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TECHNICAL PAPER

Relationship Between Missing Ballast and Development of Track Geometry Defects

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Abstract This paper presents the results of a study on the relationship between missing ballast and the development of track geometry defects. More specifically, this paper looks at the relationship between missing crib and shoulder ballast, as identified by automated ballast profile measurement systems, and the development of ballast related track geometry defects. The missing ballast data was obtained from a hy-rail-mounted laser imaging detection and ranging (LIDAR)-based ballast profile measurement system [1] and then correlated to track geometry defects that developed along the inspected track locations on a major US class 1 railroad. The focus was on those track geometry defects that have been traditionally considered ballast-related, which is then compared with the calculated volume of missing ballast to see if there is a correlation. Further analyses looked at the effect of curve vs. tangent track as well as that of individual geometry defect classes. The results of this analysis showed that there was in fact a direct relationship between volume of missing ballast and the development of track geometry defects.

Keywords Railroad · Ballast · Track maintenance · Track geometry · Ballast shoulders

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Introduction

This paper presents the results of a study of the relationship between the volume of missing ballast in a track section and the development of track geometry defects in that section. While the relationship between some key track geometry defects such as alignment defects and buckles has been related to the lateral strength of the track structure and as such to the size of the ballast shoulders, no formal relationship has been developed between missing volume of ballast and development of track geometry defects.

The recent introduction of ballast profile measurement technology, such as the LIDAR (laser imaging detection and ranging) technology [1], allows for the measurement of the ballast profile at discreet intervals along the track. By overlaying digitized LIDAR data onto an idealized track structure representing the top of tie, the shoulders, and the shoulder slope (see Fig. 1), it is possible to calculate the missing volume area in the ballast shoulders and cribs [1]. The LIDAR unit measures a cloud of points with a statistical error of 12 mm. In controlled testing, the standard deviation of the volume measurement was 0.10 ballast cars/km (0.17 ballast cars/mile), which is approximately 17.8 m^3/km (391 ft^3/mile). The calculation of the missing profile ballast can be visualized in Fig. 1, where the missing ballast is clearly seen as the gap between the idealized (desired) profile and the actual profile. Thus, it can be seen that the left shoulder is missing ballast at the top of the shoulder and, 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.

This missing ballast can then be compared to the location of track geometry defects as identified by a track geometry inspection car for the same track locations. In this study, the ballast deficiency data was obtained from Georgetown Rail Equipment Company (GREX) and the track geometry defects were received from the class 1 railroad owner of the inspected tracks.

Data Analysis

The data for the volume of missing ballast consisted of information regarding the location, volume of missing ballast, if it was on a curve or tangent, length of the segment, and date of collection. The ballast data consisted of 187,025 segments of approximately 15.24 m (50 ft) length for a total length of approximately 2893 km (1798 miles) of track [2]. The 15.24-m (50 ft) segment length was selected after analysis of alternate segment lengths, based on the accuracy of location measurement

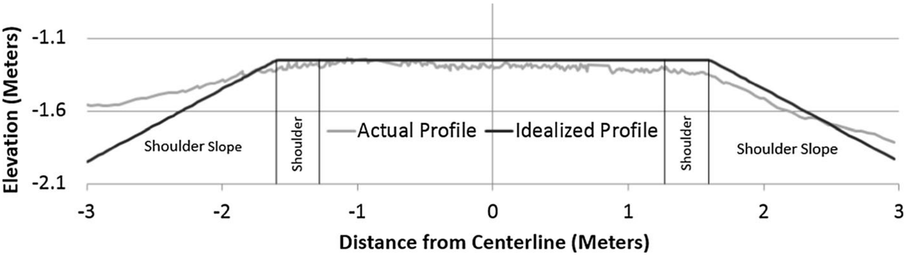


Fig. 1 Overlay of LIDAR (actual) profile and idealized ballast profile

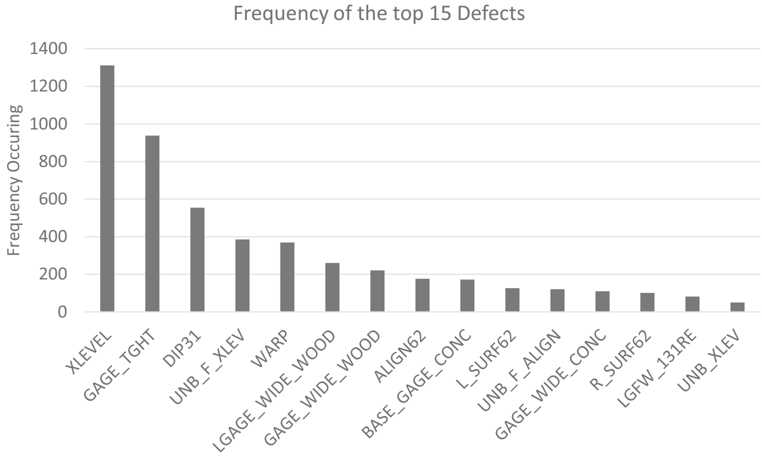


Fig. 2 Frequency of the top 15 track geometry defects

for both the LIDAR measurement vehicle and the track geometry vehicle (so as to allow for matching of geometry defect locations with ballast sections).

The track geometry defect information consisted of the defect type, location, defect amplitude, defect length, date defect was identified, etc. Originally, there were 96 types of defects; however, many of these were similar defect types some of which were consolidated into combined defect classes. Figure 2 presents a graph of the top 15 most numerous defects (by frequency of occurrence) after combining defects categories, and Table 1 lists the definitions of the defects themselves.

Initially, the calculations were focused on the total number of defects; however, due to the defect data containing multiple defects in the same location, either due to the same defect being recorded multiple times or from multiple individual defects, this resulted in a defect rate that was significantly higher than the number of segments with defects. Since the analysis focused on the percentage of segments containing geometry defects ("defective segments") in a larger overall population of segments, the final

Table 1 Major defect types and definitions

Defect type	Defect information
XLEVEL	A deviation from vertical profile as measured to the reference rail
GAGE	An error relating to the width of the track gage, may be either tight or wide
DIP	A variation in vertical track profile over a given interval
WARP	Warp is the difference between two cross-level defects in a specified interval
ALIGN	A variation in lateral track profile over a specified interval
SURF	A defect relating to the surface of the track
GFW	Gage face wear of the rail
CANT	An unwanted rotation of the rail or superelevation on a curve

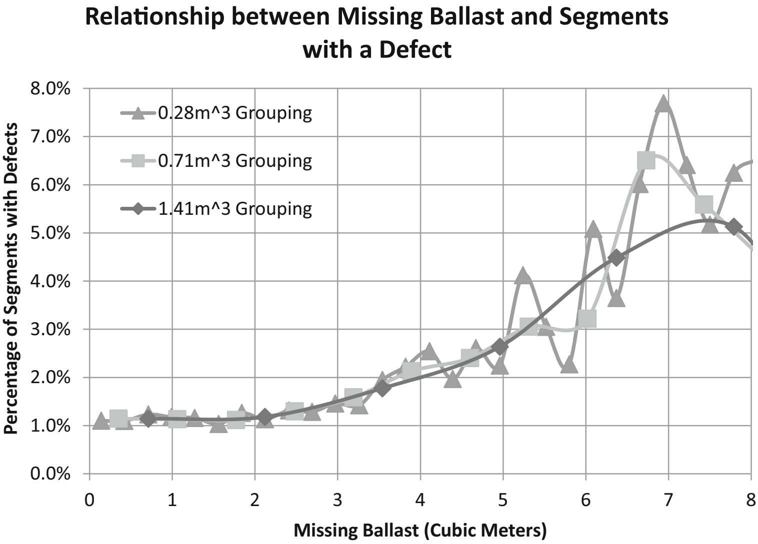


Fig. 3 Percentage of segments with defects vs. volume of missing ballast for three volume groupings

analysis looked at the number of segments with geometry defects, irrespective of how many defects were in a segment identified as having a defect. Thus, the analysis looked at the percentage of segments with geometry defects as a function of total inspected segments (also referred to as "percentage of segments with defects").

Once the initial matching was completed, a determination of the appropriate grouping size (based on cubic yards of missing ballast) was performed. Three higher-level groupings were examined, a 0.28 m^3 (10 cubic foot) grouping, a 0.71 m^3 (25 cubic foot) grouping, and a 1.41 m^3 (50 cubic foot) grouping. As shown in Fig. 3, the 1.41 m^3 (50 cubic foot) grouping appeared to provide the smoothest behavior and as such was selected for use in the analysis.

Figure 4 presents the 1.41 m^3 (50 cubic foot) grouping information as a bar chart. (Note, all the segments with volumes greater than 5.66 m^3 (200 cubic feet) were consolidated into a single >5.66 (>200) category because of the relatively small number of segments in these

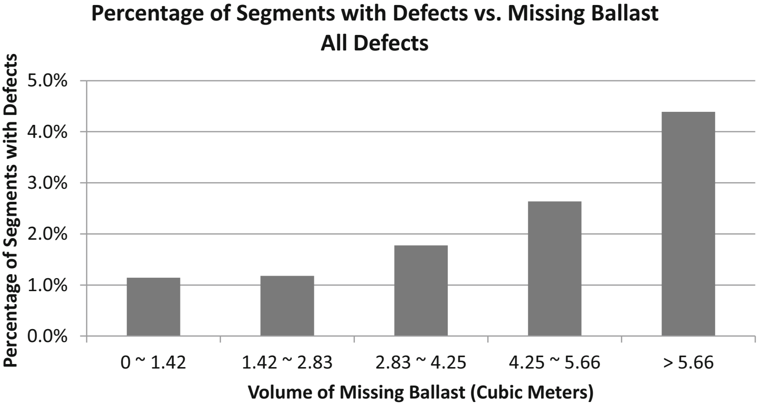


Fig. 4 Percentage of segments with defects vs. missing ballast for all defects [1.41 m^3 (50 cubic foot) groups]

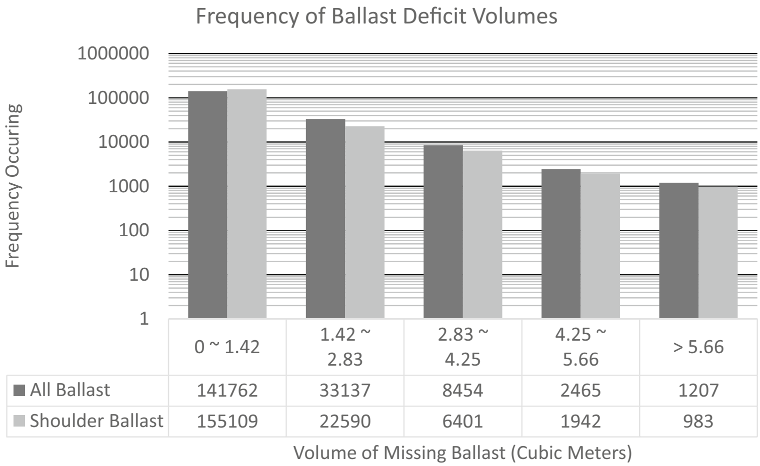


Fig. 5 Frequency count of segments by volume of missing ballast [1.41 m^3 (50 cubic foot) groups]

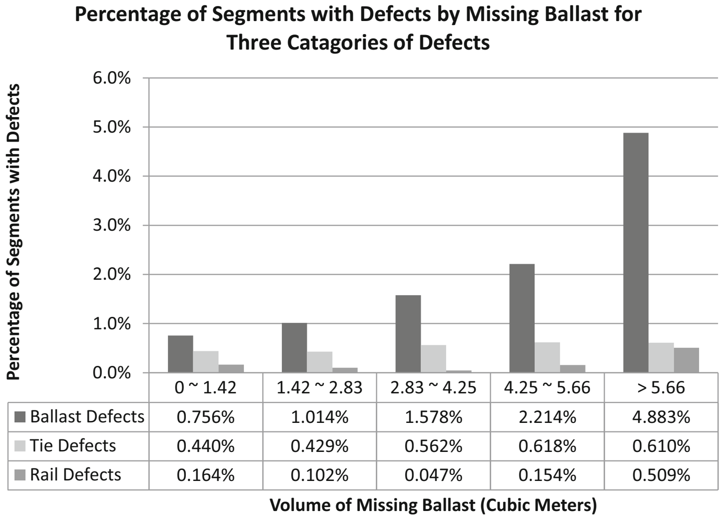
categories). This can be seen in Fig. 5 which shows that the number of segments with missing ballast volume of 5.66 m^3 (200 cubic feet) or greater is 1 % of the number with missing ballast volumes less than 1.41 m^3 (50 cubic feet). Figure 5 also indicates the majority of the missing ballast occurs in the shoulders with the balance in cribs.

Table 2 presents a summary of the defect and segment data together with some relevant data statistics. It should be noted that approximately 54 % of the reported defects were able to be correctly matched to a ballast segments. This is due to limitations in the data collected, such as gaps in the ballast data (i.e., the ballast data was not continuous for the entire length of track for which the geometry defect data was provided.)

It should be noted that 44 different defect types were reported. These defects types were further divided into ballast-related defects (e.g., alignment, profile, cross-level, warp, etc.), tie-related defects (e.g., wide gage, tight gage, etc.), and rail-related defects

Table 2 Summary statistics of data used [2]

Number of ballast segments	187025
Number of defects	5440
Number of matching defects	2963
Number of segments with matching defects	2278
Number of defect types	44
Number of ballast-related defect types	23
Number of tie-related defect types	14
Number of rail-related defect types	16
Average length of ballast segment meters (feet)	15.47 (50.76)
Average missing ballast volume cubic meters (cubic feet)	1 (35.29)
Maximum number of defects occurring in a segment	10
Maximum number of the same defect occurring in a segment	9



	0 ~ 1.42	1.42 ~ 2.83	2.83 ~ 4.25	4.25 ~ 5.66	> 5.66
Ballast Defects	0.756%	1.014%	1.578%	2.214%	4.883%
Tie Defects	0.440%	0.429%	0.562%	0.618%	0.610%
Rail Defects	0.164%	0.102%	0.047%	0.154%	0.509%

Fig. 6 Percentage of segments with defects by missing ballast for the three categories of defects

reported by the geometry car (e.g., rail wear). As can be seen from Table 2, multiple defects were found in many of the segments; however, as noted previously, the focus of this analysis was on segment with defects vs. segments without defects and specifically the rate of defective segments (segment with defects/segments without defects) vs. volume of missing ballast.

Analysis Results

Figure 4 presented the total percentage of segments with defects for all defects. As can be seen from this figure, there is a well-defined trend of increasing percentage of segments with defects (i.e., increased number of segments where defects are present) as a function of increasing volume of missing ballast. Figure 6 further breaks this data into the three different defects categories, ballast, tie, and rail defects. As expected, this

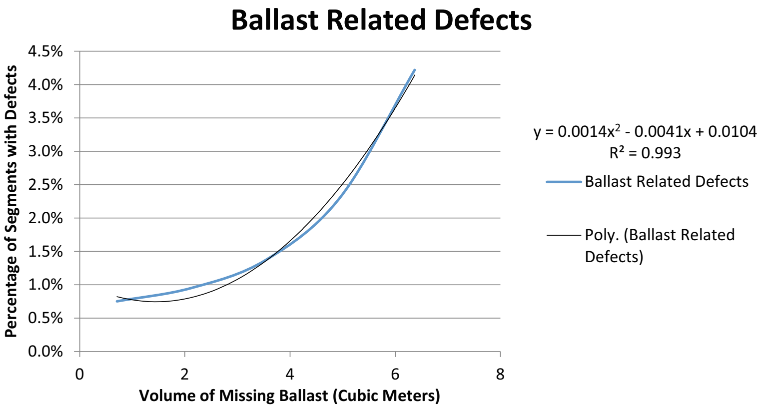


Fig. 7 Polynomial relationship between segments with ballast defects and missing ballast using the midpoint value of each grouping

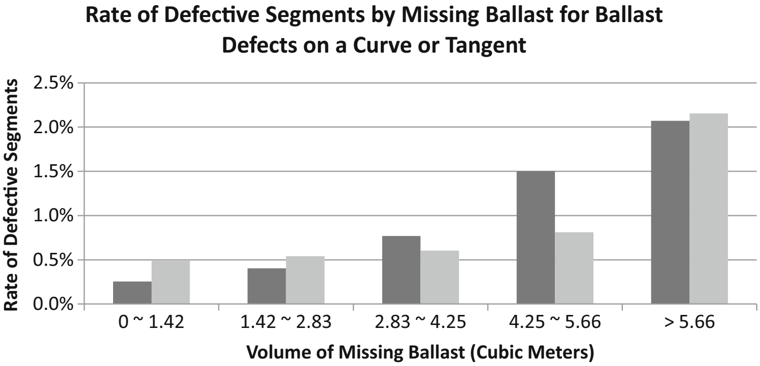


Fig. 8 Percentage of segments with defects for ballast-related defects on curve vs. tangent track [1.41 m^3 (50 cubic foot) groups]

relationship between increasing segments with defects (rate) with increased volume of missing ballast result is primarily the result of the ballast-related defects which account for a majority of the defects present in the data.

The results presented in Fig. 6 initially show that the rate development of ballast-related defects is positively correlated to the volume of missing ballast and that this relationship increases non-linearly as shown in Fig. 7. Note, the extremely good curve fit, as represented by the very high R^2 value. Thus, this data strongly supports the idea that missing ballast section (specifically shoulder and crib ballast) will contribute to the development of ballast related track geometry defects.

This behavior does not seem to hold for the tie related defects, which appears to remain fairly constant with increasing volume of missing ballast thus suggesting that at least for this data set, tie-related defects such as wide gage are not directly related to the volume of missing ballast. This also appears to be the case with the rail defects, as identified by the track geometry car (e.g., wear), again suggesting that rail wear-related defects are not, in general, directly related to the volume of missing ballast. However, given the fact that the rate of rail-related defects do show an increase with large

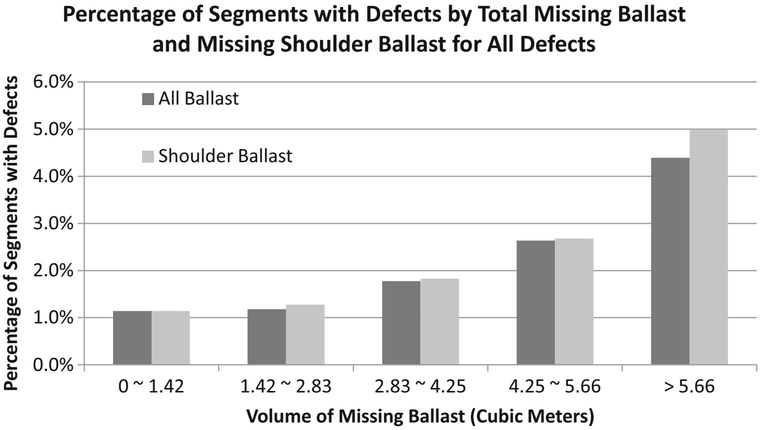


Fig. 9 Segments with defects vs. missing ballast/shoulder ballast for all defects [1.41 m^3 (50 cubic foot) groups]

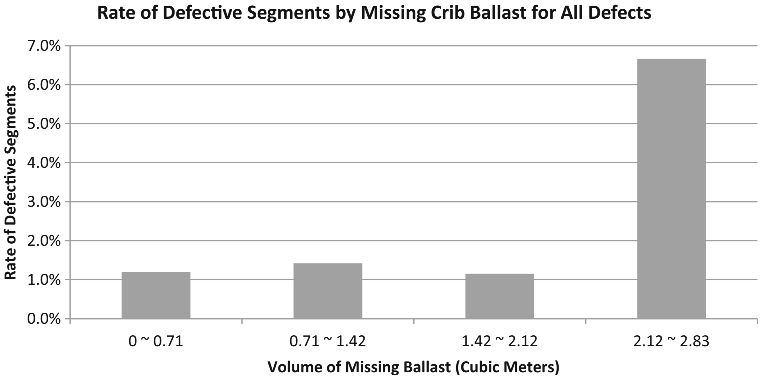


Fig. 10 Percentage of segments with defects vs. missing crib ballast for all defects

volumes of missing ballast and that the actual number of rail related defects in this analysis is relatively small, this may be an area of further analysis, with a larger data set.

Since the geometry data provided information on whether a segment was on a curve or on tangent track, the defect data was further separated by curve vs. tangent. These results are presented in Fig. 8 which presents the rate of ballast-related defect occurrence (by segment) as a function of increased volume of missing ballast separately for curve and tangent track. As shown in Fig. 8, the segment defect rate on a curve follows a steady trend upwards with increasing volumes of missing ballast, similar to that presented in Fig. 6 for all ballast-related defects. The rate of defects on a tangent follow a lower steady rate until a highest volume of missing ballast, which causes the rate to jump up to the same level as curve-based defects. This appears to suggest a threshold effect of tangent track, such that small amount of missing ballast have a modest effect on defect occurrence, but large volumes of missing ballast have a significant effect. This is similar to the behavior of missing ballast and track buckling for tangent track where a small amount of missing shoulder ballast has a minimal effect on lateral resistance but a large amount of missing shoulder ballast can have a significant effect [3].

An additional set of analyses was performed looking at the difference between missing shoulder and crib ballast. A key aspect of this analysis is that the range of

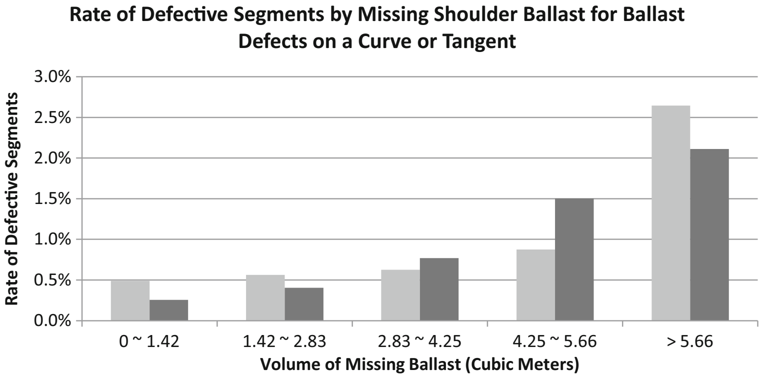


Fig. 11 Effect of missing shoulder ballast for ballast-related defects on curves or tangents [1.41 m^3 (50 cubic foot) groups]

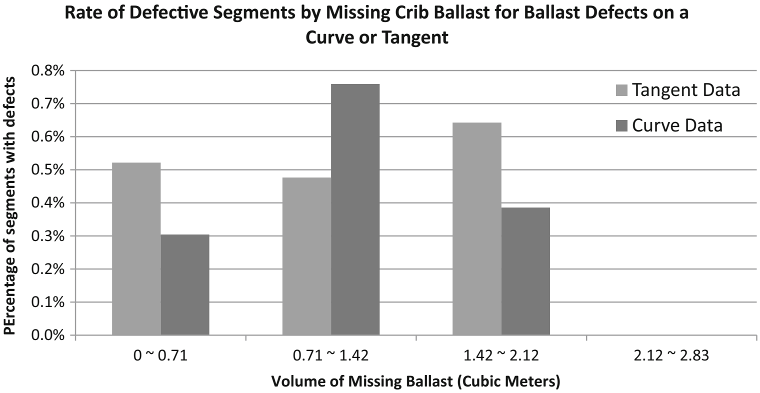


Fig. 12 Effect of missing crib ballast for ballast related defects on a curve or tangent [1.41 m^3 (50 cubic foot) groups]

missing shoulder ballast was similar to the range of total missing ballast, as shown in Fig. 4, while the range of volumes for missing crib ballast effectively was significantly less, with a maximum of 2.83 m^3 (100 cubic feet) of missing crib ballast (as opposed to over 5.66 m^3 (200 cubic feet) for missing shoulder ballast). Thus, in order to plot the rates when looking at the volume of missing crib ballast, a grouping of 0.71 m^3 (25 cubic feet) was used as higher groupings prevented detailed analysis of the results. The analyses of the shoulder ballast continued the use of 1.41 m^3 (50 cubic feet) grouping presented previously.

The results of the analysis of rate of segments with defects vs. volume of missing shoulder ballast and missing crib ballast are shown for all defects in Figs. 9 and 10. The behavior of the shoulder ballast analysis (Fig. 9) is very similar to the previous analyses looking at total volume of ballast primarily due to dominance of the shoulder ballast in the determination of missing ballast volume. The analysis of the crib ballast effect shows a potential threshold type behavior, with a spike in the percentage of segments with defects in the 75 to 100 cubic foot range; though due to the limited data, these results should be used with caution.

Analysis of the effect of missing shoulder ballast on curve vs. tangent track, as shown in Fig. 11, likewise shows a relationship similar to that presented in Fig. 8, with the development of track geometry defects directly related to an increase in missing ballast. Analysis of missing crib ballast, Fig. 12, is not as well defined.

Conclusions

The results of the study show that increasing volumes of missing ballast results in increases in the occurrence of track geometry defects and in particular the ballast-related track geometry defects, in those segments that have the missing ballast. This is consistent with basic industry practices and guidelines which show a relationship between missing shoulder and/or crib ballast and reduced track strength [4–7]. The results provide a quantifiable relationship, in form of a quadratic equation, between missing ballast and the rate of development of segments with geometry defects (defective segments). Examination of specific classes of geometry defects shows a clear and well-defined relationship between segments having ballast-related track geometry defects as opposed to tie- or rail-related geometry defects where the relationship is not as well defined. Thus for such ballast-related defects such as cross-level and dip, well-defined positive relationships with the volume of missing ballast were seen which support the previously held belief that these defects are related to the missing ballast. However, tie and rail (wear) related defects were found to not have that clearly defined a relationship with the volume of missing ballast.

This relationship furthermore extends to analysis of curve vs. tangent track, where curve track exhibits the same quadratic type of relationship, while tangent track appears to have more of a threshold effect, where a small volume of missing ballast has a relatively mild effect but a large volume of missing ballast has a significant effect on the rate of development of geometry defects. This curve vs. tangent relationship is also evident based on the type of individual geometry defects. Thus, for example, unbalance cross-level defects which are predominately located on curves show a strong curve behavior but virtually no tangent behavior.

Analysis of missing shoulder ballast vs. crib ballast provided further insight into the relationship between missing ballast and the occurrence of track geometry defects. Missing shoulder ballast exhibits behavior similar to the more general total missing ballast categories, while the missing crib ballast has a modest tangent track effect but no well-defined curve track effect. This suggests that the lateral resistance of the shoulders is the dominant effect on curves, but on tangent crib lateral resistance/and or vertical load effect takes on increased importance.

The effect of the cribs and many of the individual classes of defects (e.g., profile and alignment) may be due to the limited amount of data points in those categories and as such, would benefit from a broader and more wide-reaching analysis, encompassing significantly more miles of data from several railroads, particularly with variations in maintenance practices.

References

1. Zarembski, A.M., Grissom, G.T., Euston, T.L.: "Use of ballast inspection technology for the prioritization, planning and management of ballast delivery and placement". American Railway Engineering Association Annual Conference, Indianapolis (2013)
2. Cronin, J.: On the development of weighting factors for ballast ranking prioritization & development of the relationship and rate of defective segments based on volume of missing ballast. University of Delaware, Newark (2014)
3. Kerr, A.: Fundamentals of railway track engineering. Simmons-Boardman Books, Omaha (2003)
4. Arema, LMD., American railway engineering and maintenance-of-way association, "Manual for railway engineering (2013)
5. Kish, A., On the fundamentals of track lateral resistance, American Railway Engineering and Maintenance of Way Association (2011)
6. Samavedan, G., et al., "Track resistance characterization and correlation study", FRA Report DOT/FRA/ORD-94/ 07 Jan 1995
7. Dogneton, P.: "Axial and lateral track ballast resistance", Railroad track mechanics and technology. Pergammon Press, New York (1978)