertical load/damage was calculated as follows:

High Speed	1.06 to 1.11
Heavy Axle Load	1.08 to 1.12

Subgrade Problem
Similarly using the Talbot equation for subgrade stress (under the tie) [8], the additional damage due to a mud spot was calculated to be:

Mud Spot	1.11 to 1.16

Using these calculated factors, a set of weighting factors was developed as a function of the ballast cross-section Zone and the presence of one of these supplemental conditions as follows:

Table 1: Cross-Section Weighting Factors

	Zone	Curve*	Grade	HAL	Buckle Risk	Speed	Mud Spot/ soft soil
1	Left shoulder	1.08			1.15		
2	Ballast crib	1.08	1.18		1.08		
3	Right shoulder	1.08			1.15		
4	Ballast under bottom of tie			1.0875		1.06	1.11
5	Ballast under left shoulder						
6	Ballast under right shoulder						

As noted in the weighted cross-section equation above, these weighting factors are applied to the appropriate zone defined in Table 1 to get the weighted cross-section missing ballast area A_w. This value is calculated for each measured cross-section and multiplied by the cross-section spacing to give the volume of missing ballast, after compensating for the presence of the cross-ties in this volume. For a given segment, the total weighted missing volume is then calculated by adding up the individual cross-section volumes (cross-sectional area multiplied by the interval between cross-sectional profiles). Thus for example, if the cross-sectional spacing is 7" (based on an inspection speed of 20 mph and a scanning frequency of 50 Hz), there would be 9,050 cross-section profiles per mile. By summing up the missing weighted cross-sectional volumes of ballast, a segment weighted volume V_w can be calculated as follows:

$$\text{Weighted segment volume } V_w = \sum_{i=1}^{n} s * A_{w_i} - V_t$$

where s is the cross-section spacing, A_{wi} is the weighted cross section for each segment i, and V_t is any adjustment necessary to compensate for the volume of the cross-ties in the segment.

In addition to these cross-section zone weighting factors, a second set of weighting factors were development for application at the segment level (V_w). These segment weighting factors (b_i) are designed to differentiate routes or segments based on importance to the railroad operations, or broad severity of traffic.

Thus for example, these weighting factors would be applied if the segment or route is:

- Passenger route
- Hazmat Route
- Key Route
- High Tonnage Route

The resulting weighted segment or route volume is calculated as

$$\text{Weighted segment volume} \quad Vs_w = V_w * b_i$$

Where b_i are the segment weighting factors.

These segment weights were developed from risk based modeling activities [10, 11] as follows:

Passenger Carrying Line/Hazmat Weighting Factor 1.25 to 1.3	
Key Route (railroad defined) Weighting factor 1.1 to 1.125	
High speed other than passenger	
Class 5	1.1 to 1.125
Class 4	1.05 to 1.06
Class 3	1.0
Tonnage	
High Tonnage	1.1 to 1.22

Based on the above, the following segment weighting factors (b_i) are defined

Table 2: Segment Weighting Factors

Passenger Carrying Line/Hazmat	1.25
Key Route (railroad defined)	1.11
High speed other than passenger	
Class 5	1.10
Class 4	1.05
Class 3	1.0
Tonnage	
High Tonnage	1.15

This weighted segment volume can then be used for prioritization of maintenance operation in general and specifically for prioritization of ballast placement.

Sensitivity Analysis and Examples

In order to examine the sensitivity of the weighted ballast volume to the cross-section weighting factors defined in Table 1, a sensitivity analysis was performed for three of the key weighting parameters: curve, grade and heavy axle load. This sensitivity analysis was performed on an actual LIDAR-generated ballast cross-sectional profile (Figure 12) with a longitudinal spacing of 7 inches (the LIDAR profile acquisition rate). It should be noted from Figure 12 that the missing shoulder ballast is the largest single missing area value in this cross-section and as such it represents the largest weighted missing ballast volume.

Table 3 and Figure 13 present a sensitivity analysis for 16 measured ballast cross-sections representing a total length of approximately 10 feet of track (based on 7 inch sampling interval). Noting that this sensitivity analysis is ballast section sensitive, it can be seen that the combined heavy axle load/Buckle risk set of factors generates the greatest weighted value (approximately 9% greater than the base unweighted case), and the combined heavy axle load/curve set of factors generates the second greatest weighted value (approximately 8% greater than the base unweighted case). The grade effect is the smallest with only a 1.7% effect. That is because the missing crib ballast volume is minimal and as such does not have a significant effect.

Table 3: Sensitivity Analysis for 16 Measured Cross-Sections within 10 ft.

Cross Sectional Property	**Weighted Ballast Deficiency (cu yd)**
Base value (no weighting)	2.4
Grade	2.439
Mudspot	2.455
Curve	2.542
Curve + HAL*	2.586
Buckle Risk + HAL	2.617

*HAL = Heavy Axle Load

Table 4 and Figure 14 present a sensitivity analysis for the same 16 measured ballast cross-sections representing a total length of 10 feet of track (based on 7 inch sampling interval). The base case chosen for this sensitivity analysis was the Curve weighted missing ballast from Table 3 (2.542 cubic yards). It can be seen that the passenger/Hazmat risk factors generates the greatest weighted value (25% greater than the base case), and the High Tonnage factors generates the second greatest weighted value (12.5% greater than the base unweighted case). The Class 4 speed effect is the smallest with only a 5% effect.

Table 4: Segment Weighting

Segment Property	**Weighted Ballast Deficiency (cu yd)**
Curve	2.542
Pass/Hazmat	3.178
Key route	2.822
High Speed Cl 5	2.822
Speed Cl 4	2.669
High Tonnage	2.924

Table 5 and Figure 15 present the results of a cross-section weighting application for 20 segments of actual track data, each approximately 100 feet in length (total of approximately

2400’ between MP 166.36 and 166.82) and the corresponding prioritization. Both the Figure and Table present and compare the unadjusted volume of missing ballast and the weighted volume of missing ballast together with their relative prioritization. As can be seen in Table 5, use of the weighting index changes the priorities of segments 25 and 27 (numbers 3 and 4 in priority in the unweighting ranking changing to 4 and 3 in the weighting ranking) as well as segments 13 and 24 (numbers 14 and 15 in priority in the unweighting ranking changing to 15 and 14 in the weighting ranking). Thus the effect of the weighting on reprioritization can be seen.

Table 5: Cross-Section Weighting for 20 Short Segments (MP 166.36 to 166.82)

Segment #	Segment Length (ft)	Unweighted Volume Deficiency (cu yd)	Weighted Volume Deficiency (cu yd)	Unweighted Prioritization Rank	Weighted Prioritization Rank	Rank Difference
9	145.17	0.5651	0.6821	8	8	0
10	99.98	0.0780	0.0934	20	20	0
11	121.27	0.6058	0.7416	7	7	0
12	121.16	0.6064	0.7458	6	6	0
13	99.98	0.1774	0.2142	15	14	1
14	115.95	1.9277	2.4191	1	1	0
15	115.85	0.4722	0.5794	9	9	0
16	99.98	0.1186	0.1435	18	18	0
17	106.5	0.0870	0.1054	19	19	0
18	106.4	0.7781	0.9386	2	2	0
19	99.98	0.2231	0.2635	11	11	0
20	99.98	0.1422	0.1670	17	17	0
21	99.98	0.2641	0.3156	10	10	0
22	99.98	0.1652	0.1965	16	16	0
23	99.98	0.2024	0.2433	13	13	0
24	103.93	0.1801	0.2133	14	15	-1
25	103.86	0.6716	0.7858	3	4	-1
26	99.98	0.6276	0.7705	5	5	0
27	99.98	0.6512	0.8089	4	3	1
28	99.98	0.2203	0.2634	12	12	0

Table 6 and Figure 16 similarly present the results of a cross-section weighting application for 40 segments of actual track data, each approximately one mile in length (total of approximately 40 miles) and the corresponding prioritization. Both the Figure and Table present and compare the unadjusted volume of missing ballast and the weighted volume of missing ballast together with their relative prioritization. As can be seen in Table 5, use of the weighting index changes the priorities of numerous segments, in some cases quite significantly. Thus for example Mile 5 moves up in priority from number 6 to number 4; while Mile 6 moves up significantly from number 18 to number 13. Mile 10 moves up dramatically from number 28 out of the 40 to number 17. Thus the effect of the weighting on reprioritization can be clearly seen.

Table 6: Segment Weighting for 40 One-Mile Long Segments

Segment #	Unweighted Volume Deficiency (cu yd)	Weighted Volume Deficiency (cu yd)	Unweighted Prioritization Rank	Weighted Prioritization Rank	Rank Difference
1	2881.6	3276.31	33	28	5
2	3155.9	3583.83	27	22	5
3	3675.5	4155.17	14	14	0
4	5776.24	6762.62	3	2	1
5	4809.56	5642.08	6	4	2
6	3644.52	4303.7	18	13	5
7	1555.55	1845.07	40	40	0
8	2084.7	2476.32	39	38	1
9	6529.73	7742.87	1	1	0
10	3144.52	3756.06	28	17	11
11	4581.01	5481.49	7	5	2
12	3646.49	4361.51	17	10	7
13	4230.22	5037.08	8	7	1
14	2904.9	3205.21	31	29	2
15	3322.23	3685.79	24	19	5
16	2418.99	2681.52	37	36	1
17	3840.94	4306.95	12	12	0
18	4011.42	4490.88	9	9	0
19	3395.07	3807.7	23	16	7
20	3879.28	4325.8	11	11	0
21	3424.18	3424.18	22	26	-4
22	2864.24	2864.24	34	34	0
23	3666.73	3666.73	16	21	-5
24	3967.57	3967.57	10	15	-5
25	4957.26	4957.26	5	8	-3
26	3669.51	3669.51	15	20	-5
27	3163.29	3163.29	26	30	-4

28	2964.79	2964.79	30	32	-2
29	2787.76	2787.76	35	35	0
30	3477.65	3477.65	20	24	-4
31	3701.05	3701.05	13	18	-5
32	3442.8	3442.8	21	25	-4
33	2887.83	2887.83	32	33	-1
34	2481.31	2481.31	36	37	-1
35	3301.88	3301.88	25	27	-2
36	2140.93	2140.93	38	39	-1
37	5799.76	5799.76	2	3	-1
38	5391.43	5391.43	4	6	-2
39	3540.69	3540.69	19	23	-4
40	2970.91	2970.91	29	31	-2

To more realistically compare to the way railroads actually add ballast, these 40 one-mile segments were in turn consolidated into 8 five-mile segments as shown in Table 7 and Figure 17. Here too, the significant effect of the weighting reprioritization can be seen. For the five mile segment 36-40, its priority dropped from number 2 (unweighted) to number 4 (weighted), while the five mile segment 6-10 rose from number 6 (unweighted) to number 3 (weighted). Thus, if the railroad's program had only allocated 15 miles of ballast for this 40 mile stretch there would have been a significant shift in locations where the ballast would be assigned, with segments 1-5, 6-10, 11-15, getting ballast and previous priority segments 36-40 and 21-25 no longer receiving any ballast, because the consequences of the missing ballast would be less for these segments.

Table 7: Segment Weighting for 8 Five-Mile Long Segments

Consolidated Segment #	Unweighted Volume Deficiency (cu yd)	Weighted Volume Deficiency (cu yd)	Unweighted Prioritization Rank	Weighted Prioritization Rank	Rank Difference
1-5	20299	23420	1	1	0
6-10	16959	20124	6	3	3
11-15	18685	21771	4	2	2
16-20	17546	19613	5	5	0
21-25	18880	18880	3	6	-3
26-30	16063	16063	7	7	0
31-35	15815	15815	8	8	0
36-40	19844	19844	2	4	-2

Conclusion

Maintenance of a proper ballast profile and depth is of critical importance to railroads from both a safety and ongoing maintenance point of view. Inadequate ballast sections can result in rapid loss of track geometry (alignment, profile, cross-level, twist or warp, etc.) as well as potential catastrophic failure such as track buckling, which is directly assisted with inadequate ballast resistance.

New generation inspection technologies such as the LIDAR based Ballast Saver inspection system for profile measurement and Ground Penetrating Radar (GPR) for ballast depth measurement provide good information about ballast profile and depth and can be used to determine the amount of missing ballast. This includes determination of where and how much ballast should be placed, such as ballast at end of ties (shoulders), under ties, and in cribs.

These systems, and the resulting ballast deficiency measurements can be used to help effectively manage the ballast placement process. This can be further assisted and enhanced by the development of prioritization values to determine not only how much ballast should be added (e.g. ballast cars/mile) but the priority of each individual segment (e.g. mile of track). Prioritization is extremely important in conditions when there are not sufficient resources to correct all of the problems, such as having a limited budget or a limited amount of equipment that can be used. In this manner, the higher priority locations can be addressed first.

In developing prioritization rules, the ability to tie in the prioritization to performance or 'risk" of failure has been shown to be very valuable. This can be accomplished by using performance-based weighting factors such as vertical, lateral and longitudinal track performance requirements, adequate lateral resistance, or adequate distribution of vertical load. This is particularly important for ballast placement, since in many cases, there are often only limited resources available, and thus the ability to place ballast at "high risk" locations is important. In addition to weighting the track segments based on performance, it is often very important to also weigh track segments based on the priority of importance of the line segment itself. Thus high density routes, passenger routes and hazmat routes usually require a higher priority because of the desire to minimize risk of degradation, slow orders, or derailments on these lines.

This paper demonstrates how such performance based prioritization algorithms can be used in conjunction with the ballast profile inspection technologies to allow for the prioritization of significant miles of track in an effective and useful manner.

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Figure 1: Track with a Full Ballast Section

Figure 2: Key Ballast Cross-Section Zones

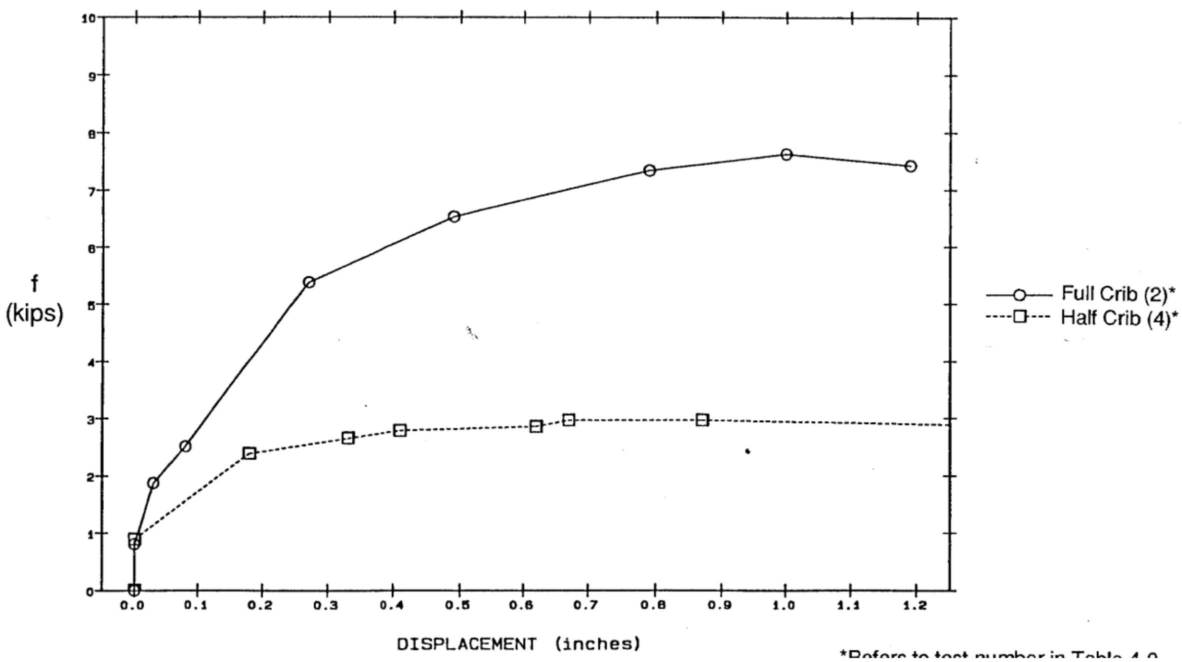


Figure 3: Effect of Crib Ballast Level on Track Longitudinal Resistance [2]

Figure 4: GREX Ballast Saver Ballast Profile Inspection Vehicle

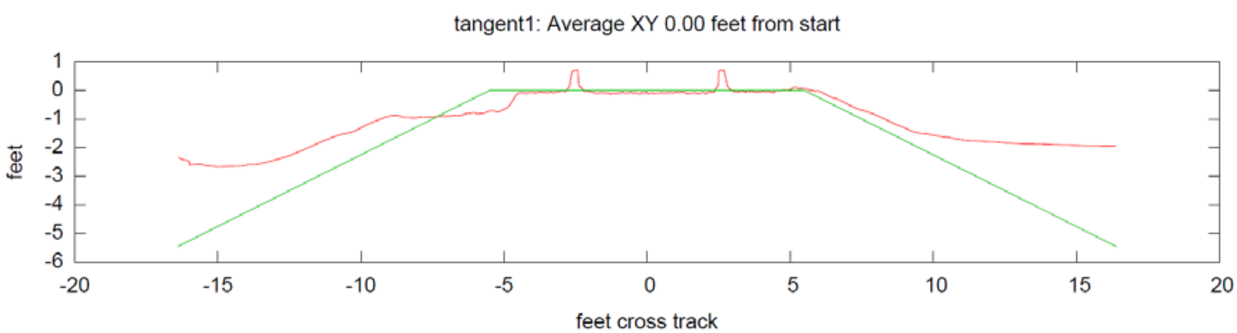


Figure 5: LIDAR Inspection Profile Overlay on Idealized Railroad Profile

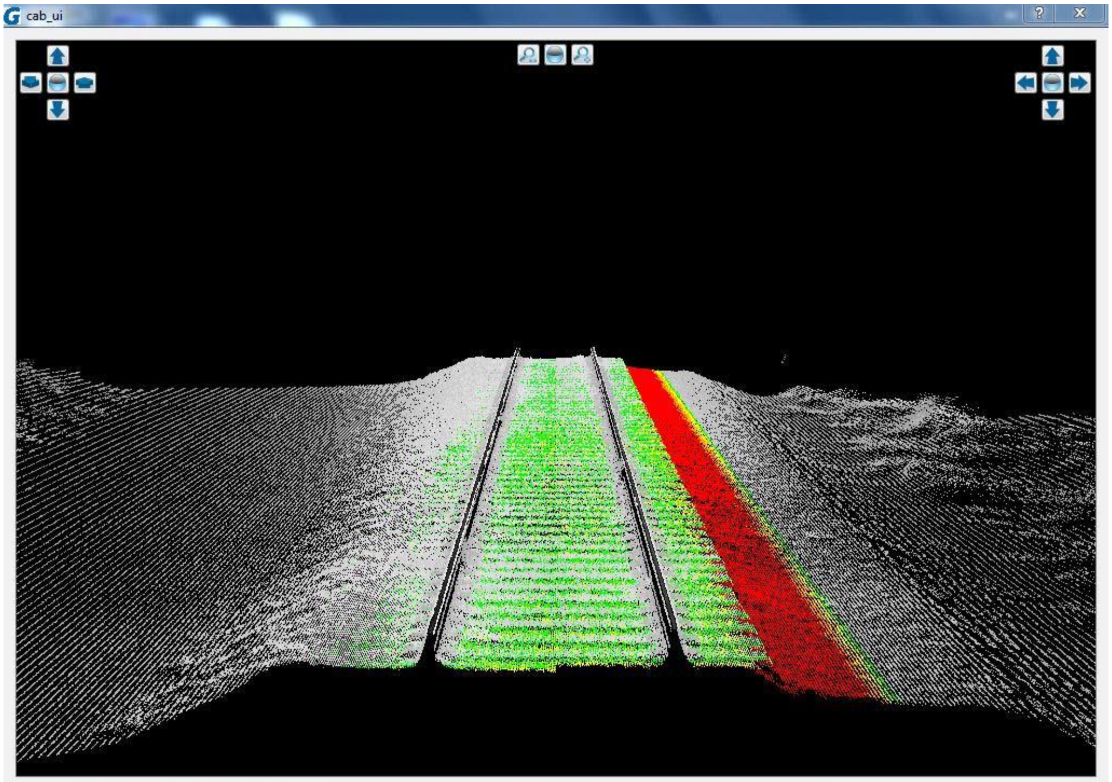


Figure 6: LIDAR Ballast Profile Image: Deficient Ballast Zones in Red

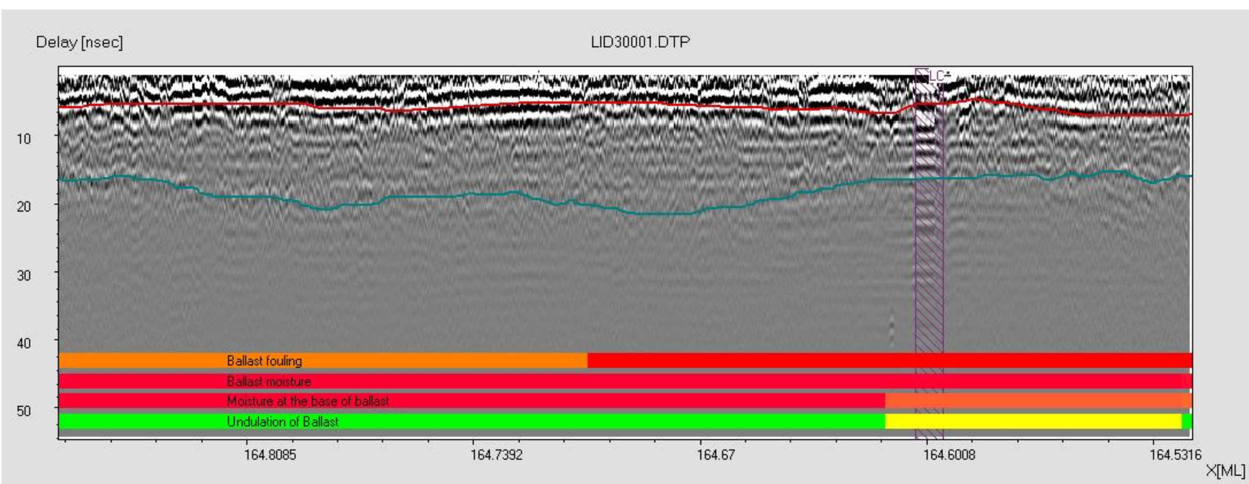


Figure 7: GPR Data showing bottom of ballast layer (red) and top of subgrade(blue)

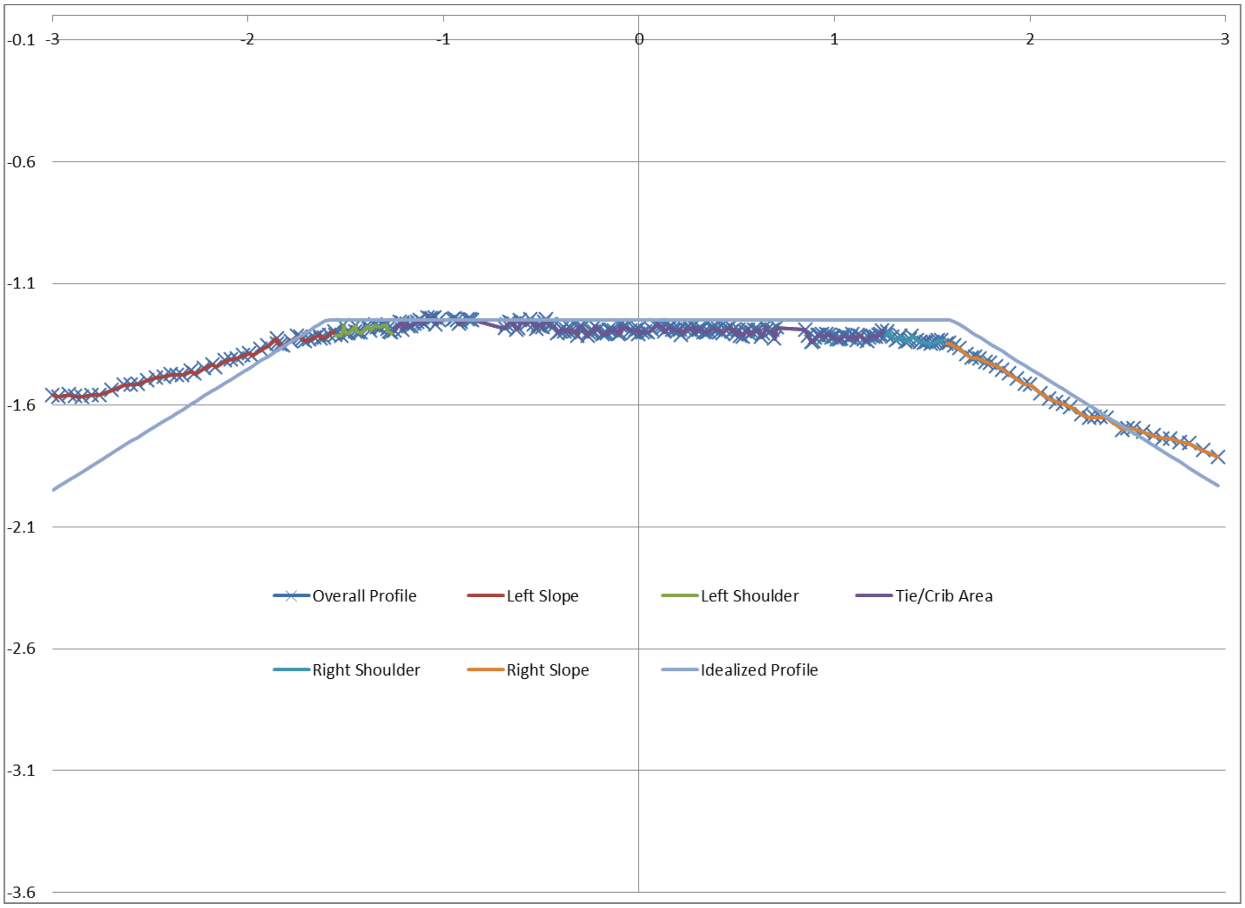
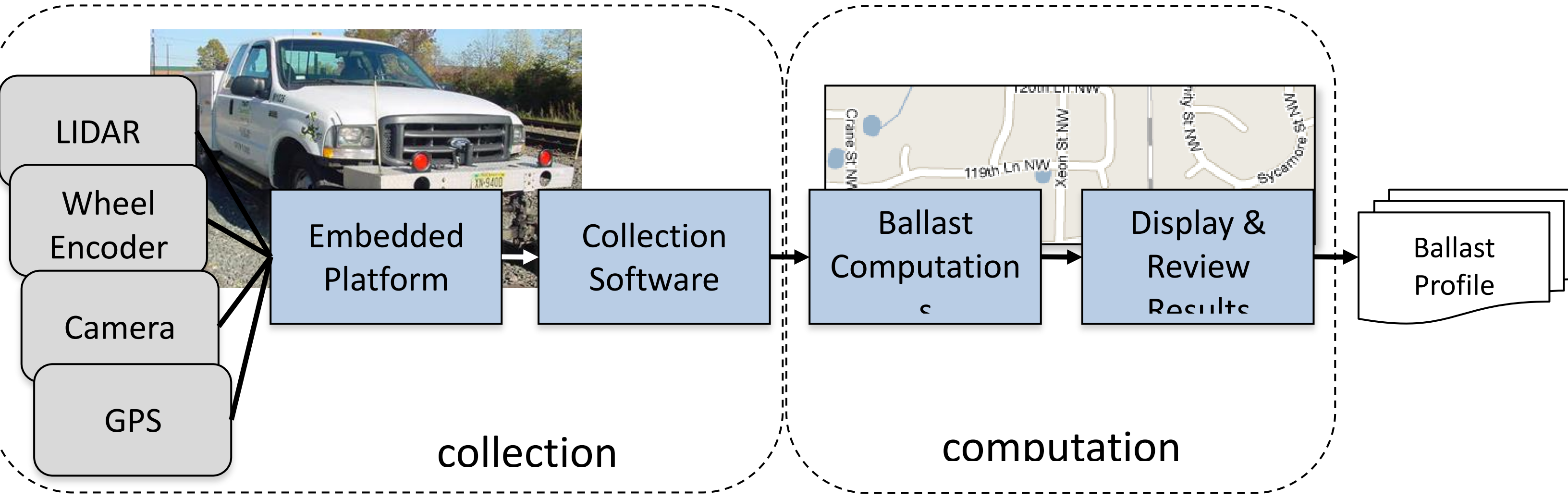


Figure 8: Digitized LIDAR Ballast Profile with Ideal Profile Overlay

Figure 9: GREX BallastSaver System and Software



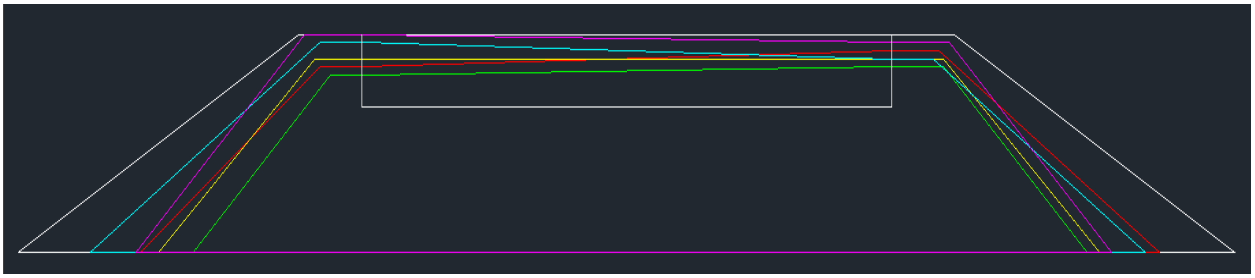


Figure 10: Example Overlay of Multiple Profiles

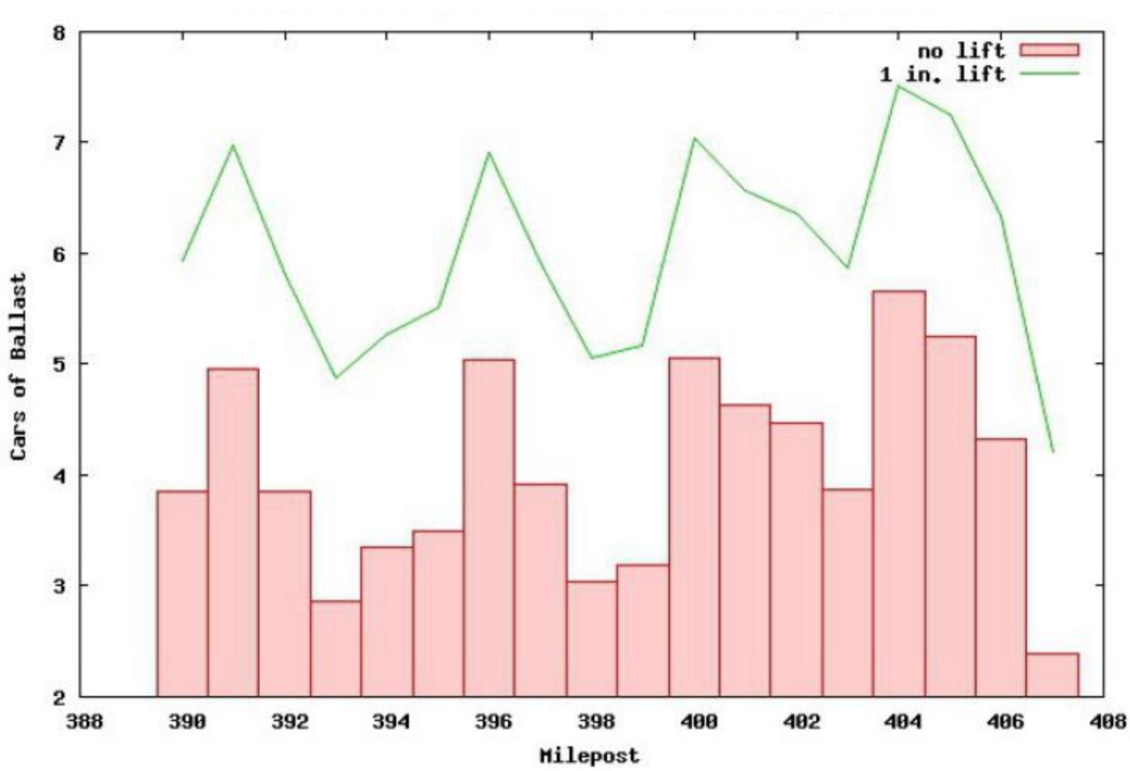


Figure 11: Required Carloads of Ballast by Milepost

Figure 12: LIDAR Ballast profile (green) vs. Desired ballast profile (purple) used in Sensitivity Analysis

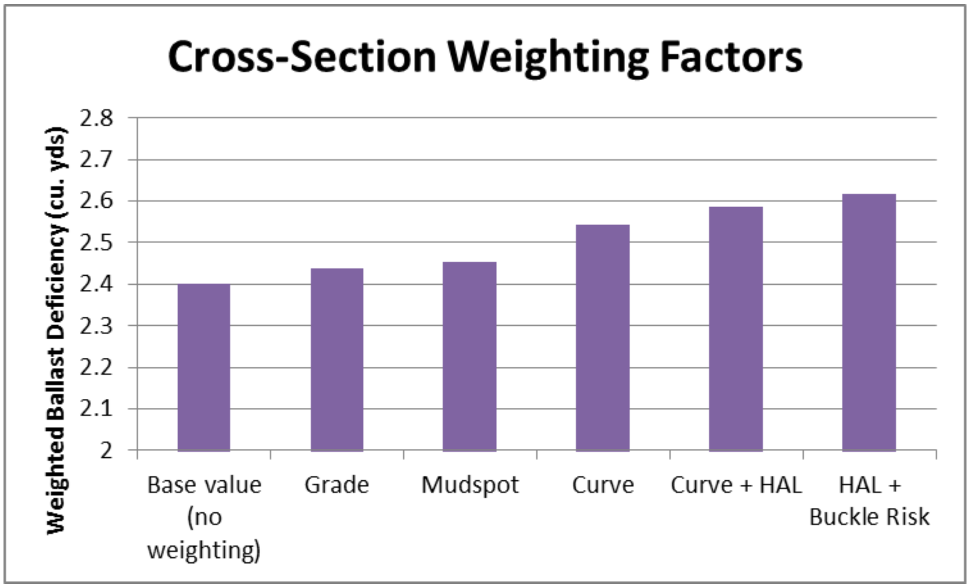


Figure 13: Cross-Section Weighting

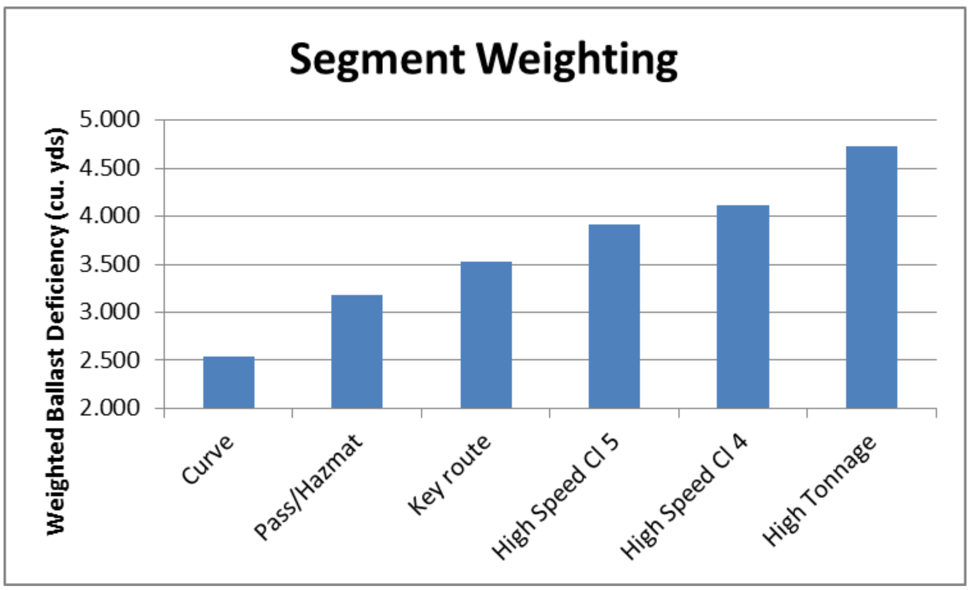


Figure 14: Segment Weighting

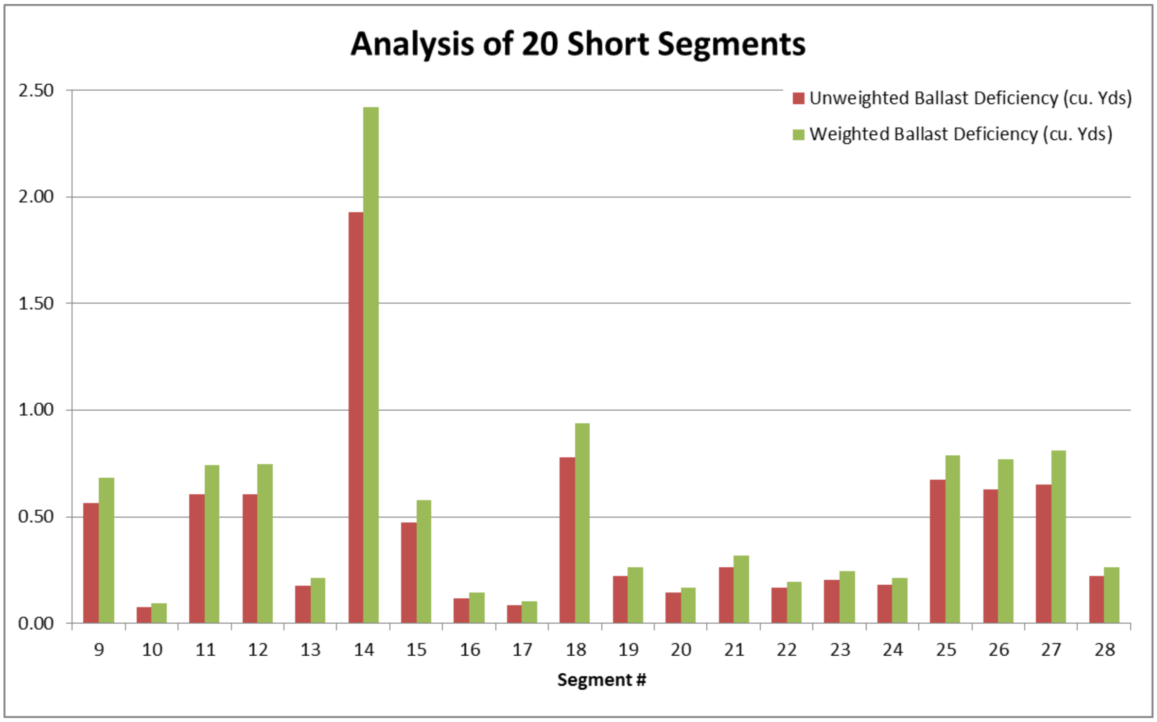


Figure 15: Sample Weighted vs. Unweighted Ballast Deficiency (MP 166.36-166.82)

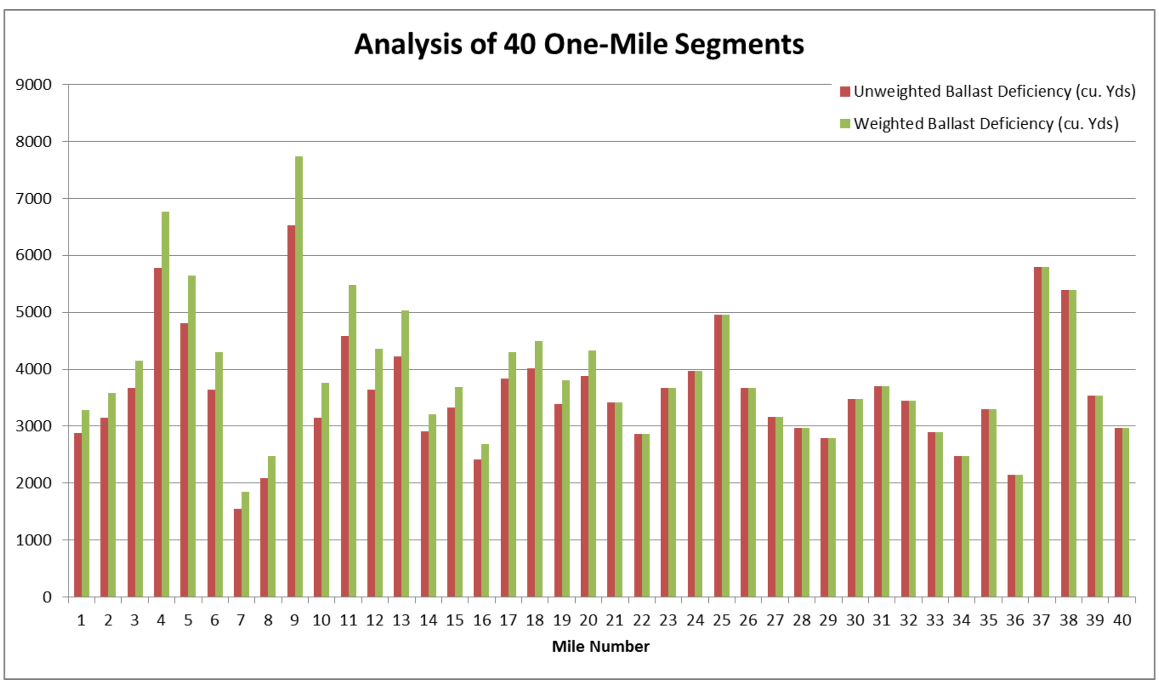


Figure 16: Sample 40 One-Mile Segment Analysis Weighted vs Unweighted Ballast Deficiency

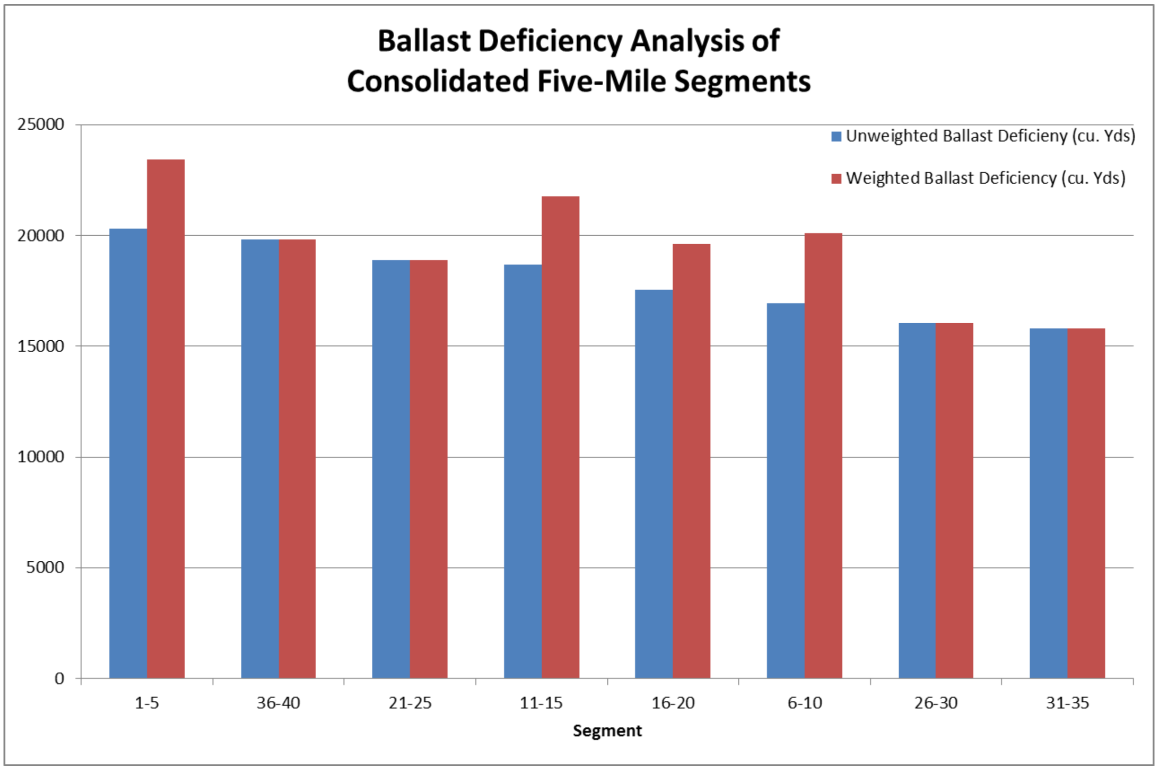


Figure 17: Sample Consolidated Five-Mile Segment Analysis

Weighted vs Unweighted Ballast Deficiency