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# Evaluation of a Lidar-Based Ballast-Section Mapping System

Rafael Jimenez, David Davis, Travis Wolgram, and Michael M<sup>c</sup>Henry

## Summary

On March 26, 2012, Transportation Technology Center, Inc. (TTCI) tested a Lidar (Light Detection and Ranging) based ballast-section mapping system (BallastSaver) developed by Georgetown Rail Equipment Co. (GREX<sup>TM</sup>). The test was conducted at the Transportation Technology Center, Pueblo, Colo., to evaluate BallastSaver's capability in determining the ballast deficiency of the track with reference to a design cross-section profile.

BallastSaver has the potential to increase productivity and reduce the costs associated with dumping more ballast than is required. Based on the test results, it appears the system has the capability to approximate ballast deficiency quantities. The difference between BallastSaver's preliminary ballast deficiency values and the final values presented in its formal report indicates that post-processing/reviewing by experienced personnel was necessary.<sup>1</sup>

It is clear that given the directional repeatability of the Lidar profiles and the shape similarity of the same profiles with TTCI's Global Navigation Satellite System (GNSS)-measured profiles, BallastSaver has the capability to identify and capture the surface of the ballast section. However, the differences between each of the following suggest that improvements to the BallastSaver deficiency calculation will be beneficial: (1) the BallastSaver preliminary and final ballast deficiency values, (2) scan directions, and (3) between BallastSaver and GNSS values. TTCI recommends that a user-specified threshold based on practical experience be automated to exclude deficiencies identified in places where the difference between the existing ballast and the railroad design profile is so small that adding ballast would be unnecessary or result in a surplus. A track engineer would likely consider these deficiencies to be insignificant, thus the term "practical threshold." Because of the visual inspection of the test zones, TTCI implemented the practical threshold when it excluded the very small deficiencies measured between the rails.

This test was designed to evaluate BallastSaver's capability to quantify the ballast deficiency in the shoulders of the ballast section. The system's capability to quantify ballast deficiency between the ties, as typically occurs when the track is raised, was not evaluated. TTCI recommends additional testing to evaluate that capability.

A comparison of the ballast deficiencies reported by the BallastSaver system and those calculated from GNSS measurements indicates, for the majority of cases (15 of 16), the BallastSaver deficiency values were larger than the GNSS-derived values. The differences were from as low as 2.7 ft<sup>3</sup> (166.0 ft<sup>3</sup> vs. 163.3 ft<sup>3</sup>) to as high as 97.7 ft<sup>3</sup> (99.8 ft<sup>3</sup> vs. 2.1 ft<sup>3</sup>). The differences reported for 8 of the 16 cases were greater than 50 percent, with the four largest percentage differences involved small volumes (Part 2, restored ballast section). In the four cases where the variation between the track profile and the railroad design profile was large (Part 1, reconfigured), the results were better, and in 6 of the 8 cases, the differences were less than 22 percent. When the practical threshold is applied to the total deficiency values, the insignificant deficiency between the rails is excluded and the amount of required ballast in the 100-foot test zone is reduced 53 percent from 99.8 ft<sup>3</sup> to 65.2 ft<sup>3</sup> (No. 2 above). Applying the practical threshold to the remainder of the final ballast deficiency values presented in the BallastSaver formal report should result in proportional reductions.

GREX submitted a preliminary dataset 4 days after testing was completed. The volume deficiencies displayed within minutes of each scan run were not available, and therefore were not evaluated in this test. The final dataset became available when GREX submitted its formal report to TTCI.<sup>1</sup> The percent difference between the total ballast deficiencies reported in the preliminary BallastSaver dataset and those presented in the formal report ranged from 23 percent to 105 percent (139.7 ft<sup>3</sup> vs. 68.3 ft<sup>3</sup>). This extrapolates to about 2,700 ft<sup>3</sup> and about 3,700 ft<sup>3</sup> of additional ballast per mile. The preliminary values were consistently larger than the final values. The differences (preliminary vs. final) in the deficiency values reported for 8 of the 16 cases were greater than 50 percent.

The results also indicate differences in the quantity of ballast deficiency reported by the BallastSaver system depending on the direction the test zones were scanned. Details are presented in the Scan Direction Comparison section of this *Technology Digest*.



## INTRODUCTION

The ballast volume quantity required for new track construction is calculated based on a “design” trapezoidal cross section (profile) and the length of the track. The depth of ballast under the ties and the width and slope of the shoulders are determined based on the type of service expected over the track.

Ballast in existing track is replenished for various reasons, including: (Case 1) after track surfacing operations, (Case 2) after undercutting, (Case 3) to restore ballast lost through degradation, and (Case 4) to complete the ballast section after a profile revision.<sup>2</sup>

Track engineers rely on various methods for determining the amount of ballast required for safe and efficient train operations, including visual inspection, nomographs (2-dimensional diagrams designed to allow the approximate graphical computation of a function), and practical experience.

GREX defines the BallastSaver, Figure 1, as a Lidar-based system intended, primarily, to automate the process of identifying ballast deficiency, calculating the amount of ballast required based on a railroad design profile, and identifying key locations along the track with GPS coordinates. The system is intended to be operated in test mode at speeds up to 20 mph. TTCI tested BallastSaver to evaluate these basic capabilities.



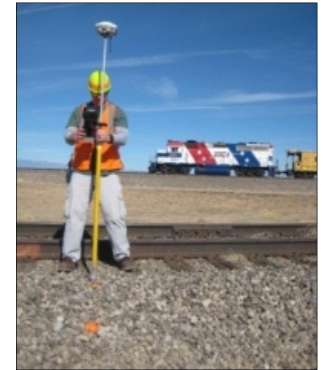
**Figure 1. GREX's BallastSaver  
Hi-rail Vehicle Platform**

## TEST ZONES AND PROCEDURE

TTCI designed the GREX BallastSaver test to replicate Case 4, as described above, with the objective of evaluating the system's basic capability to identify and quantify ballast deficiency in the shoulders of the test zones based on a railroad design profile. The design profile specifies a ballast section with shoulders that are 12 inches beyond the end of the ties and 2:1 slopes for single, tangent track. For single track in curves, it specifies 12-inch shoulders on the low side, 15-inch shoulders on the high side, and 2:1 slopes. A two-part test was designed that included the reconfiguration of the existing ballast shoulders and their subsequent restoration.

Four 100-foot test zones were selected, two in tangent track and two in a 1° 30" curve with 3.25-inch superelevation. A ballast regulator was used to reconfigure the shoulders of the four zones for Part 1 of the test. Eleven ballast section profiles were marked at 10-foot intervals in each of the test zones. Each profile consisted of nine ballast-surface measurement locations (one at track center and four on each side of the track). This provided ten 10-foot subzones, with calculated ballast deficiencies. Three hundred ninety six GNSS ballast-surface measurements (4 test zones x 11 profiles x 9 measurements per profile) were taken for each part of the two-part test. TTCI used a Trimble NetR9 GNSS Reference Receiver (base

station) and a Trimble R8 GNSS Receiver (kinematic surveying – roving unit) to determine the ballast section profiles (see Figure 2). The ballast section profiles derived from the GNSS ballast-surface measurements were used for qualitative comparison with the BallastSaver profiles. They were then used to calculate the ballast deficiencies to compare with the deficiencies reported by BallastSaver. The accuracy of the GNSS equipment in conjunction with the method used to measure the profile areas and the simplicity of the traditional volume calculation provide a high level of confidence in the values used to evaluate automated ballast-mapping systems. GREX reports that the BallastSaver collected over 1.75-million measurements (4 test zones x 1,279 profiles x 344 measurements per profile).



**Figure 2. GNSS Measurements  
of the Ballast Cross-Sectional  
Profile for Volume Calculations**

After the GNSS ballast section profile measurements were taken for Part 1 of the test, BallastSaver made one pass in scan mode in each direction over the four test zones. Although the published maximum BallastSaver scan speed is 20 mph, the test was conducted at a much slower speed to allow the system to stop and capture GPS coordinates at the beginning and end of the 100-foot zones. The lower speed will not adversely affect accuracy, as more profiles per foot of track were collected.

For Part 2 of the test, the ballast regulator restored the shoulders of the ballast section. Once again, BallastSaver made one scan pass in each direction, and all of the GNSS ballast cross-sectional profile measurements were retaken.

In addition to the four test zones used for cross-sectional profile and ballast deficiency comparisons, BallastSaver made two scan runs over the 6°, 5" superelevation curve of the High Tonnage Loop. This curve provided a longer (about 2,700 ft) section of track for BallastSaver to scan.

## EVALUATION

TTCI requested data and graphics from GREX that is not typical of a BallastSaver report. These requests included xy coordinates for plotting 176 Lidar ballast section profiles to correspond with the GNSS measurement locations (4 test zones x 11 profiles per zone x 2 scan directions x 2 test parts), GPS coordinates for the beginning and end of test zones, and ballast surplus. GREX developed a preliminary ballast surplus algorithm specifically for this test as a result of our request.

TTCI created two sets of graphs to evaluate the BallastSaver results: one for a qualitative comparison of the Lidar data and the GNSS data and a second showing the quantitative calculation of surplus and deficiency areas from the GNSS data.

## Qualitative Study

A visual inspection of the four test zones conducted as part of the qualitative study indicated that additional ballast was not required between the rails in any of the zones. A minimum layer of typical AREMA 4A ballast, whose gradation specifies about 75 percent by weight particles 1 inch or larger, would have resulted in excess ballast.

Each of the graphs developed for the qualitative study included two Lidar (BallastSaver) profiles, the GNSS-measured profile, and the

design profile. The two BallastSaver profiles, one taken in each scan direction, were compared for directional repeatability. Secondly, the BallastSaver profiles were compared to the GNSS profile for similarity in their shapes. Finally, all measured profiles were compared to the design profile to qualitatively assess the surplus volume, deficiency volume, and any inconsistencies to expect in the final volume calculation table. Figure 3 is representative of the directional repeatability and profile shape similarity with the GNSS profile of the BallastSaver dataset. Figure 3 shows where the ballast regulator transferred material away from the ends of the ties, creating both an area of deficiency and an area of surplus on the low side of the curve.

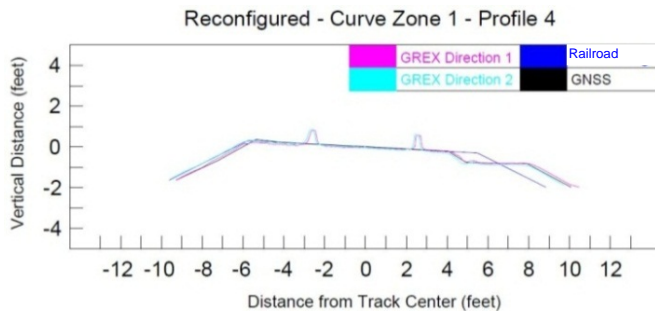


Figure 3. TTCI Overlay of BallastSaver Scan Profile, GNSS-Measured Profile and the Railroad Design Profile – Typical of the Dataset

### Quantitative Study

The second set of graphs plotted the GNSS-measured profiles against the design profile. Those graphs, like the one in Figure 4, quantify the areas of ballast deficiency and surplus used in the ballast volume calculations. The beginning and end of the GNSS-measured profiles were taken at the toe of the ballast on each side of the track. The end points of these profiles represent the intersection of the ballast shoulder with the ground adjacent to the track, thereby defining the horizontal limits of the ballast section. A horizontal line, simulating the ground level, was drawn from the GNSS-measured profile endpoints to the design profile to define areas of ballast deficiency and surplus. Surplus ballast is identified with green hatch indicating areas where the measured ballast profile is above the design profile. Conversely, deficient ballast areas are shown in red hatch, where the measured ballast profile is below the design profile.

The average deficiency area of each pair of consecutive profiles was multiplied by the GNSS-measured distance between the two profiles to calculate the GNSS-based volume of ballast deficiency in a test zone. This was repeated for each of the 10 subzones and the 10 subzone volumes were summed to arrive at the total deficiency of the test zone. This process was repeated for each of the four test zones for both parts of the test to calculate deficiency and surplus. This methodology was used to duplicate that of the BallastSaver system. BallastSaver does not quantify the volume of the entire ballast section using the traditional method; i.e., area of the trapezoid (where the bottom of the trapezoid is the depth of ballast below the ties) times the length of track minus the volume of the ties. Instead, BallastSaver “looks” at the variations between the existing ballast profile and the design profile along the top and the two slopes.

Figure 5 illustrates the difference between a reconfigured ballast profile (Figure 4) in Part 1 of the test and the same profile location after the shoulders were restored for Part 2.

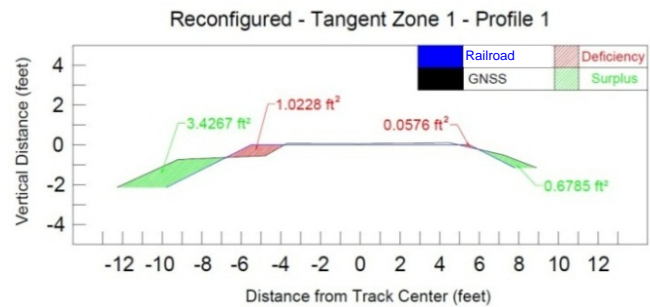


Figure 4. TTCI Overlay of a GNSS-Measured Profile on the Railroad Design Profile with Areas of Ballast Deficiency and Surplus

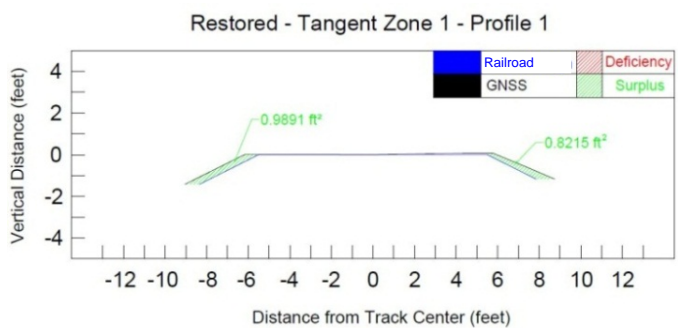


Figure 5. TTCI Overlay of the Same Profile Location as Figure 4 after the Ballast Shoulders were Restored

### RESULTS

Table 1 (page 4) lists the test zones, the measured length of each test zone, and the volumes of ballast deficiency in cubic feet. Included are two BallastSaver derived ballast deficiency datasets. GREX submitted the first complete dataset (preliminary data including curve test zones) 4 days after testing was completed; GREX’s final dataset was submitted with its formal report three working days later. The table also contains the ballast deficiency that TTCI calculated based on the ballast section profiles measured in each test zone using the GNSS equipment.

BallastSaver measured the test zone lengths using an electronic encoder in contact with the rail. The test zone lengths in the TTCI dataset were derived from GNSS coordinates. The data indicates small differences between the test zone lengths reported by the BallastSaver system as compared to those recorded by TTCI, where the largest difference was less than 4 percent and the rest were 1 percent or less.

### BallastSaver Data — Preliminary vs. Final

The difference between the total ballast deficiencies of the preliminary BallastSaver dataset and those of the final dataset for the four 100-foot test zones ranged from 23 percent (270.8 ft<sup>3</sup> vs. 219.4 ft<sup>3</sup>) to 105 percent (139.7 ft<sup>3</sup> vs. 68.3 ft<sup>3</sup>), where the preliminary values were consistently larger than the final. In terms of cubic feet per mile, these discrepancies account for about 2,700 ft<sup>3</sup> to 3,700 ft<sup>3</sup> per mile. Eight of the total volume differences were greater than 50 percent and eight were less than 50 percent. The GREX formal report indicates that the preliminary versus final deficiency difference shown in Table 1 for the longer (about 2,700 ft) zone is attributed to BallastSaver using a railroad design profile with an 18-inch high-side shoulder instead of the 15-inch shoulder.

### BallastSaver Data Scan Direction Comparison

Opposite-direction scans of the four 100-foot test zones with the BallastSaver system resulted in total ballast deficiency volume differences that ranged from 1 percent to 21 percent in the preliminary dataset. In the final dataset, the directional differences ranged from 1 percent (Part 1, Tangent Zone 2, direction 1, 156.4 ft<sup>3</sup> vs. direction 2, 154.9 ft<sup>3</sup>) to 62 percent (Part 2 Tangent Zone 1, direction 1, 99.8 ft<sup>3</sup> vs. direction 2, 61.5 ft<sup>3</sup>). In terms of cubic feet per mile, the final data directional differences range from about 100 ft<sup>3</sup> to about 2,000 ft<sup>3</sup> per mile. All except one of the directional differences were less than 45 percent. The directional differences of the preliminary versus final data for the longer (about 2,700 ft) test zone in Section 25 are within the same range as the differences in the 100-foot test zones.

### BallastSaver Data vs. GNSS Data

A comparison of the total ballast deficiencies reported by the BallastSaver system and those calculated from the GNSS data indicates differences from as low as 2.7 ft<sup>3</sup> (166.0 ft<sup>3</sup> vs. 163.3 ft<sup>3</sup>) to as high as 97.7 ft<sup>3</sup> (99.8 ft<sup>3</sup> vs. 2.1 ft<sup>3</sup>). When a practical threshold based on the visual inspection was applied to the BallastSaver data, where the insignificant deficiency measured between the rails was excluded, the net total deficiency, and therefore the amount of required ballast was reduced 53 percent from 99.8 ft<sup>3</sup> to 65.2 ft<sup>3</sup>.

Eight of the total volume differences were greater than 50 percent and eight were less than 50 percent. The four largest differences occurred in the tangent track test zones during Part 2 of the test, where the ballast sections had been restored. All of the BallastSaver deficiency values, except one, were larger than the GNSS-derived values. The four largest percentage differences involved small volumes. This test was designed to evaluate BallastSaver’s capability to quantify the ballast deficiency in the shoulders of the ballast section. The system’s capability to quantify ballast deficiency between the ties, as typically occurs when the track is raised, was not evaluated. TTCI recommends additional testing to evaluate that capability.

### BallastSaver Ballast Surplus Data Scan Direction Comparison

GREX provided the ballast surplus data for each of the test zones. The scan direction differences of this developing capability were relatively small between 3 percent and 32 percent (42.6 ft<sup>3</sup> vs. 32.2 ft<sup>3</sup>), which is less than those reported for ballast deficiency. Although ballast surplus was extracted from the GNSS data, it is not compared to the BallastSaver data because different calculation methodologies were used.

### FINAL ANALYSIS

It is clear that given the directional repeatability of the Lidar profiles and the shape similarity of those same profiles with the GNSS-measured profiles, the BallastSaver has the capability to identify and capture the surface of the ballast section. However, the differences between each of the following suggest that improvements to the BallastSaver deficiency calculation will be beneficial: (1) the BallastSaver preliminary and final ballast deficiency values, (2) scan directions, and (3) between BallastSaver and GNSS values.

A user-specified practical threshold should be a useful addition to the BallastSaver deficiency calculation, where, for example, a deviation from the railroad design profile of 1 1/2 inch or less is considered insignificant and is ignored. This will help reduce the overestimation of ballast requirement.

### ACKNOWLEDGEMENTS

TTCI acknowledges the tremendous effort on the part of GREX, and in particular Carlos Martinez and Greg Grissom, for participating in the Automated Track Inspection Test Program and for going out of their way to provide the special data/graphics that were used to evaluate their system.

### REFERENCES

1. Martinez, Carlos and Greg Grissom. April 2012. “BallastSaver Evaluation: Final Report for TTCI,” Georgetown Rail Equipment Company.
2. Hay, William W. 1982. *Railroad Engineering*, Second Edition. John Wiley & Sons.

Table 1. Ballast Deficiency in the Four Test Zones for Test Parts 1 and 2

Test	Test Zone	Direction	Ballast Deficiency ft <sup>3</sup>									
			GREX BallastSaver Preliminary Data		GREX Final Data			TTCI GNSS Data				
			Test Zone Distance (ft)	Total Deficiency	Road Side Deficiency	Field Side Deficiency	Total Deficiency	Test Zone Distance (ft)	Road Side Deficiency	Field Side Deficiency	Total Deficiency	
Part 1 Ballast Section Reconfigured	Tangent 1	Road Right <sup>1</sup>	100.1	269.9	48.6	133.5	182.1	99.5	1.3	103.8	105.1	
		Road Left <sup>2</sup>	100.6	254.4	19.6	172.4	192.0					
	Tangent 2	Road Right <sup>3</sup>	100.2	244.8	59.6	96.8	156.4	99.6	2.8	144.5	147.3	
		Road Left <sup>4</sup>	100.0	234.1	19.1	135.8	154.9					
	Curve 1	Road Right <sup>3</sup>	100.1	259.1	148.3	49.8	198.1	99.4	106.9	56.4	163.3	
		Road Left <sup>4</sup>	100.4	234.3	121.4	44.6	166.0					
	Curve 2	Road Right <sup>3</sup>	100.0	270.8	65.7	153.7	219.4	100.3	37.6	149.8	187.4	
		Road Left <sup>4</sup>	100.3	267.2	40.4	142.6	183.0					
Part 2 Ballast Section Restored	Tangent 1	Road Right <sup>3</sup>	103.2	148.2	61.8	38.0	99.8	99.5	2.1	0	2.1	
		Road Left <sup>4</sup>	100.2	122.7	15.0	46.5	61.5					
	Tangent 2	Road Right <sup>3</sup>	100.1	141.1	58.9	22.1	81.0	99.5	4.7	0	4.7	
		Road Left <sup>4</sup>	100.0	139.7	21.1	47.2	68.3					
	Curve 1	Road Right <sup>3</sup>	100.3	184.8	63.0	72.3	135.3	99.6	1.2	58.1	59.2	
		Road Left <sup>4</sup>	100.2	171.1	29.6	64.6	94.2					
	Curve 2	Road Right <sup>3</sup>	100.1	181.8	48.0	77.5	125.5	100.2	9.4	74.6	83.9	
		Road Left <sup>4</sup>	100.2	177.8	22.1	77.9	100.0					
HTL Section 25	Road Right <sup>3</sup>	2691.8	4966.2	323.5	926.0	1249.5						
	Road Left <sup>4</sup>	2710.9	4404.5	93.2	1334.1	1427.3						

<sup>1</sup>Road Right = Direction 1; <sup>2</sup>Road Left = Direction 2; <sup>3</sup>Road Right = Direction 2; <sup>4</sup>Road Left = Direction 1.

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