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

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

Spring 2014

ON THE DEVELOPMENT OF WEIGHTING

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& DEVELOPMENT OF THE RELATIONSHIP AND RATE OF

DEFECTIVE SEGMENTS BASED ON VOLUME OF MISSING BALLAST

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ACKNOWLEDGMENTS

My Family

Prof. Faghri

Prof. Zarembski

The University of Delaware

Georgetown Rail Equipment

Burlington Northern Santa Fe Railroad

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ABSTRACT

This thesis explores the effects of missing ballast on track behavior and degradation. As ballast is an integral part of the track structure, the hypothesized effect of missing ballast is that defects will be more common which in turn leads to more derailments. In order to quantify the volume of missing ballast, remote sensing technologies were used to provide an accurate profile of the ballast. When the existing profile is compared to an idealized profile, the area of missing ballast can be computed. The area is then subdivided into zones which represent the area in which the ballast performs a key function in the track structure. These areas are then extrapolated into the volume of missing ballast for each zone based on the distance between collected profiles. In order to emphasize the key functions that the zones previously created perform, weighting factors were developed based on common risk-increasing hazards, such as curves and heavy axle loads, which are commonly found on railways. These weighting factors are applied to the specified zones' missing ballast volume when such a hazard exists in that segment of track. Another set of weighting factors were developed to represent the increased risk, or preference for lower risk, for operational factors such as the transport of hazardous materials or for being a key route. Through these weighting factors, ballast replenishment can be prioritized to focus on the areas that pose a higher risk of derailments and their associated costs. For the special cases where the risk or aversion to risk comes from what is being transported, such as the case with hazardous materials or passengers, an economic risk assessment was completed in order to quantify the risk associated with

their transport. This economic risk assessment looks at the increased costs associated with incidents that occur and how they compare to incidents which do not directly involve the special cargos.

In order to provide support for the use of the previously developed weightings as well as to quantify the actual impact that missing ballast has on the rate of geometry defects, analyses which quantified the risk of missing ballast were performed. In addition to quantifying the rate of defects, analyses were performed which looked at the impact associated with curved track, how the location of missing ballast impacts the rate of geometry defects and how the combination of the two compared with the previous analyses.

Through this research, the relationship between the volume of missing ballast and ballast-related defects has been identified and quantified. This relationship is positive for the aggregate of all ballast-related defects but does not always exist for individual defects which occasionally have unique behavior. For the non-ballast defects, a relationship between missing ballast and their rate of occurrence did not always appear to exist. The impact of curves was apparent, showing that the rate of defects was either similar to or exceeded the rate of defects for tangent track. For the analyses which looked at the location of ballast in crib or shoulder, the results were quite similar to the previous analyses.

The development, application and improvements of a risk-based ballast maintenance prioritization system provides a relatively low-cost and effective method to improve the operational safety for all railroads.

Chapter 1

BACKGROUND

1.1 Background Introduction

In order to thoroughly explain the topics covered in this paper, a simple background into Railway Engineering is required to make sure that the topics are properly understood. In addition to a background in Railroad Engineering, a list of terms and definitions used in this paper will also be presented in this chapter. This is required as some terms used have different and/or very specific definitions within Railroad Engineering and/or this paper.

1.2 Background to Railroad Engineering

Railroads can be considered to consist of three major departments; Rolling Stock, such as locomotives and freight cars, Operations, which covers the management, maintenance, operation and safety of the railroad and Infrastructure, which covers the trackage, signals, right-of-way, stations and terminals and electrification, when applicable. The interaction of forces from the operation of trains on the track and track-ballast are the basis for this research. The weight of the rolling stock, when applied by the wheel to the rail, produces a deflection and induces a moment in the rail/tie structure. The deflection is imparted into the ballast while the moment is spread in the rail in a localized section. These interactions can be modeled through equations developed over time in the railroad industry [2, 3]; the rail deflection is modeled after a beam on elastic foundation model and the ensuing moment is derived from that. First, to calculate the wheel load of a single unit, the static wheel load is generated by taking the weight of the car and dividing it by the number of wheels. For these calculations, it is assumed that each wheel bears an equivalent share of the total load. From the static load, the dynamic load can be found through the use of the AREMA dynamic load formula shown in Equation 1. The AREMA dynamic load formula uses the wheel diameter *D*, the velocity, *V*, and the static load *P_static* to give an approximation of the dynamic load *P_dynamic*.

$$P\_dynamic = (1+(33V/100D))*P\_static \qquad \text{Eq. 1}$$

The interaction of forces from the wheel load onto the rail and ballast has commonly been represented as a beam on an elastic foundation. The basics of this model is that a beam, in this case a rail, is supported by elastic springs which are located relatively close together. A representation of this behavior and some of the variables used in calculations is shown in Figure 1.

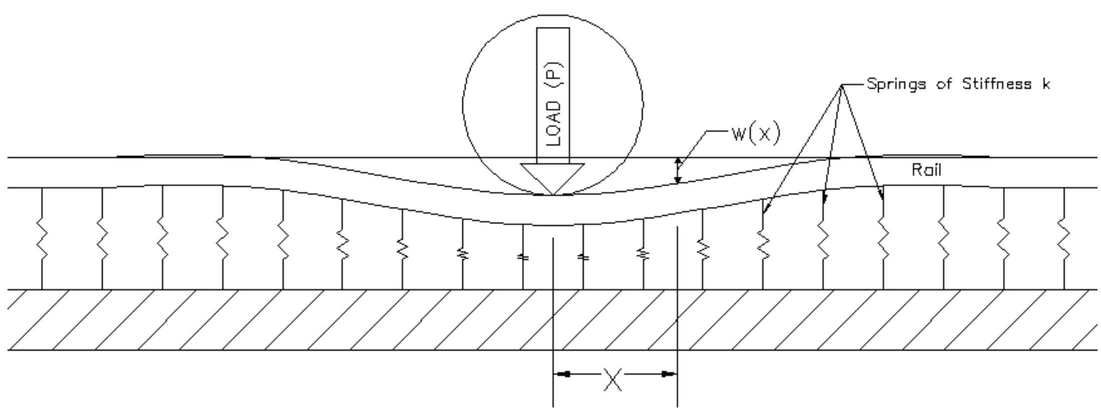

Figure 1: Representation of Beam on Elastic Foundation with the application of a single wheel load.

For the beam on elastic foundation model, two equations are used to calculate the behavior. Equation 2 defines the deflection of the rail *w(x)* due to a single wheel load *P* at a distance *x*. The vertical track stiffness, *k*, represents how stiff the track structure, ballast, sub-ballast and sub-grade are to forces applied. Equation 3 is the formula for finding the moment induced in the track due to that single wheel load. *EI* is the flexural rigidity of the rail which is calculated by multiplying the moment of inertia of the rail around its horizontal axis by Young's modulus for rail steel. Equation 4 is used in finding *β*, which is used in multiple places in the previous formulas.

$$w(x)=(P\beta/2k)*e^{(-\beta|x|)}*[\cos(\beta|x|)+\sin(\beta|x|)] \qquad \text{Eq. 2}$$

$$M(x)=-EIw''(x)=P/4\beta*e^{(-\beta|x|)}*[\cos(\beta|x|)-\sin(\beta|x|)] \qquad \text{Eq. 3}$$

$$\beta=\sqrt[4]{(k/4EI)} \qquad \text{Eq. 4}$$

The function of ballast is multipart; drainage, force dissipation and redistribution, track alignment, and the prevention of the growth of interfering vegetation. Deficiencies in the surface of the ballast or a depth of ballast that is insufficient to properly dissipate loadings can have a disastrous effect on the rail infrastructure, usually resulting in issues related to track alignment, such as cross-level. Located below the ballast is the subballast, which operates in a manner similar to the ballast above it, though with a greater focus on the dissipation of forces to the subgrade. The subgrade is the pre-existing soil and governs the required depth of ballast. A representation of the location of the track, ballast and sub-ballast is shown in Figure 2.

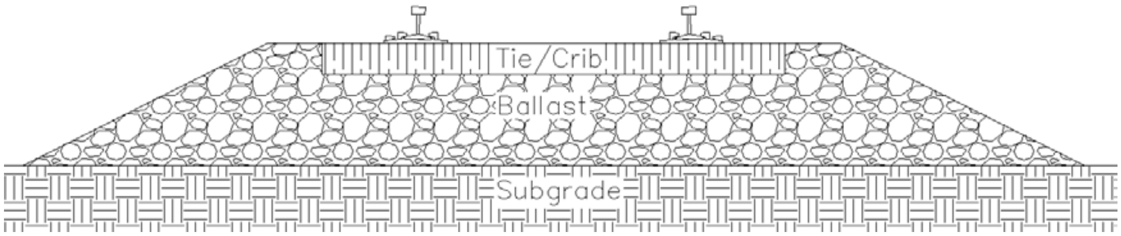

Figure 2: Ideal ballast cross-section view.

Deficiencies in the ballast are currently cataloged in several ways which have their associated good and bad aspects. The most common yet non-exact method is visual inspection by track inspectors who are able to relay the location of areas with ballast problems but do not have the capabilities to generate the volume of missing ballast in a reliable manner. As track inspectors are required to inspect track regularly, they are able to monitor known problem sections and can provide an estimate of the rate of degradation. A step up from this is the use of LIDAR[1], either on a Hi-Rail[2] vehicle, as one of the components of a track inspection vehicle, or, potentially, from aerial vehicles such as planes and eventually, drone aircraft. LIDAR allows the calculation of the actual volume of the deficit to a relatively good degree of accuracy but obstructs the operation of the railway, as the Hi-Rail LIDAR cannot travel too fast due to limitations with LIDAR which results in LIDAR use being very infrequent. Aircraft equipped with LIDAR pose different problems, primarily cost and by association their infrequent use, and are, to my knowledge, not used at this time for

[1] LIDAR: Light Detection and Ranging; a method which uses electromagnetic waves to determine the location of objects.

[2] Hi-Rail: A vehicle that is able to operate on roadways and railroad track, usually through the use of flanged wheels that can be lowered.

finding ballast deficiencies. Ground Penetrating Radar (GPR) is a method which uses radar to determine the makeup of the ground without requiring the disturbance of that area. This non-destructive method of detection allows information on the depth of ballast, sub-ballast and subgrade, as well as issues such as mud-spots, to be found without requiring expensive and time-consuming destructive testing, such as bore holes, to interrupt operations. GPR is commonly mounted on Hi-Rail vehicles in a manner similar to LIDAR; this also imposes the same limitation to the use of GPR as Hi-Rail mounted LIDAR. Another system which is used primarily for the detection of defects is a Geometry Car. Geometry Cars can be mounted several ways, most commonly as a dedicated Hi-Rail vehicle, as an unpowered rail car or as a self-powered rail car. Though they have multiple methods of being mounted, the processes used to determine defects are the same; ultrasonic testing provides information on defects within the rail while laser imagery is used to determine rail wear and geometric issues such as the unwanted rotation of the rail. Hi-Rail mounted geometry cars are subject to similar limitations mentioned for Hi-Rail mounted GPR and LIDAR systems. With rail car mounted systems, higher speeds are allowed which result in less obstruction to the normal operations; in some cases the geometry cars can be appended to an existing train consist to allow geometry information to be gathered without obstructing normal operations.

There are multiple ways to remedy ballast problems, each method being focused on one problem. One of the simplest is to drop ballast from MOW trains and reshape the new ballast to the proper profile. While this works in areas that only have ballast missing on the shoulders and cribs, it is not suitable for areas that have issues with the depth of ballast, unless it is acceptable to raise the track to compensate.

When there is an issue with the depth of ballast and it is not possible to raise the track, usually due to vertical clearance limits, the existing ballast is "cleaned". This process lifts the track, removes the ballast underneath, cleans the ballast, places that ballast back into position and then lowers the track. This process prevents the use of the track during the maintenance well as imposing a limit on travel speeds afterwards, as the ballast must be compacted in order to provide suitable resistance.

As discussed, one of the main issues with ballast maintenance is that it requires the track in question to be out of service for some time. While there is ongoing work in speeding up these processes, increasing their effect on reducing derailments through non-mechanical means allows current technology to be utilized to produce results befitting future developments. This not only allows future developments to have a much greater effect but also allows those who are unable to upgrade, such as short line railroads, to increase their efficiency without substantial material investment.

1.3 Terms and Definitions

- AREMA: The American Railway Engineering and Maintenance-of-Way Association. Multiple formulas, such as for dynamic loads, come from their research.

- Ballast: A layer of stone aggregate which supports the tie and rail structure, provides drainage and facilitates maintenance operations.

- BallastSaver: A program which uses LIDAR imaging and computer software to generate information about missing ballast along a section of track.

- BNSF: Burlington Northern Santa Fe. A Class 1 Railroad which predominately operates in the northern parts of the central and western United States.

- Buckle, Track: Also known as a Sunkink, this is a buckling of the track due to longitudinal forces, most commonly as a result of thermally induced stress.

- Class X Railroad: Where "X" is 1, 2 or 3; the classifications are based on yearly operating revenue. Class 1 requires the highest amount of minimum operating revenue, at $433.2 Million for the year of 2011.

- Class X Speed: Where "X" ranges from 1 to 9; the FRA's classification of track type based on maximum possible speed, with Class 1 having the lowest maximum possible speed. Class 1 to Class 5 have different limits for freight and passenger trains.

- Crib: A section of the ballast that is located in the area between the ties. This ballast transfers and resists longitudinal and lateral forces to the entire ballast structure.

- FRA: Federal Railway Administration. The sub-group of the United States Department of Transportation that focuses on railways. This focus covers the safe operation of railways, research into new technologies and policy development, among other things.

- Georgetown Rail Equipment Company (GREX): A company which operates multiple Maintenance-of-Way programs which are focused on ballast. These programs include ballast transportation and unloading equipment as well as inspection technologies such as BallastSaver.

- GPR: Ground Penetrating Radar. This is the use of radar (electromagnetic waves) and trained people/computer programs to determine the composition of the soil below the surface.

- LIDAR: Either the acronym of "Light Detection And Ranging" or a portmanteau of Light and Radar. The system uses a laser reflected off of a surface to determine the distance to that surface.

- Section: A collection of contiguous segments. This usually contains the total volume, both unmodified and modified, and the total length of the section.

- Segment: The smallest applicable group of information that results in a volume. This is usually a cross-section multiplied by a length, though some analyses have the volume already calculated.

- Shoulder: Area of ballast that is to the side of the ties and track. This ballast resists lateral and vertical forces.

- Sub-Ballast: A layer of ballast which is commonly made of smaller stone. Acts as a barrier separating the ballast and the sub-grade and provides drainage for the sub-grade.

- Sub-Grade: The existing soil after being worked to provide a suitable surface for the construction of the track structure.

1.4 Order of Research

The analyses presented follow the order that they were researched. This order is a result of trying to minimize the time spent not working on the research and the order in which the data was received. The first analysis covered the development and application of weighting factors which prioritize ballast deliveries in order to improve their efficiency and resulting safety. The next analysis looked at improving some of the weighting factors and their application in order to further improve their efficiency and safety. The third analysis looked at the relationship between the volume of missing ballast and the rate of defects. This analysis included multiple sub-analyses which looked at specific defects, the location of the ballast and the impact of curves. While the third analysis shows that several situations are more likely to contain a defect, these results are not the only supporting evidence to the development of the weighting factors.

Chapter 2

MISSING BALLAST ANALYSIS & DEVELOPMENT OF BALLAST WEIGHTING FACTORS

2.1 Origin of Research

This research projects was initiated by Georgetown Rail Equipment (GREX) as a way to improve the marketability of their BallastSaver program. The original goal was to tie together their BallastSaver information with GPR data to provide a method of informing users of the subgrade status. Another aspect to this data combination is the implantation of weightings to provide a risk-based ranking system to provide users a more-effective ballast-replenishment method. As a way to showcase the usefulness of a different method of ranking deficient ballast volumes, an ideal and several degraded profiles were created and a simple analysis was applied to them. The ideal profile with zones is shown in Figure 3 while the degraded profiles used are shown in Figure 4.

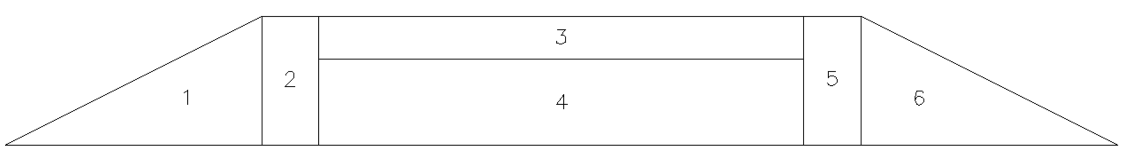

Figure 3: Ideal Profile and Zones

Each of the profiles have arbitrary ballast degradation applied in order to provide some variation to the analysis. The zones shown, numbered 1 through 6, are representative of important functional zones of the ballast profile. The functions for each zone is shown in Table 1. The information on each of these ballast zones, Missing Area, Length, Volume and Rankings, is located in Table 2. In order to generate the values for missing ballast, the hypothetical profiles' total area was subtracted from the idealized profile's area to provide the total missing area of the profile cross-section. This missing area is then multiplied by the length of the profile; as this was an example, the lengths were arbitrarily assigned. As shown in the rankings, the Green and Blue profiles switch rankings due to the change from By Area to By Volume.

Table 1: Initial Zone Locations and Definitions

Zone	Zone Name	Ballast Use
1, 6	Slope of the Shoulder	Transfers and dissipates lateral and vertical forces.
2, 5	Lateral Extension of the Shoulder	Resists lateral loading and transfers forces to
3	Crib Area	Resists longitudinal and lateral loadings as well as transferring the forces to other zones.
4	Below the Crib	Resists vertical loading and transfers forces to the subballast.

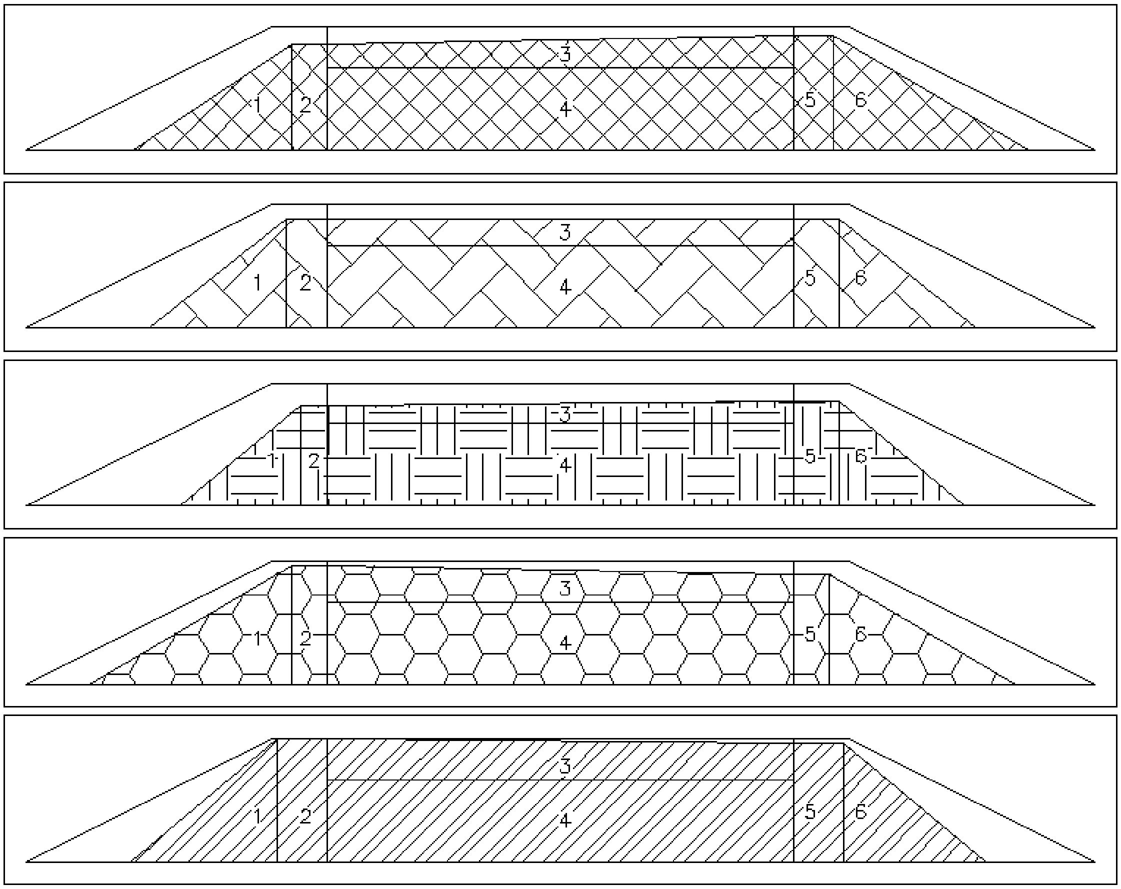

Figure 4: The five sample profiles overlaid on an idealized profile. From top to bottom, they were originally labeled Red, Yellow, Green, Blue/Cyan and Purple profiles. Due to Grayscale issues, hatching was done to increase their visibility; Red is hatched with diagonal boxes, Yellow with herringbone, Green with alternating vertical and horizontal lines, Blue/Cyan with regular hexagons and Purple with diagonal lines.

Table 2: Analysis of 5 Sample Profiles

Section	Missing Area		Length	Volume	Rankings	
	IN^2	YD^2	FT	Cu Yd.	By Area	By Volume
Red	1075	0.83	100	17.35	3	3
Yellow	1236	0.95	200	40.67	2	2
Green	1595.2	1.23	50	12.85	1	4
Blue	845.8	0.65	300	41.89	4	1
Purple	731	0.56	80	10.51	5	5

2.2 Preliminary Work

In order to expand from the initial work, raw BallastSaver data was acquired from GREX. This data consisted of numerous LIDAR-generated ballast profiles; each profile consisted of coordinates on a metric Cartesian coordinate system as well as other data relating to the generation of the coordinates that was not used in any analyses done. In order to apply the weightings in a manner similar to how they would be used in industry, a few ballast sections were picked from the data GREX provided, as analyzing the entirety of the data would require significant effort for relatively little improvement to the analysis. These profiles were a combination of data received from two LIDAR units mounted over the rails; one LIDAR unit over each rail. As shown in Figure 5, there are areas in which the LIDAR is blind to what is occurring; this is due to the rail returning the LIDAR's signal and results in no useable data for the area blocked. This is compensated for by the use of two LIDAR units; each LIDAR unit is able to see into the area the other LIDAR unit is unable to, except for the area directly below the rail. Compensation due to this possible error was not undertaken as this area is relatively minor compared to the rest of the data.

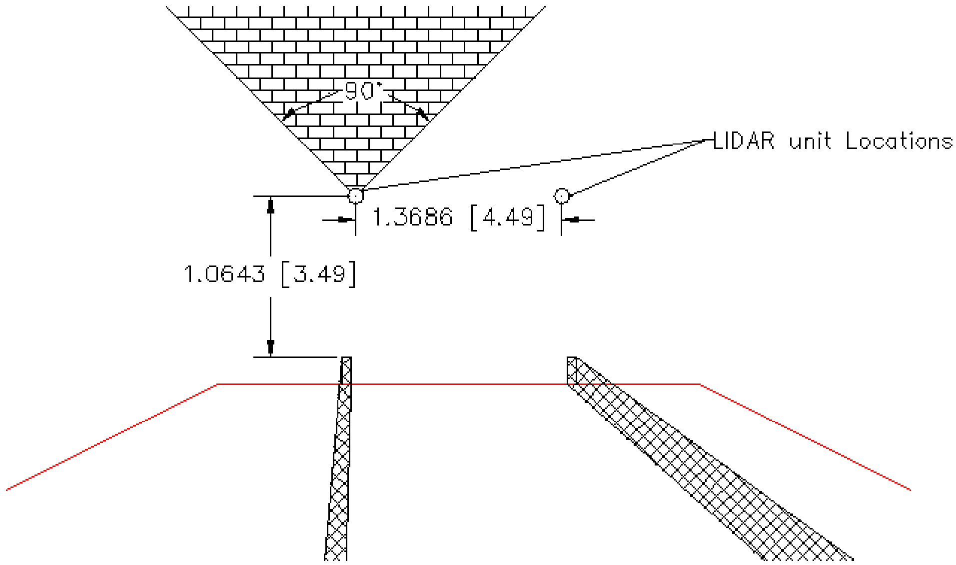

Figure 5: LIDAR Scan Range. The brick hatching is the natural un-scanned area of the LIDAR unit and the crosshatched area is the blind-spot caused by the rails.

Figure 6 shows the coordinate points from a single section. As shown, there are many superfluous points included in the data that had to be removed in the analysis. A key point is that the origin of this coordinate system is located between the two LIDAR units, approximately 1.24 meters above the tie. This can be seen in Figure 6; the two sets of points hovering over the profile were produced when each LIDAR unit generated data based off of the beams being returned from the other LIDAR unit's mounting. The cleaned result is shown in Figure 7, which also has the ideal profile overlaid on the cleaned data.

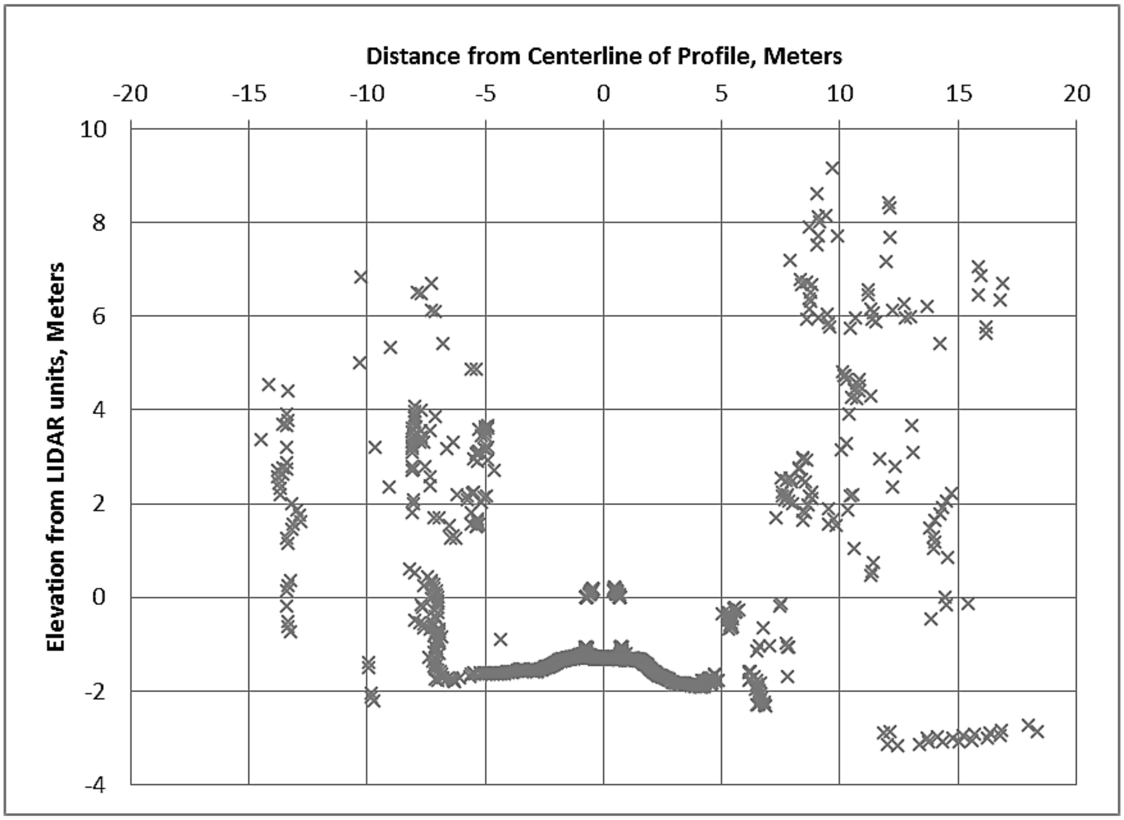

Figure 6: Raw BallastSaver data points on a metric coordinate system

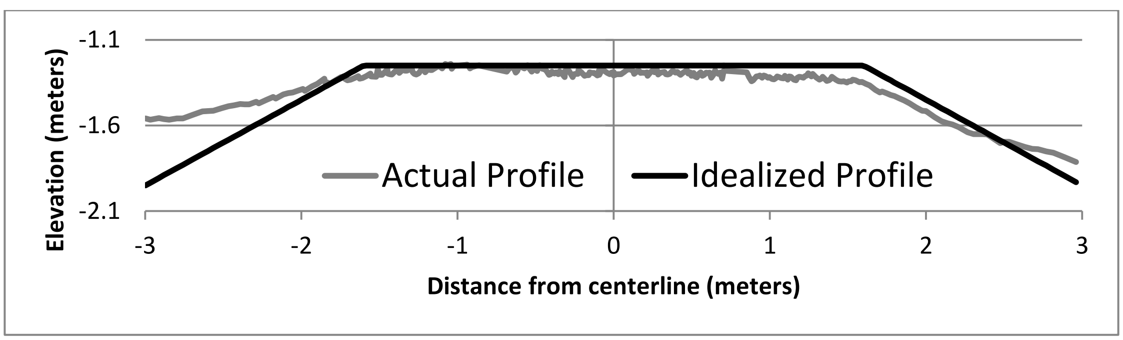

Figure 7: Idealized profile overlaid on an actual profile

In order to remove these superfluous points, a series of conditional statements were included in the initial calculations. These conditional statements were tied into user-defined variables; this allowed changes to be made quickly in the event that an analysis using a different ideal profile was to be calculated. A graphical representation of these conditional statements is shown in Figure 8 while a representation of the actual formula used is shown as Equation 5. While there have been studies that have shown that having ballast on top of the shoulders can help, this analysis looked at the missing ballast and as such, did not want to compensate for missing ballast with ballast located on top of the shoulders/crib. An example of a trimmed profile overlaid on the ideal profile is shown in Figure 7.

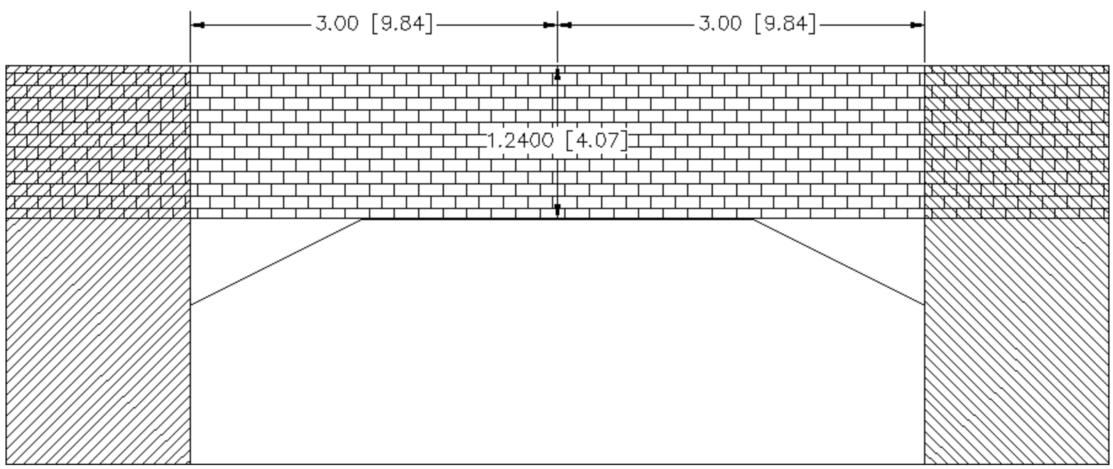

Figure 8: Exclusion Zones and Ideal Profile. The distances labeled are in Meters (Feet). The Ideal profile is the set of lines inside of the area marked off by the exclusion zones.

```
IF('Front End'!$B$8>=$B5,IF(AND($B5>='Front End'!$B$3,$B5<='Front End'!$B$6,$C5<='Front End'!$B$7,$D5<0),$B5,""),IF(AND($B5>='Front End'!$B$3,$B5<='Front End'!$B$6,$D5>=0,$C5<='Front End'!$B$7),$B5,""))
```

Eq. 5

Where

'Front End'!$B$8	User-defined value separating left and right LIDAR scans.
$B5	The X value of the point currently being looked at.
'Front End'!$B$3	The absolute left limit of X values
'Front End'!$B$6	The absolute right limit of X values
$C5	The Y value of the point currently being looked at.
'Front End'!$B$7	The upper limit to Y Values
$D5	A dummy variable that specified if the data was from the right or left LIDAR unit.

Once the data was trimmed, the next step was to calculate the areas and, by association, the volumes for existing and missing ballast. In order to calculate the area, an application of trapezoidal Riemann Sums was used. In order to choose which method of area calculation was to be used, a quick analysis using the various Riemann Sum formulas was completed. This resulted in an error of approximately 125 square inches between the left-hand side Riemann Sum and the Trapezoidal/Middle Riemann Sum. As this error would not be symmetrical, specifically, under-representing the left-hand side of the profile and over-representing the right-hand side, it was decided to use the Trapezoidal formula. Due to the data consisting of discrete points instead of a function, the use of either the Trapezoidal or Midpoint formulas would return the same results. This behavior is shown in Figure 9.

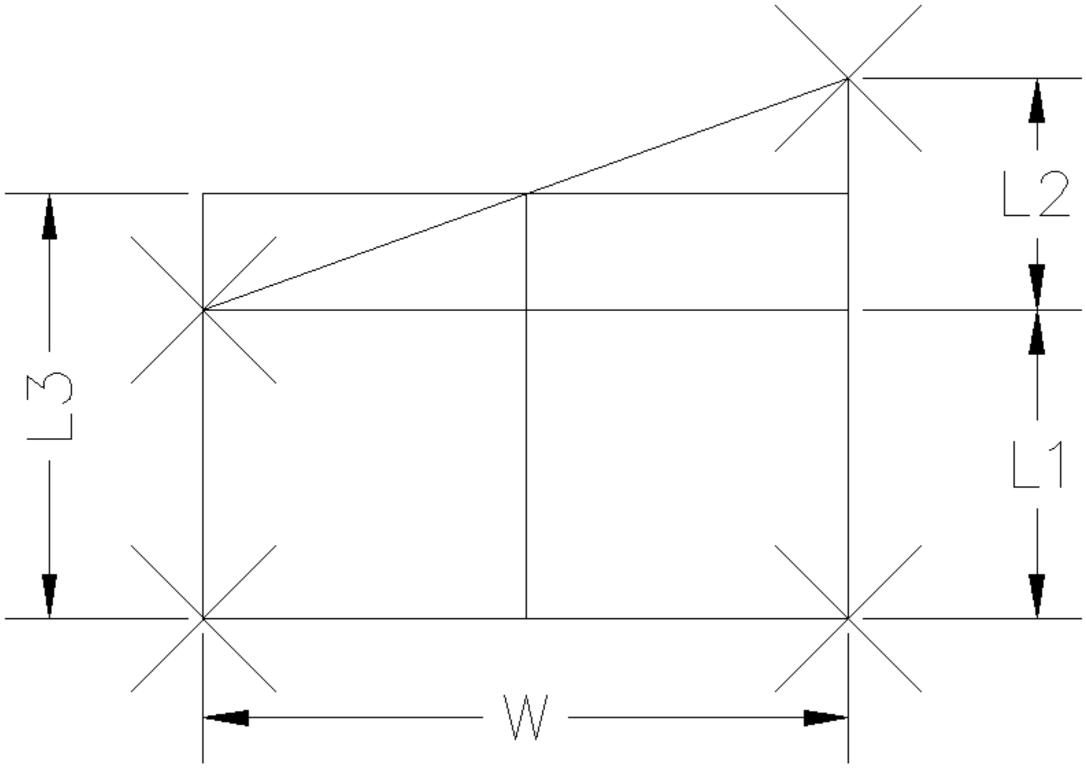

Figure 9: Graphical Representation of Area Calculation using Midpoint and Trapezoidal formulas. "W" is the width of the area.

The formulas used are shown below, with Equation 7 being the formula for finding the area based on the average length and Equation 8 being the trapezoidal formula.

$$L1+(L2/2)=L3 \tag{Eq. 6}$$

$$(L3)*W=Area \tag{Eq. 7}$$

$$((L1+(L1+L2))/2)*W=Area \tag{Eq. 8}$$

These calculations also underwent some evolution over time due to the increasing knowledge of Excel and associated functions inside of the program. Originally, the areas for each of the zones for each profile was calculated separately, requiring new calculation groups for each zone which increased the complexity of any changes. Upon learning about and testing out Excel's "SUMIFS" function, the area calculations were able to be reduced to one set of calculations. The "SUMIFS" function works as a conditional summation function, only adding values which are true based on the conditions given. For these calculations, the conditions given were that the X value had to be within a certain range, as the zones were primarily split up based on those values. An example of the use of "SUMIFS" is shown below as Equation 9. The first variable, Volume Range, refers to the full range of volumes that are to be conditionally summated. "X Range" refers to the same-size range of X values to be tested. "<Y" and ">Z" are the conditional statements, restricting the range of summated values to those which are within the Z and Y boundaries. In order to calculate this function, each row of data is compared. For row 1 of the volume range, row 1 of the X range is checked to see if it satisfies the conditional statements; if it is true, then row 1 of the volume range is added to the summation.

SUMIFS(Volume Range,X Range,"<Y",X Range,">Z") Eq. 9

Initially, the zones used were the same as those used previously, with each of the zones, except for zone 3, extending to the subgrade. This lead to two major issues: there was, at that point, no way to determine the width of the lateral extension of the shoulder as it varied with each profile and there was no way to apply a weighting to only the upper part of the ballast shoulder. Due to these issues, a new set of zones, as shown in Figure 10, were created and implemented.

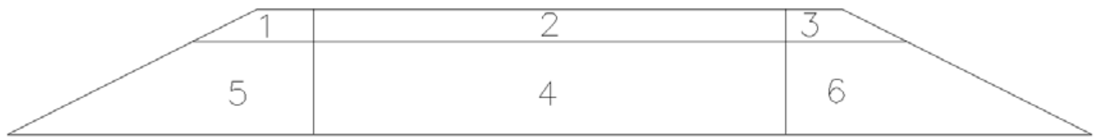

Figure 10: The zones as applied to an idealized profile.

These new zones were easier to implement in the calculations as well as providing a better reasoning behind the zones. As shown in Table 3, all of the zones, except for Zone 4, had some changes applied to them. The boundary between the upper zones (1, 2 and 3) and the lower zones (4, 5 and 6) is the base of an ideal tie which, in this case, was 7 inches below the top of the tie. Appendix A contains the calculations done in order to calculate the area for each zone.

Table 3: Definition of New Zones

Zone Number	Zone Name	Zone Definition/ Primary Function
Zone 1	Left Shoulder	Resists and redirects lateral forces.
Zone 2	Crib Area	Restrains the ties and transfers lateral, longitudinal and vertical loads to the neighboring areas.
Zone 3	Right Shoulder	Resists and redirects lateral forces
Zone 4	Ballast Below the Tie	Transfers and dissipates vertical loadings to the subgrade
Zone 5	Ballast Below the Left Shoulder	Transfers and dissipates loadings from the Left shoulder
Zone 6	Ballast Below the Right Shoulder	Transfers and dissipates loadings from the Right shoulder

Once the area for each zone was computed, the volume was generated by multiplying the area by an arbitrary value; in this case, one mile. As the area was in square meters, due to the use of a metric Cartesian coordinate system, the values had to be converted to a U.S. Customary unit for ballast volume, cubic yards; this is due to the use of cubic yards as the standard unit of volume for ballast for American railroads. Another aspect to the volume calculations is that, as zone 2 occupies the same area as the tie, a compensation had to be included in order to prevent an over-representation of the missing crib volume. This compensation factor was generated based on the assumption that there would be 9 inches of tie every 19.5 inches of length. The factor used was 54%; this factor was applied to the initial calculated missing volume of the crib area to produce the missing volume of the crib area after taking into account the ties.

2.3 Creation of Weighting Factors

There are two sets of weighting factors that were created; segment weighting which modified the area/volume on the ballast profile level and section weightings, which modified the now-modified volumes for a group of segments. A display of how sections and segments work in relationship to each other in this scenario is shown in Figure 11. The use of two levels was required as there are some conditions that, while applicable to segments, are not applicable to sections as they are dependent on the location being examined; examples include mud-spots and curves. Sections are used to combine consecutive segments which have similar conditions such as high speed rail or high tonnage; factors that depend on the railway line and operations and which do not change their applicability over short distances.

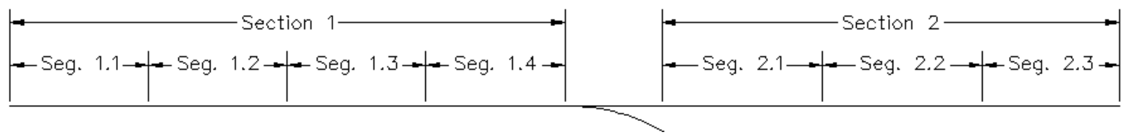

Figure 11: Relationship between Segments and Sections

The factors developed by Dr. Zarembski [1] were separated into two categories as mentioned previously; segment weighting factors and section weighting factors. As mentioned in [1], the risk associated with loss of lateral resistance for cribs and shoulders was calculated using previous research on lateral resistance and buckle risk. The risk assessment for speed and heavy axle loads (HAL) were computed through the use of dynamic loading and damage models previously researched. For subgrade risk, the Talbot equation was used to determine the effect that a mud-spot would have on the stresses generated. The values for these weighing factors is shown in Table 4, reproduced from [1]. These factors are applied to the respective missing volume of a segment's zones. The sum of these modified volumes results in the total modified volume of the segment. This behavior is shown in Equation 10, with "i" being the Zone Number and "j" being the weighting factor and Dij being a dummy variable that controlled if the weighting was to be applied.

$$V_{mod} = \sum_{i=1}^{6} V_i * \left(\sum_{j=1}^{6} (W_j - 1) * D_{ij}\right) \quad \text{Eq. 10}$$

Table 4: Segment Weighting factors

Zone	Curve	Grade	HAL	Buckle Risk	Speed	Mud Spot
1 Left Shoulder	1.08			1.15		
2 Crib	1.08	1.18		1.08		
3 Right Shoulder	1.08			1.15		
4 Below the Crib			1.0875		1.06	1.11
5 Below Left Shoulder						
6 Below Right Shoulder						

The next set of weighting factors were defined for sections. As mentioned in [1], these weighs were defined through the use of risk-based modeling activity. As sections are based on the accumulated volume of several segments, these weights are applied to the sum of the modified segment volumes.

Table 5: Section Weighting factors

Weighing Name	Weighting
Passenger/Hazmat line	1.25
Key Route (As defined by the railroad)	1.11
Class 5 speed – Not Passenger	1.10
Class 4 speed – Not Passenger	1.05
Class 3 speed – Not Passenger	1
High Tonnage	1.15

Multiple analyses were done using these factors; some were to see the effect that combining multiple factors would produce and others were to provide examples of how they would work. For the full set of analyses, please see Appendix B. An example of one of these analyses is shown in Tables 6, which contains the initial volumes, Table 7, which contains the volumes after being modified for buckle risk, and Figures 13A and 13B, which show the change in ranking for all of the segments and a group of segments to better show the change in rankings, respectively.

Table 6: Example of Weightings applied to 100 1-mile long segments, Unmodified Volumes in cubic feet

ID	Mile	Left Volume	Center Volume	Right Volume	Total Volume
1	204	753.17	464.85	2249.85	3467.87
2	205	437.60	479.89	2378.15	3295.64
3	206	542.49	1436.16	1641.61	3620.26
4	207	879.17	1613.23	1561.04	4053.44
5	208	324.60	1661.02	466.81	2452.43
6	209	461.00	1710.74	984.30	3156.04
7	210	769.69	1963.22	1666.28	4399.19
8	211	169.52	1281.30	694.86	2145.69
9	212	16.14	129.28	186.64	332.06
10	213	2.77	26.32	28.66	57.74
11	214	8.02	52.00	56.70	116.72
12	215	5.71	173.18	184.11	363.00
13	216	47.37	165.42	209.89	422.68
14	217	0.43	7.82	3.49	11.74
15	218	26.49	176.18	189.57	392.24
16	219	2.41	9.99	37.53	49.93
17	220	0.37	10.89	15.04	26.30
18	221	1.31	38.29	1337.21	1376.81
19	222	9.49	36.35	75.09	120.93
20	223	0.38	14.73	25.47	40.58
21	224	0.01	11.09	13.50	24.61
22	225	0.69	15.39	28.20	44.27
23	226	13.71	87.32	106.56	207.59
24	227	2.86	28.37	19.07	50.30
25	228	7.82	47.19	53.52	108.53
26	229	7.84	37.21	29.92	74.96
27	230	16.61	53.50	129.17	199.28
28	231	289.04	339.14	864.57	1492.74
29	232	314.57	491.14	378.64	1184.34
30	233	858.09	335.77	2176.77	3370.63
31	234	801.80	536.16	1543.63	2881.60
32	235	329.64	649.43	2176.83	3155.90
33	236	304.66	1023.58	2347.27	3675.50
34	237	878.69	1303.71	3593.85	5776.24
35	238	540.62	1207.43	3061.51	4809.56
36	239	287.79	1222.80	2133.93	3644.52
37	240	119.10	610.67	825.79	1555.55
38	241	94.23	857.80	1132.67	2084.70

Table 6 Continued

ID	Mile	Left Volume	Center Volume	Right Volume	Total Volume
39	242	672.32	2540.07	3317.34	6529.73
40	243	140.85	1520.30	1483.37	3144.52
41	244	430.40	2318.82	1831.79	4581.01
42	245	37.17	1826.52	1782.80	3646.49
43	246	110.54	1873.16	2246.51	4230.22
44	247	306.72	1934.54	663.63	2904.90
45	248	566.07	1925.35	830.82	3322.23
46	249	230.84	1433.10	755.04	2418.99
47	250	476.80	1573.20	1790.94	3840.94
48	251	779.64	1746.41	1485.36	4011.42
49	252	625.47	1380.54	1389.06	3395.07
50	253	479.44	1933.97	1465.88	3879.28
51	254	103.38	1783.62	1537.18	3424.18
52	255	425.11	1493.46	945.66	2864.24
53	256	319.52	1935.49	1411.73	3666.73
54	257	419.15	2206.03	1342.39	3967.57
55	258	292.74	1872.31	2792.21	4957.26
56	259	351.46	1868.98	1449.06	3669.51
57	260	194.80	1472.64	1495.85	3163.29
58	261	55.63	1776.73	1132.43	2964.79
59	262	449.18	1709.37	629.21	2787.76
60	263	364.32	1723.65	1389.68	3477.65
61	264	597.24	1953.20	1150.61	3701.05
62	265	631.95	1790.61	1020.24	3442.80
63	266	227.03	1249.17	1411.64	2887.83
64	267	116.97	1257.39	1106.95	2481.31
65	268	103.47	689.61	2508.81	3301.88
66	269	241.48	651.45	1248.00	2140.93
67	270	1710.76	1756.41	2332.60	5799.76
68	271	878.97	1587.88	2924.58	5391.43
69	272	218.96	2317.92	1003.81	3540.69
70	273	192.83	1855.46	922.62	2970.91
71	274	574.19	1486.97	1413.32	3474.47
72	275	137.82	2051.20	477.69	2666.71
73	276	81.02	2112.03	731.79	2924.85
74	277	219.89	648.02	943.38	1811.29
75	278	169.89	539.86	1506.86	2216.61
76	279	487.84	452.18	587.81	1527.84
77	280	381.35	803.58	554.49	1739.41

Table 6 Continued

ID	Mile	Left Volume	Center Volume	Right Volume	Total Volume
78	281	254.51	818.46	392.51	1465.47
79	282	389.82	453.94	512.03	1355.78
80	283	259.49	301.17	361.35	922.01
81	284	113.48	462.28	260.23	835.99
82	285	251.39	349.56	338.90	939.85
83	286	212.27	360.80	333.27	906.33
84	287	137.40	1933.51	583.74	2654.66
85	288	327.64	1596.36	812.42	2736.43
86	289	557.98	1127.26	897.22	2582.46
87	290	330.04	1690.46	493.76	2514.27
88	291	798.24	1921.35	842.15	3561.74
89	292	682.06	1987.09	903.89	3573.05
90	293	1354.04	428.40	501.33	2283.77
91	294	1680.39	363.81	675.99	2720.20
92	295	560.44	1232.25	542.45	2335.14
93	296	184.67	1855.70	540.49	2580.87
94	297	82.88	1699.45	344.69	2127.03
95	298	103.00	1420.83	459.00	1982.82
96	299	448.99	1280.27	480.31	2209.57
97	300	804.74	1094.53	1299.82	3199.09
98	301	626.89	1260.27	720.00	2607.16
99	302	130.37	1649.69	465.90	2245.96
100	303	657.09	1118.91	636.63	2412.63

Table 7: Example of Weightings applied to 100 1-mile long segments, weighted using Buckle Risk, Modified Volumes in cubic feet

ID	Left Volume	Center Volume	Right Volume	Total Volume	Initial Ranking	Modified Ranking	Rank Change
1	866.15	502.03	2587.33	3955.51	27	24	3
2	503.24	518.28	2734.87	3756.40	34	32	2
3	623.86	1551.05	1887.85	4062.77	21	21	0
4	1011.04	1742.29	1795.20	4548.53	10	10	0
5	373.29	1793.90	536.83	2704.02	57	57	0
6	530.15	1847.60	1131.94	3509.69	37	39	-2
7	885.14	2120.27	1916.22	4921.64	8	8	0
8	194.95	1383.81	799.09	2377.85	65	66	-1

Table 7 Continued

ID	Left Volume	Center Volume	Right Volume	Total Volume	Initial Ranking	Modified Ranking	Rank Change
9	18.56	139.62	214.63	372.82	86	86	0
10	3.18	28.42	32.95	64.56	93	93	0
11	9.22	56.16	65.21	130.59	90	90	0
12	6.56	187.04	211.73	405.32	85	85	0
13	54.48	178.65	241.37	474.50	83	83	0
14	0.49	8.44	4.01	12.95	100	100	0
15	30.46	190.27	218.01	438.75	84	84	0
16	2.77	10.79	43.16	56.72	95	94	1
17	0.42	11.76	17.30	29.48	98	98	0
18	1.51	41.35	1537.79	1580.65	76	76	0
19	10.91	39.26	86.35	136.52	89	89	0
20	0.44	15.90	29.29	45.64	97	97	0
21	0.01	11.98	15.53	27.52	99	99	0
22	0.79	16.62	32.43	49.84	96	96	0
23	15.77	94.30	122.55	232.62	87	87	0
24	3.29	30.64	21.93	55.86	94	95	-1
25	8.99	50.96	61.55	121.50	91	91	0
26	9.01	40.18	34.40	83.60	92	92	0
27	19.11	57.78	148.55	225.43	88	88	0
28	332.39	366.27	994.25	1692.91	74	74	0
29	361.75	530.43	435.44	1327.62	78	78	0
30	986.81	362.63	2503.28	3852.72	31	28	3
31	922.07	579.05	1775.18	3276.31	45	42	3
32	379.09	701.38	2503.36	3583.83	38	36	2
33	350.35	1105.46	2699.35	4155.17	16	15	1
34	1010.49	1408.00	4132.92	6551.42	3	2	1
35	621.71	1304.03	3520.73	5446.47	6	6	0
36	330.96	1320.62	2454.02	4105.60	20	17	3
37	136.97	659.52	949.65	1746.14	72	72	0
38	108.36	926.42	1302.57	2337.36	68	67	1
39	773.17	2743.27	3814.94	7331.38	1	1	0
40	161.97	1641.92	1705.88	3509.77	39	38	1
41	494.95	2504.33	2106.56	5105.84	7	7	0
42	42.75	1972.64	2050.22	4065.61	19	20	-1
43	127.12	2023.02	2583.49	4733.63	9	9	0
44	352.73	2089.31	763.17	3205.21	43	45	-2
45	650.98	2079.37	955.44	3685.79	32	34	-2
46	265.47	1547.75	868.30	2681.52	58	59	-1

Table 7 Continued

ID	Left Volume	Center Volume	Right Volume	Total Volume	Initial Ranking	Modified Ranking	Rank Change
47	548.33	1699.05	2059.58	4306.95	14	14	0
48	896.59	1886.13	1708.17	4490.88	11	11	0
49	719.29	1490.99	1597.42	3807.70	30	31	-1
50	551.35	2088.68	1685.76	4325.80	13	13	0
51	118.88	1926.31	1767.75	3812.95	29	30	-1
52	488.88	1612.94	1087.51	3189.33	46	46	0
53	367.44	2090.33	1623.48	4081.26	18	19	-1
54	482.03	2382.51	1543.75	4408.28	12	12	0
55	336.65	2022.10	3211.04	5569.79	5	5	0
56	404.18	2018.50	1666.42	4089.10	17	18	-1
57	224.02	1590.45	1720.23	3534.70	36	37	-1
58	63.97	1918.87	1302.30	3285.14	41	41	0
59	516.55	1846.12	723.59	3086.27	47	48	-1
60	418.97	1861.54	1598.13	3878.64	25	27	-2
61	686.82	2109.45	1323.20	4119.48	15	16	-1
62	726.74	1933.86	1173.28	3833.88	28	29	-1
63	261.08	1349.11	1623.38	3233.57	44	43	1
64	134.52	1357.98	1272.99	2765.49	56	56	0
65	118.99	744.78	2885.13	3748.89	33	33	0
66	277.71	703.56	1435.20	2416.47	66	65	1
67	1967.37	1896.92	2682.49	6546.78	2	3	-1
68	1010.81	1714.91	3363.27	6088.99	4	4	0
69	251.80	2503.35	1154.38	3909.54	24	25	-1
70	221.76	2003.89	1061.01	3286.66	40	40	0
71	660.32	1605.92	1625.31	3891.55	26	26	0
72	158.49	2215.29	549.35	2923.14	50	50	0
73	93.17	2281.00	841.56	3215.73	42	44	-2
74	252.87	699.86	1084.89	2037.62	70	70	0
75	195.38	583.05	1732.88	2511.31	63	62	1
76	561.02	488.36	675.99	1725.36	73	73	0
77	438.55	867.86	637.66	1944.07	71	71	0
78	292.68	883.93	451.39	1628.00	75	75	0
79	448.29	490.25	588.83	1527.38	77	77	0
80	298.42	325.26	415.55	1039.23	80	80	0
81	130.50	499.26	299.27	929.03	82	82	0
82	289.10	377.53	389.74	1056.36	79	79	0
83	244.11	389.66	383.26	1017.02	81	81	0
84	158.02	2088.19	671.30	2917.51	51	51	0

Table 7 Continued

ID	Left Volume	Center Volume	Right Volume	Total Volume	Initial Ranking	Modified Ranking	Rank Change
85	376.79	1724.07	934.29	3035.15	48	49	-1
86	641.67	1217.44	1031.81	2890.92	53	53	0
87	379.55	1825.70	567.83	2773.08	55	55	0
88	917.97	2075.06	968.47	3961.51	23	23	0
89	784.37	2146.06	1039.48	3969.91	22	22	0
90	1557.14	462.68	576.53	2596.35	61	61	0
91	1932.45	392.92	777.39	3102.76	49	47	2
92	644.51	1330.83	623.82	2599.15	60	60	0
93	212.38	2004.16	621.57	2838.10	54	54	0
94	95.32	1835.41	396.40	2327.12	67	68	-1
95	118.45	1534.49	527.85	2180.79	69	69	0
96	516.34	1382.69	552.35	2451.38	64	64	0
97	925.45	1182.09	1494.79	3602.33	35	35	0
98	720.92	1361.09	828.00	2910.01	52	52	0
99	149.93	1781.66	535.79	2467.38	62	63	-1
100	755.65	1208.43	732.12	2696.20	59	58	1

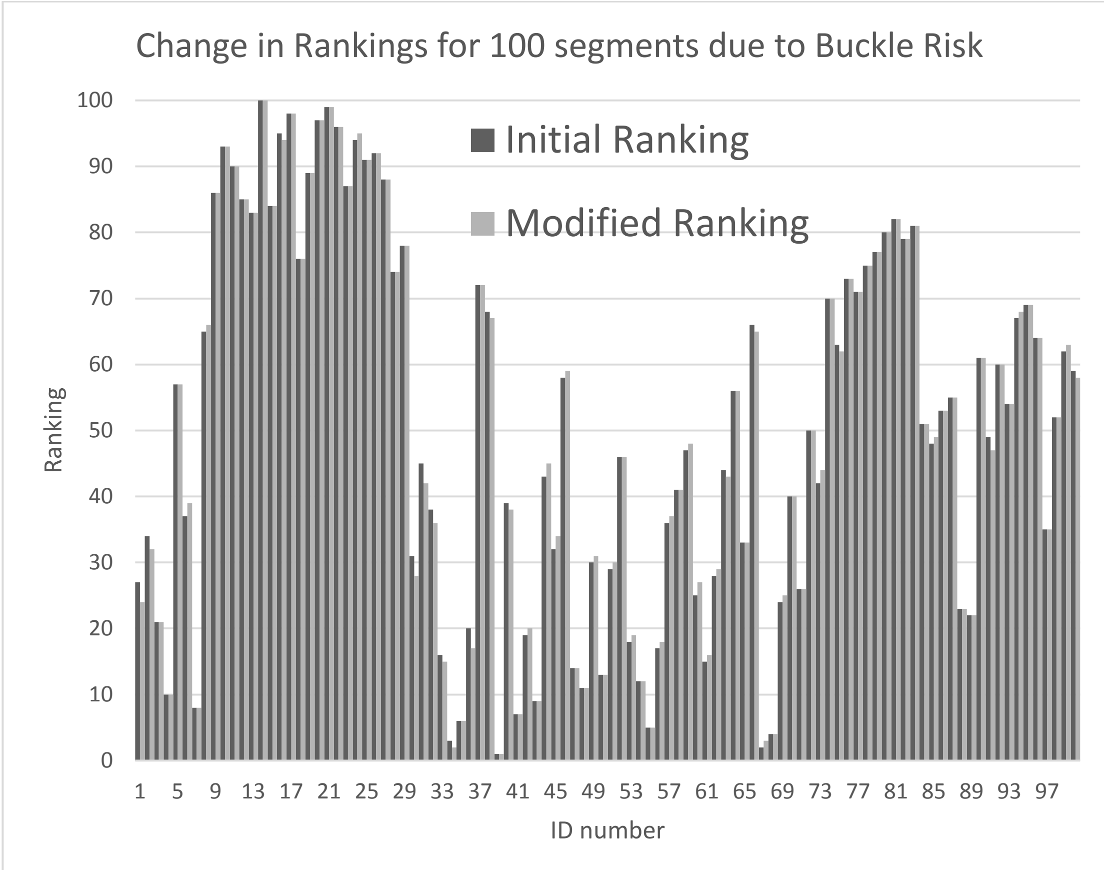

Figure 12A: Change in Ranking for 100 Segments due to Buckle Risk

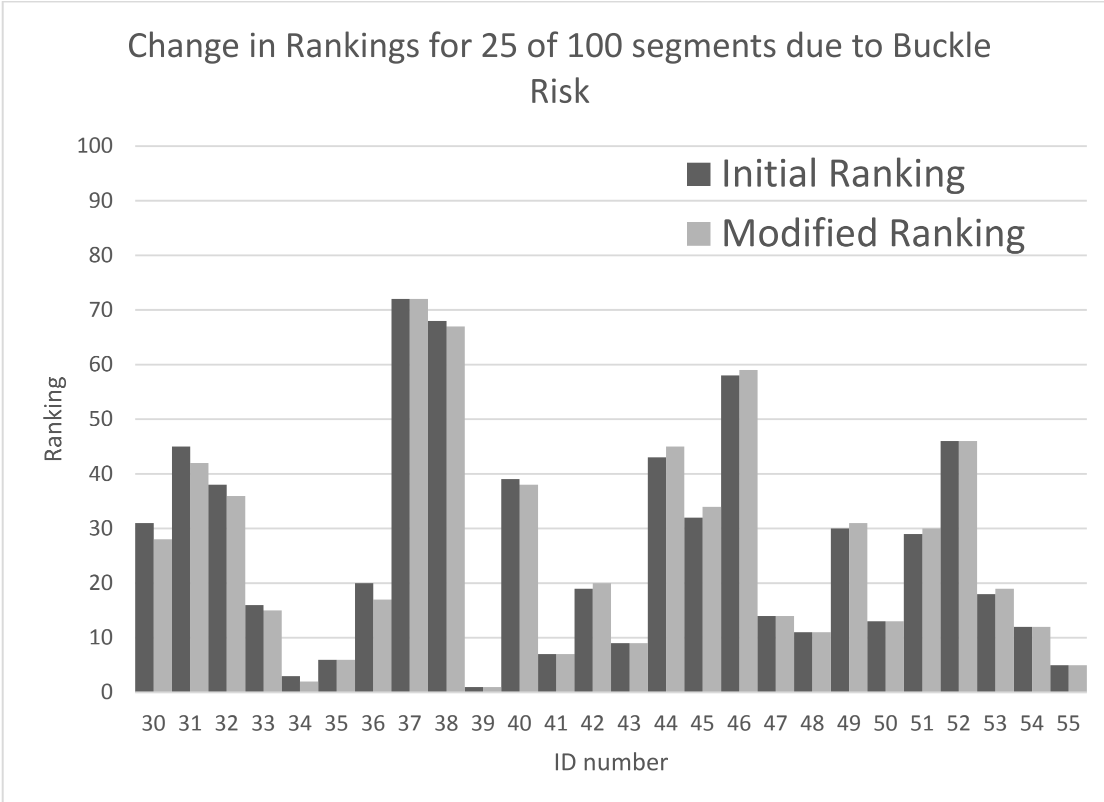

Figure 12B: Change in Ranking for 25 of 100 Segments due to Buckle Risk

Another analysis looked at applying the curve factor for track that had curves in it. In order to apply the weighting realistically, missing volume data that had accompanying degree of curvature (DoC) information was used. The actual degree of curvature was not used; that is, a higher degree of curvature did not result in a higher weight applied. Research into the impact that the degree of curvature has on the development of defective segments was not done in this project and should be undertaken in future efforts. The results of this curvature weighting application are shown in Tables 8 and 9, which are the initial values and post-weighting values respectively. As shown in the tables and Figure 13, several segments, such as the

Rank 3 and 4 segments, switch position after having the curvature weighting applied. In the case of the Rank 3 and 4 segments, the initially rank 4 segment is located on a curve while the initially rank 3 segment is not. This behavior shows that applying the weightings can have a beneficial effect to safety by changing the rankings.

Table 8: Example of Weightings applied to 38 segments. Initial Missing Volume by Zone, Total Volume, Degree of Curvature and Initial Rank

ID	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Total Volume	DoC	Rank
1	4.83	53	183.5	0	5.27	0	246.61	0	6
2	0.33	2.06	3.48	2.29	1.02	0	9.19	4	38
3	504.29	9.43	33.49	0.29	4.48	0	552	0	1
4	43.9	6.39	2.63	2.29	4.9	0	60.13	0	15
5	3.16	5.96	4.41	0	4.9	0	18.45	0	31
6	40.85	4.05	37.68	0	2.53	0.17	85.31	0	10
7	22.27	3.47	62.46	0	2.53	0.17	90.92	0	9
8	2.4	3.45	7.66	0	1.02	0	14.54	0	34
9	5.15	3.29	4.74	0	2.53	0	15.73	0	32
10	78.44	10.16	38.62	2.66	6.42	1.74	138.07	0	8
11	27.39	7.3	18.02	1.87	6.42	0	61.02	0	14
12	24.97	5.77	11.46	0.71	4.9	2.17	50.01	0	17
13	47.43	6.34	305.25	3.45	6.06	2.96	371.52	0	3
14	8.61	0.06	0.29	0	0	0.59	9.56	0	37
15	196.91	4.33	242.01	0.29	6.42	0.59	450.57	1	2
16	266.14	2.56	82.84	0	0	0	351.56	1	4
17	110.31	3.39	133.21	0	5.27	0	252.2	1	5
18	3.81	8.45	3.53	3.87	7.21	1.38	28.27	0	24
19	1.97	6.84	5.43	1.08	7.21	0.59	23.15	0	27
20	3.05	8.29	4.61	1.5	8	0.95	26.44	0	26
21	3.68	5.54	30.47	3.45	9.95	4.18	57.28	0	16
22	19.91	5.22	106.17	3.87	6.85	2.6	144.64	0	7
23	0.16	1.91	2.78	3.45	3.32	0	11.64	0	36
24	7.62	5.77	47	3.45	5.63	0.95	70.45	0.5	12
25	2.23	6.09	3.45	2.29	7.64	0.17	21.89	0	28
26	1.67	4.76	3.77	1.08	4.9	3.75	19.95	0	30
27	1.08	5.91	3.06	0	5.63	0	15.7	0	33

Table 8 Continued

ID	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Total Volume	DoC	Rank
28	4.37	19	12.73	0.29	5.27	0	41.68	0	21
29	4.8	14.19	29.73	3.45	8	3.75	63.95	0	13
30	3.13	8.79	24.48	3.45	4.48	1.38	45.73	0	19
31	10.89	14.22	14.14	1.87	5.63	2.96	49.73	0	18
32	8.6	13.7	61.05	0	0	0.95	84.32	0	11
33	3.56	9.09	25.8	1.08	3.32	0	42.87	0	20
34	0.93	7.76	6.44	1.08	4.48	0	20.7	0	29
35	1.58	10.82	3.54	4.24	6.06	1.38	27.64	0	25
36	1.64	9.37	7.1	3.08	5.63	4.18	31.02	0	23
37	3.76	13.67	11.6	1.87	7.21	2.96	41.1	0	22
38	0.66	2.89	2.89	5.45	0	0	11.91	0	35

Table 9: Example of Weightings applied to 38 segments. Curve Weighting conditional on curve existing. Modified Volumes and Rankings.

ID	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Total Volume	Modified Ranking	Change in Rank
1	4.83	53	183.5	0	5.27	0	246.61	6	0
2	0.35	2.23	3.75	2.29	1.02	0	9.67	37	1
3	504.29	9.43	33.49	0.29	4.48	0	552	1	0
4	43.9	6.39	2.63	2.29	4.9	0	60.13	15	0
5	3.16	5.96	4.41	0	4.9	0	18.45	31	0
6	40.85	4.05	37.68	0	2.53	0.17	85.31	10	0
7	22.27	3.47	62.46	0	2.53	0.17	90.92	9	0
8	2.4	3.45	7.66	0	1.02	0	14.54	34	0
9	5.15	3.29	4.74	0	2.53	0	15.73	32	0
10	78.44	10.16	38.62	2.66	6.42	1.74	138.07	8	0
11	27.39	7.3	18.02	1.87	6.42	0	61.02	14	0
12	24.97	5.77	11.46	0.71	4.9	2.17	50.01	17	0
13	47.43	6.34	305.25	3.45	6.06	2.96	371.52	4	-1
14	8.61	0.06	0.29	0	0	0.59	9.56	38	-1
15	212.66	4.67	261.37	0.29	6.42	0.59	486.03	2	0
16	287.44	2.77	89.47	0	0	0	379.68	3	1
17	119.13	3.67	143.87	0	5.27	0	271.95	5	0
18	3.81	8.45	3.53	3.87	7.21	1.38	28.27	24	0

Table 9 Continued

ID	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Total Volume	Modified Ranking	Change in Rank
19	1.97	6.84	5.43	1.08	7.21	0.59	23.15	27	0
20	3.05	8.29	4.61	1.5	8	0.95	26.44	26	0
21	3.68	5.54	30.47	3.45	9.95	4.18	57.28	16	0
22	19.91	5.22	106.17	3.87	6.85	2.6	144.64	7	0
23	0.16	1.91	2.78	3.45	3.32	0	11.64	36	0
24	8.23	6.23	50.76	3.45	5.63	0.95	75.28	12	0
25	2.23	6.09	3.45	2.29	7.64	0.17	21.89	28	0
26	1.67	4.76	3.77	1.08	4.9	3.75	19.95	30	0
27	1.08	5.91	3.06	0	5.63	0	15.7	33	0
28	4.37	19	12.73	0.29	5.27	0	41.68	21	0
29	4.8	14.19	29.73	3.45	8	3.75	63.95	13	0
30	3.13	8.79	24.48	3.45	4.48	1.38	45.73	19	0
31	10.89	14.22	14.14	1.87	5.63	2.96	49.73	18	0
32	8.6	13.7	61.05	0	0	0.95	84.32	11	0
33	3.56	9.09	25.8	1.08	3.32	0	42.87	20	0
34	0.93	7.76	6.44	1.08	4.48	0	20.7	29	0
35	1.58	10.82	3.54	4.24	6.06	1.38	27.64	25	0
36	1.64	9.37	7.1	3.08	5.63	4.18	31.02	23	0
37	3.76	13.67	11.6	1.87	7.21	2.96	41.1	22	0
38	0.66	2.89	2.89	5.45	0	0	11.91	35	0

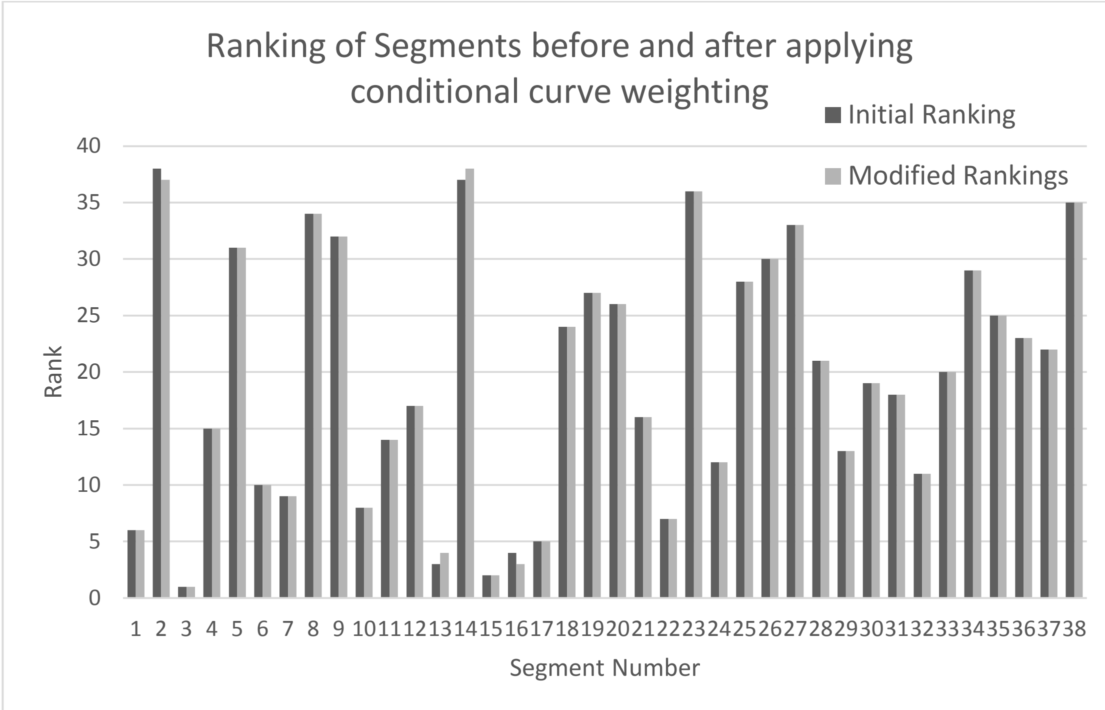

Figure 13: Rankings of segments before and after applying conditional Curve modifiers

2.4 Use of GPR Data

From the start, the calculations had variables tied to the level of subgrade in order to accommodate GPR data. Since there was no accompanying GPR data for the previous calculations, an assumed ballast depth was used. This changed when GREX supplied information about missing ballast and accompanying GPR data for a stretch of track. The GPR data included information on the moisture of the ballast, ballast fouling, depth of the ballast layer and depth to the sub-ballast layer. The information given covered the left, center and right sections of the ballast cross-section. This data is contained in Appendix C. The use of the depth of ballast value is shown in Figure 14. From an initially ideal profile, the depth of ballast has been decreased by the sub-ballast intruding into the ballast layer, resulting in a missing area and volume for zone

4. This missing ballast volume is then used in the application of the weightings, though only zone 4 currently has weightings that can result in a change to the ballast volume.

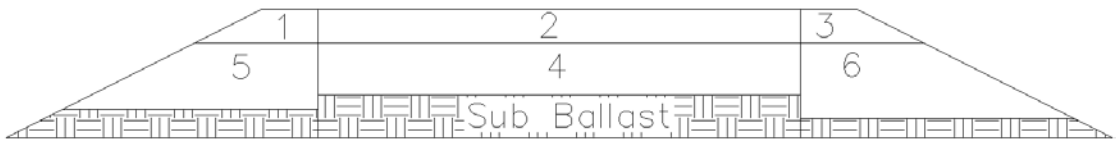

Figure 14: Representation of the application of Depth of Ballast GPR data.

At first, only the depth of the ballast layer was used, as this was the original goal. Another analysis also included the moisture content of the ballast as an indicator of a mudspot in order to see how the inclusion of the mudspot weighting factor would affect the results. In order to apply the mudspot weighting, areas with reported moisture content above 225 (out of 255) were considered to be representative of areas containing mudspots. An example of this is shown in Table 10 and Figure 15. The change of the initially ranked 38 segment to rank 37 after the application of curve and mudspot weightings shows that, even at small volumes of ballast missing, the impact of these weighting factors can improve ballast maintenance efforts.

Table 10: Application of Curve and Mudspot Weighting factors to Ballast and GPR data

ID	DoC	Ballast Moisture	Missing Ballast	Modified Ballast	Initial Rank	Modified Rank	Change in Rank
1	0	255	246.61	246.61	6	6	0
2	4	255	9.19	9.92	38	37	1
3	0	255	552	552.03	1	1	0

Table 10 Continued

ID	DoC	Ballast Moisture	Missing Ballast	Modified Ballast	Initial Rank	Modified Rank	Change in Rank
4	0	255	60.13	60.38	15	15	0
5	0	255	18.45	18.45	31	31	0
6	0	246	85.31	85.31	10	10	0
7	0	248	90.92	90.92	9	9	0
8	0	255	14.54	14.54	34	34	0
9	0	255	15.73	15.73	32	32	0
10	0	255	138.07	138.36	8	8	0
11	0	255	61.02	61.23	14	14	0
12	0	255	50.01	50.09	17	17	0
13	0	255	371.52	371.9	3	4	-1
14	0	255	9.56	9.56	37	38	-1
15	1	255	450.57	486.03	2	2	0
16	1	255	351.56	379.68	4	3	1
17	1	255	252.2	271.95	5	5	0
18	0	185	28.27	28.7	24	24	0
19	0	255	23.15	23.15	27	27	0
20	0	199	26.44	26.6	26	26	0
21	0	192	57.28	57.66	16	16	0
22	0	172	144.64	144.64	7	7	0
23	0	250	11.64	12.02	36	35	1
24	0.5	211	70.45	75.66	12	12	0
25	0	198	21.89	22.14	28	28	0
26	0	255	19.95	19.95	30	30	0
27	0	255	15.7	15.7	33	33	0
28	0	132	41.68	41.68	21	21	0
29	0	126	63.95	63.95	13	13	0
30	0	157	45.73	45.73	19	19	0
31	0	255	49.73	49.73	18	18	0
32	0	240	84.32	84.32	11	11	0
33	0	219	42.87	42.87	20	20	0
34	0	137	20.7	20.7	29	29	0
35	0	63	27.64	27.64	25	25	0
36	0	131	31.02	31.36	23	23	0
37	0	148	41.1	41.31	22	22	0
38	0	255	11.91	11.91	35	36	-1

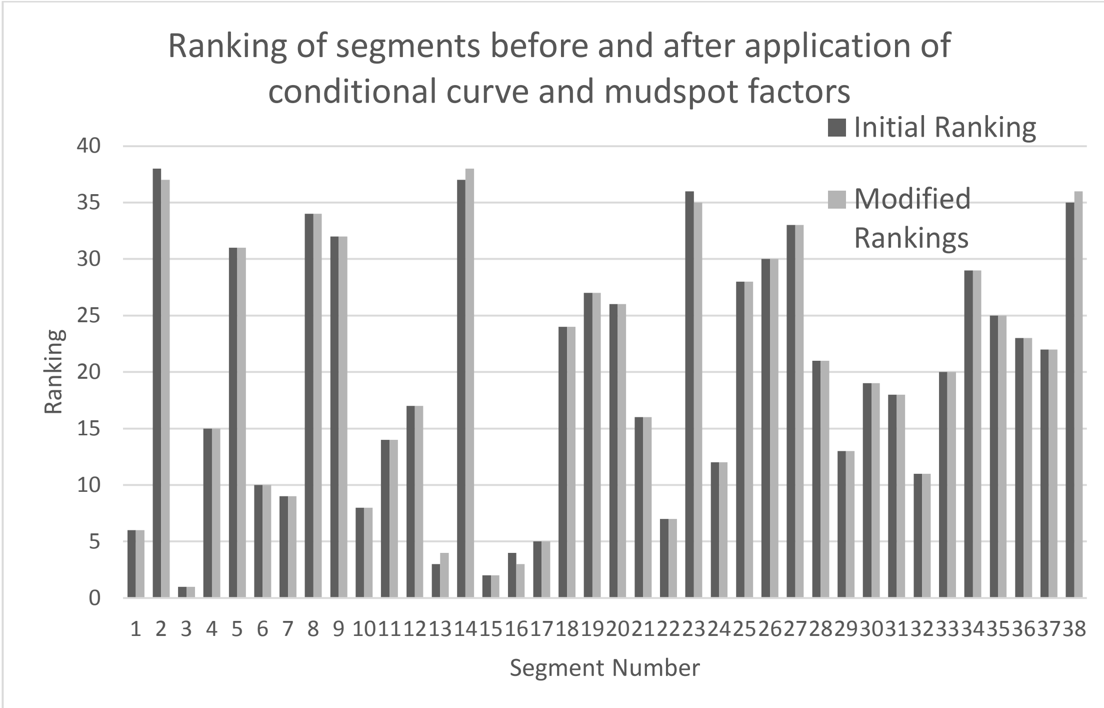

Figure 15: Ranking of segments before and after applying conditional curve and mudspot weighting factors.

2.5 Creation of Weighing Factors Using a Cost Based Method

The original weighting factors were based off of the risk of an incident occurring and not the expected severity of the incident. For instance, the cost of a derailment due to the existence of a curve in a classification yard, where operational speeds are typically low, are usually lower than a derailment due to a curve on a mainline, where operational speeds are typically higher, even though the cause of both would be weighted the same. Another issues is that, while creating weighting factors based on the change in forces works well for engineering-related causes, the risk associated with certain non-engineering conditions surpasses the risk calculated based on engineering principles. As such, the focus of this analysis were the Hazmat and Passenger weightings as those had non-engineering costs; Hazmat costs are typically related to the type of material involved and the associated cleanup while the cost of a passenger injury/death are tied to litigation efforts on behalf of those injured/killed. These two factors are also some of the most notable as well; major Hazmat spills and passenger injuries/deaths are commonly reported in the news, potentially causing issues with publicity that are beyond the scope of this research.

The potential use in a special weighing for Hazmat material transport stems from the complicated cleanup and extensive damages that occur with major Hazmat incidents. As information regarding the cost of environmental cleanup was scarce, the cost of equipment and track damages, for the year of 2012[3], as reported to the FRA [4] was used as a substitute, as it was hypothesized that Hazmat events would have a higher equipment and track damage cost than non-Hazmat events. This FRA data is freely accessible from their website but holds the caveat that the reportable damages do not include clearing a wreck, damaged lading, environmental cleanup costs and other costs not directly related, which is acceptable under the previous hypothesis. The actual data used is shown in Appendix D. For this analysis, a series of regressions, using Total Cost as the dependent variable, were run in order to first, weed out variables which did not explain the variation in the data, second, to determine if the removal of the intercept value caused a major change in the regressions run which used the remaining variables, and third, to determine the actual values to use. As shown in Table 11, the initial set of variables used attempted to cover a majority of the important factors that can potentially impact the resulting cost of a derailment.

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[3] At the time this analysis was done, 2012 was the latest year with complete data.

Table 11: Initial variables used in Hazmat Regression Analysis

Data Name	Definition	Minimum Value	Maximum Value
Loco	Number of locomotives involved in the derailment	0	6
DerailLoco	Number of derailed locomotives	0	1
Cars	Total number of cars involved in the derailment	0	137
DerailCars	Number of derailed cars	0	45
Speed	Last known speed before the derailment	2	68
EqpDmg	Reported cost of equipment damages	$ 0	$ 2,778,964
HAZMAT	Number of Hazmat cars involved in the derailment	0	105
Derail	Number of derailed Hazmat cars	0	17
Released	Number of Hazmat cars which released contents	0	12
Evac	Number of people evacuated due to Hazmat release	0	0
TrkDmg	Reported cost of track damages	$ 0	$ 3,704,500
Dead	Number of people who died due to the derailment	0	2
Injured	Number of people injured in the derailment	0	0
TotCost	Total reported cost of the derailment (EqpDmg + TrkDmg)	$ 10000	$ 5,218,829
NormCar	Number of non-Hazmat cars involved the derailment (Cars – HAZMAT)	0	137
NormDerail	Number of non-Hazmat cars involved in the derailment (DerailCars – Derail)	0	45

Before the analyses were run, several variables were removed due to a lack of information, such as Evac and Injured, which were zero for all values and as such, would have no impact on the regression analysis. The regression analyses were run using SAS, a statistical software package. The code used to run these regression analyses is located in Appendix E. After running the first analysis, it was determined that all of the variables, except Derail and NormDerail, did not contribute significantly to the regression. The next set of regressions used these two variables to determine the impact of the inclusion of an intercept variable. The results of these two regressions are shown in Table 12 and Table 13. The full results of all of these regression analyses is located in Appendix F.

Table 12: Results of Regression Analysis with Intercept

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	-181,325	65829	-2.75	0.0074
Derail	104,502	23608	4.43	<0.0001
NormDerail	77,227	5377	14.36	<0.0001

Table 13: Results of Regression Analysis without Intercept

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Derail	90,669	24,059	3.77	0.0003
NormDerail	67,999	4,386	15.50	<0.0001

These results show that when applied to derailments with very few cars derailed, using the regression values that include the intercept returns negative values, which is nonsensical given the application. From these results, a new Hazmat factor of 1.33~1.35 was created based off of the ratio of the Parameter Estimates of the cost of a derailed Hazmat car compared to the cost of a derailed non-hazmat car.

In order to develop a new weighting factor for passenger operations, a cost-benefit analysis utilizing the Value of Statistical Life was completed. A Value of Statistical Life (VSL) is calculated using multiple methods; one method used the expected wages while another is based on the amount that a person is willing to pay for a specified reduction in risk. For the year of 2012, the United States Department of Transportation identifies $9.1 Million as the VSL to be used [5]. As this VSL is for an actual life, not an injury, a set of weighing factors based on the severity of injury was used to project the estimated cost of an injury. This set of weighing values come from [6] and are specifically the weights for transferring from an unknown injury severity to the Abbreviated Injury Scale (AIS) that is used by the National Highway Traffic Safety Administration. An issue with using this scale is that it is designed for use with automobiles and not railways; due to limited information on the severity of railway injuries, it was decided that using this information instead of generating factors based on limited information would be acceptable, as long as it was mentioned. Future work that investigates the actual severity of injuries due to railroad incidents should be able to be integrated into this analysis and better results can then be generated.

The data used in generating the average cost, number of fatalities and injuries and number of incidents was sourced through the FRA's Train Accidents by Cause [4] from January 2002 to December 2012. This data, like the previous data from the FRA, does not include the cost of injuries or fatalities; only the reportable damages to track and equipment are provided. A portion of this data is reproduced in Table 14.

Table 14: FRA Reported Ballast-Related Incidents for 2002~2012

Cause	# of Incidents	Total Cost	Average Cost	Fatalities	Injuries
T001- Roadbed settled or soft	267	$42,093,946	$157,655	0	17
T099- Other roadbed defects	31	$7,639,850	$246,447	0	1
T101- Cross level of track irregular(joints)	288	$23,644,948	$82,101	0	1

Table 14 Continued

Cause	# of Incidents	Total Cost	Average Cost	Fatalities	Injuries
T102- Cross level track irreg.(not at joints)	290	$48,758,650	$168,133	0	3
T103- Deviate frm uniform top of rail profile	38	$5,432,510	$142,961	0	0
T104- Disturbed ballast section	7	$211,714	$30,245	0	0
T105- Insufficient ballast section	8	$800,252	$100,032	0	0
T106- Superelevation improper, excessive,etc.	49	$6,652,976	$135,775	0	0
T107- Superelevation runoff improper	6	$675,574	$112,596	0	0
T108- Trk alignmnt irreg-not buckled/sunkink	165	$27,983,423	$169,597	0	1
T109- Track alignment irreg(buckled/sunkink)	331	$138,037,018	$417,030	6	141
T199- Other track geometry defects	123	$30,464,267	$247,677	1	46
Total	1603	$332,395,128	$207,358	7	210

From the incident data, the dominating impact of Buckle/Sunkink derailments was noticed; it accounted for ~85% of fatalities, ~67% of injuries and 42% of the total cost for only occurring about 20% of the total number of incidents. A possible reason for this behavior is that buckles/sunkinks are harder to detect; they don't result in broken rails which can break the signal circuit and are not picked up by existing defect detection measures as they are not the result of an actual defect. This results in trains either having to attempt to stop within sight distance or the buckling occurs as the train passes over the track, both of which results in trains traveling through the buckled track while at speeds exceeding the safe limit more often than with other defects that can be detected. As this results in incidents that have higher initial kinetic energy, more damage to the track and equipment is to be expected. This lead to an adjustment in the calculations for the weighting factor; another factor was generated for areas where buckle risk is the dominating derailment cause. Table 16 on page 45 shows the calculations for the estimated average cost for a single injury/death. The sum of the weighted costs is $175,925.76; this corresponds to the estimated cost of an unknown injury/fatality occurring. In order to generate the weighting factors, several analyses were run in order to properly represent the contributing factors. The analysis which was used looked at the "rate of injury" (RoI), which was the rate at which any injury or fatality occurred per incident, the expected cost associated with an unknown injury/fatality and the equipment and track damages cost. As this analysis is focused on the safety of the passengers, the percentage of the total cost that accounted for passenger injury costs was used in calculating the weightings. As shown in Table 15 and in more detail in Appendix G, the analysis used three conditions: No Buckle/Sunkink, which is a hypothetical high-passenger-safety condition as the Buckle and Sunkink data was not used in those calculations, Average, which is representative of the average of all of the data, and Only Buckle/Sunkink, which is a hypothetical low-passenger-safety condition.

Table 15: Calculations for creating a Passenger Weighting based on estimated cost of injury/fatality.

Case	Estimated cost of an Injury/Fatality	Estimated cost of an Injury/Fatality per incident	Track and Equip Damages	Total Estimated Cost
Average	$175,925	$23,815	$207,358	$231,173
Buckled/Sunkink	$296,088	$131,495	$417,030	$548,525
No Buckle/ Sunkink	$144,092	$7,929	$152,797	$160,726

Table 15 Continued

Case	Injury/Fatality % of Total	Normalized to No Buckle/Sunkink
Average	10.3%	2.088
Buckled/Sunkink	24.0%	4.859
No Buckle/ Sunkink	4.9%	1

From this analysis, the percentage of the total cost that injury/fatality take up for the safest case is approximately five percent while the worst case (only Buckle/Sunkink) has an injury/fatality costs taking up approximately twenty four percent of the total cost. When normalized to the safest case, the average case results in a weighting factor of approximately two and the worst case results in a weighting factor of approximately 4.9.

Table 16: Calculation of the estimated cost for an injury/fatality

	AIS 0	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	Fatality
Occurrence of Severity per Unknown Injury	0.21538	0.62728	0.104	0.04817	0.00617	0.00279	
Estimated Rate of injury/fatality per incident	0.02821	0.082176	0.013624	0.03858	0.00442	0.01034	0.004366
Adjustment to include fatality as a potential from each incident.	0.21363	0.622204	0.103158	0.047780	0.00612	0.002767	0.004331
Cost ratio from VSL	0	0.003	0.047	0.105	0.266	0.593	1
Cost per injury/severity level in 2012 dollars	0	27,300	427,700	955,500	2,420,600	5,396,300	9,100,000
Weighted Estimated cost for an injury in 2012 dollars	0	16,986.19	44,120.91	45,654.04	14,814.26	14,933.86	39,416.47

2.6 Adjustment to Method of Calculating Ballast Section Volumes for Ballast Weighting Factors

In the original analysis using the one-mile segments, the Section factors were applied to sections that were constructed from a set number of consecutive segments. This results in sections with varying initial ballast volumes and resulted in few changes in the rankings. This method ignores the limitations on ballast deliveries; changing the ballast delivery consist to suit each and every section would induce expenses that do not need to be included. As an alternative, a method of section creation based on the initial missing ballast volume was created.

This method uses a user-defined value for the limit of total ballast able to be dispersed and then computes the segments that are included in each section. From the first segment, the section calculates the sum of the section and, if the result is less than the defined volume, adds that segment to the section group. If the result is higher than the defined volume, it creates a new section starting with that segment. In the special case that a single segment contains enough missing volume to warrant at least an entire delivery of ballast, it is defined as its own section.

In order to do a comparison analysis, the data from the second weighting analysis, which used 100 one-mile segments[4], was used as there was already ranking information computed for it. In order to group the sections, a limit to the volume of ballast missing was required; this limit was chosen arbitrarily at 15,000 cubic feet, approximately 5 car loads, but may be changed based on the volume available to be dispersed. The results of this analysis are shown in Table 17. The new method's

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4 The segment data is shown in Table 6 and 7 and is located in Appendix A's Electronic File, Sheet "2nd data set"

behavior is quickly obvious; the maximum change in ranking is +7 and more of the sections move around compared to the previous method's swapping of two pairs.

Table 17: Change in rankings for sections: Old vs. New method.

Old Method				New Method			
ID	Existing Rank	Modified Rank	Rank Change	ID	Existing Rank	Modified Rank	Rank Change
1-5	7	7	0	1-4	3	3	0
6-10	14	14	0	5-17	7	8	-1
11-15	19	19	0	18-32	4	5	-1
16-20	18	18	0	33-35	5	1	4
21-25	20	20	0	36-39	9	2	7
26-30	17	17	0	40-42	16	15	1
31-35	1	1	0	43-46	11	11	0
36-40	6	5	1	47-49	17	18	-1
41-45	4	3	1	50-53	8	9	-1
46-50	5	6	-1	54-56	12	12	0
51-55	3	4	-1	57-60	14	14	0
56-60	8	8	0	61-64	13	13	0
61-65	9	9	0	65-67	18	17	1
66-70	2	2	0	68-70	15	16	-1
71-75	11	11	0	71-76	1	4	-3
76-80	16	16	0	77-85	10	10	0
81-85	15	15	0	86-90	2	6	-4
86-90	10	10	0	91-96	6	7	-1
91-95	13	13	0	97-100	19	19	0
96-100	12	12	0				

2.7 Discussion of Results

The development of risk-based and cost-based factors which adjust the prioritization of ballast maintenance in favor of safer operations is an important aspect of railway safety. These factors help to improve the efficiency of ballast maintenance, providing better safety for the same volume of ballast replenished, which can provide significant savings to railroads in terms of fewer derailments.

The application of these weightings depend on several factors, of which the reliance that there are at least some segments and/or sections which do not have the same weightings applied as the rest. This is due to the fact that multiplying all segments/sections by the same factor will not produce any change in the rankings. A similar issue exists when the segments and/or sections have such a difference in volume between each other that applying the weightings results in no change to the rankings. As such, applications of these weightings which do not result in any change between initial and final rankings should have the data checked for these pitfalls.

The new factors are more variable than the previously developed ones; they depend on recent data which can result in fluctuations over time. In the case of the Passenger factor, while keeping the injury/fatality cost the same, decreasing the average equipment and rail damage cost results in a higher factor while increasing the average cost of equipment and rail damages results in a lower factor. The impact of changes on the VSL are more direct; keeping the average cost of rail and equipment damage the same, a higher VSL results in a higher factor while a lower VSL results in a lower factor. A similar situation exists with the Hazmat factor; if Hazmat-related derailments start to decline in cost relative to non-Hazmat derailments, the factor will decrease. As there exists the possibility that with new information these factors will change, care must be taken to ensure that these changes are in line with the expected trend; that is, if there occurs an odd year with many or few incidents, then calculations that use that year should be delayed until more information as to the reason for such behavior is found and analyzed.

Table 18: Original and Alternate Weightings

Weighting	Original Weighting	Alternative Weighting
Hazmat	1.25	1.35
Passenger (Normal Risk)	1.25	2.1
Passenger (High Risk)	1.25	4.9

Chapter 3

CORRELATION BETWEEN BALLAST DEFICIT AND DEFECTS

3.1 Objective

The objective of this research was to formally develop a relationship between the volume of deficits in the ballast profile and defects relating to track geometry, to confirm that defects that have been traditionally considered ballast-related are related to the volume of missing ballast and that defects which have traditionally been considered non-ballast-related are not directly related to the volume of missing ballast. In addition to these analyses, sub-analyses were run after completing the analysis into the relationship between the volume of ballast missing and the reported defects; these analyses looked at the general location of the missing ballast (shoulder vs crib) and if the segment was located on a curve or tangent. In order to develop the analyses which would test these hypotheses, two sets of data were required: the amount of missing ballast along various tracks and the corresponding list of defects for those locations. For this analysis, the ballast deficiency data was sourced from GREX and the track defects were asked for and received from BNSF.

3.2 Initial Work

The data for the volume of ballast missing consisted of information regarding the location, volume of missing ballast, if it was on a curve or not, length of the segment and date of collection. This data is located in Appendix H, with a portion of it located in the appendix itself and the full amount located on the electronic file. The ballast data consisted of 187,025 segments of approximately 50ft length for a total length of approximately 1,798 miles of track. In order to manage this data efficiently, grouping the data into ranges of missing ballast volume was done. The smallest grouping done was in 1 cubic foot increments; this range was chosen as it allowed the data to be used in multiple higher-level groupings without requiring added calculations to split the data; for example, if the initial groupings were of 2 cubic feet and a higher-level grouping was 9 cubic feet, the data would have to be recalculated in the 8~10 range in order to provide accurate information. A histogram of the volumes using 1 cubic foot groupings is shown in Figure 16 and a histogram of the same volumes using 50 cubic feet groupings is shown in Figure 17. As shown, there appears to be a trend in the frequency of the volume of missing ballast. This trend was not analyzed to any degree as the impacts of the trend, outside of resulting in higher variation in rates of defects in the range of high amounts of ballast missing, did not seem to have any importance in these analyses. A possible reason for this trend is that maintenance efforts are directed at areas with higher amounts of ballast missing, in a way similar to the topic discussed in the previous chapter.

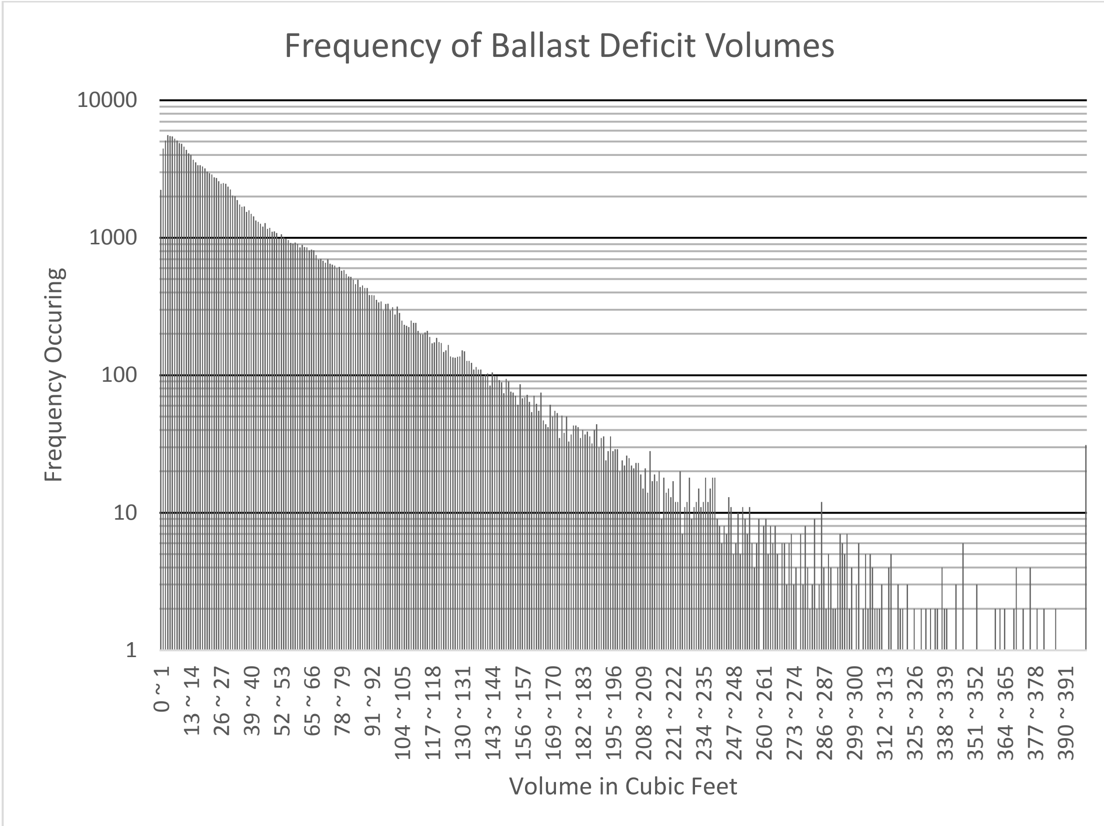


Figure 16: Histogram of Missing Ballast Volumes up to 400 cubic feet of missing ballast. Note: Y axis is in Log scale. The right-most column is the number of segments above 400 cubic feet.

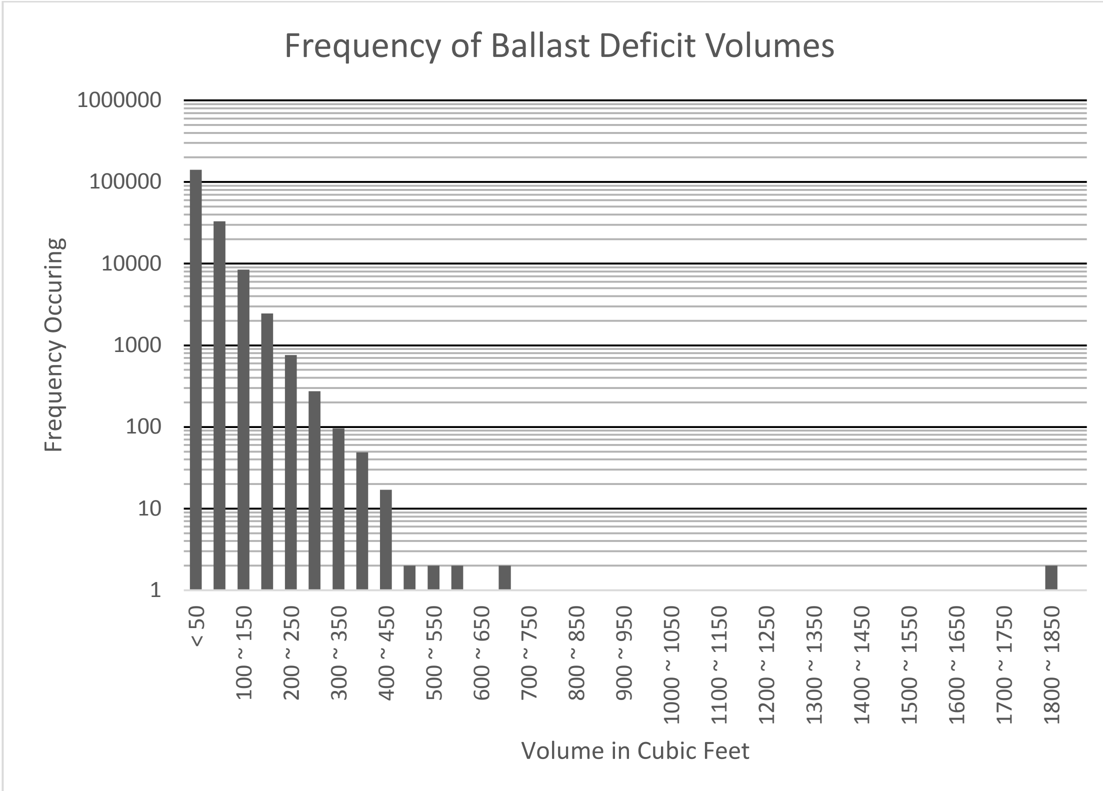


Figure 17: Histogram of Missing Ballast Volumes using 50 cubic feet grouping

The defect information consisted of the defect type, location as a milepost, amplitude of the defect, length of the defect and other pieces of information not used in the analyses completed in this discussion. Originally, there were 96 types of defects, a majority of which were Warp defects of varying degrees. As the warp defects were, for this analysis, equivalent, they were combined into one general “WARP” type in order to better represent themselves and simplify the calculations.

Table 19: Major Defect Types and their Groupings

Defect Type	Defect Grouping	Defect Information
XLEVEL	Ballast	A deviation from vertical profile as measured to the reference rail
GAGE	Tie	An error relating to the width of the track gage
DIP	Ballast	A variation in vertical track profile
WARP	Ballast	Warp is the difference between two cross-level defects in a specified interval
ALIGN	Ballast	A variation in lateral track profile over a specified interval
SURF	Ballast	A defect relating to the surface of the track
VHW	Rail	Vertical head wear of the rail
GFW	Rail	Gage face wear of the rail
CANT	Ballast, Tie	An unwanted rotation of the rail or superelevation on a curve
JOINTS	Ballast	Excessive, alternating-rail, cross-level in all six consecutive pairs of joints. A common cause of "rock and roll".
HOPPER	Ballast	An exception which has been identified as a common cause of hopper derailments. Essentially a Warp defect.
GWP	Tie	Gage Widening Projection

A graph of the top 15 most numerous defects after the combining of warp defects is shown in Figure 18.

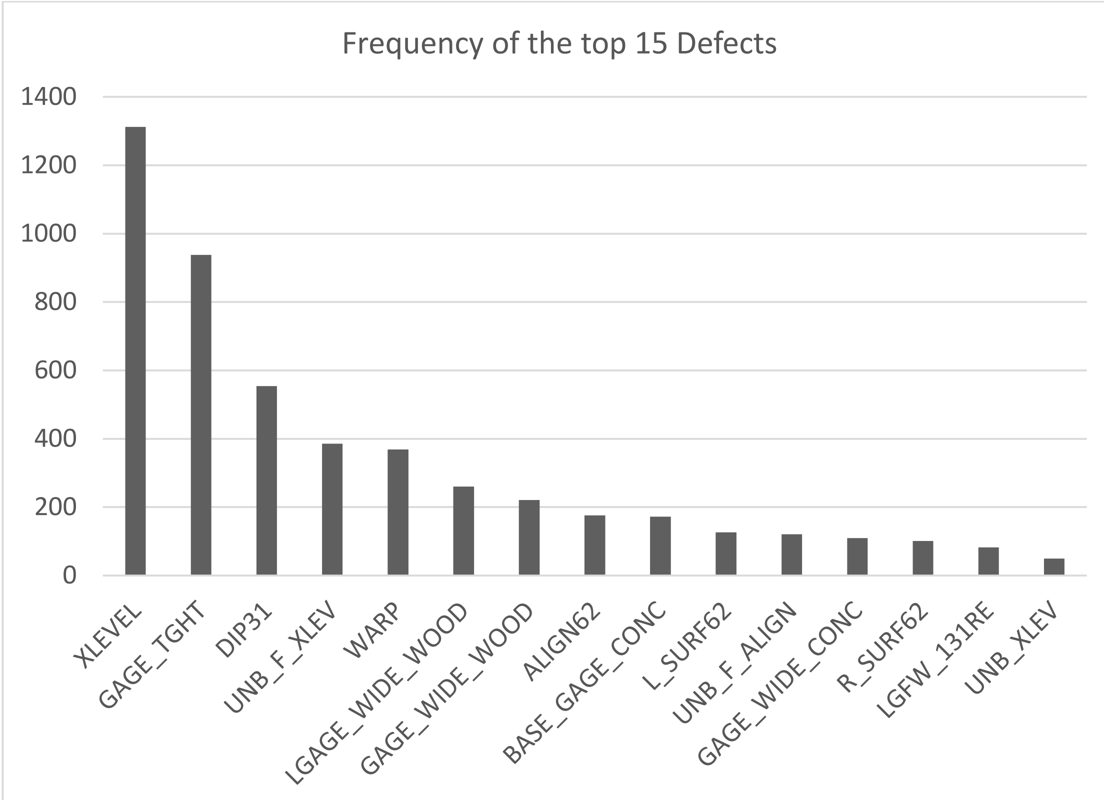


Figure 18: Frequency of the top 15 defects.

Some of these defects are labeled using terms which may not be representative of terminology used elsewhere so information on these defects, including several which are not in the top 15 shown in Figure 18, can be found in Tables 19 and 20 and a graphical representation of some of these defects can be found in Figures 19 through 22. For the actual defects used in the analyses, they were initially grouped according to their overall causation, ballast-related, tie-related and rail-related, as shown in Table 18; additional analyses focused on the top five individual defects. The grouping into ballast, tie or rail is based on the primary cause of the defect. The inclusion of Cant in both Tie and Ballast categories is based on the assumption that the cant defect is caused by a mixture of tie and ballast causes. Some of these base defects also had prefixes or suffixes attached to them; prefixes are shown in Table 20 while the suffixes are split between the interval distances, such as the case with DIP31 or the size of the rail, such as with LGFW_131RE.

Table 20: Defect Prefixes

Prefix	Defect Type(s)	Information
UNB	XLEVEL, ALIGN	Unbalance over 155ft caused by cross-level or alignment
UNB_F	XLEVEL, ALIGN	Unbalance over 155ft based on two inch unbalance design for freight trains
HARM	XLEVEL	Harmonic crosslevel defect; two cross-level defects which occur under a special set of circumstances.

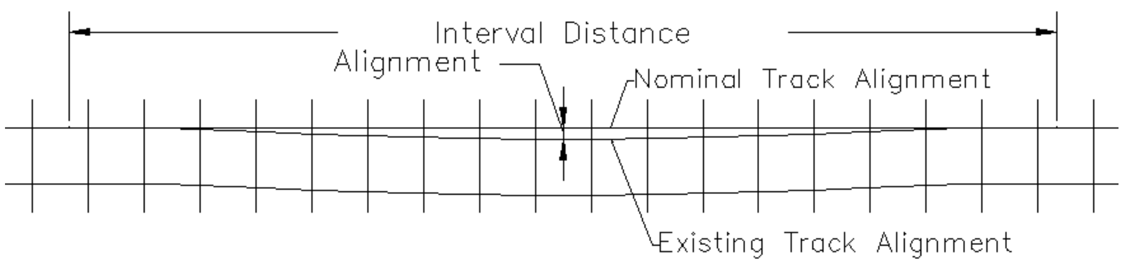


Figure 19: Alignment Defect

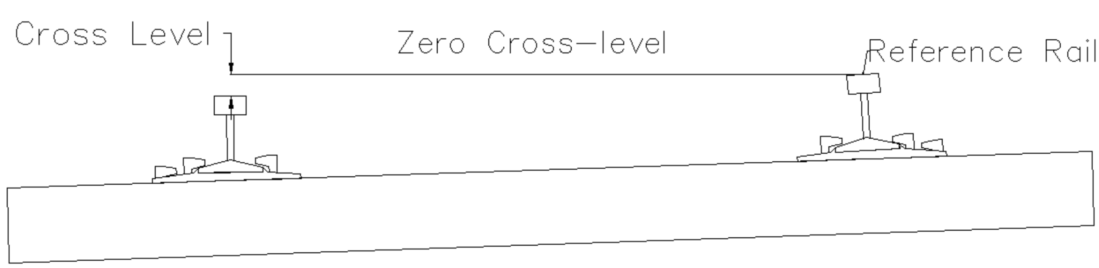


Figure 20: Cross-Level Defect

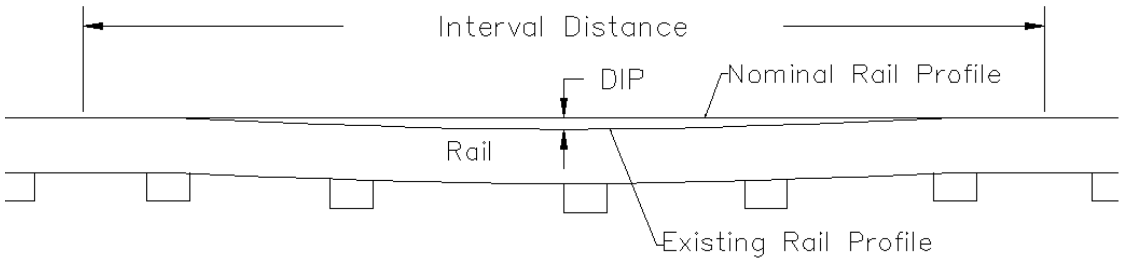


Figure 21: Dip Defect

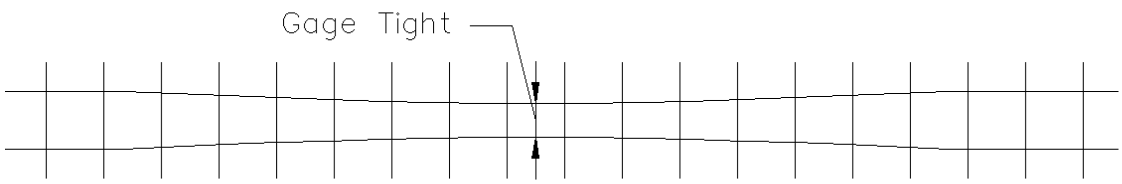


Figure 22: Gage Tight Defect

The initial work consisted of matching defects with their locations in the ballast data. This was accomplished through the use of conditional statements which checked to make sure that the track, division and line-segment matched exactly and that the defect's milepost was within the range of the ballast segment being examined. This method also matched based on defect name in order to provide a way to analyze the rates for each defect for future analyses. An example of the data used in matching the defects to the segments is shown in Table 21 and 22. As shown in this example, the cross-level defect located on Line Segment 4, Track 1 at Milepost 308.99 is matched to the ballast segment on Line Segment 4, Track 1, between MP 308.9894 and MP 308.9989 which is not on a curve.

Table 21: Example of Defect data

Line Segment	Track	MP	Defect Type
4	1	308.99	XLEVEL
4	1	330.84	DIP31
4	2	361.57	UNB_F_XLEV

Table 22: Example of Ballast data

Line Segment	Track	Start MP	End MP	Volume	Curve
4	1	308.9894	308.9989	167.208978	N
4	1	308.9989	309.0084	130.054594	R
4	1	309.0084	309.0178	106.212778	N

Initially, the calculations were focused on the number of defects per segment and used the function "SUMIFS", mentioned previously. 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 rate of defective segments that was actually representative of the rate of defects in a population of segments. As the analysis is focused on the rate of defective segments in a population of segments, having the same defect counted multiple times would result in an over-estimation error; this resulted in the calculations being redone using "COUNTIFS", a conditional counting function in Excel. By changing "SUMIFS" to "COUNTIFS", the function added a 1 instead of the actual value if there was a value and the conditions were satisfied. This change resulted in conservative estimates as a result of the analysis, as shown in Figure 23. The rates of defective segments for each grouping was calculated based on the formula shown in Equation 11.

(Number of Defective Segments within grouping range)/(Total Number of Segments within grouping range) = Rate of Defective Segments for grouping range Eq. 11

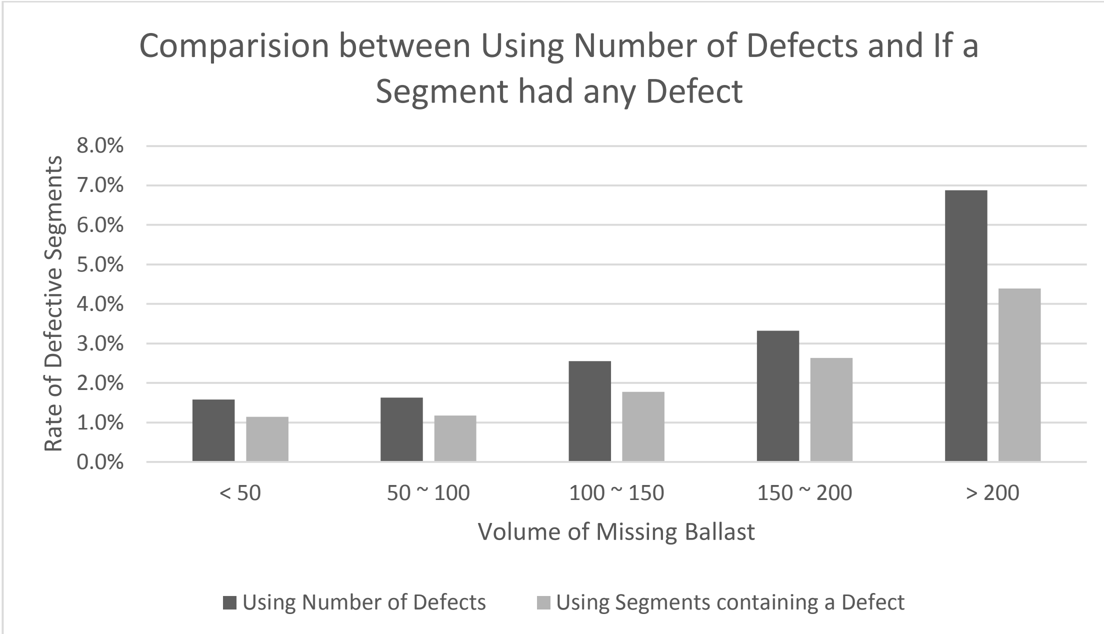


Figure 23: Comparison between using Number of Defects and If a Segment had a Defect in calculating the rate of Defective Segment

Once this initial matching was done, a determination of the appropriate grouping size was done. First, the use of a grouping of 1 cubic foot was used in order to provide a basis for future grouping attempts. The next part was to determine the size of the higher-level groupings, as the 1 cubic foot grouping had issues with the results due to the low number of segments at the higher end of missing ballast. The application of higher-level groupings would allow the range of results to be extended by averaging the rate across the segments within the range. Three higher-level groupings were created; a 10 cubic foot grouping, a 25 cubic foot grouping and a 50 cubic foot grouping. As shown in Figure 24 through 27, the range of low volume of missing ballast range had each of the groupings around the same value. As the volume of missing ballast increased, the rate had an upward trend though there was increasing amounts of variation in the data for decreasing size of the grouping. This variation is a direct result of the lower number of segments at the higher range of missing ballast.

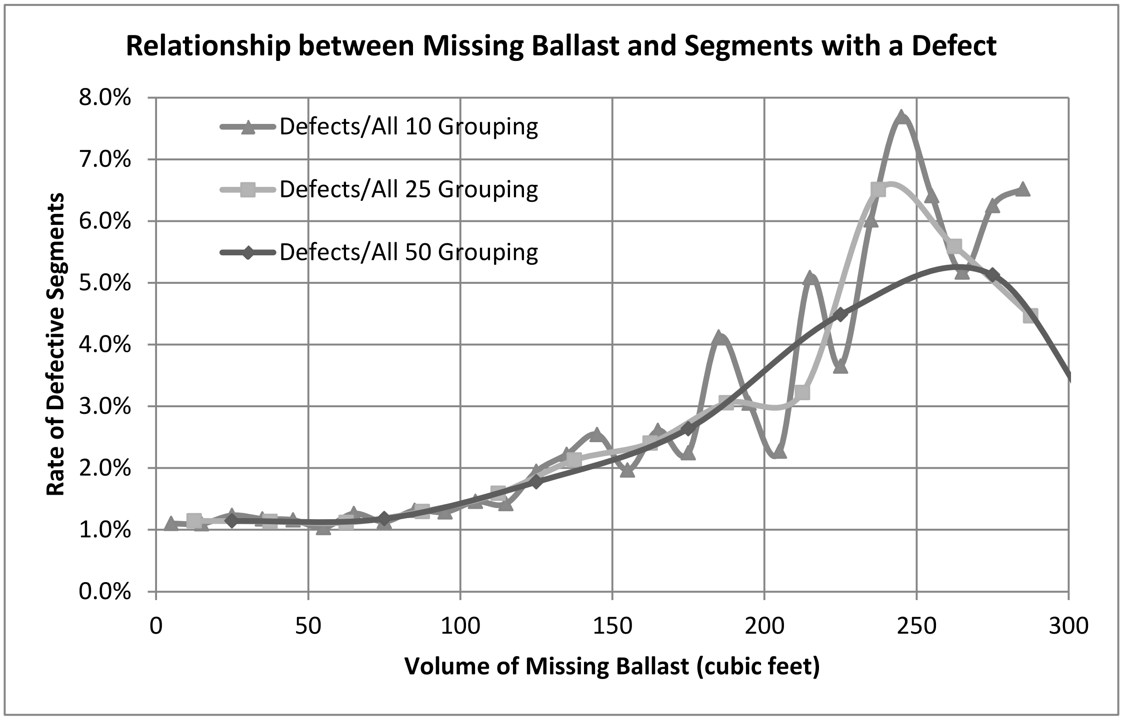


Figure 24: Variations in Rate of Defective Segments for three volume groupings

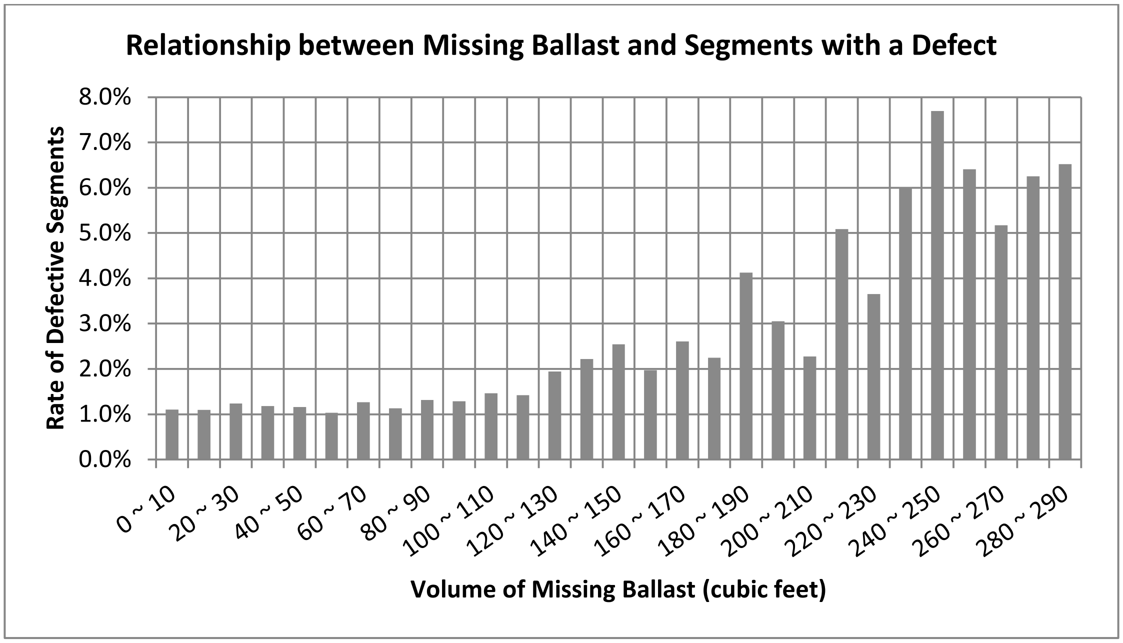


Figure 25: Rate of Defective Segments using 10 cubic feet groupings

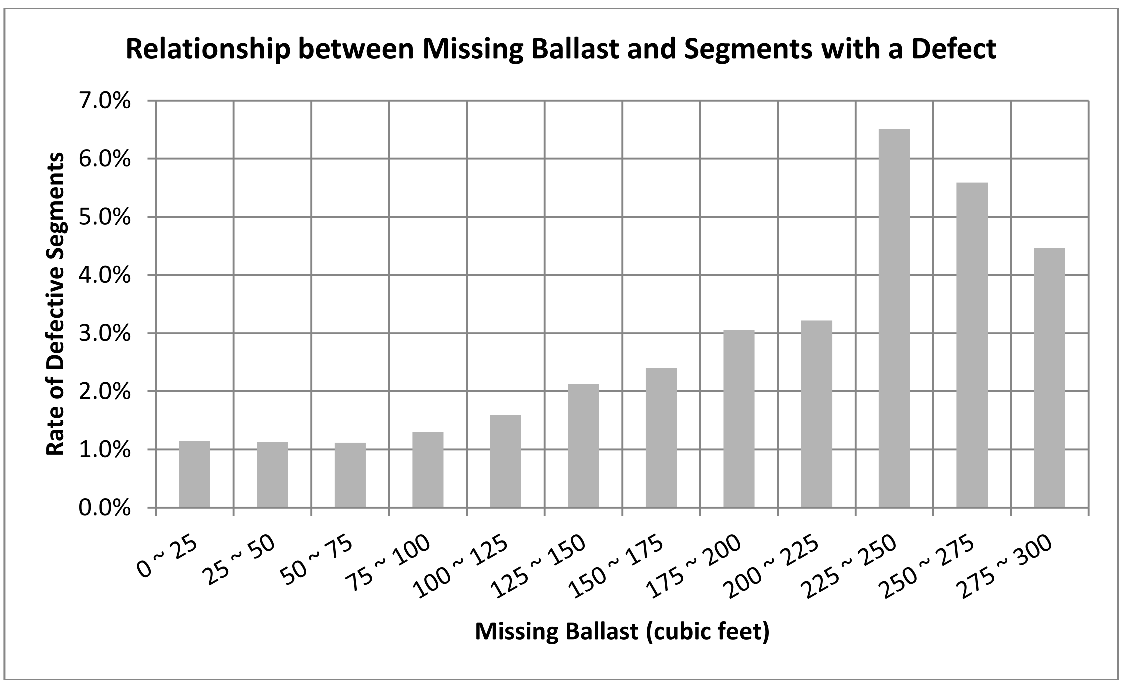


Figure 26: Rate of Defective Segments using 25 cubic feet groupings

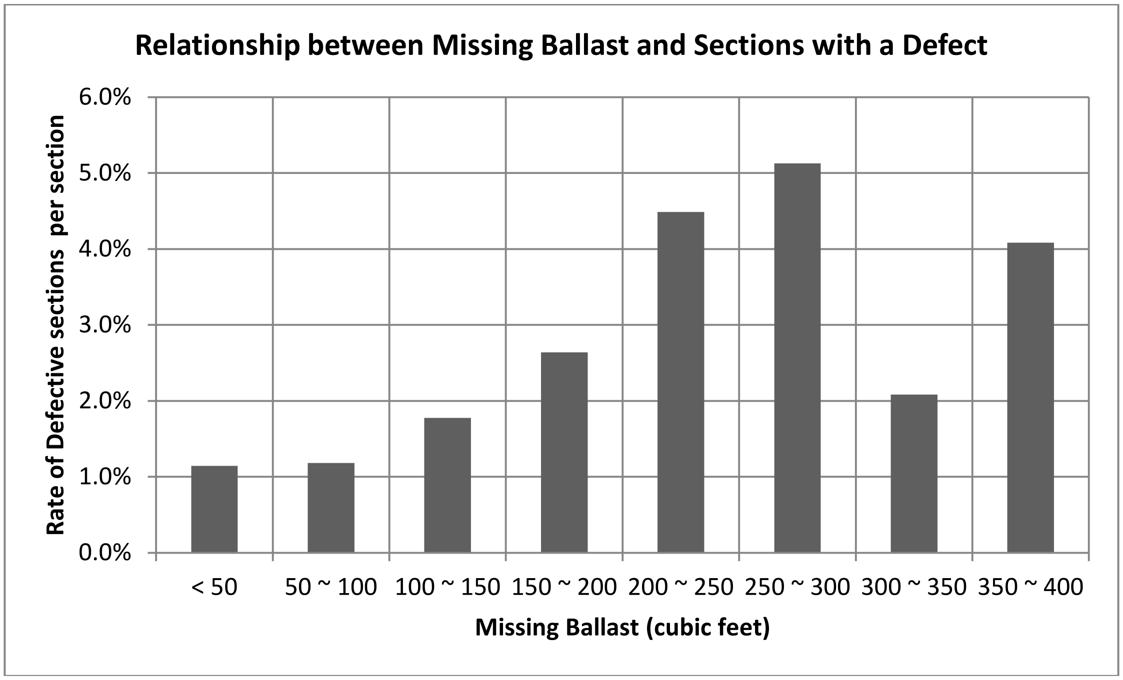


Figure 27: Rate of Defective Segments using 50 cubic feet groupings

The next adjustment to the data was the development of a "catchall" grouping to provide a reasonable result for the highest range of missing ballast volume. Initially, there was no catchall and the range of data continued until the first grouping which either had an error, such as divide by zero, or was zero, that is, there were no defects in the entire grouping, resulted in the plotting of zero values. This resulted in data showing odd trends, such as a peak followed by a fall in the rate of the defective segments as shown in Figures 24 through 28.

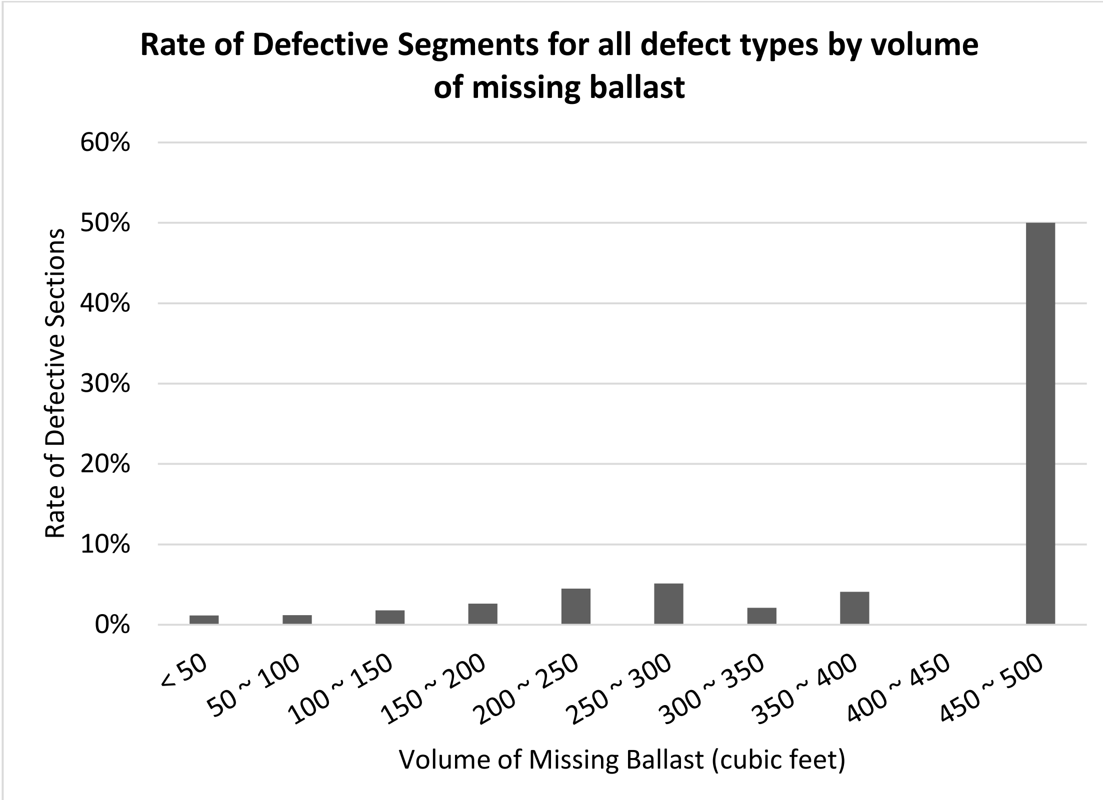


Figure 28: Rate of Defective Segments for all defects without a catchall grouping.

This is also the reasoning behind the use of a catchall for missing volumes above 200 cubic feet. If such a catchall was not used and the actual rates were given, there would be incredibly higher rates of defective segments, such as the 50% shown in Figure 27, due to there being one defective segment out of two known segments. The results of applying a catchall for volumes greater than 200 cubic feet is shown in Figure 29.

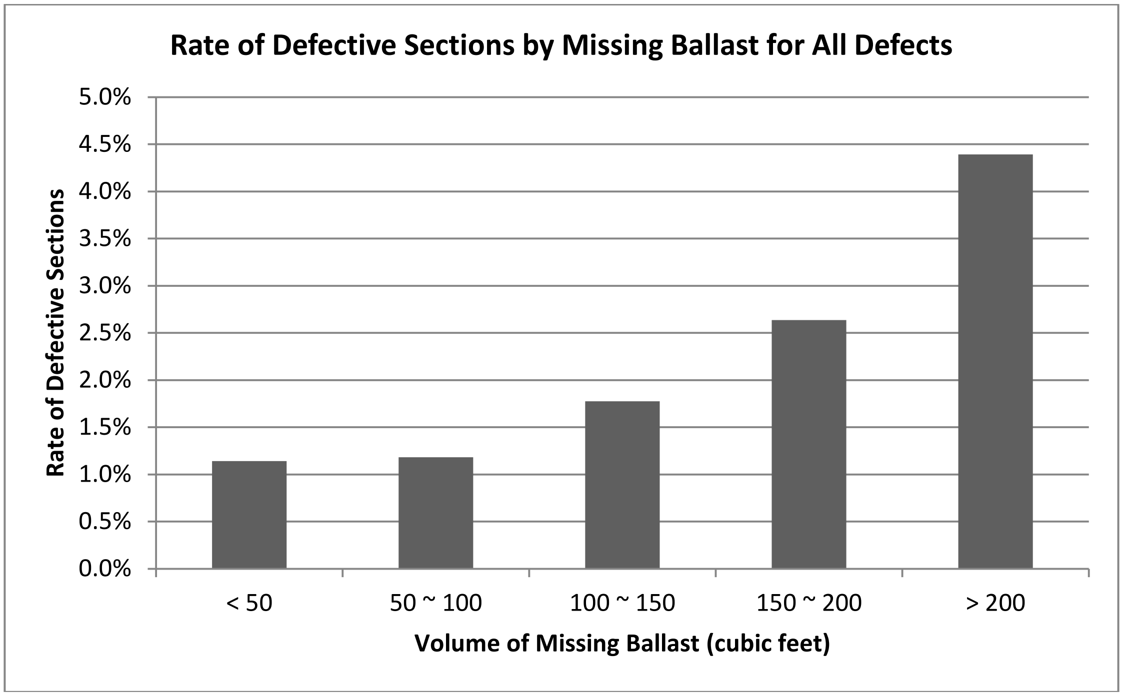


Figure 29: Rate of Defective Segments by Missing Ballast for all defects.

In order to fill out the volume groupings which do not have any defects and appear as anomalies in the data, increasing the amount of data received, such as by adding data from other railways, can fill out the gaps in the higher end of the volume range and as well as allow the use of the smaller grouping which may increase the accuracy of any predictions.

Before going into the results of the analyses, summery statistics are provided in Table 23. The matching rate is the rate at which defects were able to be successfully matched to the correct segment of missing ballast. Overall, there was about a 54% matching rate for all defects to the correct ballast segments; some individual defects had higher rates (~75%) while others were not matched at all. This is due to multiple issues, such as the ballast data only covering a fraction of the network that was used in gathering defect data and there only being one or two reported defects of a given type. As this is caused by limitations in the data collected, future efforts on this topic should look at minimizing these gaps in order to present a better analysis.

Table 23: Summary Statistics of Defect Matching

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 (Feet)	50.76
Average Missing Ballast Volume (Cubic Feet)	35.29
Maximum number of defects occurring in a segment	10
Maximum number of the same defect occurring in a segment	9

The initial result is the total rate of defective segments for all defects. This is shown in Figure 29. The general trend of increasing volume of missing ballast resulting in an increase in the rate of defective segments is prevalent. As shown in Figure 30, this result is primarily the result of the ballast-related defects which account for a majority of the defects present in the data.

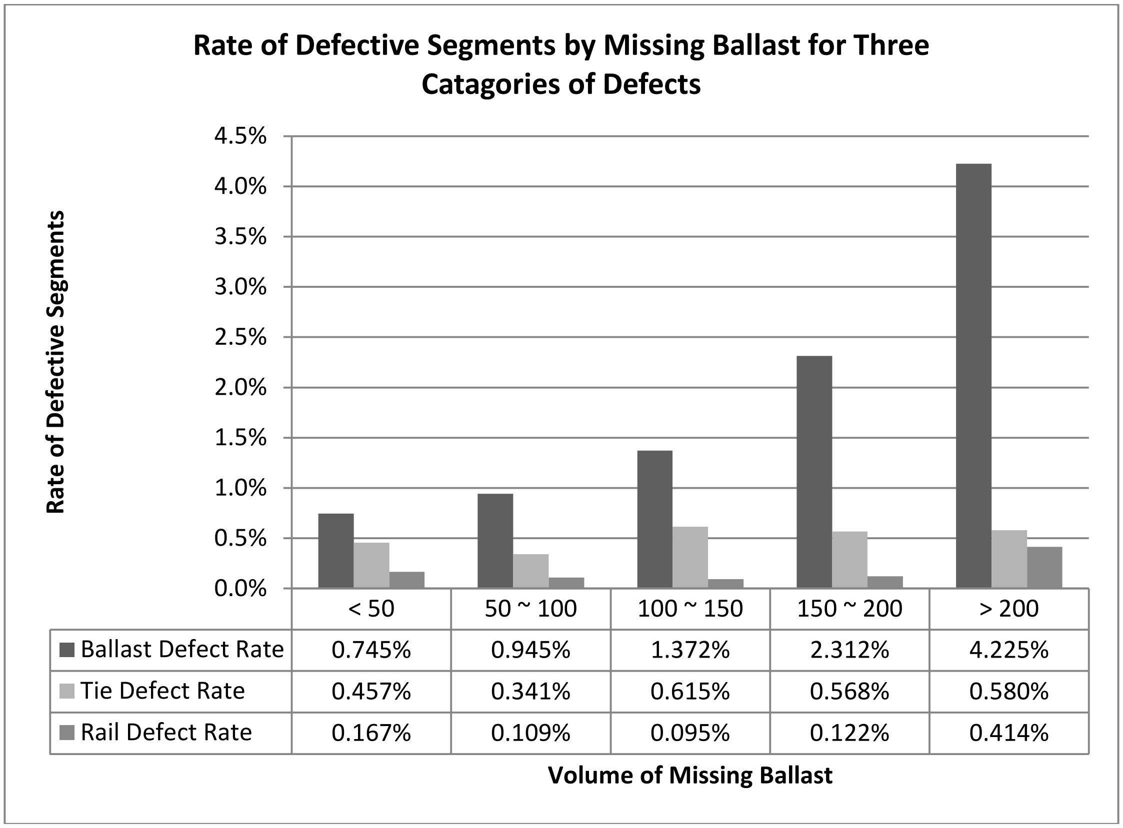


Figure 30: Rate of Defective Segments by Missing Ballast for the three categories of defects.

This initial result prominently shows that the rate of ballast-related defects is positively correlated to the volume of missing ballast and that this relationship is non-linear. As shown, there is a modest increase in the rate of ballast-related defects between the less than fifty cubic feet grouping and the fifty to one hundred cubic feet grouping followed by an almost exponential growth in the defect rate for the next three groupings. This behavior is most likely due to the missing ballast not being present in the right area to influence the rate of defective segments; with higher amounts of missing ballast, there is a greater chance that the missing ballast is located in an area which influences the rate of defective segments. The actual location(s) which influence the rate of defective segments is not directly known at this time; that is to say, the impact on the rate of defective segments that a missing cubic foot of ballast has depending on its location is not well known.

The rather steady rate of Tie Defects, holding steady around 0.5%, shows that they are most likely not directly related to the volume of missing ballast. The action of Rail Defects, starting at a relatively high rate which then drops as the volume of missing ballast increases and then rises to a new high at the end, suggests that Rail defects are not directly related to the volume of missing ballast. The high value at the end may be explained away by the relationship between high values of missing ballast and rail defects being related through a common factor; in this case, the rate of maintenance efforts.

The effect of missing ballast on the rate of defective segments for the top five defects was also analyzed. As shown in Figure 31, cross-level defects occur at a rate of approximately one half to one third of the higher-level grouping of all ballast-related defects. The trend is also similar, showing a positive relationship between missing ballast and the rate of defective segments.

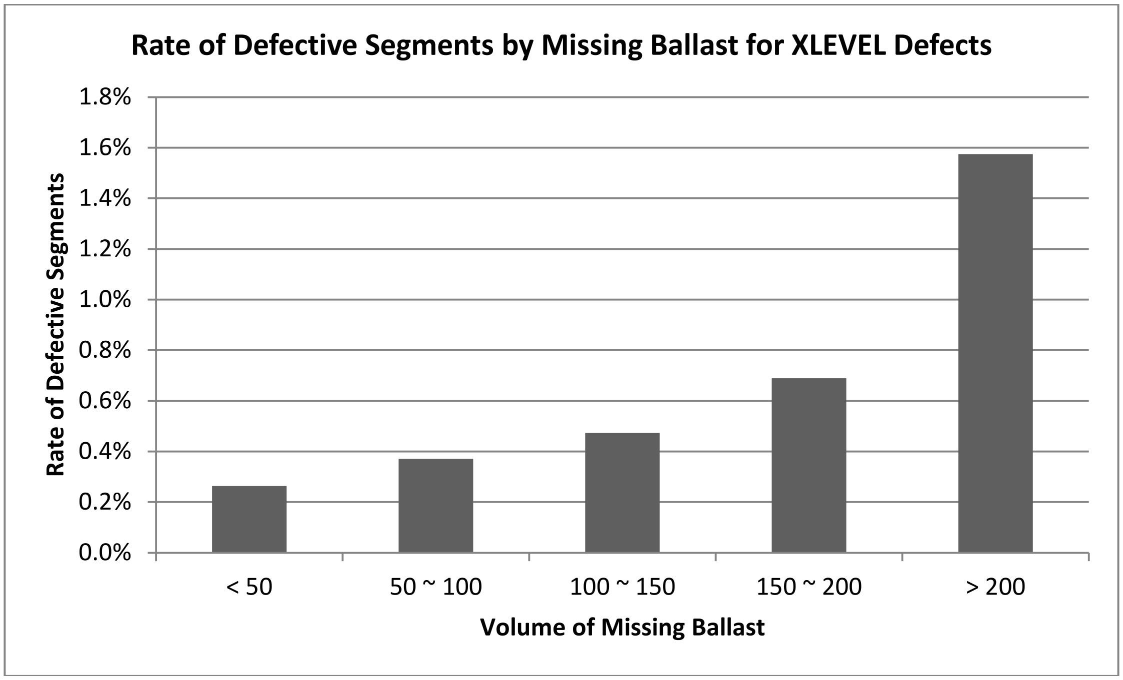


Figure 31: Rate of Defective Segments by Missing Ballast for Cross-level defects.

As shown in Figure 32, Gage Tight defects do not appear to have a reliable trend in the rate of defective segments. This shows that gage tight defects are not positively or negatively related to the volume of ballast missing.

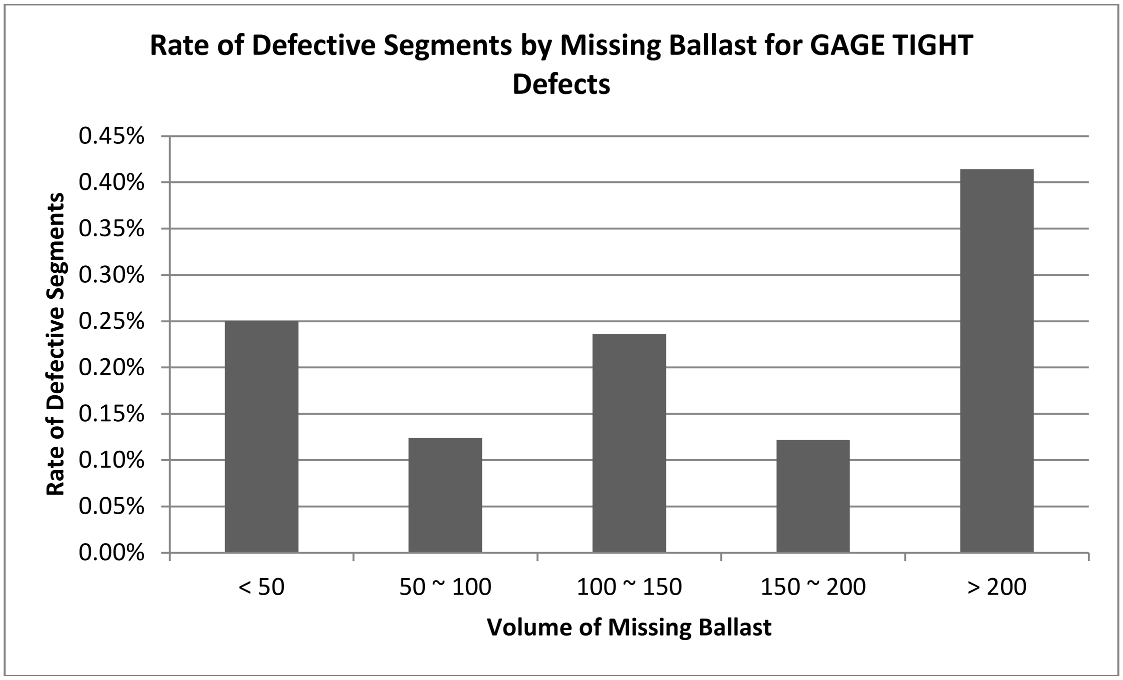


Figure 32: Rate of Defective Segments by Missing Ballast for Gage Tight defects

As shown in Figure 33, the rate of Dip31 defective segments remains within the range of 0.1% to 0.14% until the volume of ballast missing exceeds 200 cubic feet, at which point the rate of defective segments approximately triples. This trend of the Dip31 defective segments can be attributed to a threshold effect similar to the situation mentioned concerning the rate of defective segments for ballast related defects in the less than fifty and fifty to one hundred groupings.

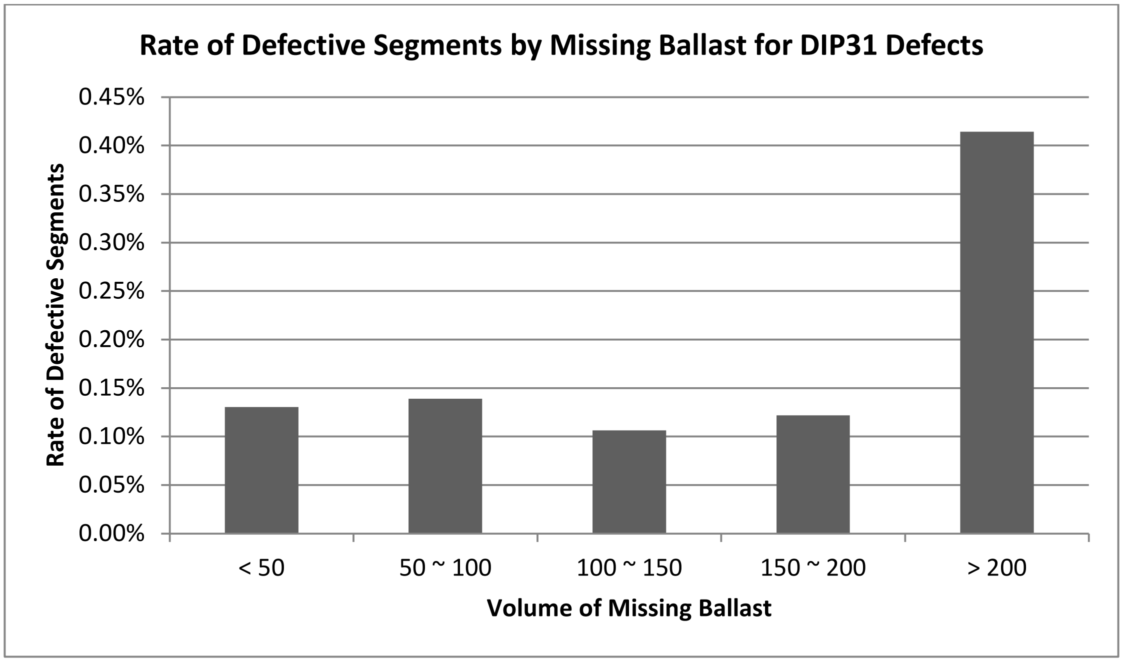


Figure 33: Rate of Defective Segments by Missing Ballast for Dip31 Defects

The rate of defective segments containing an unbalanced freight cross-level defect has a similar trend to the previous cross-level defect shown in Figure 31 but occurs at a lower rate. As both of these defects are nearly identical, with the major difference being that cross-level occurs on tangent track and unbalanced cross-level occurs on curved track, this result is to be expected.

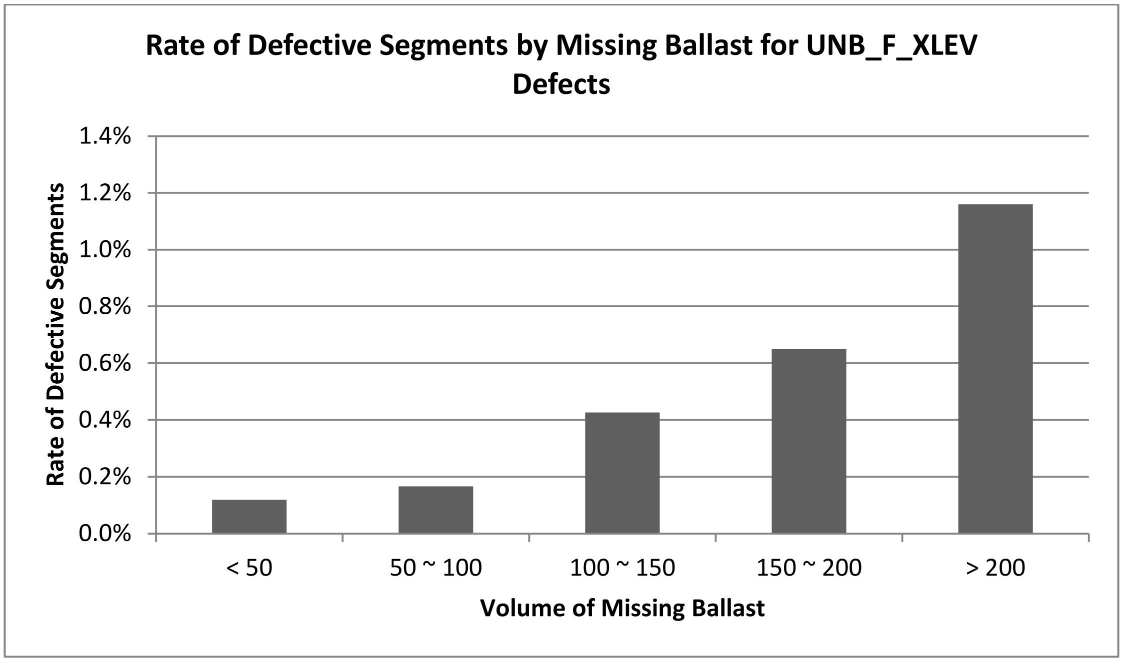


Figure 34: Rate of Defective Segments by Missing Ballast for Unbalanced Freight Cross-level defects.

As with the previous comparison between unbalanced freight cross-level and cross-level, warp defects are created by a pair of cross-level defects and as such, exhibit behavior that is similar to the standard cross-level defect but at a lower rate. This lower rate is due to the requirement that the two cross-levels must be within a certain distance and that their difference is significant enough to be categorized as a warp defect.

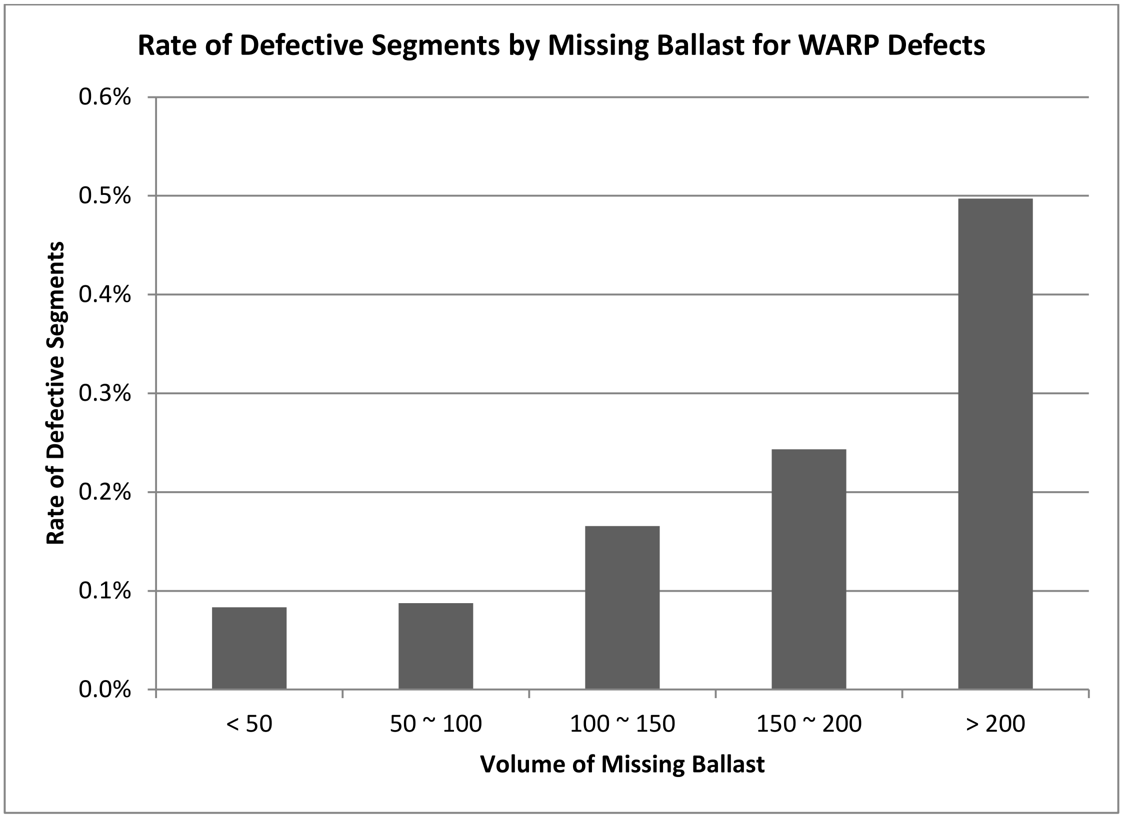


Figure 35: Rate of Defective Segments by Missing Ballast for Warp Defects

The next analysis looked at the impact that a curve will have on the rate of defective segments for ballast-related defects. As shown in Figure 36, the rate of defects on a curve follows a steady trend upwards with increasing volumes of missing ballast. The rate of defects on a tangent follow a lower steady rate until the highest volume of missing ballast, which causes the rate to jump up to the same level as curve-based defects. This behavior applies when looking at the complete group of ballast defects but does not always hold true for the individual defects

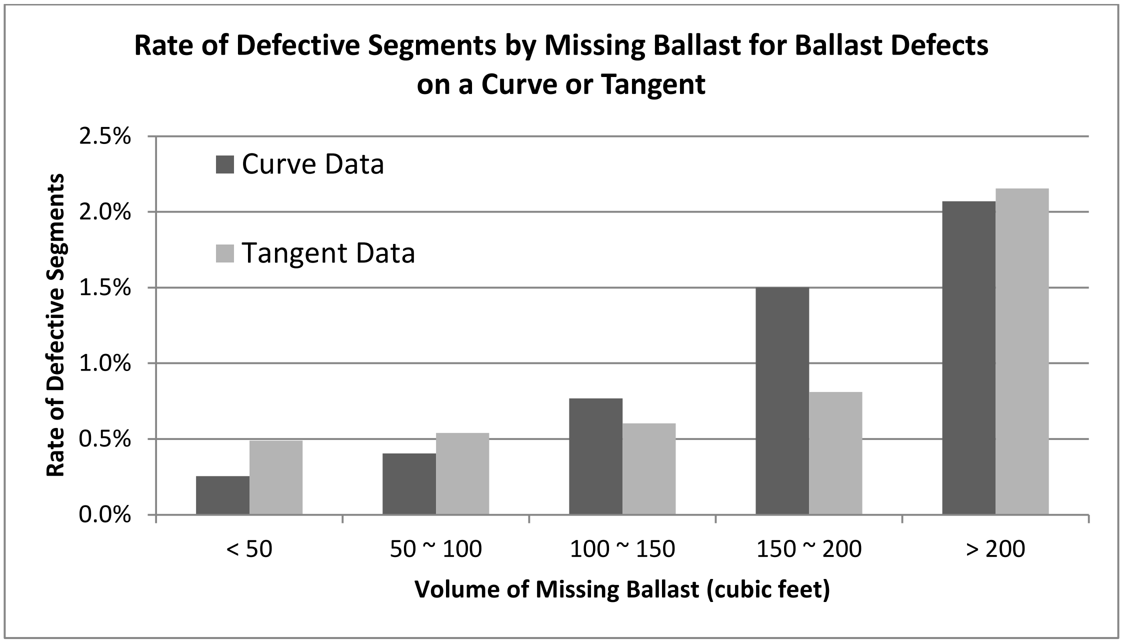
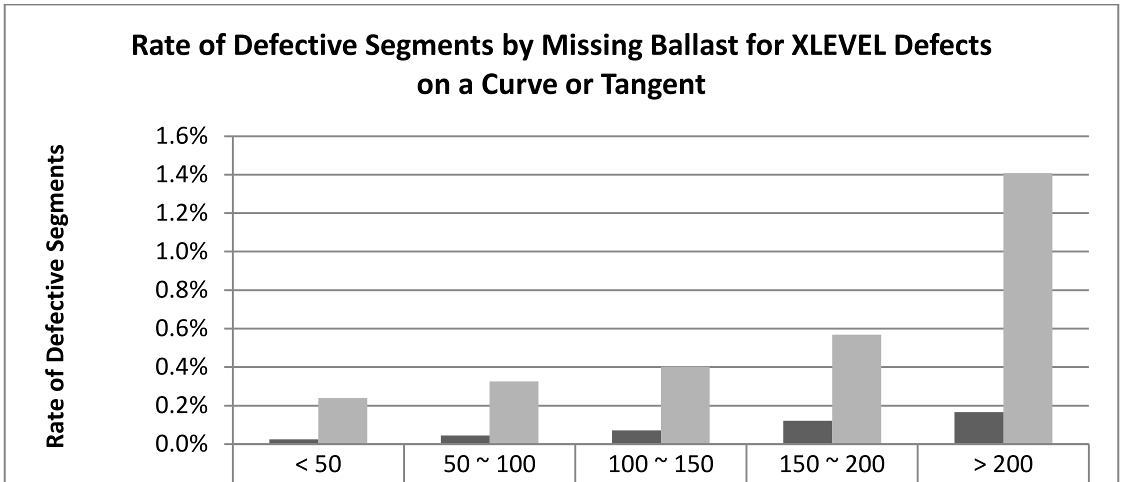


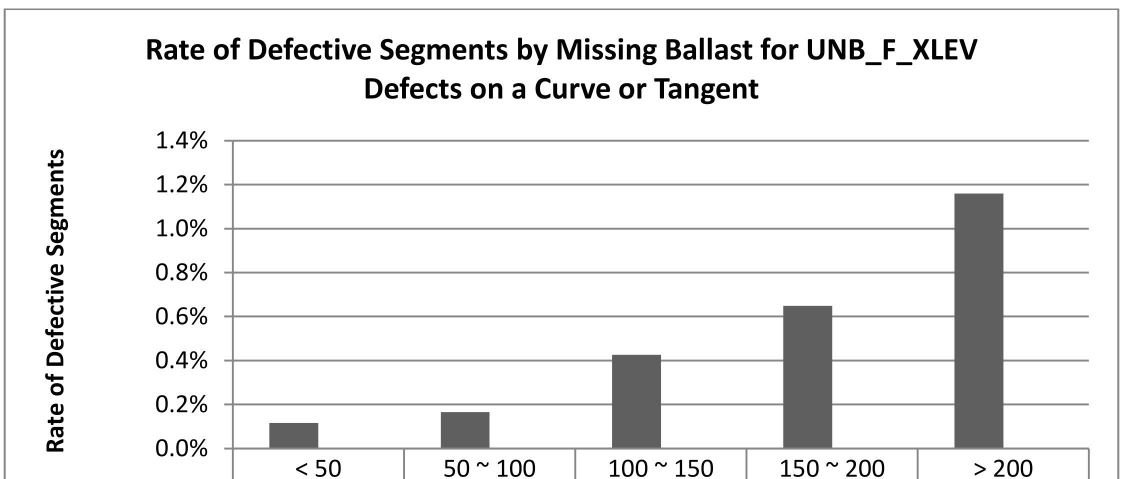
Figure 36: Rate of Defective Segments by Missing Ballast for Ballast-related defects on Curve and Tangent segments.

For cross-level and unbalanced cross-level, Figures 37 and 38 respectively, there is a clear difference between their behavior based on the existence of a curve. Cross-level has some existence on curves, perhaps due to these cross-levels not yet having the magnitude to be considered an unbalanced cross-level. Unbalanced cross-level, by definition, exists only on curves; the sole tangent segment is presumably due to an error in data collection.



	< 50	50 ~ 100	100 ~ 150	150 ~ 200	> 200
Curve Data	0.025%	0.045%	0.071%	0.122%	0.166%
Tangent Data	0.239%	0.326%	0.402%	0.568%	1.408%

Figure 37: Rate of Defective Segments by Missing Ballast for Cross-Level Defects on a Curve or Tangent



	< 50	50 ~ 100	100 ~ 150	150 ~ 200	> 200
Curve Data	0.116%	0.166%	0.426%	0.649%	1.160%
Tangent Data	0.003%	0.000%	0.000%	0.000%	0.000%

Figure 38: Rate of Defective Segments by Missing Ballast for Unbalanced Freight Cross-Level defects on a Curve or Tangent

The behavior of the tight gage defect, shown in Figure 39, is interesting, as it should not be related to volume of missing ballast but appears to have a slight negative relationship for Tangent data while Curve data follows what appears to be a positive relationship. Due to this odd behavior, more research should be done to determine if this behavior is normal or a unique result due to the data used in the analysis.

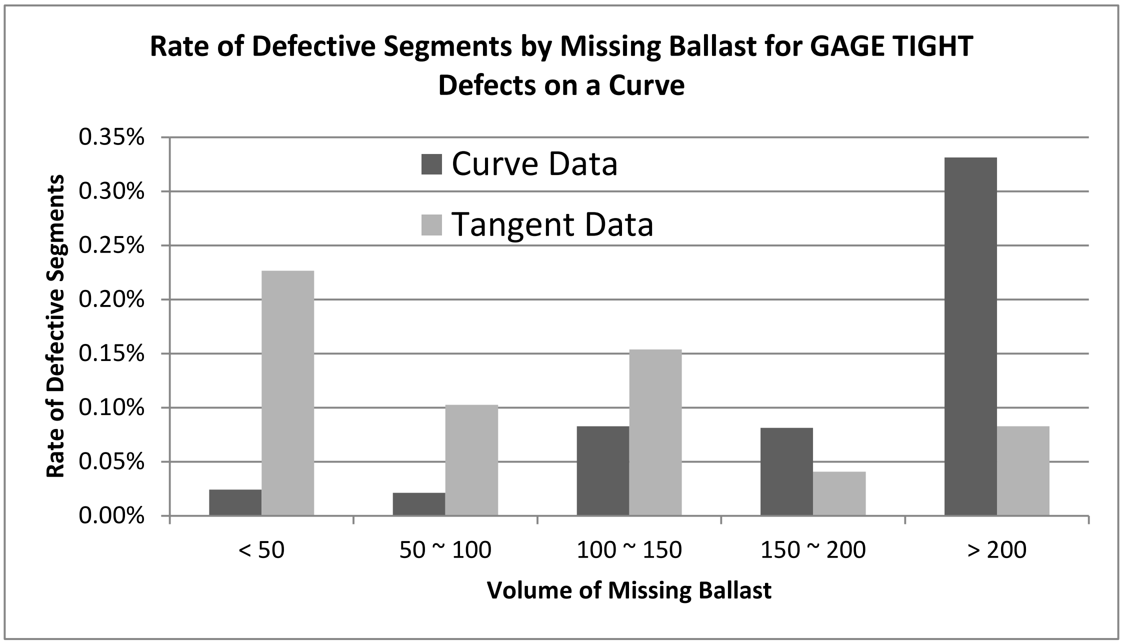


Figure 39: Rate of Defective Segments by Missing Ballast for Gage Tight defects on Curve or Tangent

Dip31 defects, shown in Figure 40, break the pattern of ballast-related defects having a well-defined positive relationship with the volume of missing ballast. As shown, occurrences on a curve follow a slight but steady positive trend with the exception of the one hundred to one hundred fifty cubic feet of missing group, which has no occurrences of dip31 defects. As dip31 defects occur at volumes greater than one hundred fifty cubic feet of missing ballast and that changes in the volume of missing ballast are not of the magnitude of fifty cubic feet except in special circumstances, this odd behavior is strictly due a quirk of the data. For tangent track, dip31 defects follow a threshold effect as mentioned earlier.

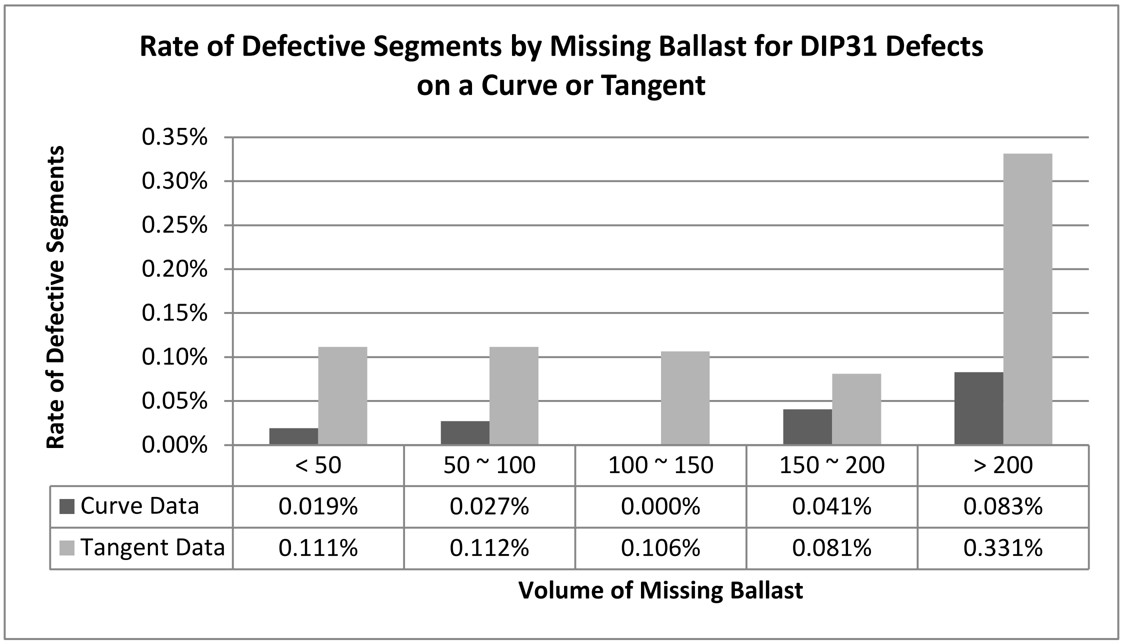


Figure 40: Rate of Defective Segments by Missing Ballast for Dip31 Defects on a Curve or Tangent

As with the dip31 defects, warp defects follow a different pattern than the cross-level defects, with a threshold effect for curves and a rise followed by a fall in the rate for tangent segments. The behavior for curve segments follows the previous explanations for the threshold effect, but the behavior on tangent segments necessitates a different hypothesis. One idea is that, since there is a significant amount of ballast missing, the degree of the warp is such that it is targeted for maintenance, which results in a lower number of segments containing warp defects at higher volumes. Since information on maintenance efforts was not available, future research where such information can be taken into account should help to prove if this hypothesis is true or not.

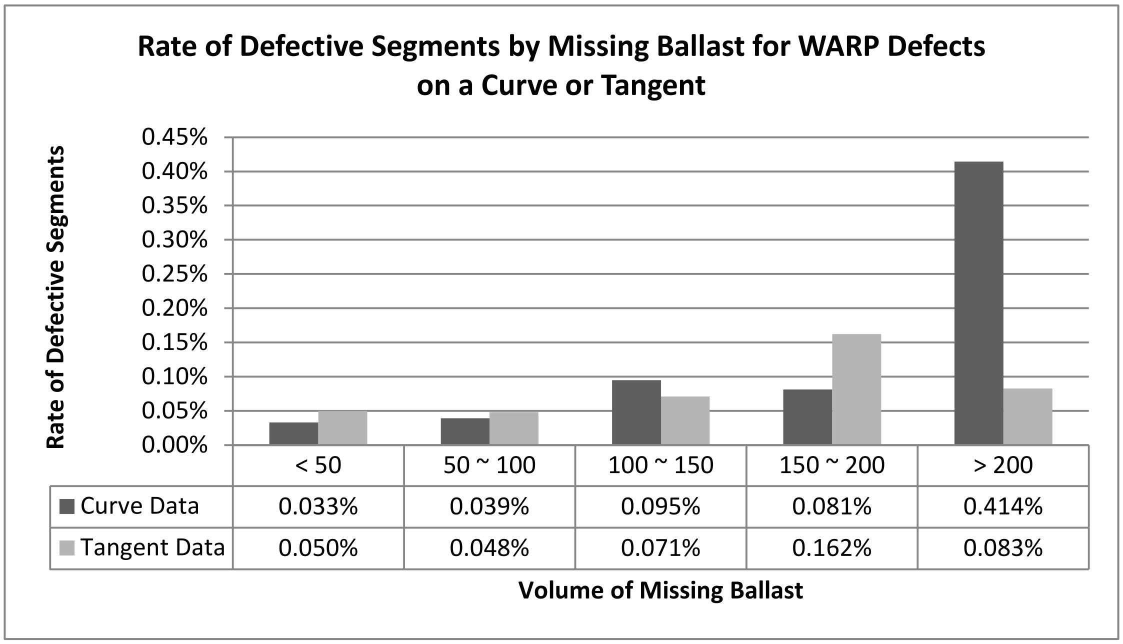


Figure 41: Rate of Defective Segments by Missing Ballast for Warp defects on a Curve or Tangent

In addition to looking at the effect of curves on ballast related defects and individual defects, an analysis into the impact of curves on rail defects was also done. As shown in Figure 42, the rate of segments containing a rail defect on a curve was relatively steady for increasing volumes of missing ballast but the rate of segments containing a rail defect on tangents decreased and then jumped up to around five times the next highest value. Comparing the behavior of the two conditions, the relatively stable rate for curve based data suggests that curves have a positive effect on the rate of defective segments containing a rail defect.

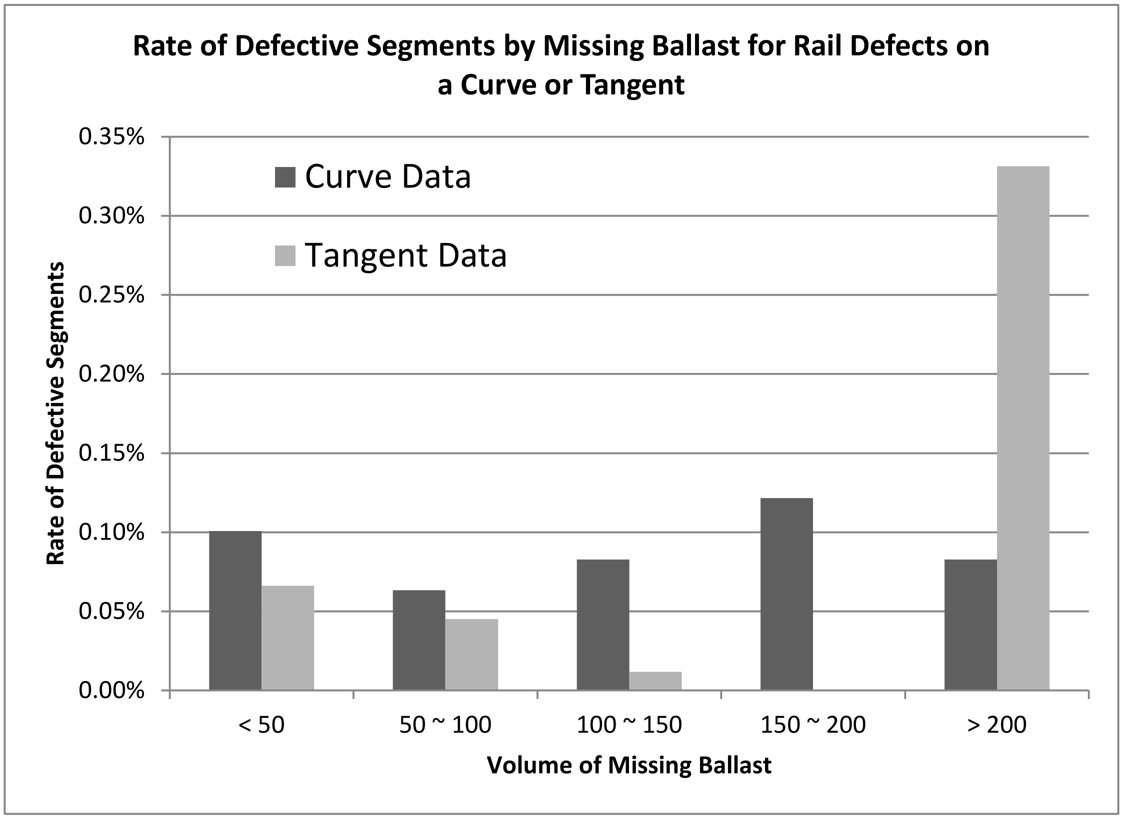


Figure 42: Rate of Defective Segments by Missing Ballast for Rail Defects on Curve or Tangent

The next analysis looked at the change in defective segment rates when using the volume of shoulder ballast and crib ballast as separate grouping factors. A key aspect of this analysis is the range of volume missing for the shoulders and the ballast; while the range of missing shoulder ballast was similar to the range of total missing ballast, as shown in Figure 43, the range of volumes for missing crib ballast effectively ended at 100 cubic feet as shown in Figure 44. In order to plot the rates when looking at the volume of crib ballast missing, a grouping of 25 cubic feet was used as higher groupings prevented detailed analysis of the results. The analyses of the shoulder ballast continued the use of 50 cubic feet grouping as the behavior was similar for both cases.

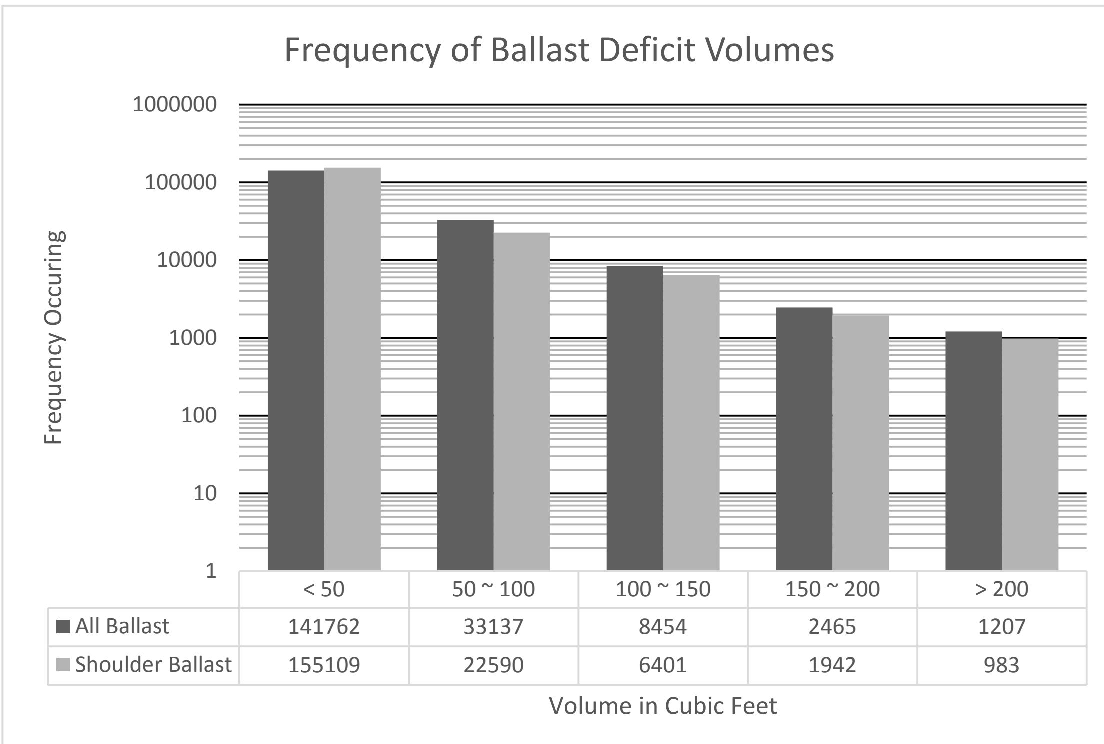


Figure 43: Frequency of Ballast Deficit Volumes based on Total Ballast Missing and Shoulder Ballast Missing

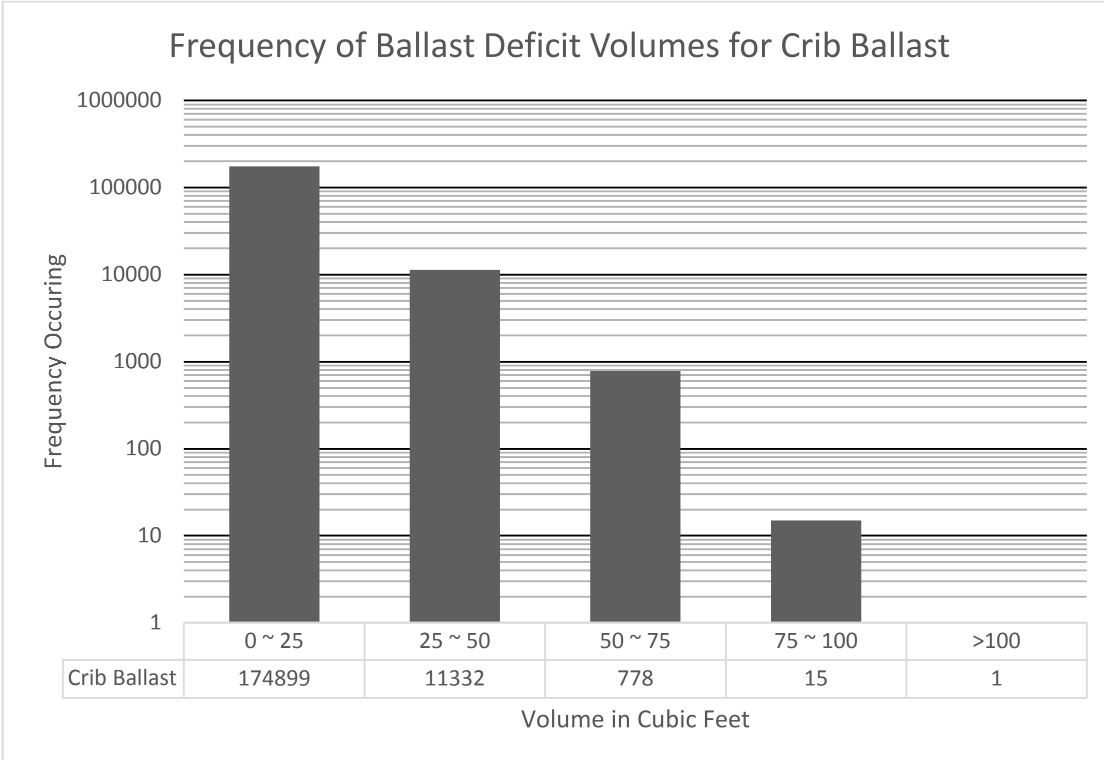


Figure 44: Frequency of Ballast Deficit Volume by Crib Ballast. Note: The value of the single >100 value is 100.9 cubic feet.

This analysis looked at the total rate of defective segments using missing shoulder ballast and missing crib ballast. The results of this analysis for all defects are shown in Figures 45 and 46. The behavior of the shoulder ballast analysis is very similar to the previous analyses looking at total volume of ballast which is primarily due to the similar distribution of ballast segments based on missing volume. The spike in the rate of defective segments when using crib ballast as the volume is due to the low number of segments in the seventy five to one hundred cubic foot range combined with a single defect.

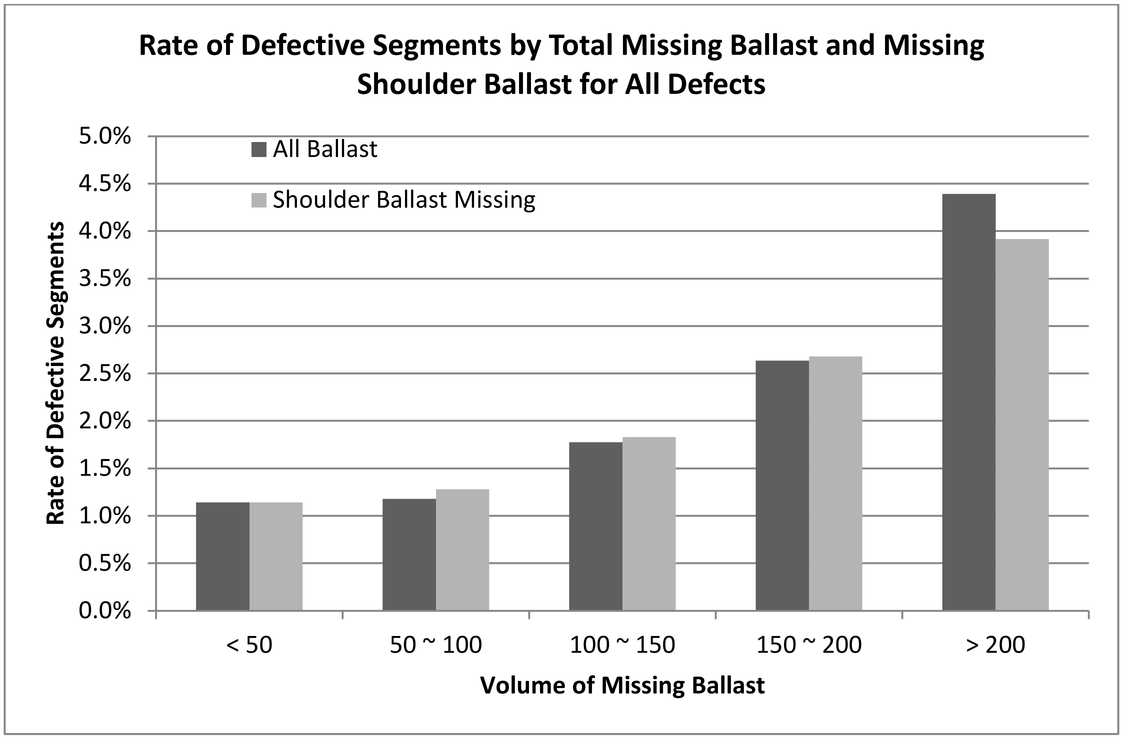


Figure 45: Rate of Defective Segments by Total Missing Ballast and Missing Shoulder Ballast for All Defects.

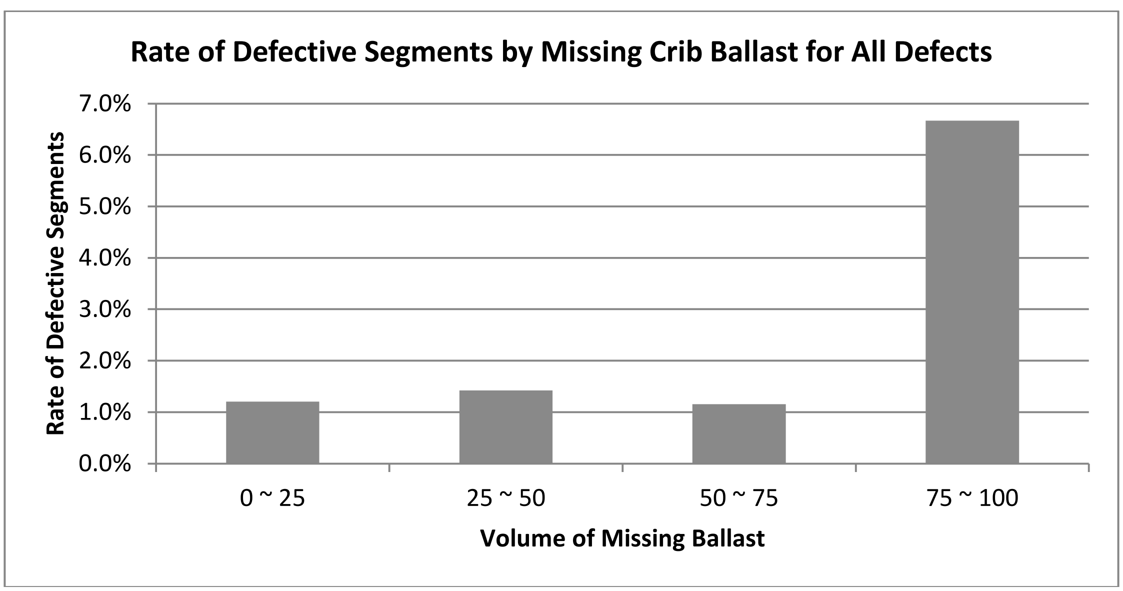
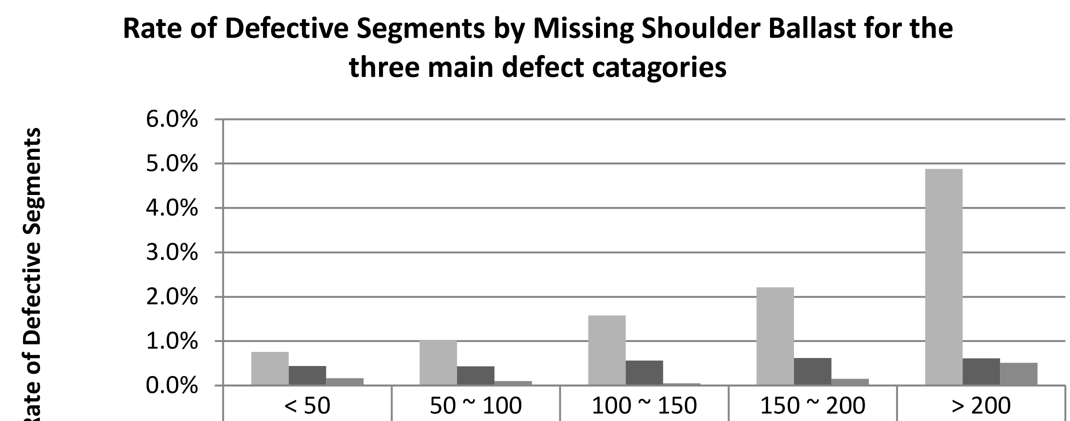


Figure 46: Rate of Defective Segments by Missing Crib Ballast for All Defects.

The behavior of the three main categories of defects is shown in Figure 47 for shoulder ballast and Figure 48 for Crib Ballast. The behavior of the three categories when using shoulder ballast is very similar to their behavior when using all ballast.



	< 50	50 ~ 100	100 ~ 150	150 ~ 200	> 200
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%

Figure 47: Rate of Defective Segments by Missing Shoulder Ballast for the three main defect categories

For the analysis of the three defect groupings when using crib ballast, ballast and tie related defects followed a relatively steady pattern while rail related defects had a steady positive relationship with the volume of missing ballast. The lone outlier, the value of 6.66% for tie defects in the seventy five to one hundred cubic foot volume range, is due to previously mentioned issue of a single defect occurring in a grouping of 15 segments. The positive relationship between the rate of segments containing rail related defects and increasing volume of missing ballast is interesting as it exhibits behavior that is unexpected in a manner similar to the behavior of the tight gage defect when comparing curve and tangent data; this also brings up the same issue: is this behavior normal or just a unique result due to the data.

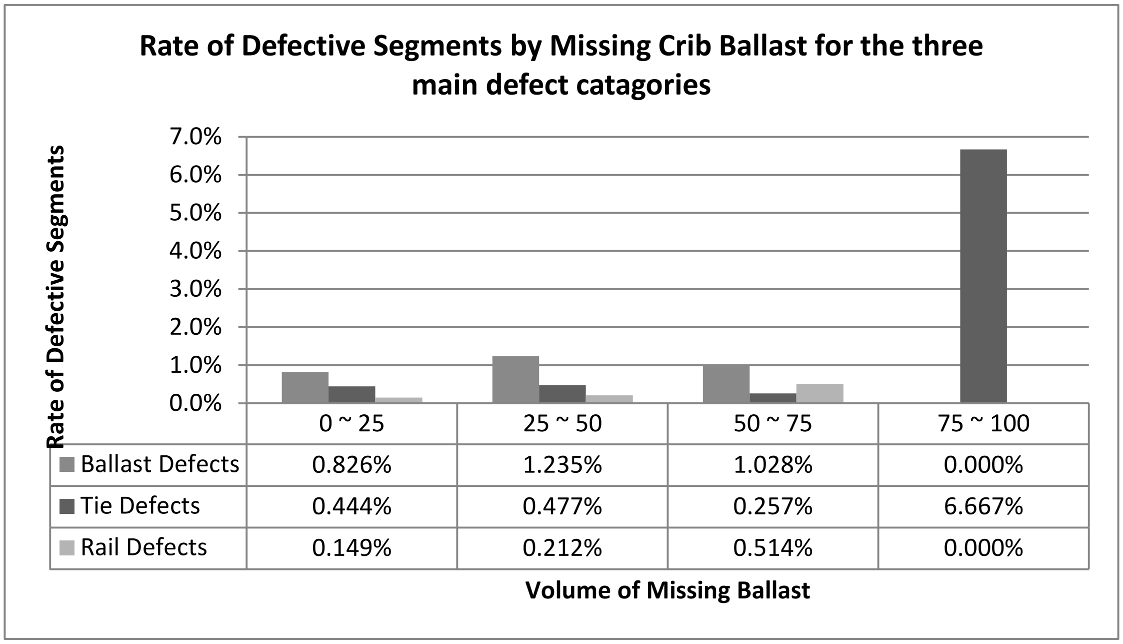
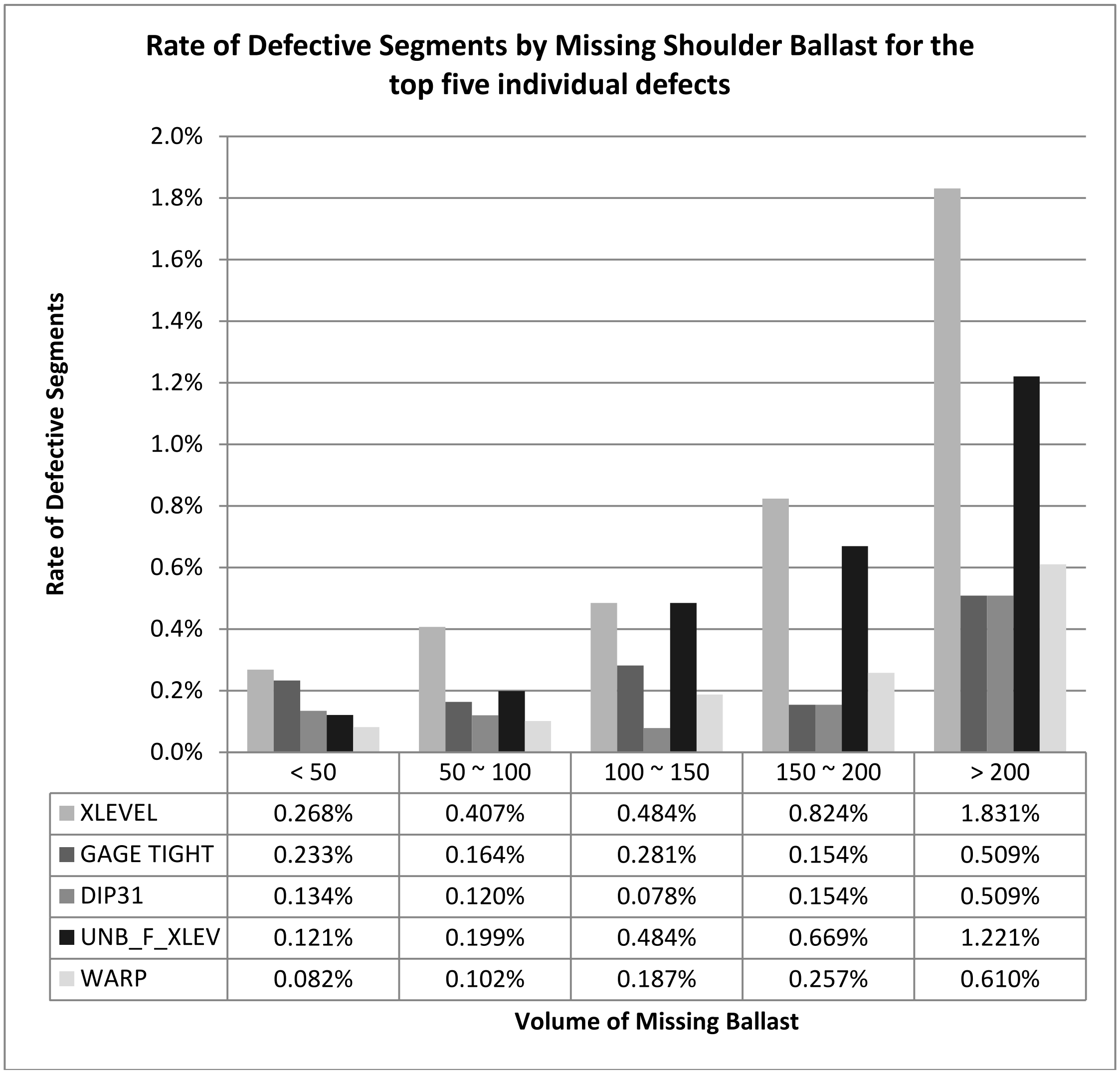


Figure 48: Rate of Defective Segments by Missing Crib ballast for the three main defect categories.

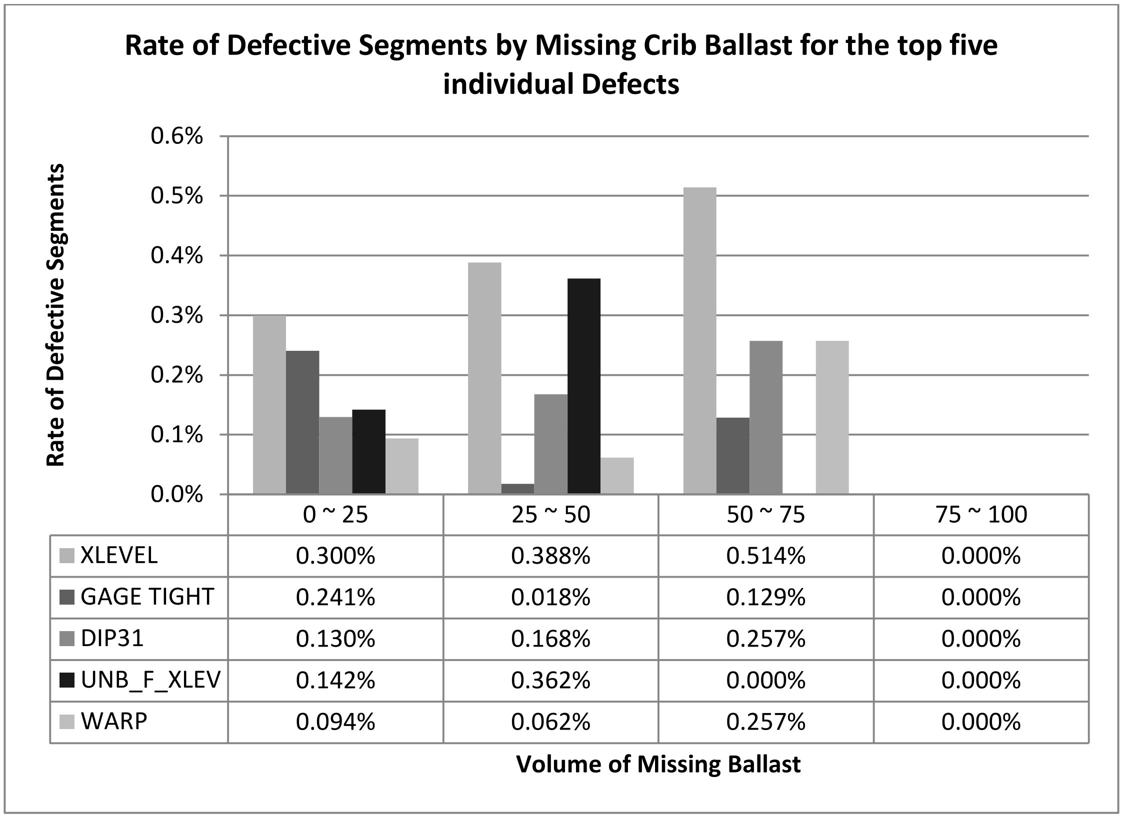
Figure 49 shows that cross-level defects and to a lesser extent unbalanced freight cross-level defects and warp defects, follow the general trend of the rate of defective segments containing ballast related defects having a positive relationship with increasing volumes of missing ballast. The Dip31 defect follows a slightly different pattern, with a slow decline in the rate of defective segments before rising. Tight Gate, being a tie related defect, follows the general non-relationship between the rate of defective segments and increasing volume of missing ballast. The same values for Gage-Tight and Dip31 in the one hundred fifty to two hundred and greater than two hundred categories is a coincidence of the data used and should not be used as evidence of any possible link between the two defects.



	< 50	50 ~ 100	100 ~ 150	150 ~ 200	> 200
XLEVEL	0.268%	0.407%	0.484%	0.824%	1.831%
GAGE TIGHT	0.233%	0.164%	0.281%	0.154%	0.509%
DIP31	0.134%	0.120%	0.078%	0.154%	0.509%
UNB_F_XLEV	0.121%	0.199%	0.484%	0.669%	1.221%
WARP	0.082%	0.102%	0.187%	0.257%	0.610%

Figure 49: Rate of Defective Segments by Missing Shoulder Ballast for the top five individual defects.

Figure 50 shows the top five individual defects when categorized according to the volume of missing crib ballast. Similar to the previous analysis, cross-level and to an extent unbalanced freight cross-level defects follow a positive relationship with increasing volumes of missing crib ballast. The rate of segments containing Dip31 defects now follows along with the other two cross-level defects in that it has a consistent positive relationship with the increasing volume of missing crib ballast. The rate of defective segments containing warp defects dips before rising in the last category it has data for; as this analysis only covers three categories, the significance of this behavior cannot be determined. As in the previous analysis, the rate of defective segments containing a tight gage defect do not follow a direct relationship with the volume of missing ballast.



	0 ~ 25	25 ~ 50	50 ~ 75	75 ~ 100
XLEVEL	0.300%	0.388%	0.514%	0.000%
GAGE TIGHT	0.241%	0.018%	0.129%	0.000%
DIP31	0.130%	0.168%	0.257%	0.000%
UNB_F_XLEV	0.142%	0.362%	0.000%	0.000%
WARP	0.094%	0.062%	0.257%	0.000%

Figure 50: Rate of Defective Segments by Missing Crib Ballast for the top five individual defects.

Another analysis into the effect of curves was done, focusing on the behavior of ballast related defects, rail-related defects and the top five individual defects when using shoulder and crib volumes as the categorization data. The behavior of ballast-related defects on a curve or tangent when using shoulder ballast as the categorization variable, Figure 51, shows an almost identical result to the analysis using the total volume of missing ballast, Figure 36. For crib ballast, Figure 52, the results do not appear to have a strict positive or negative relationship with increasing volumes of missing crib ballast.

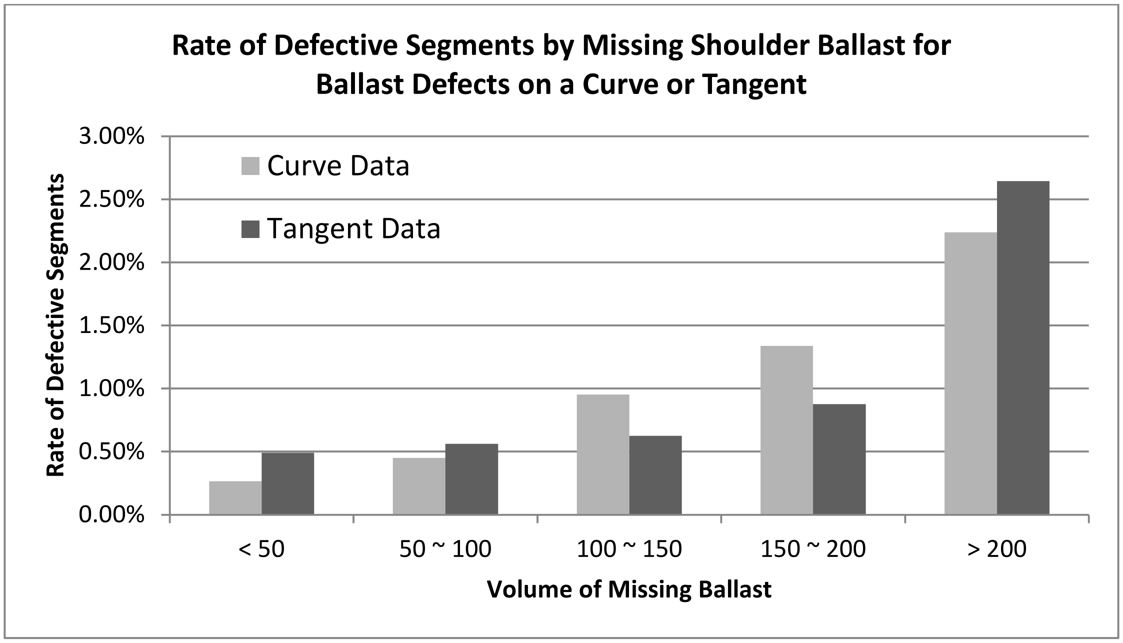


Figure 51: Rate of Defective Segments by Missing Shoulder Ballast for Ballast Related Defects on curves or tangents.

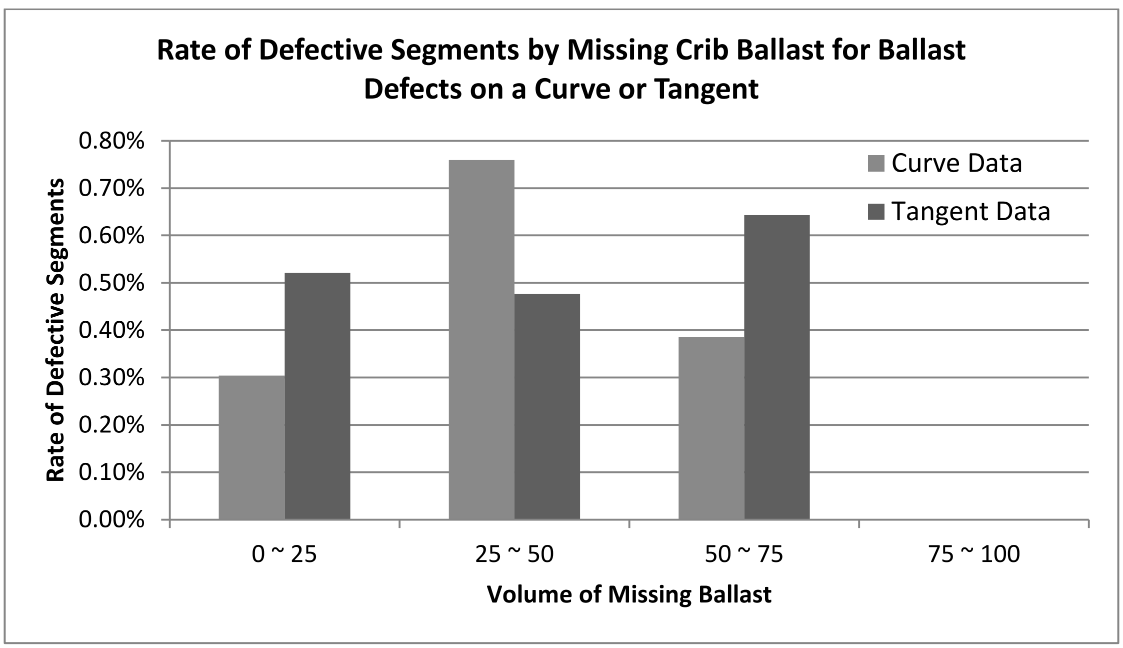


Figure 52: Rate of Defective Segments by Missing Crib Ballast for Ballast Related Defects on a curve or tangent

Comparing the following Figures 53 through 57 with the previous analyses' Figures 37 through 41 shows that the trends between the two sets of analyses are consistent. As mentioned previously, this is due to the great similarity in the distribution of segments when categorized based on total missing volume and volume of missing shoulder ballast.

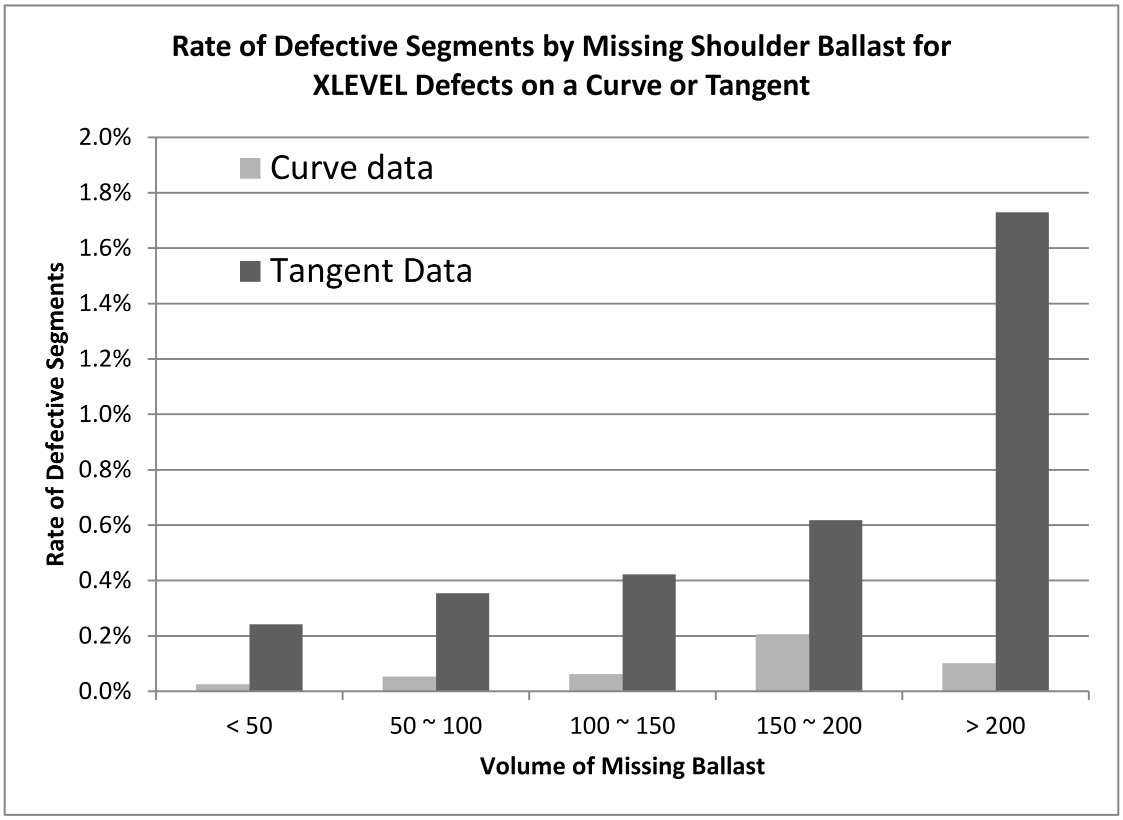


Figure 53: Rate of Defective Segments by Missing Shoulder Ballast for Cross-level defects on Curves or Tangents

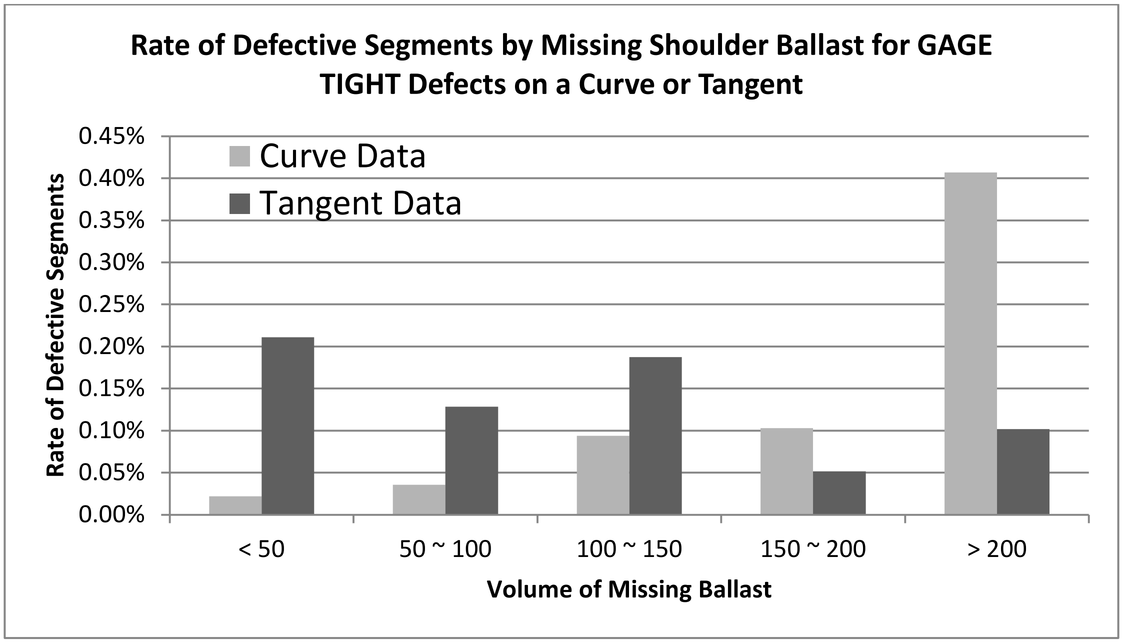


Figure 54: Rate of Defective Segments by Missing Shoulder Ballast for Gage Tight defects on a Curve or Tangent

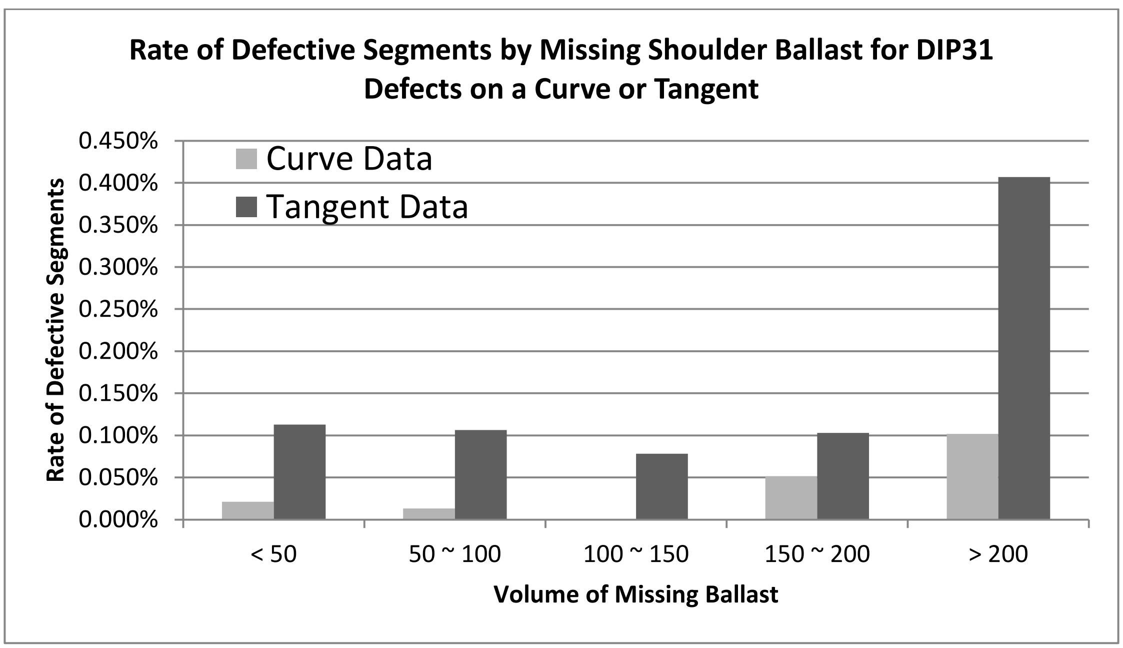


Figure 55: Rate of Defective Segments by Missing Shoulder Ballast for Dip31 defects on a Curve or Tangent

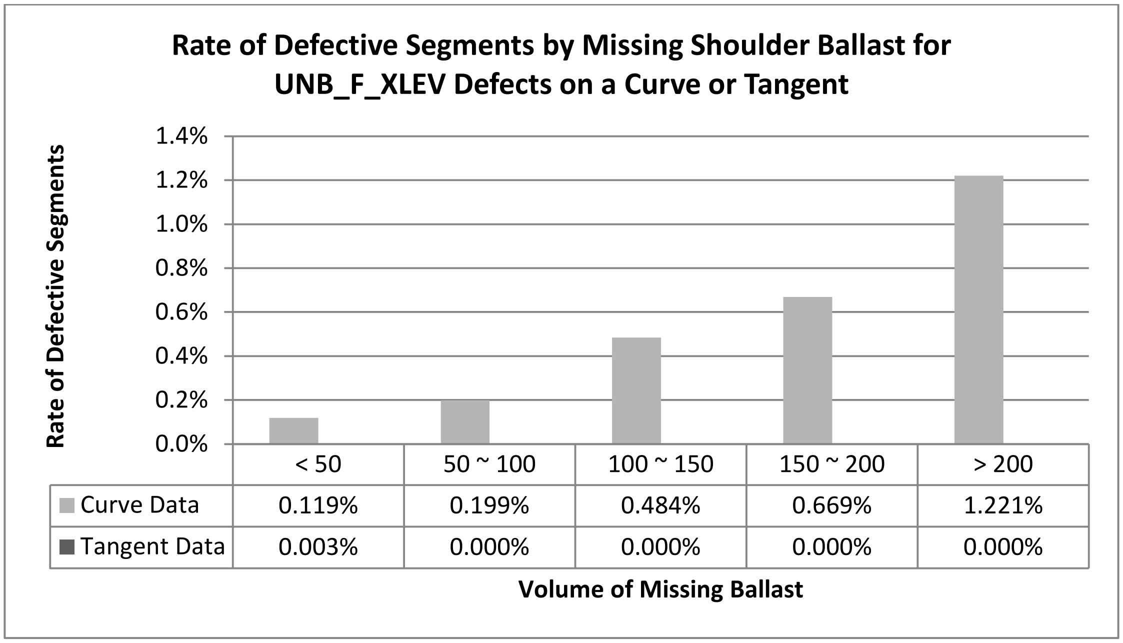


Figure 56: Rate of Defective Segments by Missing Shoulder Ballast for Unbalanced Freight Cross-level defects on a Curve or Tangent

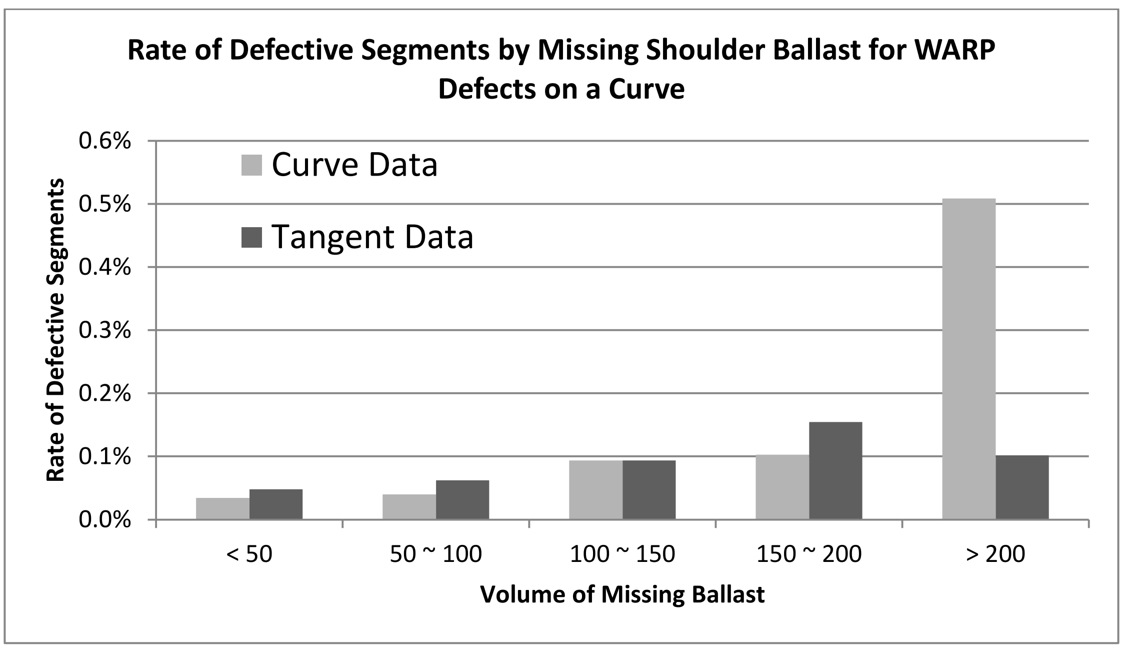


Figure 57: Rate of Defective Segments by Missing Shoulder Ballast for Warp defects on a Curve or Tangent

The companion to the previous analysis is the following analysis that uses the missing volume in the crib area as a categorization variable. For cross-level defects, there is a clear positive relationship that is of a greater magnitude for tangent segments than for curve segments. Unbalance Freight Cross-Level defects are again located exclusively on curved segments and have positive trend for the two groupings they occupy. The reasoning behind the unbalanced freight cross-level defects only occurring in those two groupings comes down to the limited data available and/or unknown maintenance efforts and should not be attributed to a possible limit in their existence.

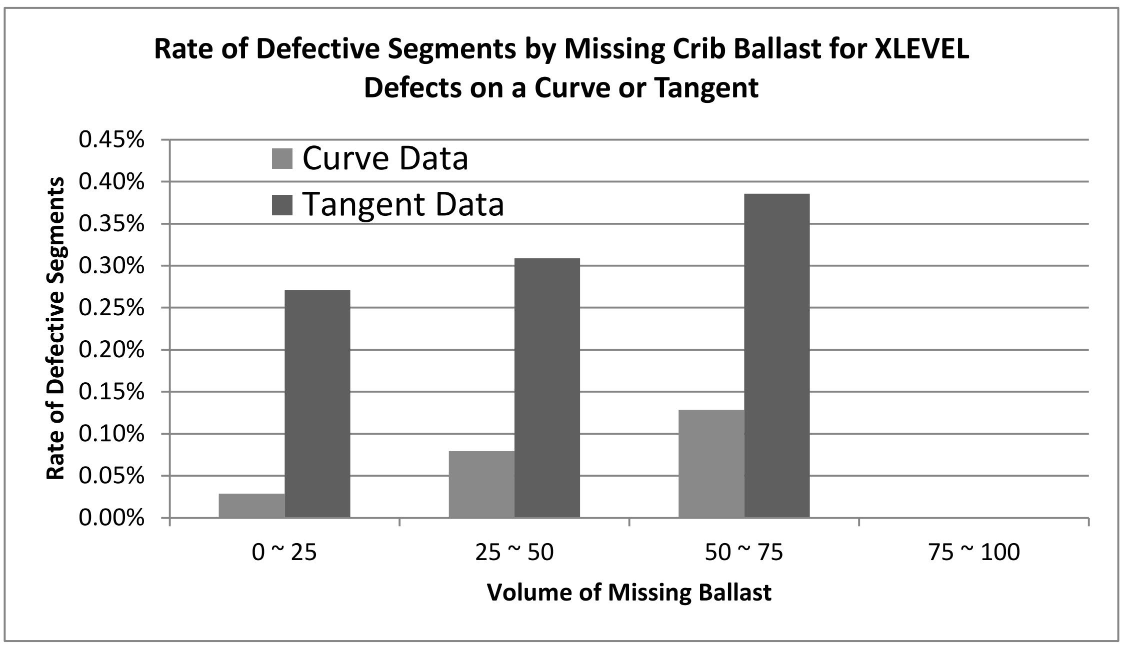


Figure 58: Rate of Defective Segments by Missing Crib Ballast for Cross-Level defects on a Curve or Tangent

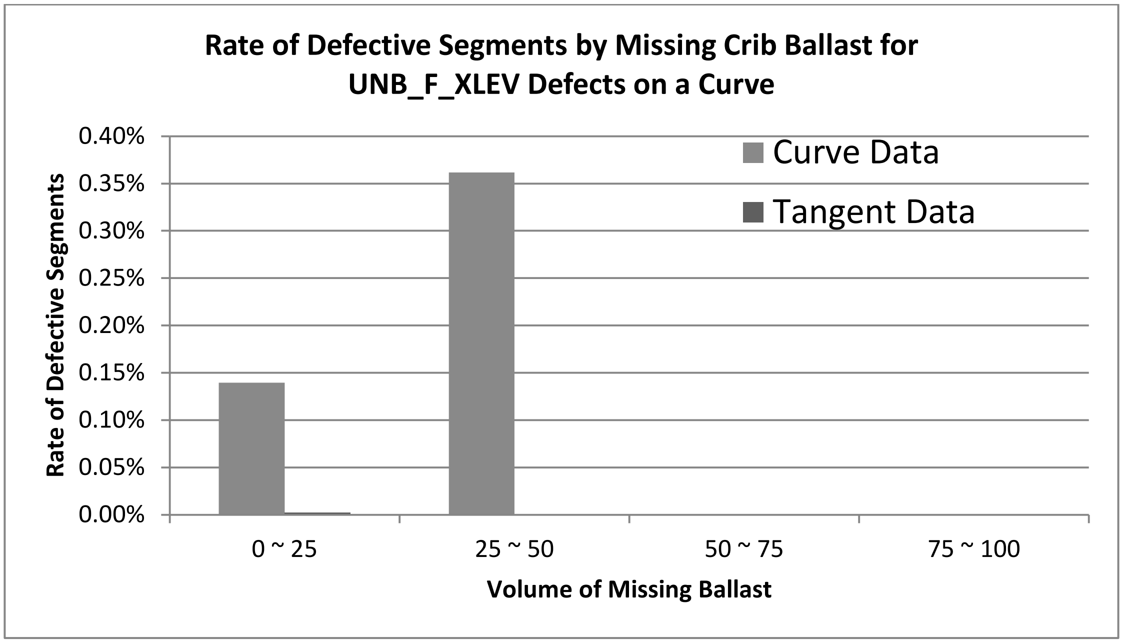


Figure 59: Rate of Defective Segments by Missing Crib Ballast for Unbalance Freight Cross-level defects on a Curve or Tangent

Gage Tight defects do not appear to have any direct relationship as shown in Figure 60. This follows the previous analyses which indicated that gage tight defects act independently of the volume of missing ballast.

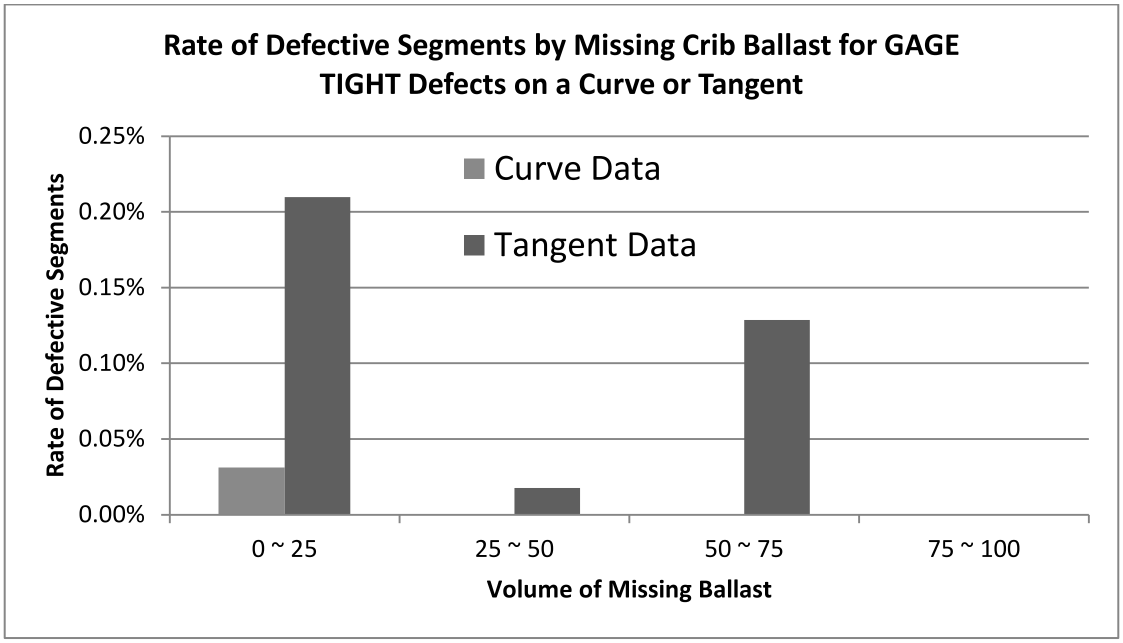


Figure 60: Rate of Defective Segments by Missing Crib Ballast for Gage Tight defects on a Curve or Tangent

Dip31 defects appear to replicate the threshold effect that has been occurring in previous analyses for tangent track, but the curve data, since it only exists for two groupings, may not be representative of the actual behavior even though there is a positive trend. As such, future research should look into this behavior in order to determine how it acts in higher volumes of missing crib ballast.

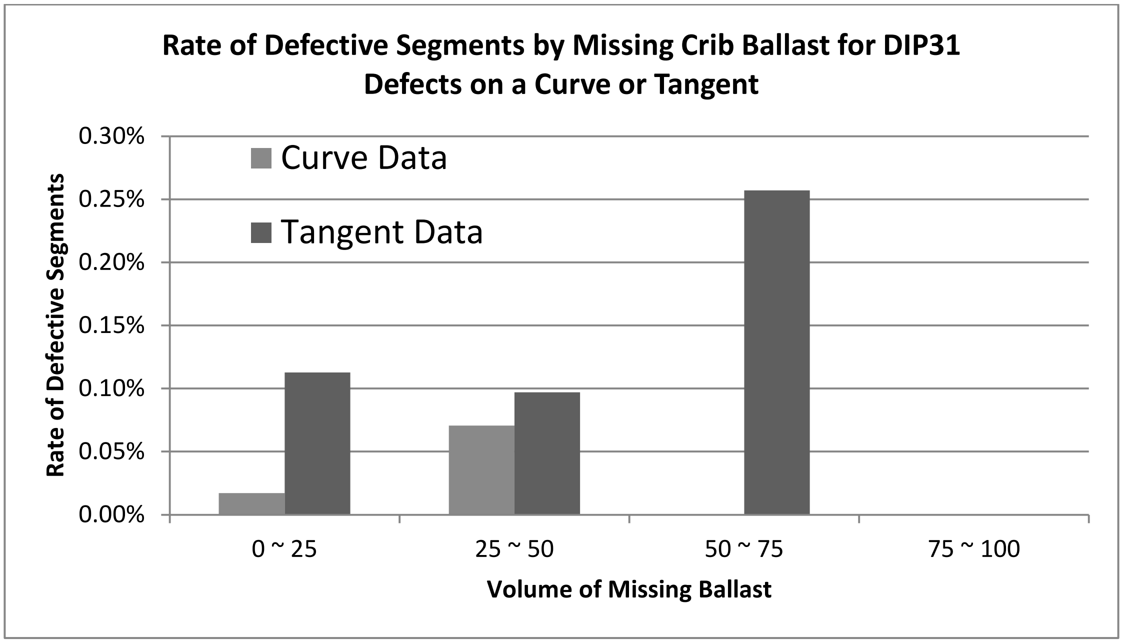


Figure 61: Rate of Defective Segments by Missing Crib Ballast for Dip31 Defects on a Curve or Tangent

Warp defects exhibit a similar set of behavior as dip31 defects. The rate of defective segments containing a warp defect follows a threshold effect while the tangent data, while only existing for two groupings, shows a negative trend. As with dip31, more research into the behavior is needed in order to determine if this behavior is representative of all warp defects or is just a quirk of the data used in this analysis.

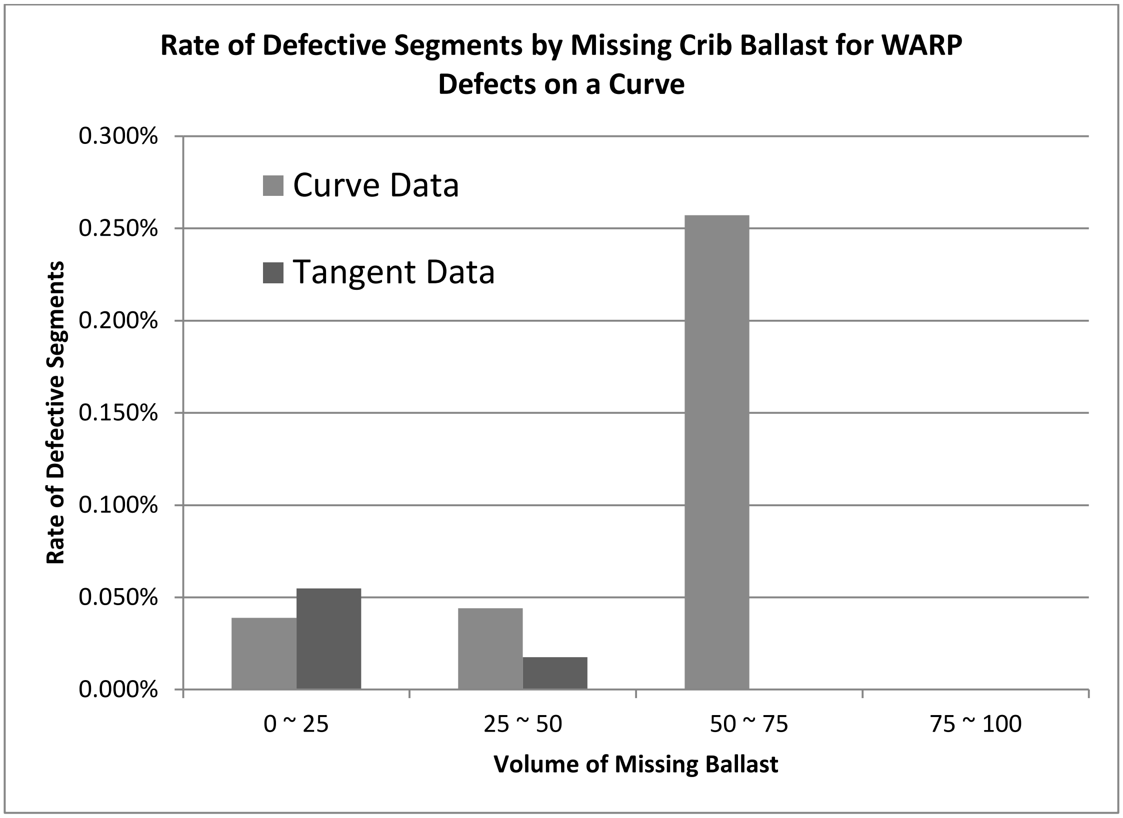


Figure 62: Rate of Defective Segments by Missing Crib Ballast for Warp Defects on a Curve or Tangent

3.3 Results of Analyses

The analyses results' show that increasing volumes of missing ballast results in increases to the rate of defective segments for ballast related defects. Tie and Rail related defects do not appear to be directly related to the volume of missing ballast, though a causal relationship through maintenance efforts may be inferred. Track curvature has an impact on the rate of defective segments that results in curved track having a rate of defective segments that is either close to or above the rate of defective segments for tangent track. This result confirms that curves are more likely to develop or contain a defect with missing ballast. The analyses that looked at shoulder verses crib categorization show that the results using missing shoulder volume are nearly identical to the results from the analyses using the total volume of missing ballast while the crib ballast based analyses are relatively unrelated to the volume of missing ballast when looking at larger groupings such as ballast related defects but that this changes when looking at the individual defects. This also holds true when looking at the differences between curve and tangent segments when categorized based on missing shoulder or crib volumes. For those instances where the results had an odd behavior, more research is needed to determine if that odd behavior is normal or an unintended result due to the data used.

Chapter 4

CONCLUSION

4.1 Discussion of Results

The development of weighting factors in [1] for the prioritization of missing ballast maintenance efforts provides a relatively low cost and effective method of improving the safety of rail operations. The proposed changes as researched can help to increase the safety of and optimize the use of these weighting factors without requiring significant changes to their use. The initial segment weighting factors, reproduced in Table 24, are based off of the change in forces in the railway environment and cover many aspects that are conditional in a relatively small area. The section weighting factors, reproduced in Table 25, are not only based on the change in forces in the railway environment but are also based on the perceived risk as well as aversion to risk across multiple consecutive segments.

Table 24: Initial Segment Weighting Factors

Zone	Curve	Grade	HAL	Buckle Risk	Speed	Mud Spot
1 Left Shoulder	1.08			1.15		
2 Crib	1.08	1.18		1.08		
3 Right Shoulder	1.08			1.15		
4 Below the Crib			1.0875		1.06	1.11
5 Below Left Shoulder						
6 Below Right Shoulder						

Table 25: Initial Section Weighting Factors

Weighing Name	Weighting
Passenger/Hazmat line	1.25
Key Route (As defined by the railroad)	1.11
Class 5 speed – Not Passenger	1.10
Class 4 speed – Not Passenger	1.05
Class 3 speed – Not Passenger	1
High Tonnage	1.15

The development of weighting factors through a cost-based risk assessment provides an alternative which focuses on the cost incurred due to an incident. Such a method is useful, as not all risks result in the same damage and that the cost of incidents can fluctuate based on economic factors as well as improvements to safety in railroad operations. The addition of a "High Risk" case to the passenger weighting factor allows limited adjustment based on the conditions of the study area. These factors, reproduced in Table 26, are applied to sections, as the weightings they can substitute for are based off of conditions that are continuous for significant lengths of track.

Table 26: Alternative Section Weighting Factors based on economic cost of associated risks

Weighting	Original Weighting	Alternative Weighting
Hazmat	1.25	1.35
Passenger (Normal Risk)	1.25	2.1
Passenger (High Risk)	1.25	4.9

The analyses into the effect of missing ballast on the rate of defective track segments provides confirmation of previously held beliefs, an insight into the quantifiable impact that missing ballast has on the rate of defective segments and poses some interesting questions regarding some unexpected results. For ballast-related defects such as cross-level and dip, positive relationships with the volume of missing ballast were seen which added evidence to the previously held belief that these defects are related to the missing ballast. Tie and rail related defects were found to be not generally related to the volume of missing ballast, adding evidence to the hypothesis that these defects are not generally related to the volume of missing ballast. Some of the odd behaviors found in these analyses can be explained by the nature of the data; Unbalanced Freight Cross-Level defects are predominately located on curves due to their nature while the occasional outlier, such as having no Dip defect reported in the one hundred to one hundred fifty cubic foot volume group while the other volume groups had defects reported, can be explained by the relatively limited data. The impact that curves have on the rate of defective segments containing ballast defects was confirmed, providing additional evidence to the increased priority that is attributed to them. While this impact holds true for the general ballast-related grouping, rail-related defects and individual defects do not always follow this pattern. The analyses which changed the categorization of defect rates from volume of total ballast missing to either volume of shoulder ballast missing or volume of crib ballast missing provided some insight into the impact that the location of ballast has on the rate of defective segments. While there was little change in the results of using volume of missing shoulder ballast compared to the use of the total volume of missing ballast, the analyses which used the volume of missing crib ballast provided some limited insights into how deficient cribs are related to the rate of defective segments.

4.2 Future Areas of Research

From these analyses, some topics for future research present themselves. The simplest is to expand on the work done through the collection and analyzing of more data with respect to the rate of defective segments. With more data, the possibility of using smaller groupings, such as the ten cubic feet grouping, in higher ranges of missing ballast volume becomes more likely. With the ability to use the smaller groupings, a better representation of the actual rate of defective segments becomes possible. As well as potentially allowing the use of smaller groupings, more data can help to explain the odd behavior seen in some instances and determine if that behavior is normal or was just due to the data being used. With this additional data, analyses that look into the relationship between missing ballast and derailments should be able to be developed. With this research into missing ballast and derailments, a more direct relationship between missing ballast and risk can be generated. Research into the actual impact that the location of missing ballast has on defective segment rates can provide a way to add another weighting factor which is focused on the location of the missing ballast as well as provide the opportunity to see if the other weighting factors could have modifiers applied to them based on the locations of missing ballast. This research should also be able to determine the behavior of the threshold effects that occur in some of the analyses presented. The new weighting factors based off of the economic cost associated with incidents should also be regularly updated as new information becomes available or when major changes are seen across the industry.

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5. United States Department of Transportation, "Guidance on Treatment of the Economic Value of a Statistical Life", 2013, http://www.dot.gov/office-policy/transportation-policy/guidance-treatment-economic-value-statistical-life

6. United States Department of Transportation, "TIGER Benefit-Cost Analysis (BCA) Resource Guide", 2012, http://www.dot.gov/sites/dot.dev/files/docs/TIGER_BCA_RESOURCE_GUIDE.pdf

Appendix A

PROFILE AREA CALCULATIONS

Data Removed Due to Copyrighting

Appendix B

CALCULATION OF VOLUME AND WEIGHTED VOLUME

Data Removed Due to Copyrighting

Appendix C

GPR DATA

Data Removed Due to Copyrighting

Appendix D

DATA USED IN REGRESSION ANALYSIS FOR WEIGHTING FACTORS

The following Data is the data used to run the regression analysis for the Hazmat factor. The data consists of, from left to right, Loco DerailLoco TotCars TotDerailCars Speed EqpDmg HAZMAT Derail Released Evac TrkDmg Dead Injured TotCost NormCar NormDerail

3,0,85,1,8,6624,43,1,0,0,5625,0,0,12249,42,0

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2,0,64,4,8,23000,0,0,0,0,232000,0,0,255000,64,4

2,0,34,1,8,6521,0,0,0,0,3500,0,0,10021,34,1

3,0,25,4,7,40037,0,0,0,0,16000,0,0,56037,25,4

2,0,26,2,9,6000,0,0,0,0,7200,0,0,13200,26,2

Appendix E

SAS REGRESSION ANALYSIS CODE

This Appendix contains the code used in SAS to run the regression analyses.

```
/* John Cronin Derailment Cost Analysis */

data Derail;
infile 'Derail.txt';
input Loco DerailLoco TotCars TotDerailCars Speed EqpDmg HAZMAT
Derail Released Evac TrkDmg Dead Injured TotCost NormCar NormDerail;
LTot=Log(TotCost);
proc means; run;

proc reg; model TotCost=DerailLoco Derail Released NormDerail; run;
proc reg; model TotCost=Loco DerailLoco TotCars TotDerailCars Speed
HAZMAT Derail Released; run;
proc reg; model TotCost=Loco DerailLoco Speed HAZMAT Derail Released
NormCar NormDerail; run;
proc reg; model TotCost=Loco DerailLoco TotCars TotDerailCars Speed
HAZMAT Derail Released Injured NormCar NormDerail; run;
proc reg; model LTot=DerailLoco Derail Released NormDerail; run;
```

```
proc reg; model TotCost=Derail NormDerail; run;
proc reg; model LTot=Derail NormDerail; run;
proc reg; model TotCost=Derail NormDerail /NOINT; run;
quit;
run;
```

Appendix F

HAZMAT REGRESSION ANALYSIS RESULTS

This Appendix contains the results of the Regression Analyses used in determining the Hazmat weighting factor.

The SAS System 20:33

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The MEANS Procedure

Variable	N	Mean	Std Dev	Minimum	Maximum
Loco	77	2.6623377	1.0955699	0	6.0000000
DerailLoco	77	0.1298701	0.3383649	0	1.0000000
TotCars	77	67.8571429	38.9604098	0	137.0000000
TotDerailCars	77	7.8311688	9.5385680	0	45.0000000
Speed	77	18.0909091	15.8680263	2.0000000	68.0000000
EqpDmg	77	265658.45	564704.08	0	2778964.00
HAZMAT	77	3.5454545	14.4254394	0	105.0000000
Derail	77	0.4025974	2.1719488	0	17.0000000
Released	77	0.1688312	1.3707719	0	12.0000000
Evac	77	0	0	0	0

TrkDmg	77	168776.34	451343.26	0	3704500.00
Dead	77	0.0259740	0.2279212	0	2.0000000
Injured	77	0	0	0	0
TotCost	77	434434.79	865029.22	10000.00	5218829.00
NormCar	77	64.3116883	39.1385057	0	137.0000000
NormDerail	77	7.4285714	9.5358445	0	45.0000000
LTot	77	11.5891854	1.6687525	9.2103404	15.4677836

The REG Procedure

Model: MODEL1

Dependent Variable: TotCost

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	4.25792E13	1.06448E13	53.63	<.0001
Error	72	1.428974E13	1.984686E11		
Corrected Total	76	5.686894E13			

Root MSE	445498	R-Square	0.7487
Dependent Mean	434435	Adj R-Sq	0.7348
Coeff Var	102.54662		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-188590	71371	-2.64	0.0101
DerailLoco	1	-16316	153960	-0.11	0.9159
Derail	1	171144	58444	2.93	0.0046
Released	1	-115322	92478	-1.25	0.2164
NormDerail	1	77500	5468.34441	14.17	<.0001

The REG Procedure

Model: MODEL1

Dependent Variable: TotCost

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	4.336191E13	5.420239E12	27.29	<.0001
Error	68	1.350703E13	1.986328E11		
Corrected Total	76	5.686894E13			

Root MSE	445682	R-Square	0.7625
Dependent Mean	434435	Adj R-Sq	0.7345
Coeff Var	102.58901		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-128543	146393	-0.88	0.3830
Loco	1	-81072	61458	-1.32	0.1915
DerailLoco	1	-1893.06054	157592	-0.01	0.9905
TotCars	1	1375.04264	1845.69244	0.75	0.4588
TotDerailCars	1	73731	7876.29374	9.36	<.0001
Speed	1	5395.52936	4390.30831	1.23	0.2233
HAZMAT	1	-2108.73248	4800.85295	-0.44	0.6619
Derail	1	95023	77375	1.23	0.2236
Released	1	-118677	112030	-1.06	0.2932

The REG Procedure

Model: MODEL1

Dependent Variable: TotCost

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	4.336191E13	5.420239E12	27.29	<.0001
Error	68	1.350703E13	1.986328E11		
Corrected Total	76	5.686894E13			

Root MSE	445682	R-Square	0.7625
Dependent Mean	434435	Adj R-Sq	0.7345
Coeff Var	102.58901		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-128543	146393	-0.88	0.3830
Loco	1	-81072	61458	-1.32	0.1915
DerailLoco	1	-1893.06054	157592	-0.01	0.9905
Speed	1	5395.52936	4390.30831	1.23	0.2233
HAZMAT	1	-733.68984	4619.03692	-0.16	0.8743
Derail	1	168755	78812	2.14	0.0358
Released	1	-118677	112030	-1.06	0.2932
NormCar	1	1375.04264	1845.69244	0.75	0.4588
NormDerail	1	73731	7876.29374	9.36	<.0001

The REG Procedure

Model: MODEL1

Dependent Variable: TotCost

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	4.336191E13	5.420239E12	27.29	<.0001
Error	68	1.350703E13	1.986328E11		
Corrected Total	76	5.686894E13			

Root MSE	445682	R-Square	0.7625
Dependent Mean	434435	Adj R-Sq	0.7345
Coeff Var	102.58901		

NOTE: Model is not full rank. Least-squares solutions for the parameters are not unique. Some statistics will be misleading. A reported DF of 0 or B means that the estimate is biased.

NOTE: The following parameters have been set to 0, since the variables are a linear combination of other variables as shown.

Injured = 0

NormCar = TotCars - HAZMAT

NormDerail = TotDerailCars – Derail

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-128543	146393	-0.88	0.3830
Loco	1	-81072	61458	-1.32	0.1915
DerailLoco	1	-1893.06054	157592	-0.01	0.9905
TotCars	B	1375.04264	1845.69244	0.75	0.4588
TotDerailCars	B	73731	7876.29374	9.36	<.0001
Speed	1	5395.52936	4390.30831	1.23	0.2233
HAZMAT	B	-2108.73248	4800.85295	-0.44	0.6619
Derail	B	95023	77375	1.23	0.2236
Released	1	-118677	112030	-1.06	0.2932
Injured	0	0	.	.	.
NormCar	0	0	.	.	.
NormDerail	0	0	.	.	.

The REG Procedure

Model: MODEL1

Dependent Variable: LTot

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	134.49045	33.62261	31.38	<.0001
Error	72	77.14941	1.07152		
Corrected Total	76	211.63985			

Root MSE	1.03514	R-Square	0.6355
Dependent Mean	11.58919	Adj R-Sq	0.6152
Coeff Var	8.93197		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	10.50568	0.16584	63.35	<.0001
DerailLoco	1	-0.16846	0.35774	-0.47	0.6391
Derail	1	0.40737	0.13580	3.00	0.0037
Released	1	-0.28269	0.21488	-1.32	0.1925
NormDerail	1	0.13315	0.01271	10.48	<.0001

The REG Procedure

Model: MODEL1

Dependent Variable: TotCost

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	4.227038E13	2.113519E13	107.13	<.0001
Error	74	1.459856E13	1.972779E11		
Corrected Total	76	5.686894E13			

Root MSE	444160	R-Square	0.7433
Dependent Mean	434435	Adj R-Sq	0.7364
Coeff Var	102.23852		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-181325	65829	-2.75	0.0074
Derail	1	104502	23608	4.43	<.0001
NormDerail	1	77227	5377.06665	14.36	<.0001

The REG Procedure

Model: MODEL1

Dependent Variable: LTot

Number of Observations Read	77
Number of Observations Used	77

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	132.52029	66.26014	61.97	<.0001
Error	74	79.11956	1.06918		
Corrected Total	76	211.63985			

Root MSE	1.03401	R-Square	0.6262
Dependent Mean	11.58919	Adj R-Sq	0.6161
Coeff Var	8.92222		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	10.50116	0.15325	68.52	<.0001
Derail	1	0.24439	0.05496	4.45	<.0001
NormDerail	1	0.13322	0.01252	10.64	<.0001

The REG Procedure

Model: MODEL1

Dependent Variable: TotCost

Number of Observations Read	77
Number of Observations Used	77

NOTE: No intercept in model. R-Square is redefined.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5.530607E13	2.765303E13	128.86	<.0001
Error	75	1.609536E13	2.146048E11		
Uncorrected Total	77	7.140143E13			

Root MSE	463255	R-Square	0.7746

Dependent Mean	434435	Adj R-Sq	0.7686
Coeff Var	106.63387		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Derail	1	90669	24059	3.77	0.0003
NormDerail	1	67999	4386.67068	15.50	<.0001

Appendix G

VALUE OF STATISTICAL LIFE CALCULATIONS

This Appendix contains the data and calculations done in calculating the weighting factors for passengers through the use of the value of statistical life value.

This Data is also shown in the Electronic File, located in the pocket of the book, called APPENDIX_G.xlsx

	total incidents	% of Total
T001- Roadbed settled or soft	267	2.8
T002- Washout/rain/slide/etc. dmg -track	78	0.8
T099- Other roadbed defects	31	0.3
T101- Cross level of track irregular(joints)	288	3
T102- Cross level track irreg.(not at joints)	290	3
T103- Deviate frm uniform top of rail profile	38	0.4
T104- Disturbed ballast section	7	0.1
T105- Insufficient ballast section	8	0.1
T106- Superelevation improper, excessive,etc.	49	0.5
T107- Superelevation runoff improper	6	0.1
T108- Trk alignmnt irreg-not buckled/sunkink	165	1.7
T109- Track alignment irreg(buckled/sunkink)	331	3.5
T199- Other track geometry defects	123	1.3
	1681	17.6
T001- Roadbed settled or soft	953	3.1
T002- Washout/rain/slide/etc. dmg -track	338	1.1
T099- Other roadbed defects	133	0.4
T101- Cross level of track irregular(joints)	1,424	4.6
T102- Cross level track irreg.(not at joints)	1,075	3.5
T103- Deviate frm uniform top of rail profile	111	0.4
T104- Disturbed ballast section	14	0
T105- Insufficient ballast section	14	0
T106- Superelevation improper, excessive,etc.	235	0.8
T107- Superelevation runoff improper	36	0.1
T108- Trk alignmnt irreg-not buckled/sunkink	507	1.6
T109- Track alignment irreg(buckled/sunkink)	1,245	4
T199- Other track geometry defects	469	1.5
	6554	21.1
	4873	3.5

% of ballast related	collisions	derailments	other
15.88%	1	258	8
4.64%	-	65	13
1.84%	-	28	3
17.13%	2	284	2
17.25%	2	284	4
2.26%	-	36	2
0.42%	-	6	1
0.48%	-	8	-
2.91%	-	49	-
0.36%	-	6	-
9.82%	-	164	1
19.69%	2	327	2
7.32%	3	113	7
	10	1628	43
14.54%	2	936	15
5.16%	-	301	37
2.03%	-	123	10
21.73%	9	1,401	14
16.40%	7	1,056	12
1.69%	2	101	8
0.21%	-	13	1
0.21%	-	14	-
3.59%	-	234	1
0.55%	-	35	1
7.74%	3	494	10
19.00%	4	1,237	4
7.16%	7	444	18
1	34	6389	131
1	24	4761	88

cost	average cost	% of total cost	Fatality
42,093,946$	157,655$	3.1	0
28,070,936$	359,884$	2	3
7,639,850$	246,447$	0.6	0
23,644,948$	82,101$	1.7	0
48,758,650$	168,133$	3.5	0
5,432,510$	142,961$	0.4	0
211,714$	30,245$	0	0
800,252$	100,032$	0.1	0
6,652,976$	135,775$	0.5	0
675,574$	112,596$	0	0
27,983,423$	169,597$	2	0
138,037,018$	417,030$	10	6
30,464,267$	247,677$	2.2	1
360,466,064$	214,435$	26.1	10
avg w/o wash outs + buckles	152,797$		
84,862,769$	89,048$	3	0
93,778,504$	277,451$	3.3	14
16,489,639$	123,982$	0.6	0
84,155,470$	59,098$	3	0
100,902,259$	93,863$	3.6	0
11,200,715$	100,907$	0.4	0
1,070,350$	76,454$	0	0
1,084,013$	77,430$	0	0
24,338,578$	103,568$	0.9	0
4,533,039$	125,918$	0.2	0
57,455,483$	113,324$	2	0
277,702,770$	223,054$	9.8	7
51,194,154$	109,156$	1.8	1
808,767,743$	123,401$	28.6	22
448,301,679$	91,997$	2.5	12

Injury	fatality %	injury %	injuries/incident
17	0.000%	6.996%	0.0101130280
33	30.000%	13.580%	0.0196311719
1	0.000%	0.412%	0.0005948840
1	0.000%	0.412%	0.0005948840
3	0.000%	1.235%	0.0017846520
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
1	0.000%	0.412%	0.0005948840
141	60.000%	58.025%	0.0838786437
46	10.000%	18.930%	0.0273646639
243	0.595%	14.456%	
31	0.000%	4.613%	0.472994%
257	63.636%	38.244%	3.921269%
14	0.000%	2.083%	0.213610%
24	0.000%	3.571%	0.366189%
16	0.000%	2.381%	0.244126%
1	0.000%	0.149%	0.015258%
0	0.000%	0.000%	0.000000%
0	0.000%	0.000%	0.000000%
1	0.000%	0.149%	0.015258%
2	0.000%	0.298%	0.030516%
26	0.000%	3.869%	0.396704%
246	31.818%	36.607%	3.753433%
54	4.545%	8.036%	0.823924%
672	0.336%	10.253%	
429			

	total incidents	% of Total
T001- Roadbed settled or soft	267	2.8
T099- Other roadbed defects	31	0.3
T101- Cross level of track irregular(joints)	288	3
T102- Cross level track irreg.(not at joints)	290	3
T103- Deviate frm uniform top of rail profile	38	0.4
T104- Disturbed ballast section	7	0.1
T105- Insufficient ballast section	8	0.1
T106- Superelevation improper, excessive,etc.	49	0.5
T107- Superelevation runoff improper	6	0.1
T108- Trk alignmnt irreg-not buckled/sunkink	165	1.7
T109- Track alignment irreg(buckled/sunkink)	331	3.5
T199- Other track geometry defects	123	1.3
Total	1603	16.8
	AIS 0	AIS 1
Occurrence of Severity per Unknown Injury	0.21538	0.62728
Estimated Rate of injury/fatality per incident	0.02822	0.08218
Adjustment to include fatality as a potential from each incident.	0.21364	0.62220
Cost ratio from VSL	0	0.003
Cost per injury/severity level	$	27,300$
weighted Estimated cost for an injury	$	16,986$

% of ballast related	Collisions	Derailments	Other
16.66%	1	258	8
1.93%	0	28	3
17.97%	2	284	2
18.09%	2	284	4
2.37%	0	36	2
0.44%	0	6	1
0.50%	0	8	0
3.06%	0	49	0
0.37%	0	6	0
10.29%	0	164	1
20.65%	2	327	2
7.67%	3	113	7
1	10	1563	30
AIS 2	AIS 3	AIS 4	AIS 5
0.10400	0.04817	0.00617	0.00279
0.01362	0.03858	0.00442	0.01034
0.10316	0.04778	0.00612	0.00277
0.047	0.105	0.266	0.593
427,700$	955,500$	2,420,600$	5,396,300$
44,121$	45,654$	14,814$	14,934$

Total Cost	Average Cost	% of Total Cost	Fatalities
42,093,946$	157,655$	13%	0
7,639,850$	246,447$	2%	0
23,644,948$	82,101$	7%	0
48,758,650$	168,133$	15%	0
5,432,510$	142,961$	2%	0
211,714$	30,245$	0%	0
800,252$	100,032$	0%	0
6,652,976$	135,775$	2%	0
675,574$	112,596$	0%	0
27,983,423$	169,597$	8%	0
138,037,018$	417,030$	42%	6
30,464,267$	247,677$	9%	1
332,395,128$	207,358$	1	7
Average (No Buckle/sunkink)	152,797$		
42%	95,888$		
	62,100$		
Fatality			
		1.00816	
0.00437		0.18172	
0.00433	1.00000	2.00000	
1.000	9,100,000$		
9,100,000$			
39,416$	175,926$		

Injuries	% occurrence of Fatalities	% occurrence of Injuries	
17	0.000%	8.095%	
1	0.000%	0.476%	
1	0.000%	0.476%	
3	0.000%	1.429%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
1	0.000%	0.476%	
141	85.714%	67.143%	
46	14.286%	21.905%	
210	0.437%	13.100%	0.135371179

	total incidents	% of Total
T001- Roadbed settled or soft	267	2.8
T099- Other roadbed defects	31	0.3
T101- Cross level of track irregular(joints)	288	3
T102- Cross level track irreg.(not at joints)	290	3
T103- Deviate frm uniform top of rail profile	38	0.4
T104- Disturbed ballast section	7	0.1
T105- Insufficient ballast section	8	0.1
T106- Superelevation improper, excessive,etc.	49	0.5
T107- Superelevation runoff improper	6	0.1
T108- Trk alignmnt irreg-not buckled/sunkink	165	1.7
T199- Other track geometry defects	123	1.3
	1272	13.3
NO BUCKLE		
	AIS 0	AIS 1
Occurrence of Severity per Unknown Injury	0.21538	0.62728
Estimated Rate of injury/fatality per incident	0.01168	0.03403
Adjustment to include fatality as a potential from each incident.	0.21440	0.62442
Cost ratio from VSL	0	0.003
Cost per injury/severity level	$	27,300$
weighted Estimated cost for an injury	$	17,047$

% of ballast related	collisions	derailments	other
15.88%	1	258	8
1.84%	0	28	3
17.13%	2	284	2
17.25%	2	284	4
2.26%	0	36	2
0.42%	0	6	1
0.48%	0	8	0
2.91%	0	49	0
0.36%	0	6	0
9.82%	0	164	1
7.32%	3	113	7
	8	1236	28
AIS 2	AIS 3	AIS 4	AIS 5
0.10400	0.04817	0.00617	0.00279
0.00564	0.00261	0.00033	0.00015
0.10353	0.04795	0.00614	0.00278
0.047	0.105	0.266	0.593
427,700$	955,500$	2,420,600$	5,396,300$
44,278$	45,817$	14,867$	14,987$

cost	average cost	% of total cost	Fatality
42,093,946$	157,655$	3.1	0
7,639,850$	246,447$	0.6	0
23,644,948$	82,101$	1.7	0
48,758,650$	168,133$	3.5	0
5,432,510$	142,961$	0.4	0
211,714$	30,245$	0	0
800,252$	100,032$	0.1	0
6,652,976$	135,775$	0.5	0
675,574$	112,596$	0	0
27,983,423$	169,597$	2	0
30,464,267$	247,677$	2.2	1
194,358,110$	152,797$	14.1	1
Fatality			
		1.00458	
0.00079		0.05524	
0.00078	1.00000	1.00000	
1.000	9,100,000$		
9,100,000$			
7,096$	144,092$		

Injury	fatality %	injury %	
17	0.000%	24.638%	
1	0.000%	1.449%	
1	0.000%	1.449%	
3	0.000%	4.348%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
0	0.000%	0.000%	
1	0.000%	1.449%	
46	100.000%	66.667%	
69	0.079%	5.425%	0.055031447

	total incidents	% of Total
T109- Track alignment irreg(buckled/sunkink)	331	3.5
Total	331	3.5
ONLY BUCKLE		
	AIS 0	AIS 1
Occurrence of Severity per Unknown Injury	0.21538	0.62728
Estimated Rate of injury/fatality per incident	0.02822	0.08218
Adjustment to include fatality as a potential from each incident.	0.21076	0.61383
Cost ratio from VSL	0	0.003
Cost per injury/severity level	$	27,300$
Weighted Estimated cost for an injury	$	16,757$
		D(f+i)/D(a)
	Total average	0.85
	Buckled/Sunkink	0.71
	No Buckle/Sunkink	0.94
		Cost of Injury compared to normal
	Total average	1.00
	Buckled/Sunkink	1.68
	No Buckle/Sunkink	0.82

% of ballast related	Collisions	Derailments	Other
20.65%	2	327	2
0.206487835	2	327	2
AIS 2	AIS 3	AIS 4	AIS 5
0.10400	0.04817	0.00617	0.00279
0.01362	0.03858	0.00442	0.01034
0.10177	0.04714	0.00604	0.00273
0.047	0.105	0.266	0.593
427,700$	955,500$	2,420,600$	5,396,300$
43,527$	45,039$	14,615$	14,733$
D(a)/D(f+i)		D(f+i)/D(f+i+a)	D(f+i+a)/D(f+i)
1.18	1.11	0.46	2.18
1.41	1.33	0.59	1.70
1.06	1.00	0.41	2.44
Normalized to No B/S			
1.22			
2.05			
1.00			

Cost	Average Cost	% of Total Cost	Fatalities
138,037,018$	417,030$	10	6
138,037,018$	417,030$	10	6
Fatality			
		1.02192	
0.01813		0.19548	
0.01774	1.00000	2.00000	
1.000	9,100,000$		
9,100,000$			
161,417$	296,088$		
Normalized to Average	Normalized from Average to No Buckle/Sunkink	D(a+i+f)/D(a)	D(a)/D(a+i+f)
1.00	1.12	1.85	0.54
1.28	1.43	1.71	0.58
0.89	1.00	1.94	0.51
1.12			

Injuries	% occurrence of Fatalities	% occurrence of Injuries	
141	100.000%	100.000%	
141	1.813%	42.598%	0.444108761
Normalized to Average			
	Normalized from Average to No Buckle/Sunkink		
1.00	1.05		
1.08	1.14		
0.95	1.00		
1.05			

		Current VSL	9,100,000$	
		Change VSL	9,100,000$	
		D(f+i)*rate of injury		
	D(f+i)		D(a)	D(f+i+a)
Total average	175,926$	23,815$	207,358$	383,284$
Buckled/Sunkink	296,088$	131,495$	417,030$	713,118$
No Buckle/Sunkink	144,092$	7,930$	152,797$	296,889$
Average/Average	1		1	1
BS / Average	1.683028782		2.011159189	1.860548669
NBS / Average	0.819050329		0.736876029	0.774593698
Average / NBS	1.220926193		1.357080379	1.290999401
BS / NBS	2.054853924		2.729304675	2.401967217
NBS / NBS	1		1	1

D(a)+(D(f+i)*Rate of Injury)	D(f+i)*rate of injury / D(a)+(D(f+i)*Rate of Injury)	Normalize to No Buckle/kink	
231,173$	0.103	2.088	0.897
548,526$	0.240	4.859	0.760
160,727$	0.049	1	0.951

Appendix H

BALLASTSAVER DATA FOR DEFECT RELATIONSHIP ANALYSIS

Data Removed Due to Copyrighting

Appendix I

CALCULATIONS FOR DEFECT RELATIONSHIP ANALYSIS

Data Removed Due to Copyrighting