U.S. Department of Transportation

Federal Railroad Administration

Wheel Failure Investigation Program: Phase I

Office of Research, Development and Technology
Washington, DC 20590

DOT/FRA/ORD-21/04

Final Report
February 2021

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. Any opinions, findings and conclusions, or recommendations expressed in this material do not necessarily reflect the views or policies of the United States Government, nor does mention of trade names, commercial products, or organizations imply endorsement by the United States Government. The United States Government assumes no liability for the content or use of the material contained in this document.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2021	Technical Report February 2016

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Wheel Failure Investigation Program: Phase I	DTFR53-12-D-00001L
6. AUTHOR(S) Matthew Dick, Narayana Sundaram, Eric Sherrock	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ENSCO Inc. 5400 Port Royal Road Springfield, VA 22151	**8. PERFORMING ORGANIZATION REPORT NUMBER** SERV-REPT-0001670
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Office of Research, Development and Technology Washington, DC 20590	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER** DOT/FRA/ORD-21/04

11. SUPPLEMENTARY NOTES
COR: Monique Ferguson Stewart

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
This document is available to the public through the FRA website.	

13. ABSTRACT (Maximum 200 words)

In February 2016, the Federal Railroad Administration's (FRA) Office of Railroad Safety (RRS) and Office of Research, Development and Technology (RD&T) established a multi-phase research program to better understand vertical split rims and other wheel failure modes with a focus on failure causes, detection and prevention, as well as an overall life cycle understanding to help mitigate the risk and minimize wheel failure-related derailments. A key element of this program is the involvement of a Stakeholders Working Group (SWG) comprised of railroads, vendors and other industry researchers as active participants. This report highlights the initial findings of the research team, including the industry's current understanding of critical wheel failure modes, as well as future efforts intended to eliminate them.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Wheel failure, vertical split rims, VSR, shattered rims, broken flange, thermal cracking in flange, plate cracking, thin rim overload, working group, committee, rolling stock	68
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

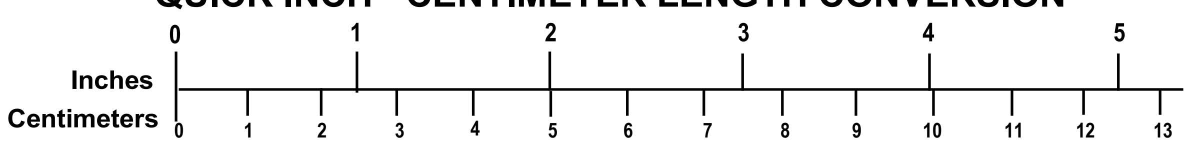
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

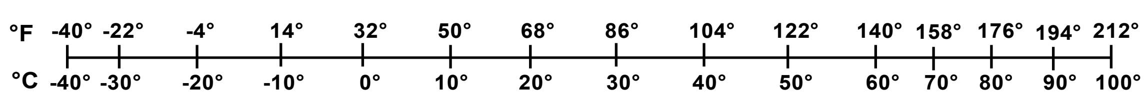
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Contents

Illustrations

Tables

Executive Summary

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology (RD&T) funded a research effort in which ENSCO, Inc. and Engineering Systems, Inc. (ESI) explored a better understanding of vertical split rims (VSRs) and other wheel failure modes to improve insight into failure causes, develop detection and prevention methods, and establish approaches to minimize wheel failure-related derailments in response to accidents associated with wheel failures that represented 11 percent of all equipment-caused train accidents between 2013 and 2015.[1]

In February 2016, researchers established a multi-phase research program to comprehensively understand various wheel failure mechanisms, identify major contributing factors to these failures, and identify potential strategies to mitigate the failures, and consequently improve the safety of rail network operations and reduce risks. There are three phases to this research, however, this report documents the initial results of Phase I and recommendations for future efforts with the creation of an industry Stakeholder Working Group (SWG) made up of members of the Association of American Railroads (AAR), car owners, and researchers as active participants in this program.

Researchers working with FRA and the SWG identified the following wheel failures: VSR; shattered rims; broken flange; plate cracking; thermal cracking in flanges; and thin rim overloads. Based on the prevalence of VSR and shattered rim failures, much of the Phase I activities were focused on these failure modes.

However, there are several aspects of VSRs that this report discusses, but further research is still required that includes:

- The various contributors to elevated tensile axial residual stress in the wheel rim at the undesirable depths from the tread surface
- The amount of tensile axial residual stress required to cause failure
- The effects of elevated wheel temperature due to braking on the creation and propagation of cracks
- The percentage of horizontal cracks that initiated a VSR that are from shelling, spalling, delamination, or other mechanism
- The cause of delamination and how can it be prevented
- The specific mechanism that causes the horizontal crack to turn downward in the vertical direction and how can that event be prevented
- The durations in miles for crack initiation, propagation and ultimate failure during the life cycle of a VSR wheel

[1] Based on accident data available from FRA's Office of Railroad Safety, November 2016.

- Whether the vertical crack occurs due to a bending load with the wheel/rail contact patch towards the front rim face, or due to stresses that occur when the contact patch is over the vertical crack area

1. Introduction

The Federal Railroad Administration (FRA) continuously evaluates derailment causes to identify trends in the industry that merit research to minimize derailments and to improve the overall safety and efficiency of railroad operations. Accidents resulting from in-service failure of freight rail vehicle wheels is one such area in which additional efforts are required.

Between 2013 and 2015, accidents associated with wheel failures represented 11 percent of all equipment-caused train accidents.[2] Broken wheel derailments tend to be more catastrophic than other derailment types due to the sudden fracture and ensuing large pile up which can occur at high train speeds. Coupled with movement of hazardous material including crude oil, this scenario poses an elevated risk to public and railroad safety. In response to this increased risk, FRA's Office of Railroad Safety (RRS) seeks to better understand vertical split rims (VSRs) and other wheel failure modes. RRS' objectives included gaining insight into failure causes, the development of detection and prevention methods, and establishment of approaches to minimize wheel failure-related derailments.

Broken wheel derailments occur when a wheel experiences a fracture that removes a significant portion of the wheel or causes the wheel to become loose on the axle. The FRA Derailment Cause Codes and the *Field Manual* of the Association of American Railroads (AAR) Interchange Rules, Rule 41 details the different types of broken wheels which can cause derailments. Wheel failures that have historically been the most problematic are:

- **Vertical Split Rim:** An example of a VSR is shown in Figure 1. A VSR occurs when near-surface tread cracking, generally shelling or spalling, reaches a critical location within the rim. This causes a rapid, vertical fracture to occur in the rim with subsequent loss of material. VSR failures have been a growing failure mode in North American heavy haul operations. Unfortunately, current wheel research has not identified the root cause of or proper mitigation actions for VSR failures. Recent research (Lonsdale, C., & Oliver, J., 2013) has identified tensile residual stress in VSR wheel rims, but the origin of the residual stress is currently unknown. Although some railroads have noted a decrease in VSR failures over the past several years, this wheel failure mode continues to represent a derailment risk.
- **Shattered Rim:** A wheel that experienced a shattered rim failure is illustrated in Figure 1. Shattered rim failures are caused by Hertzian contract stress creating subsurface fatigue cracking initiated at voids or inclusions. A thin rim thickness can often aid the Hertzian contact stress to reach subsurface voids/inclusions. The subsurface fatigue crack can generally enlarge before fracture, causing a large loss of material on the wheel rim.
- **Thermal Crack Extended into Plate:** An illustration of a wheel with a thermal crack extending into the wheel plate is provided in Figure 1. A thermal crack is a transverse fatigue crack initiated at the surface of the tread or flange that occurs when the rim hoop residual stress is transformed from the beneficial compressive stress to the detrimental tensile stress. This stress reversal occurs due to significant tread braking. If the fatigue

[2] Based on accident data available from FRA's Office of Railroad Safety, November 2016.

crack grows during repeated heating cycles to the point when it eventually reaches the critical size, a large transverse overload fracture will propagate into the plate and can turn to remove a large portion of the rim and plate, or go to the hub and cause the wheel to become loose on the axle.

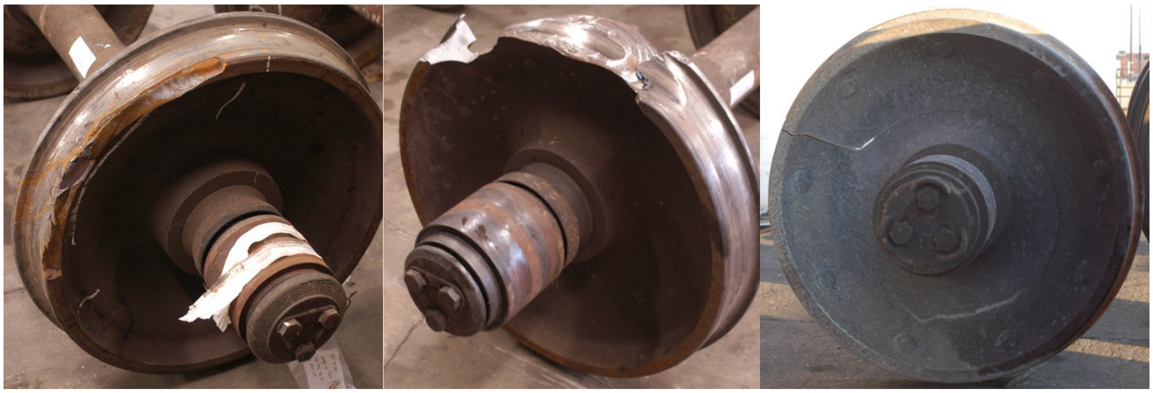


Figure 1. Example of Vertical Split Rim, Shattered Rim, and Thermal Crack Failed Wheels

Wheels can also fail due to less common causes such as plates with cracks not extending through the rim. These cracks are caused by conditions such as manufacturer defects.

1.1 Background

VSR failures have been a growing failure mode in North American heavy haul railroad operations over the last few decades. Unfortunately, current train wheel research has not identified the root cause of or proper mitigation actions for VSR failures. Regarding VSRs, it is generally understood that:

- VSR failures were extremely rare before 1990 and experienced a significant increase after 2000.
- No significant or common metallurgical deficiencies have been found with VSR wheels. VSRs are most commonly AAR Class C wheels which are heat treated with rim quenching.
- VSR failures are very rare in passenger cars and international railways.
- As described by AAR members, the number of VSR failures appear to be lower on eastern U.S. freight railways as compared to the western U.S. and Canadian freight railways. It has been noted that in the U.S. specifically, western railways tend to have different operational practices including trains with higher mileage as compared to the eastern railways. Additional work is needed to normalize the failure data considering operational practices and other relevant factors to confirm overall industry trends.
- The most common car type experiencing VSRs was the covered hopper car in which several failures were found on the B-end truck. At the same time, covered hopper cars also represent proportion similar to the car distribution population in North America.
- VSRs like other wheel defects occur more often during the winter months.

- VSR failed wheels had a wide range of rim thickness values but tended to have a thinner rim than the general wheel population. This was evident in the MD-115 data where the minimum and maximum rim thickness of VSR wheels was 0.75 and 1.75 inches, respectively. The most common rim thickness associated with VSRs considered in Phase I was 1.0 inch. Normalization of the rim thickness data using information from non-failed wheels with similar accumulated service life as the failed wheels should be considered to clarify this result.
- Wheel impact load detectors (WILD) have commonly observed elevated impact loads on VSR wheels prior to failure.
- VSR wheels often had hollow wear prior to failure. Several research teams have noted that a hollow wear condition was a significant factor with VSR failures investigated.
- A working hypothesis explaining how VSRs develop and progress is highlighted by:
  - Tensile axial residual stress occurs in the wheel rim due to service loads on the wheel. Testing by Transportation Technology Center, Inc. (TTCI) and Amsted Rail found that negligible axial residual stress occurs from the manufacturing process.
  - A tread surface or subsurface horizontal crack is initiated and grows. These horizontal cracks can be surface initiated (e.g., shelling/spalling/RCF/thermal cracking) or subsurface initiated (e.g., delamination).
  - Eventually the horizontal crack meets the tensile axial residual stress zone, turns and begins to grow rapidly in the vertical direction. This vertical crack continues to grow rapidly with periodic crack arrests.
  - Eventually the vertical crack becomes large enough around the circumference of the rim that the front rim face—or the back rim face/flange—completely fractures off the rim.

Past studies and research have focused on developing an understanding of wheel performance from various perspectives, including material properties (e.g., metallurgy, strength, and toughness), manufacturing processes (e.g., casting, forging, heat treatment, surface treatment, residual stresses), design parameters (e.g., wheel diameter, rim thickness, plate type), and the operating environment (e.g., axle load, maximum operating speed, tread braking capacity, wheel-rail interaction under curving and traction conditions, and track perturbations, etc.). However, a definitive study to determine the underlying mechanism(s) for catastrophic wheel failures such as shattered and vertical split rims and potential solution(s) and strategies to minimize derailments due to these types of wheel failures remains to be completed.

In response to this need, FRA's Office of Research, Development and Technology (RD&T), working in cooperation with RRS, established a multi-phase research program in February 2016 to establish a comprehensive understanding of the various wheel failure mechanisms, identify major contributing factors to these failures, and arrive at potential strategies to mitigate the failures and consequently improve rail network operations, safety, and reduce risks. The initial vision of this program includes the following phases with Phase I as the focus of this research:

- Phase I: Problem Definition and Scope Analysis

- Phase II: Review and Analysis of Tests and Analytic Studies on Investigation of Wheel Failure Mechanisms
- Phase III: Modeling and Analysis of Underlying Wheel Failure Mechanisms and Failure Prevention and Mitigation Strategies

1.2 Overall Approach

A key element of the FRA's approach is its creation of an industry Stakeholder Working Group (SWG) made up of railroads, car owners, and researchers as an active participant in the research program. Membership in the SWG included personnel from:

Membership Personnel List	
Association of American Railroads (AAR)	Griffin Wheel, an Amsted Rail Company
Burlington Northern Santa Fe Railway (BNSF)	Norfolk Southern Corporation (NS)
Canadian National Railway (CN)	ORX Rail
Canadian Pacific Railway (CP)	Standard Steel
CSX Transportation (CSX)	Transportation Technology Center, Inc. (TTCI)
GATX Corporation (GATX)	Union Tank Car
Greenbrier Companies	Union Pacific Railroad (UP)
Volpe National Transportation Systems Center	

Members of the research team including FRA, ENSCO, Inc., Engineering Systems, Inc. (ESI) and the SWG met on a near-monthly basis to discuss current knowledge and research needs. To date, the group has:

- Reviewed recent and ongoing research activities
- Identified fundamental information needs
- Initiated collection of failed wheels for further evaluation and lab-based testing
- Established a general analysis approach and identified sources for data to address knowledge gaps

1.3 Scope

Along with VSRs, shattered rim failures and their characteristics were also analyzed as part of this effort. Shattered rim failures are another type of wheel failures that are often confused with VSRs. Shattered rim failures are characterized as a large subsurface fatigue crack created by Hertzian contact stress resulting in a characteristic "bullseye" fatigue fracture pattern, characterized by circular patterns emanating from a specific area, roughly perpendicular to the tread surface. Eventually the bullseye fatigue fracture grows large enough to cause a final overload fracture which results in the separation of a large portion of the tread. A key physical distinction between shattered rim failures and VSRs is that in a pure shattered rim failure, the crack does not turn vertical. Interestingly, there are occasions where a shattered rim fatigue fracture can cause a VSR. The SWG agreed that if the subsurface crack is deeper than 3/8th inch, then it should be classified as a shattered rim. If the subsurface crack is shallower than 3/8th inch, then it should be classified as a VSR. The basis for this classification criteria was that the SWG members' experience indicated that subsurface cracking that is deeper than 3/8th inch most commonly had the shattered rim characteristics noted above.

Suggested research needs to further address shattered rim failures:

- Further research should be conducted to determine what WILD value and number of impacts are required to initiate a shattered rim failure. Previous studies have attempted to do this with limited success, but it is generally felt by the SWG that this is still an important area for study.
- Further research should be conducted to evaluate the correlation of thin rims and shattered rim failures.
- Additional research is required to determine if residual stress affects the creation of shattered rims.

The ENSCO research team has proposed several recommendations for FRA's consideration as part of this multiphase effort:

- Vertical Split Rim Wayside Detector Combination Criteria - A short-term, high-reward strategy to reduce VSR failures is to determine a combination criteria employing wayside detectors that correlates to a high probability of the wheel having a VSR. It is envisioned that this criteria may include a combination of rim thickness, hollow wear, WILD history and potentially hot wheel history. The wheels that are removed can be further analyzed to help understand the underlying root cause of the failures.
- Thin Rim Practices - Further research should be conducted to investigate the correlation of thin rim and VSR failures. A statistical and economic analysis should be performed to investigate changing Title 49 Code of Federal Regulations (CFR) § 215.103(c)–Defective wheel.

  Some stakeholders expressed concern that failed wheelsets comprise an extremely small fraction of the wheelset population (less than 0.0035%), whereas increasing the minimum rim thickness would shorten the average service life wheels by a certain percentage governed by the threshold that would be used to identify wheelsets. Other aspects that should be researched to better understand this potential impact include:

  - Economic and safety/risk improvement of applying a more conservative rim thickness criteria to hazardous materials and crude oil tank cars
  - Evaluation of current ultrasonic technology (UT) or current use of the technology to determine if inclusions/voids which can cause a shattered rim can be better detected
  - Investigation of the benefits of turning a wheel to remove surface defects and reduce VSR residual stress. If these practices are found to be beneficial, then an investigation should take place of the economics and safety/risk improvement of requiring wheel turning and UT testing on non-new wheels before they are returned to service and/or testing while the car is shopped.
- Residual Stress - There are still many aspects that should be researched:

- Development of test methodology to determine the peak tensile axial residual stress within a wheel accounting for relaxation caused by fracture. This process should ideally be independent of where in the wheel the test specimens were extracted from.
- How do wheel impact forces contribute to axial residual stress values and is there a correlation between WILD impact values and axial residual stress values?
- Previous researchers have proposed the usage of kip-days and kip-miles to quantify accumulated damage on wheelsets and identify a wheel that will fail from a VSR. Further investigations should be conducted to evaluate the benefits of these metrics and their use in early identification of VSR development.
- What is the correlation between braking temperature and axial residual stress values?
- Do simultaneous WILD impact conditions and tread braking affect the axial residual stress?
- In one study, axial residual stress generation rates in a new wheel and a turned wheel have been shown to be different (Lonsdale, C., & Oliver, J., 2013). A more comprehensive study of the effects of turning on residual stress generation and the location of peak stress should be conducted which could lead to potential changes to the wheel maintenance practices in North America.
- Quantification of growth rates for axial residual stress with varying combinations of normal rolling contact loading and impact loading should be conducted.

It is recommended that a test and/or analysis program be created to further the residual stress research to answer these questions.

- Rim Quenching - Further research should be conducted to investigate the role that rim quenching plays in VSRs and experimentation to determine if modifications to the rim quenching process can be made to still retain the beneficial compressive hoop residual stress, but reduce the tendency for Class C wheels to generate tensile axial residual stress during service.
- Delamination - Further research is needed to determine the root cause of delamination. The first task is to determine the percentage of VSR failures initiated by delamination. This will help determine the overall priority of the delamination failure mechanism. The initiation of the delamination should be investigated to determine if it is caused by manufacturing issues associated with inclusion/voids and if the "cigar" shaped crack growth can be defined by residual stress, brake application location and/or wheel/rail contact conditions.
- VSR Causes Data Analytics and VSR Recreation in Lab/Field Testing - A data analytics approach is proposed to determine the underlying relationship between contributing factors to create an equation to be used to predict VSR failure risk. Once this equation is developed and validated using past VSR failure data, it can be used to aid in recreating a VSR in the lab or field testing.
- Wheel Turning Economic Analysis - North American freight railroads use single wear wheels which typically have zero or one turn before end of life. It appears that the North American freight railroads are an outlier in the world for not utilizing multi-wear wheels

and routinely turning the wheels. An economic analysis should be performed to evaluate the benefits and impacts of transitioning the North American freight wheel practice from a wear-until-failure approach to one that employs preventive truing practices. It is anticipated that the economic benefits of preventive wheel truing on the wheels themselves will be modest. However, the economic benefits of prevented derailments, extended rail life and reduced rail grinding could be significant; these aspects should be considered in the overall analysis.

- Roadmap for Shattered Rim Failure Extinction - Shattered rim failures have significantly reduced over the past decades but they have not been eliminated. Further research work should be performed to determine the roadmap to reduce shattered rim failures to the levels of modern thermal crack failures.
- MD-115 Database - Additional improvements should be made to the AAR MD-115 database and associated procedures to ensure that the database can be used to identify important trends that can help identify wheel failure trends in a similar way track inspection records are used in § 213.241–Inspection records.

1.4 Organization of the Report

This report documents the initial results of Phase I efforts and recommendations for future efforts to be undertaken in subsequent research activities. The report is organized as follows:

- Section 2 summarizes the predominant wheel failure issues facing the North American rail industry.
- Section 3 presents a consideration of the current understanding of VSR wheel failures.
- Section 4 provides an overview of the current understanding of shattered rims.
- Section 5 presents the recommendations for the next steps in a comprehensive research program targeted at the elimination of wheel failures as they exist today.
- Section 6 summarizes the overall results.

2. Wheel Failure Overview

SWG established an understanding of the current state of wheel failures in North American freight railroads through conference calls and reviewing industry data that included railroad-reported wheel failures, FRA derailment data, and railroad laboratory reports.

Figure 2 depicts wheel failures by year as determined from the completed AAR Form MD-115 and failed wheel reports compiled by the railroads themselves. Using photographs of failed wheels that have been included in the MD-115 database since 2010, an AAR/TTCI review of the reported failures associated with code Why Made 68-Broken Rim (WM68) wheels determined that there were two failure types attributed to code WM68 - VSR failure and thin rim overload failure. This distinction is shown in Figure 2 in the number of types of WM68 wheel failures reported after 2010.

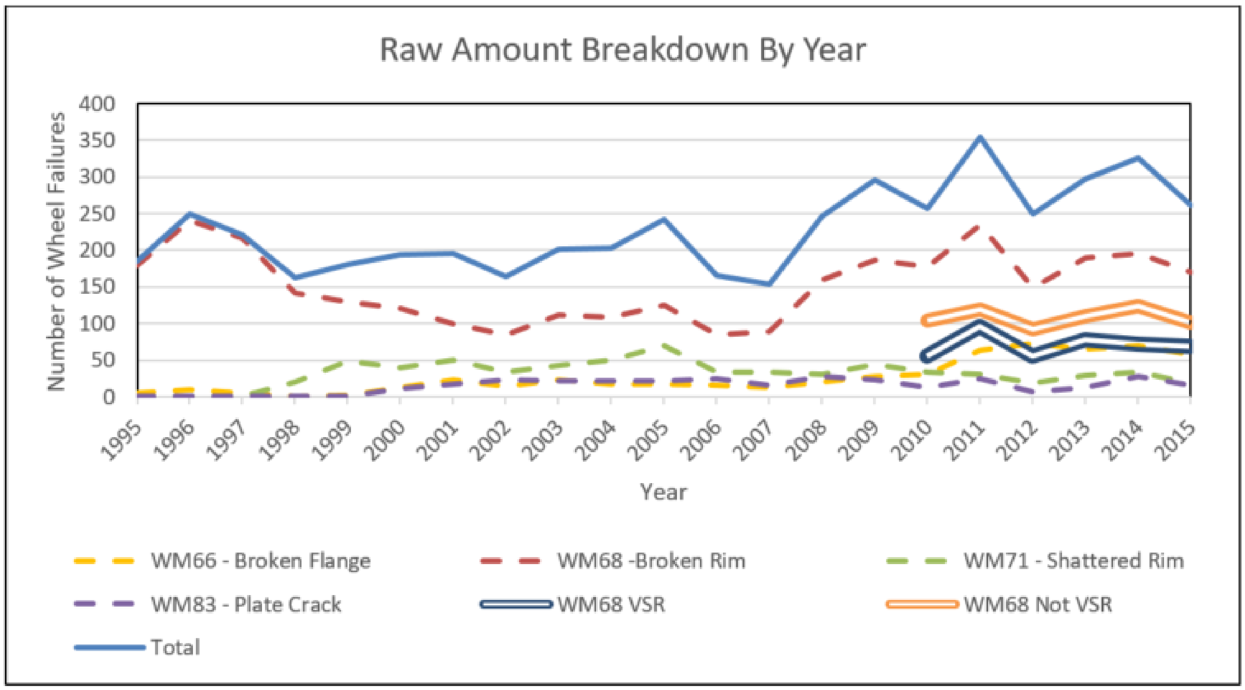


Figure 2. Wheel Failures Reported in the AAR MD-115 Database from 1995 to 2015

Figure 3 illustrates the breakdown of wheel failures incurred between 1995 and 2015 and that WM68 broken rim failures are the biggest contributor to wheel failures. TTCI's review of photographed WM68 failures indicated that confirmed VSR or vertical split flange (VSF) wheel failures accounted for 41.2 percent of the WM68 category. This number was thought to be lower than the industry belief for the proportion within the WM68 category. Further analysis should be conducted to understand the cause of the majority of the WM68 failures. The AAR Wheel, Axle, Bearing, and Lubrication (WABL) Committee, which is responsible for maintaining the MD-115 database, is considering the creation of a new category for rim overload failures which are said to be a major cause of the non VSR/VSF WM68 failures.

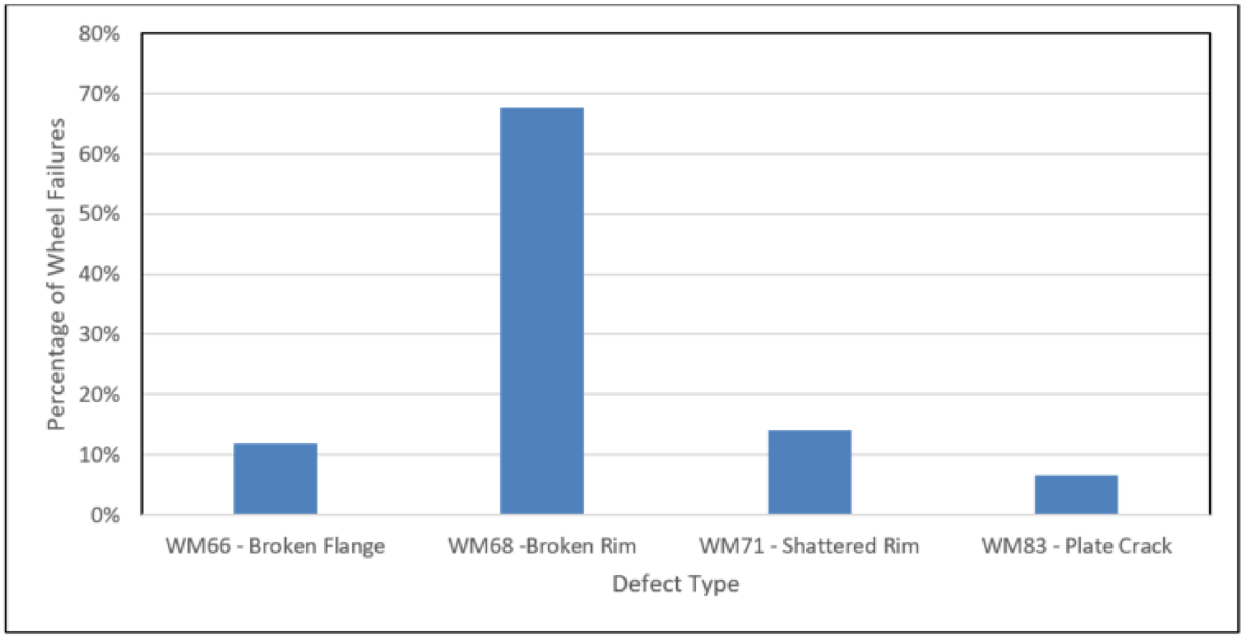


Figure 3. Breakdown of the Type of Wheel Failure Experienced by the North American Railroads, 1995 to 2015

It is important to note that results reported in the MD-115 database are not intended to be the final source of analysis. One of the original goals of the database was to serve, in part, as a distributed early warning system to the existence of wheel, axle, bearing, and casting related issues that may be affecting the industry. Results from analysis of the MD-115 database are intended to serve as a guide to further analysis and investigation.

The following table summarizes major failure modes where significant portions of the wheel are removed, presenting a derailment risk. Table 1 does not include tread surface or near-surface failure modes (i.e., shelling, spalling, rolling contact fatigue (RCF), "delamination"). The intention of Table 1 is to provide a high-level priority to the wheel failure types at the onset of this project.

Table 1. Summary of Major Wheel Failure Modes

	Summary of Major Wheel Failure Modes
Priority	1
Type	Vertical Split Rim – AAR WM68
Photo	
Notes	• VSRs are currently the most prevalent high derailment risk failure modes in the North American freight industry. • VSR failures are characterized as a large portion of the front rim face fracturing off. Occasionally it is the back rim face including the flange that fractures off which is then called a VSF. • Currently the underlying mechanism that causes a VSR is not well understood by the industry and it was a major focus of this project to investigate its root cause(s). • Further discussion is provided in Section 3.
Priority	2
Type	Shattered Rim – AAR WM71

Summary of Major Wheel Failure Modes	
Photo	
Notes	• Shattered rim failures are the second highest derailment risk failure mode in the North American freight industry. • Shattered rim failures are characterized as a large subsurface fatigue crack created by Hertzian contact stress resulting in a characteristic “bullseye” fatigue fracture. • Shattered rim failures have been on the decline due to improvements to manufacturing processes and removal of high risk wheels such as those manufactured by Southern Wheels (SO or ABEX). • However, shattered rim failures still take place in the industry so further work is still needed. • Further discussion is provided in Section 4.
Priority	3
Type	Broken Flange – AAR WM66
Photo	
Notes	• Broken flanges are characterized by portions of the flange being broken out due to an excessively thin flange. • Generally broken flanges are rare failure types, however, during the review of MD-115 data, it was found that broken flanges were responsible for a significant increase of failures since 2011. Further work is needed to investigate this increase in broken flanges.

	Summary of Major Wheel Failure Modes
Priority	4
Type	Plate Crack – AAR WM83
Photo	
Notes	• Plate cracks are characterized as fracture that initiated at the plate, which can cause a large portion of the plate and rim to fracture out. • Plate cracks are generally rare, but when they occur, they can cause derailments. • Plate cracks can be caused by several different mechanisms such as manufacturing defects.
Priority	5
Type	Thermal Cracking in Flange – AAR WM74
Photo	
Notes	• Thermal cracks are characterized as fatigue cracks originating at the flange or tread that propagate in the transverse direction into the rim. • Thermal cracks are now a very rare failure mode due to the mandatory use of rim quenching starting in 1989 which introduces beneficial compressive hoop residual stress.
Priority	6
Type	Thin Rim Overload Failure – AAR WM68

Summary of Major Wheel Failure Modes	
Photo	
Notes	• A thin rim overload failure is characterized as a portion of the front rim face fractured off due to a thin rim and a large wheel/rail impact. This failure mode differs from a VSR failure type because it is 100 percent overload. • This failure is currently classified as a WM68, which causes confusion with VSRs which are also classified as WM68. • It is anticipated that this failure mode is a relatively low derailment risk, but should still be monitored and investigated.

3. Current Understanding of Vertical Split Rim Failures

The information contained in this section represents the current understanding of VSR failures determined through data analysis, a review of existing literature, and SWG discussions.

3.1 Common Characteristics of Vertical Split Rim Failures

The following is a summary of the understanding of VSR failure characteristics:

- Anecdotally it is believed that VSR failures did not occur prior to mid-1990s (Cummings, S., Oliver, J., & Lonsdale, C., 2011). SWG members were asked about the first observations of VSR SWG members (Lonsdale & Oliver, 2011) have documented VSR failures occurring in the early 1990's. Previous work by several SWG members noted a significant increase in VSR failures after 2000 (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). It is important to note that rim quenching was made mandatory in 1989 and 286K gross vehicle load operation was instituted in 1991.
- No significant or common metallurgical deficiencies have been found with VSR wheels. Cummings (2011) noted that out of 30 VSR wheels evaluated, only 2 had metallurgy that did not meet specifications.
- VSRs commonly occur in AAR Class C wheels which are heat treated with rim quenching. It was noted that non-heat-treated AAR Class U wheels rarely incurred VSR failures (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). It should be noted that Class C wheels also represent most of the population of wheels in use by the industry.
- VSR failures are very rare in passenger cars and international railways. Cummings (2016) conducted a survey of international railways and found that VSR failures were rare, very rare, or never occurred. This was attributed to thicker rims and more frequent turning of the wheels. It is important to note that the North American freight railroads generally use single wear wheels which typically have zero or one turn before end of life.
- It is the general impression of SWG members that VSR failures are less frequent on eastern U.S. freight railways as compared to the western U.S. and Canadian freight railways. The reason for this difference is still not completely understood.
- Analysis of MD-115 data indicates that:
    - Wheel type, wear type, wheel size, car gross rail load (GRL), and car type of VSR wheels did not vary significantly from the general population distribution for the respective characteristics. For example, the most common car type experiencing VSRs was the covered hopper car (20% of the failures) in which most failures were found on the B-end truck. At the same time, covered hopper cars also represent a similar portion (25%) of the car type population on the North American freight railways.
    - VSRs like other wheel defects occur more often in the winter.
    - VSR wheels had a wide range of rim thickness values but tended to have a thinner rim than the general wheel population. Histograms of rim thickness values for failed

wheels as well as the general population considered during this initial analysis support this observation (Stratman, B., 2007). It should be noted that the initial assessment did not consider mileage and wheel age; normalization with respect to mileage and other operational factors will need to be conducted to produce a more robust analysis.

- Analysis of railroad provided laboratory reports indicates that:
  - VSR wheels often had an impacting condition prior to failure. Many research efforts noted that WILD impacting condition was a significant factor with VSR failures investigated (Meddah, A., & Stone, D., 2013), (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010), (Stone, D., Tournay, H., & Cummings, S., 2009), (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010), (Tournay, H., 2010), (Tournay, H., & Jones, K., 2016), (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008) (Cummings, S., 2011).
  - VSR wheels often had hollow wear prior to failure. Several research teams have noted that a hollow wear condition was a contributing factor with VSR failures investigated (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010), (Stone, D., Tournay, H., & Cummings, S., 2009), (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010), (Tournay, H., & Jones, K., 2016), (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008) (Kristan, Elkins, & Stone, 2004).

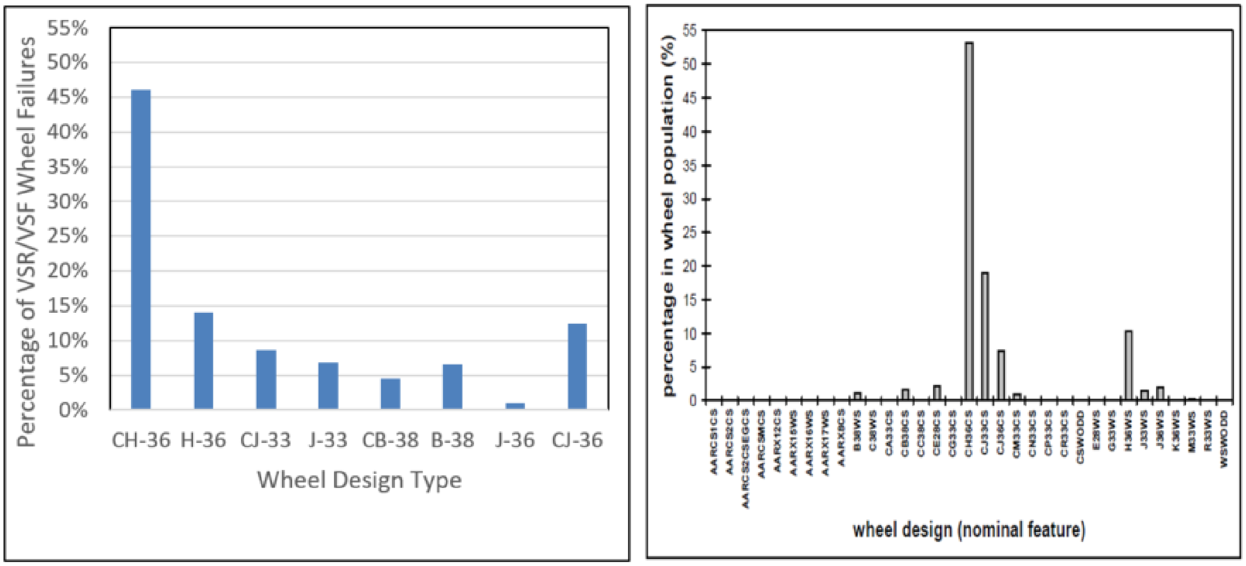
The noted common characteristics of VSR wheels as determined from Phase I data analysis are detailed in the remainder of this section. The objective of the analysis was to determine unique characteristics (e.g., car type, wheel type, wear condition, etc.) of VSR wheel failures, if any, as compared to the general population distribution. Several data sources were used under this effort including:

- MD-115 database records for confirmed VSR/VSF failures from 2010 to 2015 and laboratory reports provided by the participating railroads from 2010 to 2016; the collection of this information resulted in a total of 705 failures for initial consideration
- General population statistics from previous work done by Vanderbilt University (Stratman, B., 2007) and public reports produced by Railinc (2015)
- General wheel population statistics for rim thickness and flange thickness over a 6-day period between April 24 and April 30, 2016, made available by TTCI

The following parameters do not show any difference in the failure population statistics as compared to the general North American population:

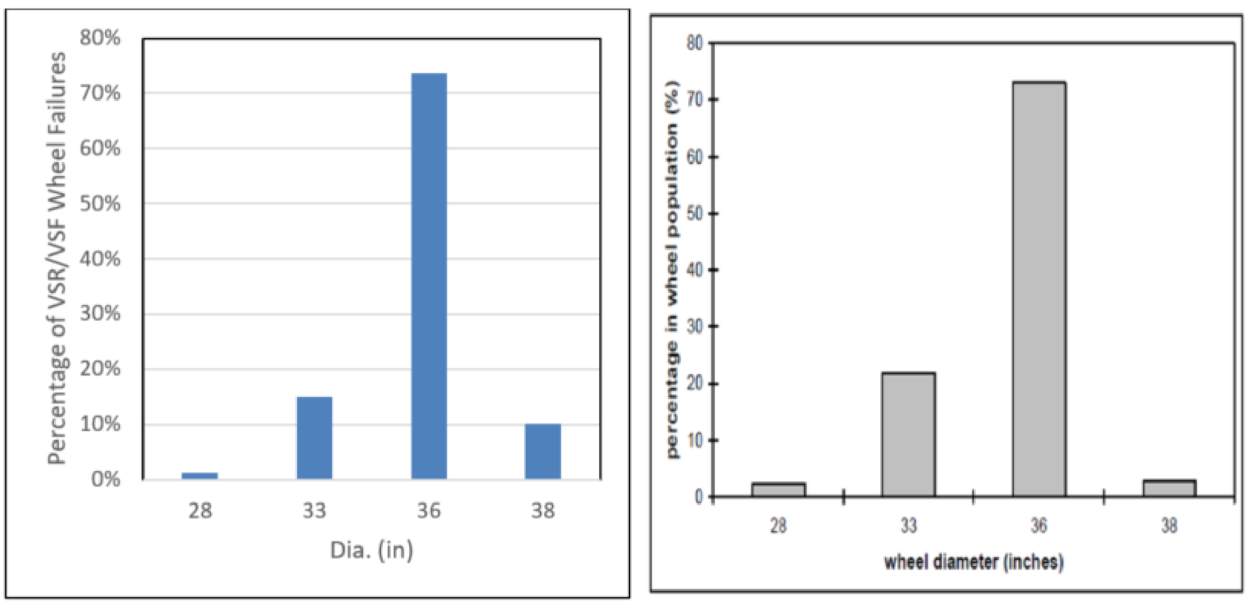
- Wheel design type as shown in Figure 4
- Wheel diameter as shown in Figure 5
- Vehicle/car type as shown in Figure 6

This would suggest that there is no direct dependence between any of these parameters and the occurrence of VSR failures.



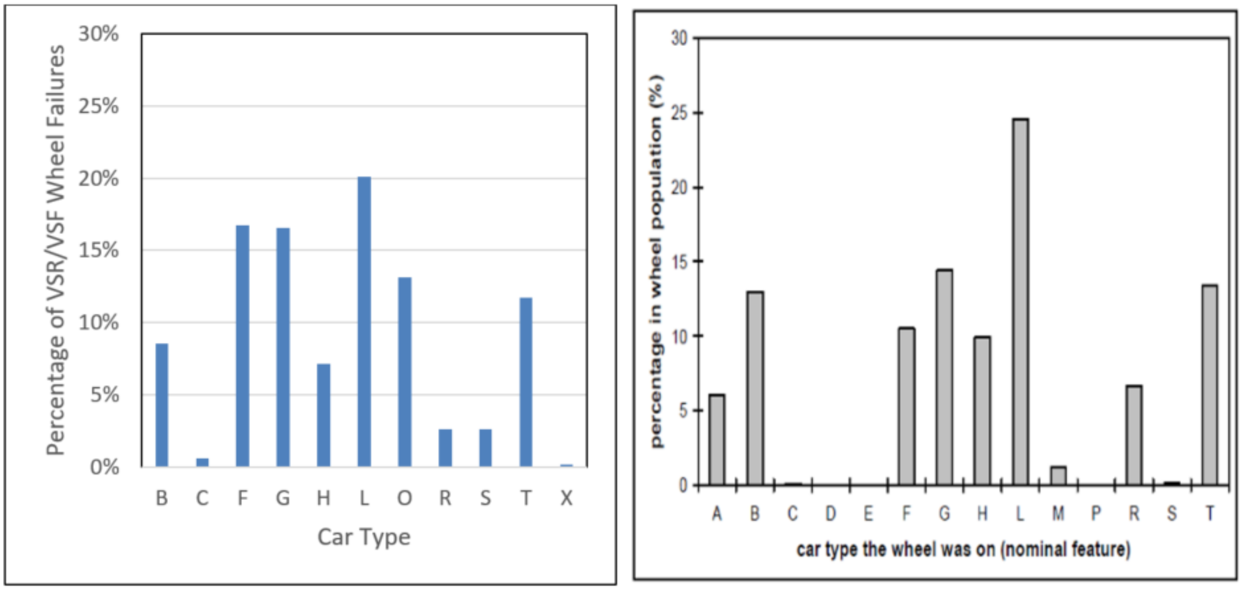
(a) VSR/VSF **(b) Wheel Population (Stratman, B., 2007)**

Figure 4. VSR/VSF Failure Rate (a) Compared to Wheel Population Distribution in North America (b) for Wheel Design Type



(a) VSR/VSF **(b) Wheel Population (Stratman, B., 2007)**

Figure 5. VSR/VSF Failure Rate (a) Compared to Wheel Population Distribution in North America (b) for Design Wheel Diameters



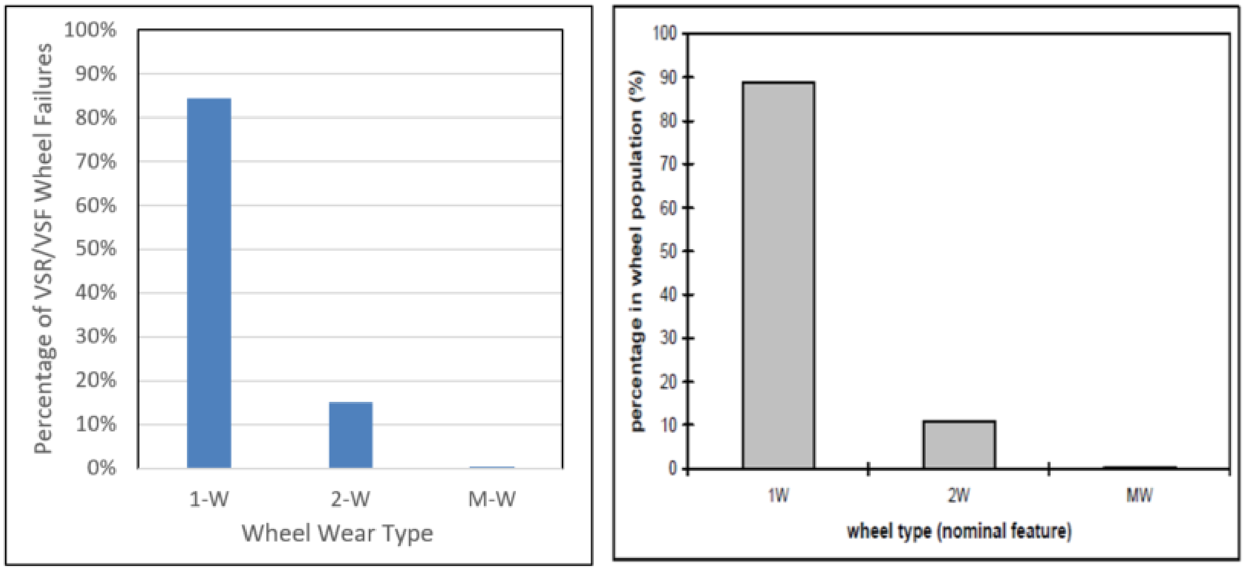
(a) VSR/VSF **(b) Wheel Population (Stratman, 2007)**

B - Box	C - Cab	F - Flat	G - Gond.	H - Hopper	L - Covhop.	O - Other	R - Refrig.	S - Stack	T - Tank	X - Loco

Figure 6. VSR/VSF Failures (a) Compared to General Population Distribution in North America (b) for Various Car Types

VSRs are extremely rare in domestic and international passenger wheels, and international freight wheels, including Australian mining railroads which operate at higher axle loads than the North American freights (Lonsdale, C., Oliver, J., Bitner, A., & Guzel, H., 2013). It is important to note that the aforementioned railroads that do not have VSR failures generally utilize multi-wear wheels and routinely turn the wheels. However, the North American freight railroads predominantly use single wear wheels which typically have one turn or less before end of life. Several other differences exist between the North American railway system and other heavy haul railway systems in the world, including the use of a higher percentage of cast wheels, a colder winter environment, and a more demanding service environment in terms of grades and curves in North America (Cummings, S., 2014).

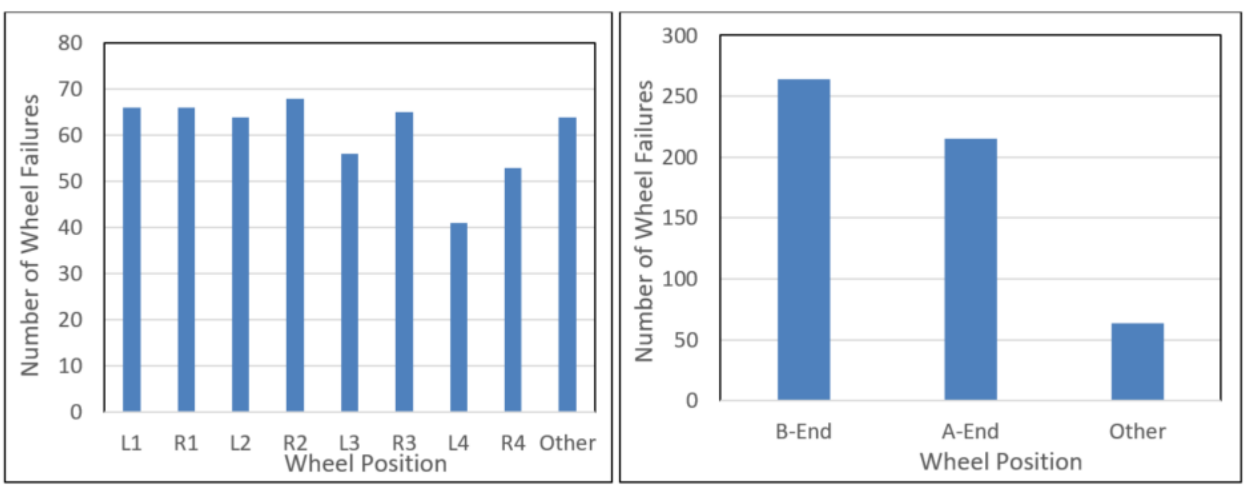
The analysis of VSR/VSF failure rate with respect to wheel wear type shown in Figure 7 indicates that the failure population rate is like the general population distribution in the North American freight industry. This also suggests that a direct correlation between VSR/VSF failure rates and wheel wear type is unlikely.



(a) VSR/VSF **(b) Wheel Population (Stratman, B., 2007)**

Figure 7. VSR/VSF Failure Rate (a) Compared to General Population in North America (b) for Wheel Wear Type

Correlations between failure rates and the position of the failed wheel were also investigated. Figure 8 shows that the B-end truck wheels grouped from individual positions L1, R1, L2, R2 have a slightly larger number of failures than wheels on the A-end truck do. At this stage of the study, it is unclear if this is due to issues associated with the braking on the B-end trucks or some other factor such as a general tendency for differential loading from one end of the car to the other. The data considered under this effort was grouped in terms of the failed position as well as car type and it was noted that 264 (55%) of 479 VSR failures were on the B-end.



(a) Wheel Position of Reported Failures **(b) Failures Grouped into Each End of Car**

Figure 8. Wheel Position of VSR/VSF Failures

The position of failed wheels was further analyzed with respect to vehicle type and indicated in Table 2, it was observed that 68 of 98 (69%) VSR failures in the covered hopper cars were on the B-end. Most covered hopper cars have truck mounted brakes and it has been hypothesized during a SWG discussion that the greater tendency of VSR failures on B-end trucks could be resulting from a potentially greater chance of hand brakes being left on in vehicles that have truck mounted brakes. Further analysis needs to be conducted in this area to understand this bias including:

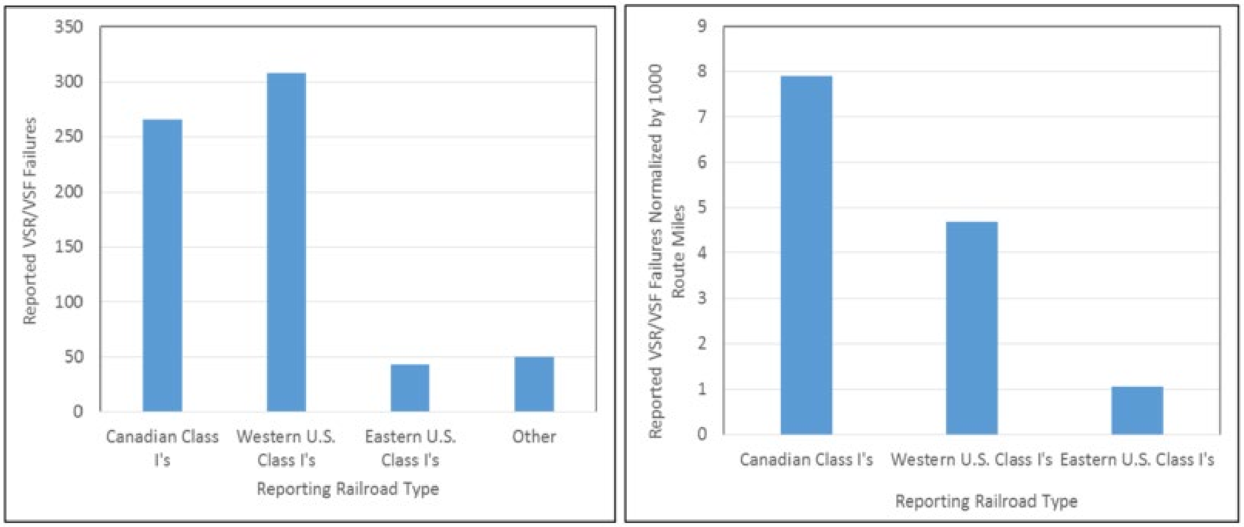
- Determining if more high-impact wheels are being replaced on the B-end for freight cars. This is available from car repair billing (CRB) data maintained by the freight railroads.
- The role of differential wheel loading, if any
- Determining whether the B-end has a greater tendency to create a wheel slide and produce impacting wheels

Table 2. VSR/VSF Failure Rate for a Combination of Vehicle Type and Wheel Position

Car Type	L1	R1	L2	R2	L3	R3	L4	R4	Other	Total Per Car
Box Car	5	6	9	8	5	3	3	1	0	40
Covered Hopper	16	22	16	14	10	9	10	1	0	98
Gondola	12	12	8	10	10	6	11	2	0	71
Flat Car	9	6	3	5	4	3	7	1	0	38
Open Hopper	3	4	2	4	3	4	2	2	0	24
Stack Car	4	4	6	5	2	7	5	4	37	74
Tank Car	8	6	9	10	6	5	4	3	0	51

VSR/VSF failures reported between 2005 and 2015 were analyzed with respect to reporting the accuracy of the general perception that western U.S. and Canadian railroads report more wheel failures of this nature than eastern U.S. railroads. Figure 9a shows the number of VSR/VSF failures reported by the various railroad categories over the period in question. To remove railroad "size" from these results, the number of VSR/VSF wheel failure reports were normalized by the total number of route miles attributed to the major Canadian, western U.S. and eastern U.S. railroads reporting the failures;[3] results provided in Figure 9b. Although normalization of these reported failures based on the general wheel population of each of the railroads would be more appropriate than normalization by route miles, results shown in both Figure 9a and Figure 9b supports the general perception regarding the relative number of failures on railroads from different parts of North America. The multitude of factors that could explain the differences in reported failures requires an additional study.

[3] Route miles collected from individual railroads' annual reports and investor summary reports from 2014 and 2015.



(a) Reported Failures Grouped by Railroad Type **(b) Reported Failures Normalized by Route Miles**

Figure 9. VSR/VSF Failures Between 2005 and 2015 Reported by Railroad Groups

Introduction of 286K GRL freight vehicles were thought to be a contributor towards the increase in VSR failures over recent years. Analysis results shown in Figure 10 shows that the failure rate population follows the general population distribution of car weights in the freight industry, indicating a lack of strong correlation between VSR failures and vehicle loads.

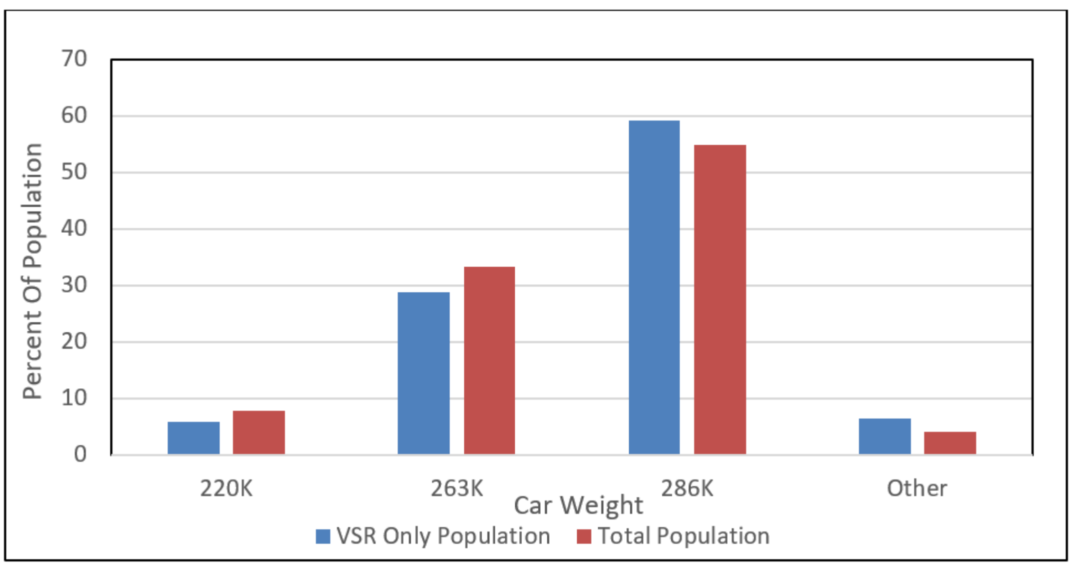


Figure 10. VSR/VSF Failure Rate as Compared to the General Population Distribution (Railinc, 2015)

VSR failures are more prevalent during the winter months as shown in Figure 11.

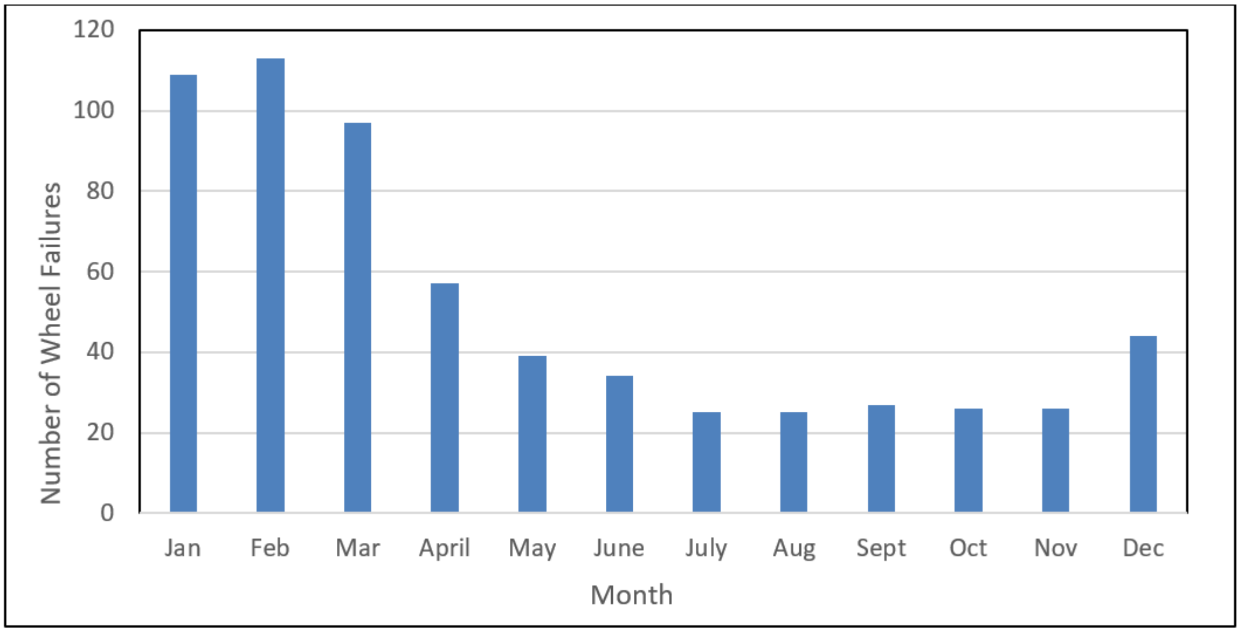


Figure 11. VSR/VSF Failures per Month of Year

An anonymized distribution of wheel manufacturer codes entered for confirmed VSR/VSF failures within the MD-115 database between 2008 and 2015 is shown in Figure 12. This distribution compared to the general wheel population cited in a 2007 study shows some noticeable differences, indicating that the occurrence of VSR/VSF failure may not be evenly distributed throughout the general population, because the wheel population distribution has changed considerably since 2007 (Stratman, B., 2007). One contribution to the changing wheel population is the removal of wheels manufactured by Southern Wheels between 1993 to 1999 when the car is in a shop or repair track required by *AAR Field Manual* Rule 41 A.2.j. Further analysis of manufacturers of failed wheels employing current wheel population statistics is required.

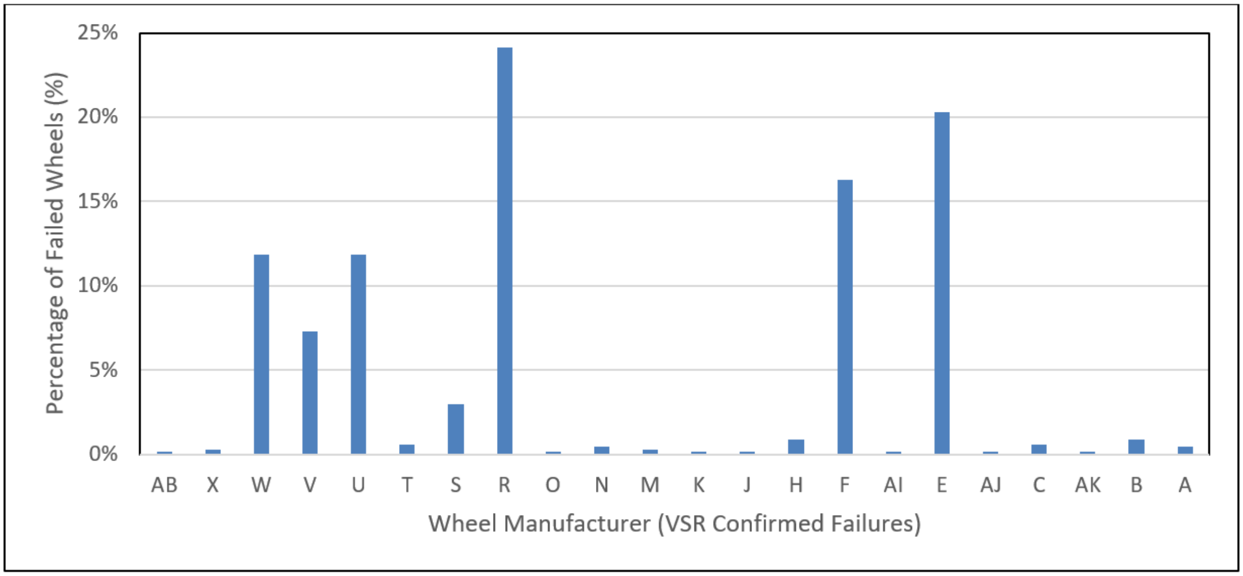


Figure 12. VSR/VSF Failures per Manufacturer

VSR/VSF wheel failure data were assessed to identify potential trends based on the manufacturing date of the failed wheels. As indicated in Figure 13, wheels manufactured in 1995 and 2005 experienced more failures than the general failure rate observed in other recent years. Based on discussions with the SWG, high failure rates for wheels manufactured in 1995 could be associated with the large number of failed wheels manufactured by Southern Wheels; as noted earlier, removal of wheels manufactured by Southern Wheels between 1993 to 1999 is required by *AAR Field Manual* Rule 41 A.2.j. It should be noted that further analysis is required to determine the cause of the high failure rates for wheels manufactured in 2005. Normalizations to consider the rate of wheels purchased per year should also be considered.

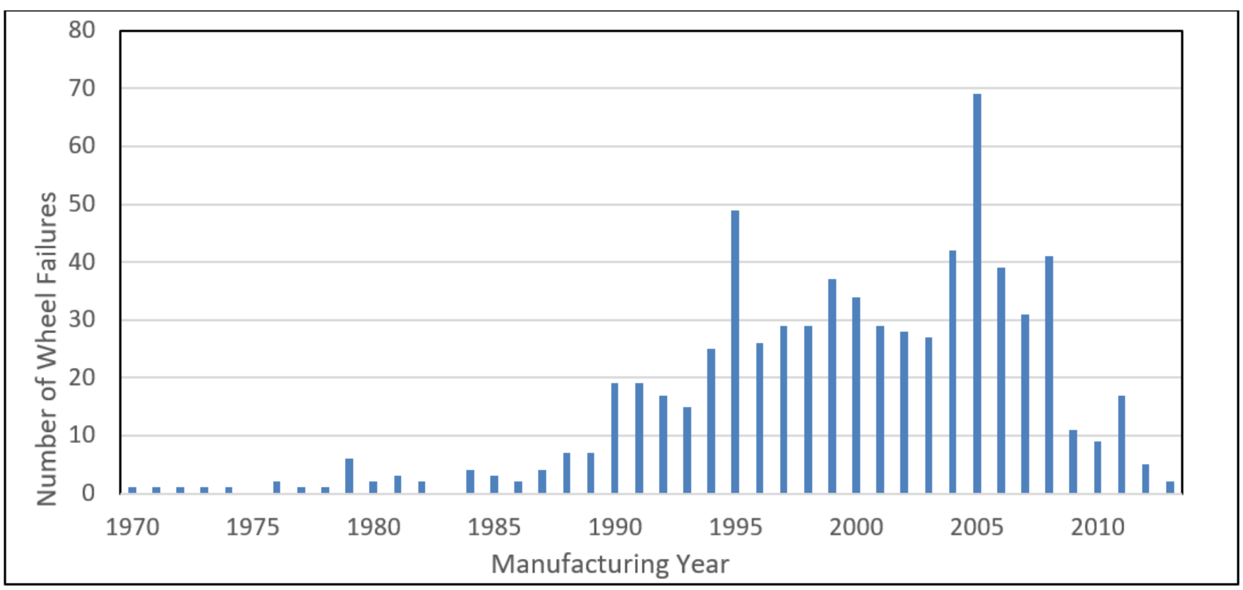


Figure 13. VSR/VSF Failures with Respect to Year of Wheel Manufacture

An analysis of service life as shown in Figure 14 indicates that wheels with VSR failures have an average life of 10 years, which is in line with findings from previous studies (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). The service life analysis conducted in this effort is preliminary in nature and should be expanded to consider combinations of mileage and loads to arrive at a metric to normalize the data with respect to operational parameters.

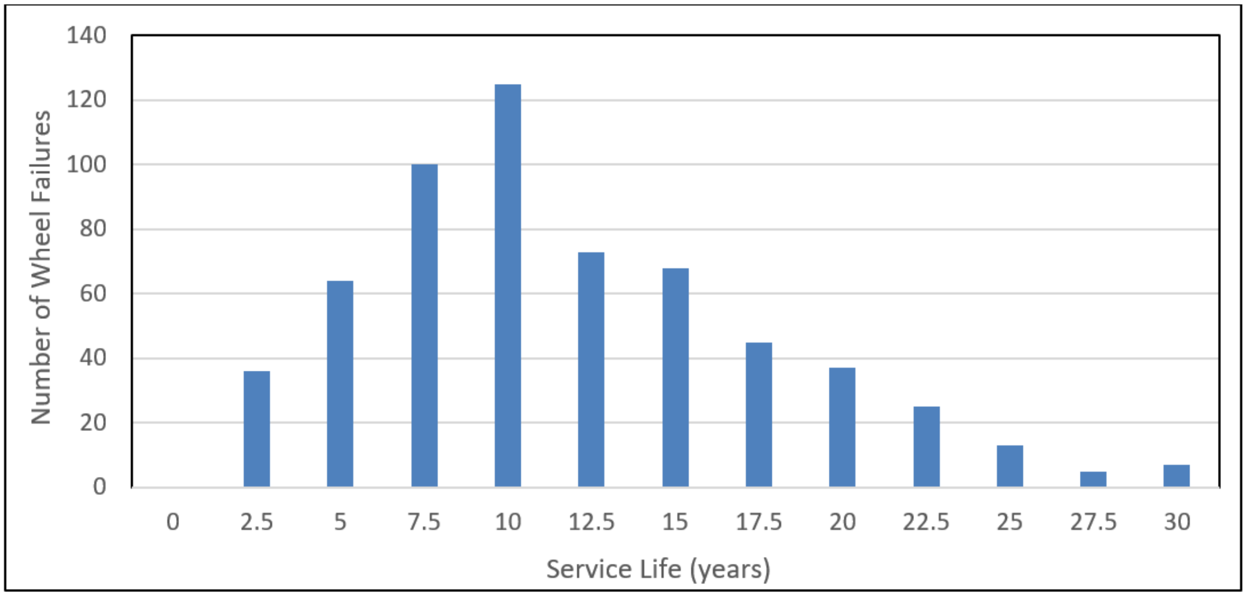


Figure 14. VSR/VSF Failures with Respect to Service Life

Rim thickness has often been cited as a characteristic relevant to VSR failures and recommendations have been made to further study the role of rim thickness (Cummings, S., 2014) (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008) (Sura, V., & Mahadevan, S., 2010) (Meddah, A., & Stone, D., 2013). Previous work by TTCI (2015) has shown that rim thickness of failed VSR wheels are on average smaller than the general population. This has resulted in changes to removal practices for freight wheels which have a high impacting condition and a thin rim as cited in *AAR Field Manual* Rule 41 A.1.h.3. Other previous work found that rim thickness is not a critical parameter to the VSR problem (Sura, V., & Mahadevan, S., 2010). Analysis conducted under this effort appears to support TTCI's previous work which shows that the average rim thickness of the VSR wheels is lower than that of the general population of wheels in service as shown in Figure 15.

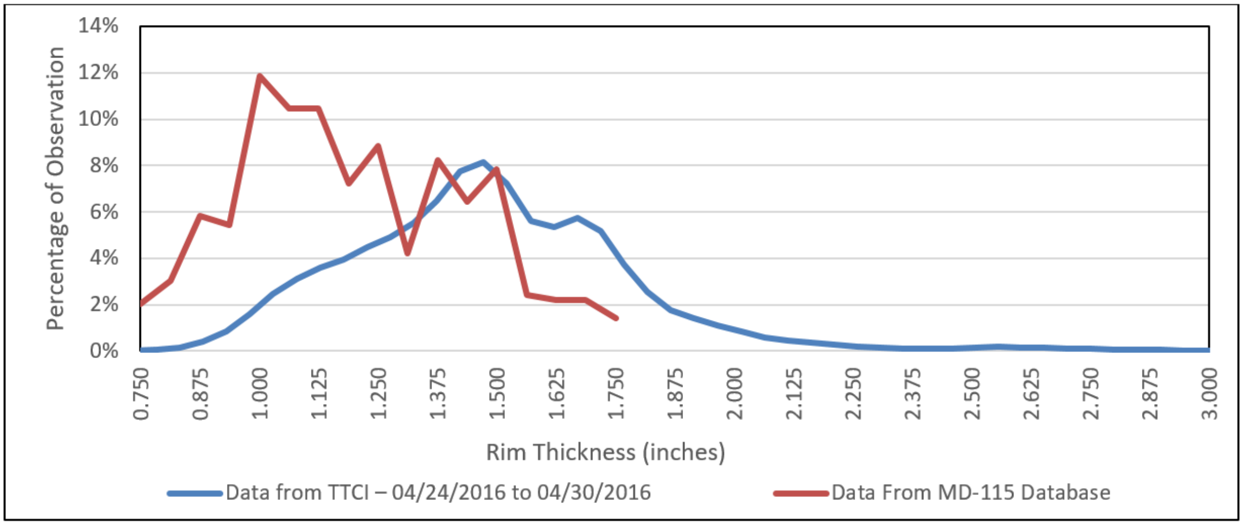


Figure 15. Rim Thickness Values for VSR/VSF Failed Wheels (Red) Compared to the General North American Freight Population (Blue)

Researchers and the SWG have set out to analyze the wayside information collected for the failed wheels, including WILD impact data, wheel profile detector data and hot wheel detector data, which is indicative of brakes that are applied to wheels longer than they should be resulting in local heating. This information has not been assembled prior to the publication of this report. As a start to this analysis, researchers initiated a preliminary assessment by considering data included in laboratory reports provided by the participating railroads for 111 failed wheelsets to identify trends and effects of:

- Wheel impacts measured at WILD sites prior to wheel failure
- Tread wear for the failed and mate wheels
- Rim and flange thickness measurements on the failed and mate wheels

The WILD impact analysis shows that 58 out of 111, 52 percent, failed wheels had impact information recorded by railroads. As illustrated in Figure 16, more than half of those wheels exhibited maximum impact values of at least 40 kips with at least one wheel impact measuring more than 140 kips. Although this confirms previous findings pertaining to VSR failures (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008) (Meddah, A., & Stone, D., 2013) (Transportation Technology Center, Inc., 2015), the analysis should be conducted for maximum wheel impacts associated with all VSR failures identified in the MD-115 database and/or railroad-provided data.

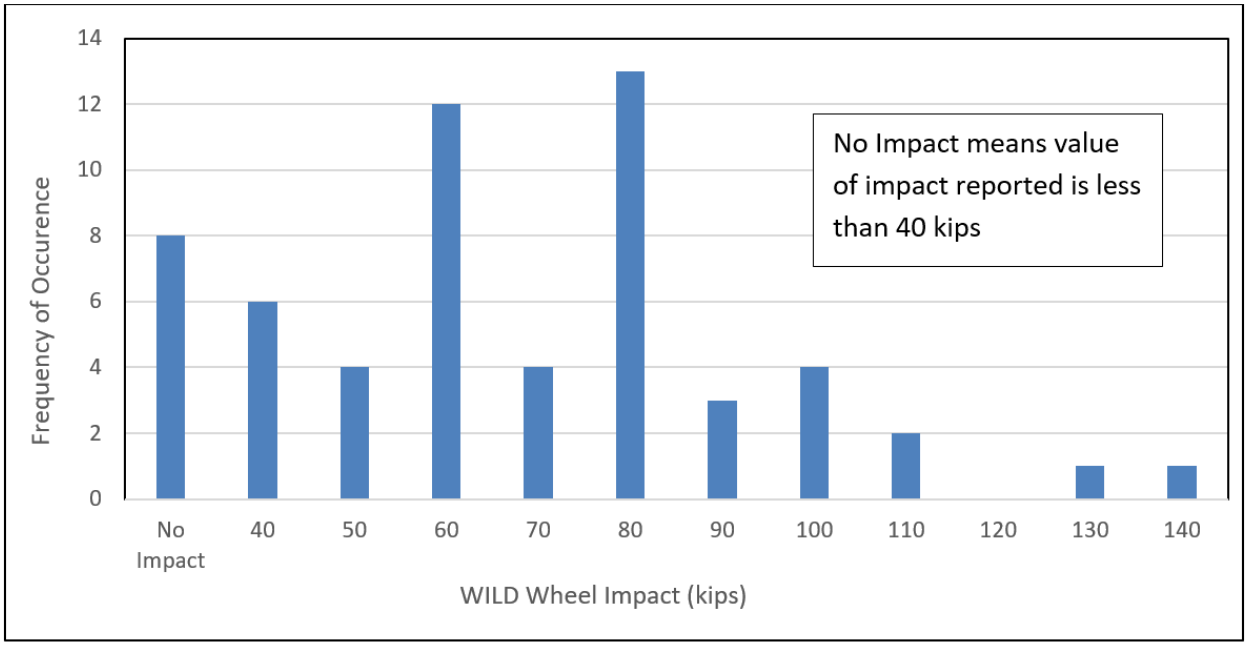


Figure 16. Maximum WILD Impact Values for VSR Failed Wheels

As noted earlier, the AAR has recommended a rule (*AAR Field Manual* Rule 41 A.1.h.3) in which wheels with measured vertical dynamic forces greater than 50 kips and rim thickness values less than 1 inch would be removed from service. Although thin rim thickness combined with an impacting condition indicates susceptibility of a wheel to a potential VSR, current thresholds being used in the AAR rule cited above only flagged approximately 3 percent of the 111 laboratory-provided wheels analyzed in this study. The SWG members had similar feedback on the effectiveness of the rule. This indicates that the approach may need to be modified to flag more potential VSRs. Cummings investigated “kip-days” to determine if it would be a useful metric to correlate impacting conditions to VSR failures (Cummings, S., 2011) (Cummings, S., 2014). A kip is a unit of force equal to 1,000 pounds. The kip-day calculation is a way to identify wheels that have been producing non-condemnable impact loads for a long time. As described by Cummings (2011), a wheel begins accumulating kip-days the first time it exceeds a dynamic load limit (impact load minus average load) of 30 kips. Each day thereafter, the highest impact load (in kips) experienced by that wheel is added to the kip-days total for the wheel. For example, a wheel with a maximum impact load of 70 kips (70,000 lb.) would have a daily accumulation of 70 kip-days. The kip-days total for a wheel is re-zeroed when the wheelset is changed. Cummings (2014) suggested that 11,000 kip-days could be used as a limit. Cummings (2011) also suggested that kip-miles, a similar metric to kip-days that uses service miles instead of time to capture accumulation, may be a more effective than a time-based parameter at identifying wheels sustaining many cycles of impact load. Discussions amongst SWG members indicated that the measure of kip-miles is a better indicator of damage accumulation on the wheelsets.

Another approach suggested by the SWG was to consider the history of impact values generated around the circumference of wheel as it passes through a typical WILD site prior to failure. A combination of lower-level impact information and flange thickness or tread hollow measurements could potentially be used to arrive at better indicators to identify potential VSR failures.

Fifty-three percent of the 111 VSR failed wheels had hollow wear noted on the railroad reports. Most VSR failed wheels have hollow wear of 1 mm or more. Figure 17 illustrates the distribution of differences in tread hollow on wheelsets with VSR wheel failures. There are 38 wheelsets with uneven wear distribution towards the mate wheel or the failed wheel; the rest of the wheelsets had even wear for both the failed and mate wheels. Although there were 19 cases with more tread wear on the failed wheel and 19 cases with more tread wear on the mate wheel, failed wheels tended to exhibit slightly higher amounts of tread hollowing than the mate wheels for the limited number of wheelsets assessed in this initial analysis.

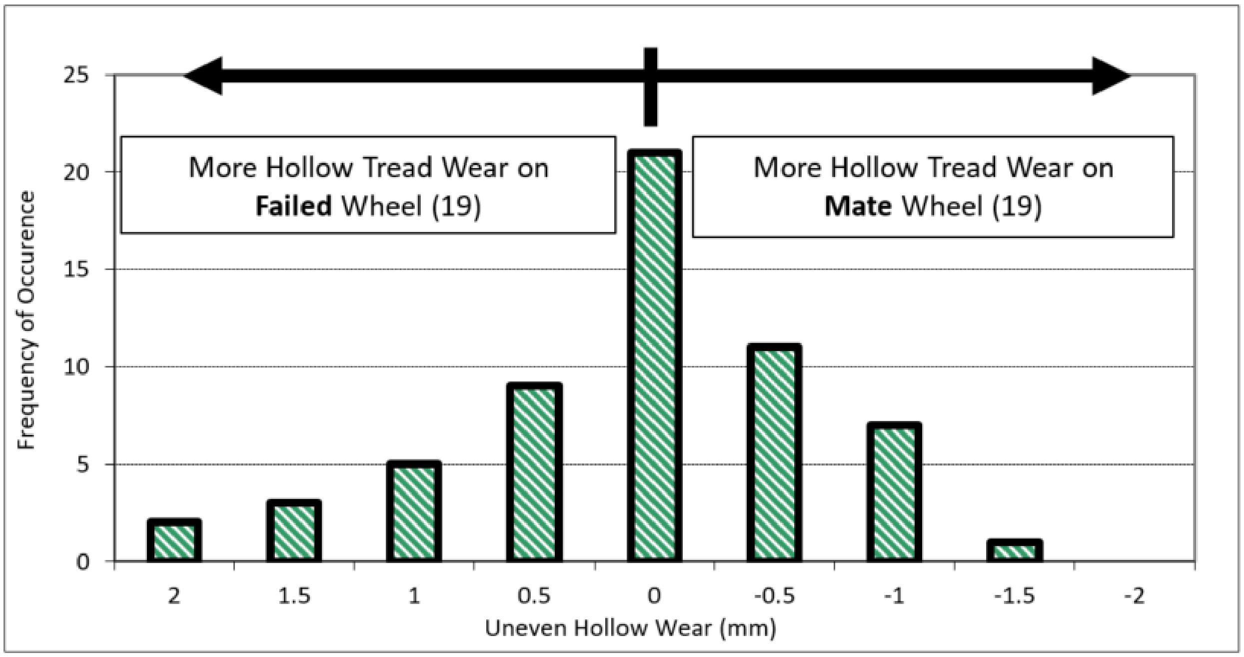


Figure 17. Uneven Hollow Wear Measurements on VSR Failed Wheelsets

A similar consideration of uneven rim thickness values based on 94 of 111 wheelsets with VSR failures is illustrated in Figure 18. Results indicate that the rim thickness wear on the failed wheel side is greater than that on the mate side on the failed wheelsets.

Figure 18. Uneven Rim Thickness on VSR Failed Wheelsets

Flange thickness data was provided for 90 out of 111 failed wheels. It is seen from Figure 19 that most wheels had flange thickness less than 1.5 inches which indicate some wear. Wheelsets with VSR failures tended to have even flange wear with a slight tendency to have the failed wheel exhibit more flange wear as seen in Figure 20.

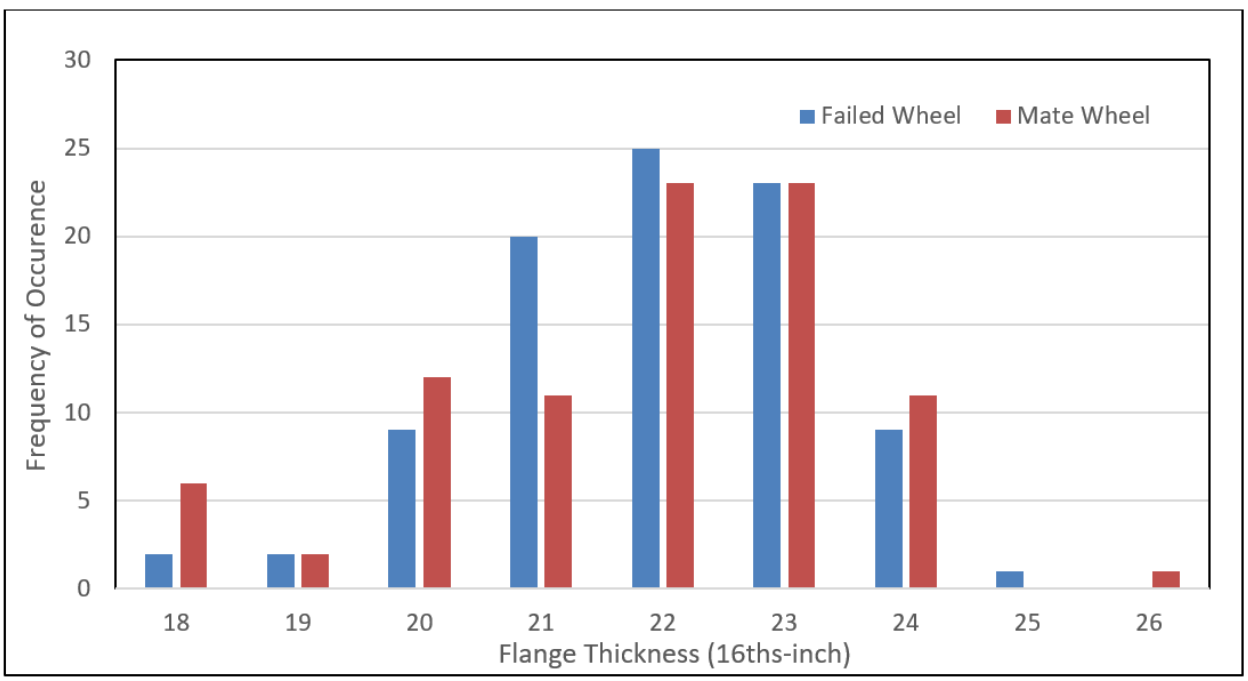


Figure 19. Flange Thickness Values for the VSR and Mate Wheels

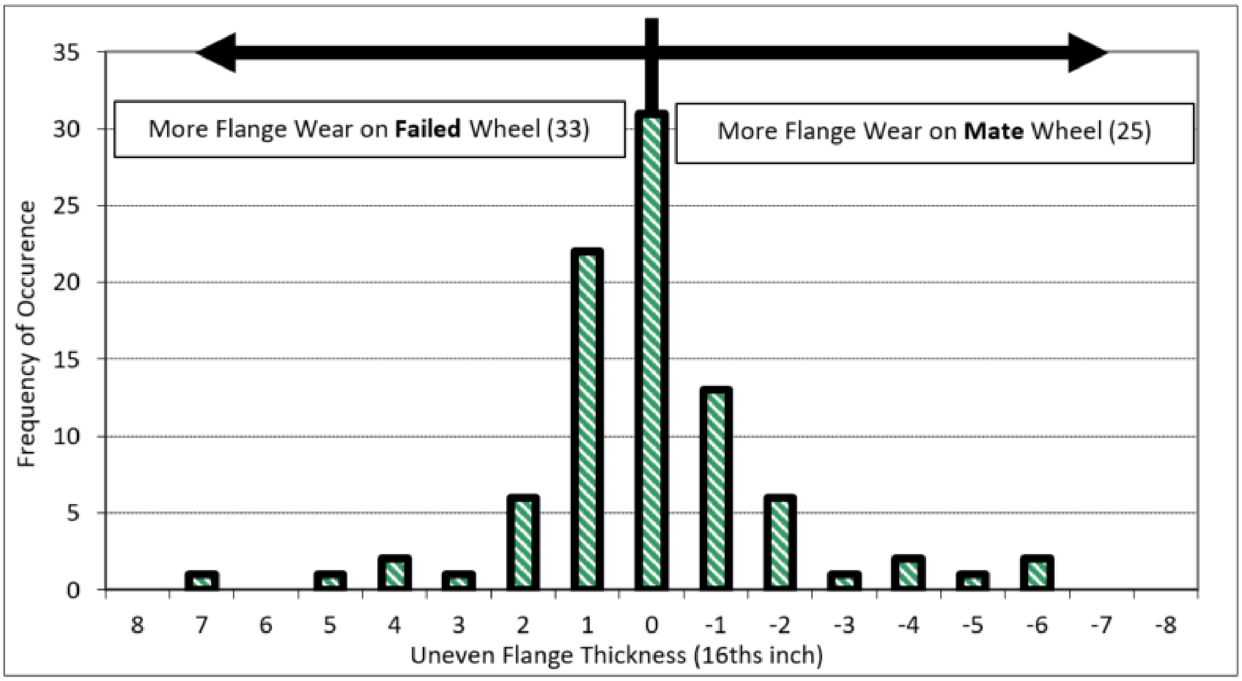


Figure 20. Uneven Flange Wear on VSR Failed Wheelsets

3.2 Current Industry Understanding of Failure Mechanism

Through discussions with the SWG and reviewing the literature, the following is a summary of the current understanding of how VSRs occur.

1. Residual axial tensile stress occurs in the wheel rim due to service loads on the wheel. Testing by TTCI and Amsted Rail have found that negligible axial residual stress occurs from the manufacturing process.
2. A tread surface or subsurface horizontal crack is initiated and grows. These horizontal cracks can be surface initiated (e.g., shelling/spalling/RCF/thermal cracking) or subsurface initiated (e.g., delamination).
3. Eventually the horizontal crack meets the residual axial tensile stress zone, turns and begins to grow rapidly in the vertical direction.
4. This vertical crack continues to grow with periodic crack arrests.
5. Eventually the vertical crack becomes large enough around the circumference of the rim that the front rim face—or the back rim face/flange—completely fractures off the rim.

The above understanding is described in part or in whole by many researchers. No author in the reviewed literature offered a significant alternate hypothesis.

However, there are several areas that the literature and the SWG do not agree upon. Those areas include:

- The various contributors to elevated tensile axial residual stress in the wheel rim at the undesirable depths from the tread surface.

- The amount of residual axial tensile stress required to cause failure.
- The percentage of VSR failures originating from horizontal cracks from shelling, spalling, delamination, or other mechanism.
- The cause and potential preventative measures of delamination.
- The specific mechanism that causes the horizontal crack to turn downward in the vertical direction and how that event can be prevented.
- Durations in miles for crack initiation, propagation, and ultimate failure during the life cycle of VSR wheel.
- The cause of the vertical crack is due to a bending load with the wheel/rail contact patch towards the front rim face or due to stresses induced when the contact patch is over the vertical crack area?

These items are discussed further in Sections 3.3, 3.4, and 3.5.

3.3 Rim Axial Residual Stress

Lonsdale and Cummings both conducted residual stress measurement tests focused on the axial direction of the wheel rim (Lonsdale, C., & Oliver, J., 2013) (Lonsdale, C., Oliver, J., Bitner, A., & Guzel, H., 2013) (Lonsdale & Oliver, 2011) (Lonsdale, C., Oliver, J., Maram, R., & Cummings, S., 2013) (Cummings, S., Oliver, J., & Lonsdale, C., 2011). Both research groups concluded that new wheels have negligible axial tensile residual stress whereas used wheels and VSR-failed wheels have axial tensile residual stress subsurface to the wheel tread. This led the Lonsdale and Cummings research groups to both conclude that the axial tensile residual stress occurs during service, not from manufacturing. It is theorized by Lonsdale and Cummings that the rolling contact loads induce plastic deformation of the tread surface which in turn causes a residual axial compressive stress on the tread surface. An axial tensile residual stress is generated subsurface to balance these stresses.

Figure 21 is an example plot from Lonsdale's work from 2011. Peak axial tensile stress was found between 0.5 to 1.125 inches below the tread surface for used Class C wheels and VSR wheels. It is important to note that the residual stress measurement on VSR wheels did not occur directly at the failure location because the fracture caused relaxation.

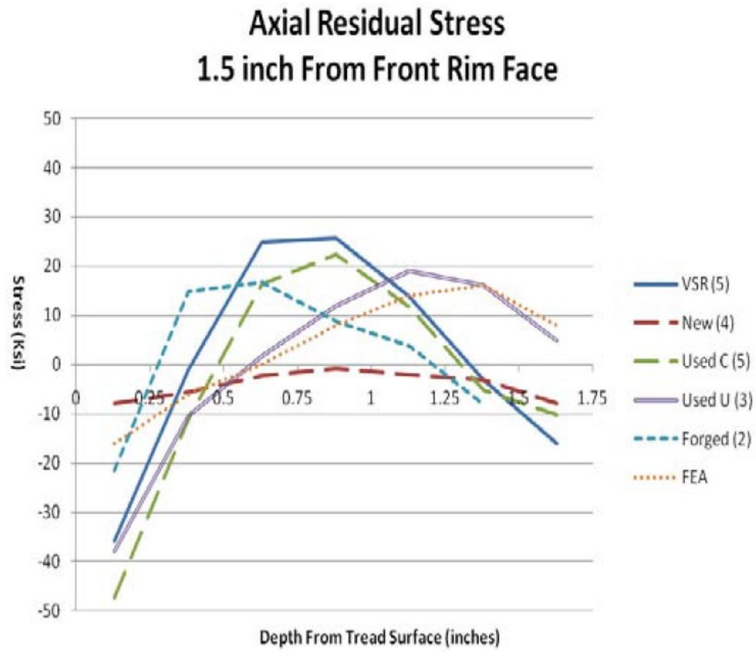


Figure 21. Axial Residual Stress for Various Wheel Types, 1.5 Inches from Front Rim Face (Lonsdale & Oliver, 2011)

Lonsdale continued performing research and discovered the following items:

- Used Class U wheels developed axial residual stress, but it was deeper within the rim than what was observed on the Class C wheels with peak stress occurring between 0.875 to 1.5 inches below the tread surface (Lonsdale & Oliver, 2011).
- A finite element analysis (FEA) model was created to determine if there is any possibility that incorrect heat treatment could create the axial residual stress measured. Results of the FEA model indicated that heat treatment alone could not account for the residual stress values measured (Lonsdale & Oliver, 2011).
- Used Class C and Class U wheels quickly generate subsurface tensile axial stress, and the balancing compressive axial stress, from rolling contact. By performing tests at TTCI's Facility for Accelerated Service Testing (FAST) track, it was discovered that significant residual stress was generated within 3,700 miles of operation (Lonsdale, C., Oliver, J., Maram, R., & Cummings, S., 2013).
- During testing at TTCI's FAST track, a test was performed by applying the brakes. It was discovered that the region of tensile axial residual stress moved deeper into the rim for Class C wheels under braking conditions. Lonsdale concluded that further work is needed to better understand the effect of braking (Lonsdale, C., Oliver, J., Maram, R., & Cummings, S., 2013).
- A drop hammer was used to impact the wheel tread of a new wheel 600 times. It was discovered that such impacts did create axial residual stress similar to the used and VSR wheels tested. Additionally, out-of-round wheels were tested and discovered to have

more tensile axial residual stress than non-out-of-round wheels (Lonsdale, C., Oliver, J., Bitner, A., & Guzel, H., 2013).

- By turning a tread damaged wheel, it was discovered that the tensile axial residual stress is reduced (Lonsdale, C., & Oliver, J., 2013).
- It was discovered that there is significant variability of the tensile axial residual stress magnitude measured around the circumference of the wheel. This highlights the need to carefully select the location of testing (Lonsdale, C., Oliver, J., Bitner, A., & Guzel, H., 2013).

The following areas of axial residual stress research have not been investigated yet:

- Determining peak tensile axial residual stress within a wheel, regardless of the location tested and accounting for relaxation caused by fracture.
- Correlating WILD values to axial residual stress values
- Correlating braking temperature and time to axial residual stress values. Dedmon (2016) discovered that slightly elevated temperatures during tread braking may assist increased work hardening and residual stress generation
- Determining whether WILD impacting conditions and tread braking at the same time effect the axial residual stress distribution
- Determining the axial residual stress after a trued wheel has been in service for more than 3,700 miles
- Determining the growth rates of axial residual stress during normal rolling contact and WILD impacting conditions over long distances

3.4 Horizontal Cracks

The SWG was in agreement that a horizontal crack forms near the surface of the tread and when it reaches the zone of tensile axial residual stress, the vertical crack forms. However, the SWG did not reach a consensus on the primary mechanism for creating the horizontal crack. Stone, Kristan, and Dick noted that shelling/spalling was the primary mechanism for the horizontal cracking as shown in Figure 22 (Stone, D., Tournay, H., & Cummings, S., 2009) (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010) (Kristan, Elkins, & Stone, 2004) (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). Shelling is surface initiated cracking caused by rolling contact fatigue, thermal cracking, and/or heat checks. Spalling is caused by wheel sliding conditions which cause untempered martensite to form creating a brittle microstructure that quickly fractures out.

(a) Shelling **(b) Spalling**

Figure 22. Example VSR Wheels with Shelling (a) and Spalling (b) at the VSR Initiation Site (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008)

Tournay (2016) and Dedmon et. al. (2016) noted a third mechanism called "delamination." Delamination is characterized as subsurface fatigue cracking caused by shear stresses that is approximately 0.5 inches to 1.0 inch in width, approximately 1/16th to 3/16th inches below the tread surface and of variable lengths running around the circumference of the rim. The peak Hertzian contact stress corresponds to the depth of delamination. Additionally, Tournay et al. (2016) noted that the delamination is associated with the edge of a work hardening layer from the tread surface. Figure 23 depicts an example VSR with delamination. Figure 24 is an example delamination fracture cut open. Figure 25 depicts a cross-sectional view of a VSR with delamination. Interestingly, Dick (2008) did note that some VSR failures did not have any visible tread damage, which may correspond to delamination.

Figure 23. Example VSR Wheel with Delamination (Photographs courtesy of SWG member Alicia Bitner)

**Figure 24. Delamination Fracture Cut Open
(Photograph courtesy of SWG member Alicia Bitner)**

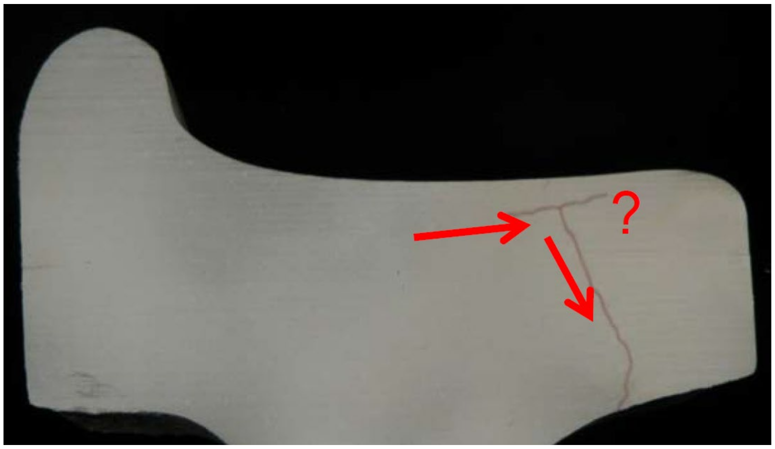


Figure 25. Cross-Sectional View of VSR Wheel Showing Horizontal Delamination Crack and Resulting Vertical Crack (Tournay, H., & Jones, K., 2016)

The following areas of horizontal crack research have not been investigated yet:

- Previous work where shelling/spalling was identified as the source of the horizontal crack involved only visual inspection. Tournay (2016) performed cross-sectional cuts (see Figure 25) and found evidence of delamination. Further work should be conducted to determine if VSRs do occur solely by shelling/spalling or if delamination exists below the shelling/spalling and represents the root cause of the horizontal crack. WILD impacting conditions are known to be associated with VSRs and WILD impacting conditions can be caused by shelling/spalling.
- Should shelling/spalling be confirmed to be associated with a VSR without delamination, further work should be conducted to determine what is the percentage of VSR wheels associated with shelling/spalling vs. delamination. It is believed by the authors of this report that quantification of the modes of failure initiation numbers would lead to better refinement of mitigation approaches.
- The root cause of delamination is not yet well understood. Further research should be conducted to identify the root cause, growth rate, and preventive measures.

3.5 Vertical Cracks

An overview of the VSR vertical crack is shown in Figure 26. It is characterized as a vertical crack originating from the horizontal crack to form an initial fracture. This initial vertical fracture quickly grows around the circumference of the wheel with periodic crack arrests. The total vertical crack ranges in length from 6 inches to the full circumference of the wheel (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). Additionally the crack is typically between 1 to 2.75 inches from the front rim face (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). The vertical fracture is a brittle overload fracture and is oxidized. Typically, the vertical crack removes a portion of the front rim face. However, occasionally the back rim face including the flange is fractured off.

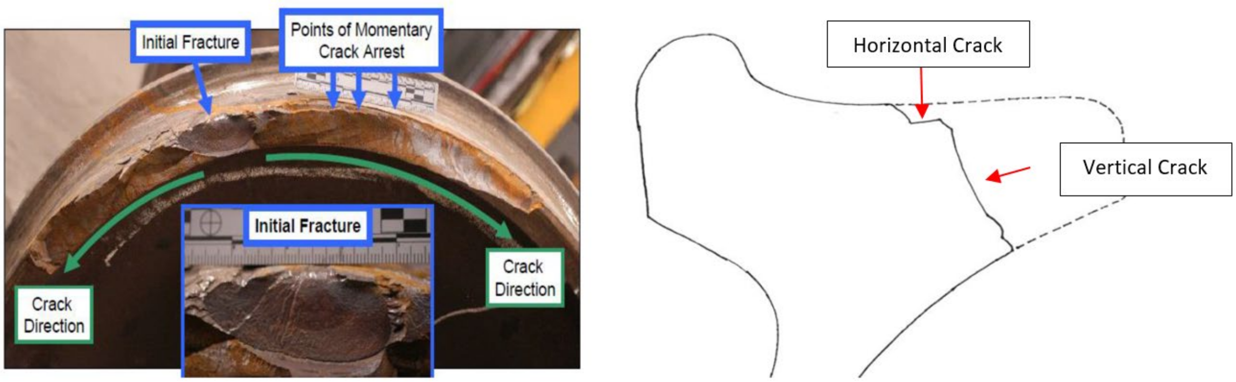


Figure 26. Example and Cross-Sectional Diagram of VSR Vertical Crack (Lonsdale, C., Oliver, J., Bitner, A., & Guzel, H., 2013)

To create a vertical crack, the horizontal crack needs to turn downward. The horizontal crack is Mode II fracture (shear), while the vertical crack is Mode I fracture (tension). The FEA work performed by Stone (2005) and Sura (2010) indicated that orientation of the horizontal crack makes a significant difference on the required stress needed to exceed the material fracture toughness, where the more the horizontal crack turns downward, the lower the stress needed to exceed the fracture toughness.

Little is known about how the horizontal crack begins to turn downward. A few hypotheses were provided by SWG and literature:

- Dedmon (2016) hypothesized that the horizontal crack acts as a thermal insulator during tread braking that causes a stress differential.
- Tournay (2016) provide a few hypotheses including axial tensile stress when the contact patch is over the delamination, surface roughness of the delamination, and martensite at the delamination.
- Lonsdale (2009) theorized that the horizontal crack turns downward due to large impacts. However drop hammer testing was unsuccessful in causing a fracture.

From the literature, there are two hypotheses regarding where the wheel/rail contact patch is located when the vertical crack occurs. Stone and Kristan provided a hypothesis that a bending moment is created when the contact patch is away from the vertical crack location (Stone, D., Tournay, H., & Cummings, S., 2009) (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010)

(Kristan, Elkins, & Stone, 2004). Through this work both Stone and Kristan identified that a thin rim would have higher bending stress as compared to a thick rim. Cummings (2010) and Sura (2010) provide a hypothesis that the contact patch is above the vertical crack. This hypothesis was developed by using an FEA model to predict the stress intensity factor. Further investigation should be conducted in this area because the FEA results appeared to combine Mode I and Mode II stress intensity factor predictions. This may cause the results to indicate high stress when the contact patch is over the crack location because of the Mode II shear stress overwhelming the Mode I tensile stress needed for the vertical crack formation.

Dedmon (2011) also noted that the hardening occurrence increases the yield strength, but decreases the fracture toughness.

The following are areas of vertical crack research that have not yet been investigated:

- Additional research is required to better understand the mechanism that causes the horizontal crack to turn downward as opposed to upward. If the crack can be steered upward, it would be a less detrimental outcome such as tread damage.
- Determining the equation that defines what combination of Mode I stress, fracture toughness, flaw size, flaw orientation, and residual stress state is required to cause the vertical fracture
- Determining a methodology to reproduce a VSR vertical crack in the laboratory or field

4. Current Understanding of Shattered Rim Failures

The root causes of shattered rims have been studied and agreed upon in the literature by Stone (2000) (2001), Sura (2010), and Cummings (2014). Effective mitigation strategies for shattered rims (e.g., tighter UT limits on allowable defects, tighter micro-cleanliness limits, and the establishment of a maximum impact load criterion for example) have been recognized and implemented by the AAR. Although shattered rim occurrence has come down to a steady number of approximately 20 per year, they have not been eliminated from the North American freight industry.

4.1 Common Characteristics of Shattered Rim Failures

Shattered rim failures are characterized as a large subsurface fatigue crack created by Hertzian contact stress resulting in a characteristic "bullseye" fatigue fracture roughly parallel to the tread surface. Eventually the bullseye fatigue fracture grows large enough to cause a final overload fracture which removes a large portion of the rim.

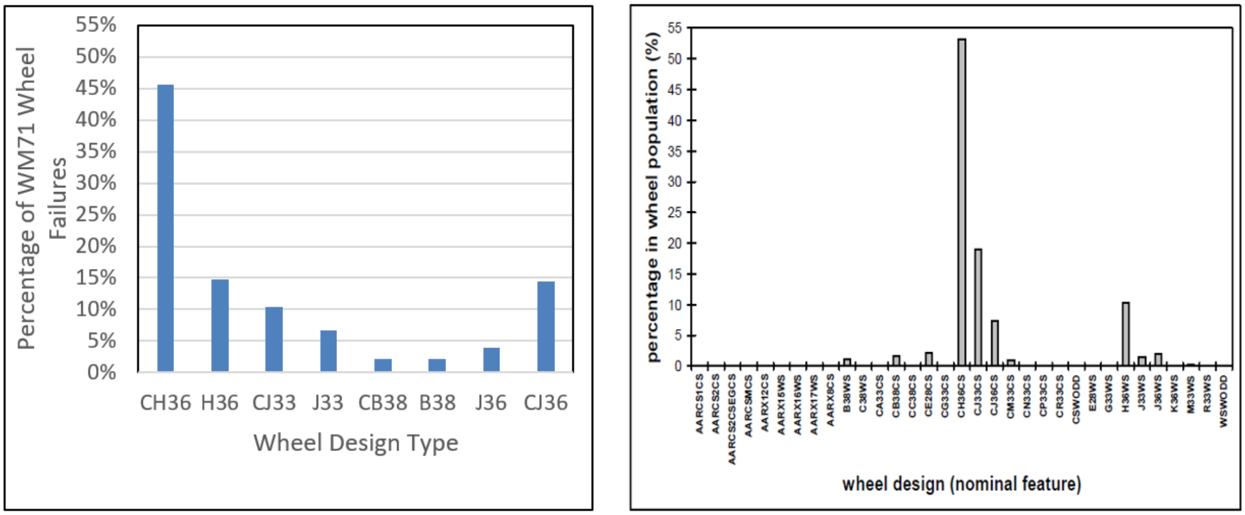
Interestingly, there are occasions where a shattered rim fatigue fracture can cause a VSR. This causes confusion when inspecting wheels to determine if it is a shattered rim or VSR failure. The SWG agreed that if the subsurface crack is deeper than 3/8th inch, then it should be classified as a shattered rim. If the subsurface crack is shallower than 3/8th inch, then it should be classified as a VSR.

Data analysis conducted under this effort has shown that the industry has observed an average of approximately 20 shattered rim failures per year for the last 8 to 10 years. Within the last 20 years, shattered rim failures peaked at about 70 in 2005 as shown in Figure 2.

Analyses like those conducted for VSR failures (see Section 3.1) were conducted for shattered rim failures. Characteristics of 691 WM71 failures found between 1995 and 2015 were evaluated using data within the MD-115 database to determine signature characteristics. An evaluation of a smaller subset of 47 confirmed WM71 failures documented in railroad-provided lab reports contained wheel impact and other information from 2010 through 2016.

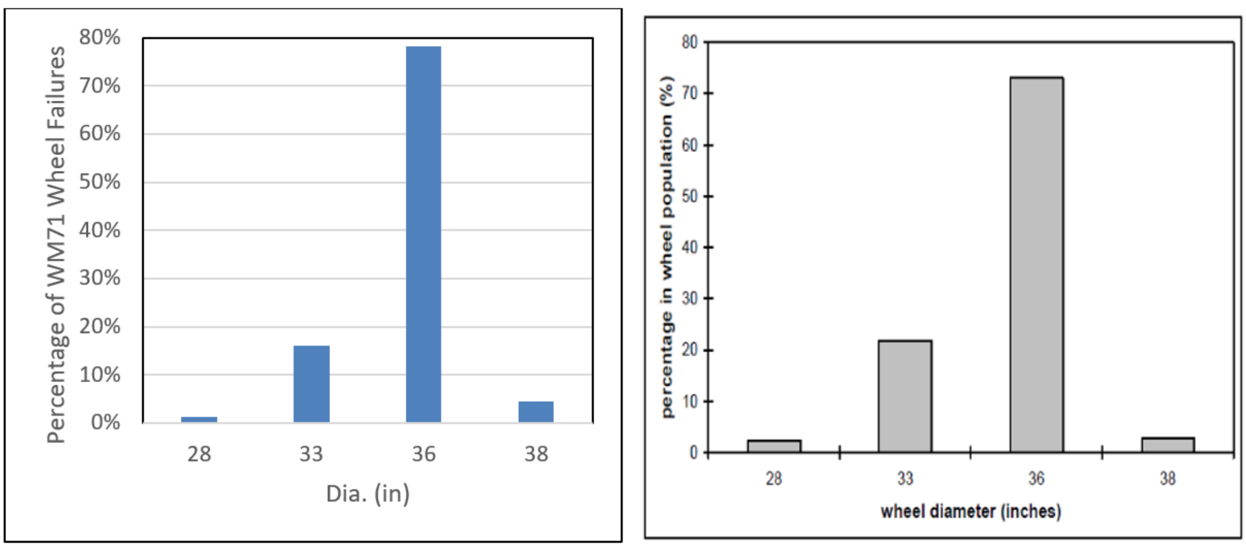
The following parameters do not indicate any significant differences between shattered rim failure rates and the general population distribution:

- Wheel design type as shown in Figure 27
- Wheel diameter as shown in Figure 28
- Vehicle/car type as shown in Figure 29
- Wheel wear type as shown in Figure 30
- Car weight for the failed wheels as shown in Figure 31



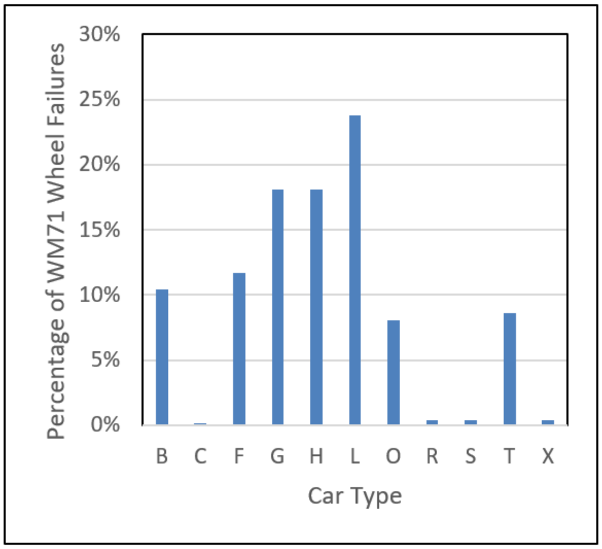
(a) Shattered Rims **(b) Wheel Population (Stratman, B., 2007)**

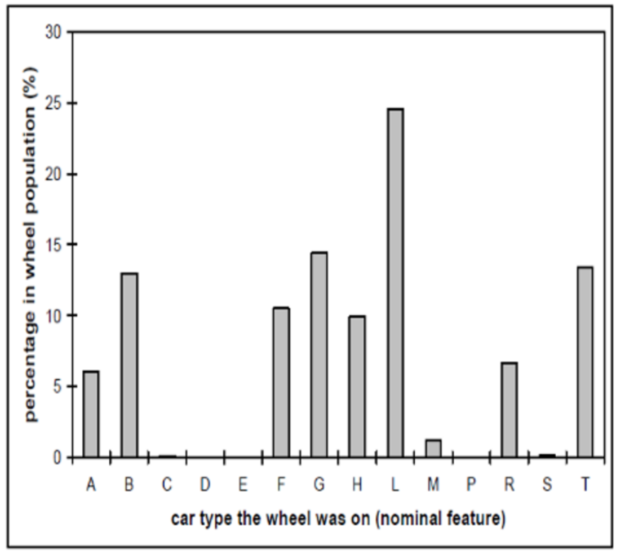
Figure 27. Shattered Rim Failure Rate (a) vs. General Population Distribution (b) for Wheel Design



(a) Shattered Rims **(b) Wheel Population (Stratman, B., 2007)**

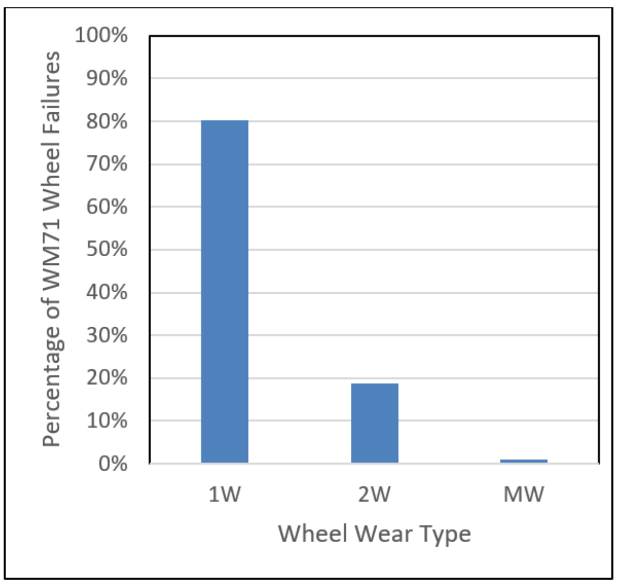
Figure 28. Shattered Rim Failures (a) vs. General Wheel Population Distribution (b) for Wheel Diameters

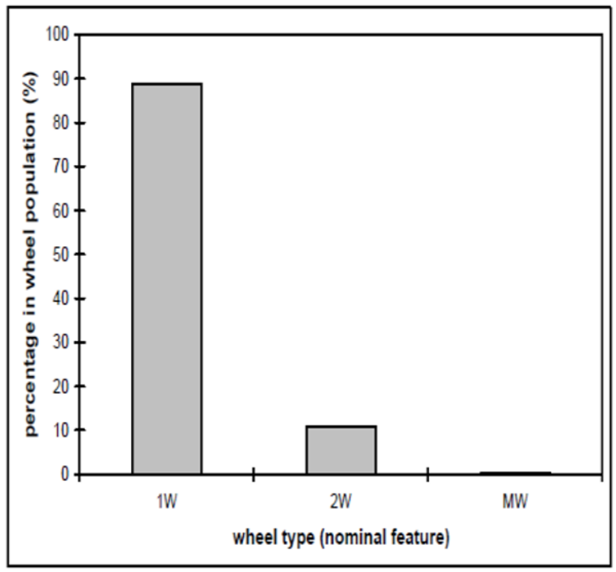




(a) Shattered Rims (b) Wheel Population (Stratman, B., 2007)

Figure 29. Shattered Rim Failures (a) vs. General Wheel Population Distribution (b) for Car Types





(a) Shattered Rims (b) Wheel Population (Stratman, B., 2007)

Figure 30. Shattered Rim Failures (a) vs. General Population Distribution (b) for Wheel Wear Type

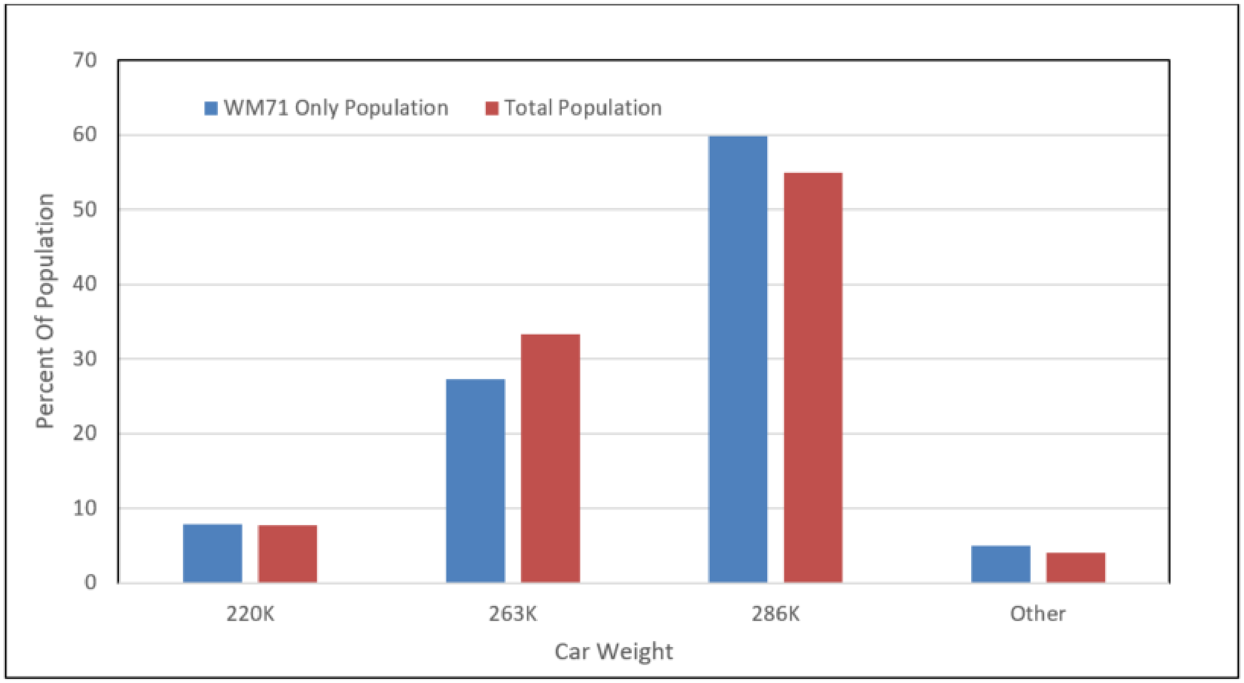


Figure 31. Distribution of Shattered Rim Failures and General Car Population for Different Car Weights

Analysis of the wheel position in the car shows that 267 of the failures occurred at the A-end out of a total of 548 wheels for which the information was available. Figure 32 indicates that shattered rim failures do not tend to be found on a particular truck in a vehicle.

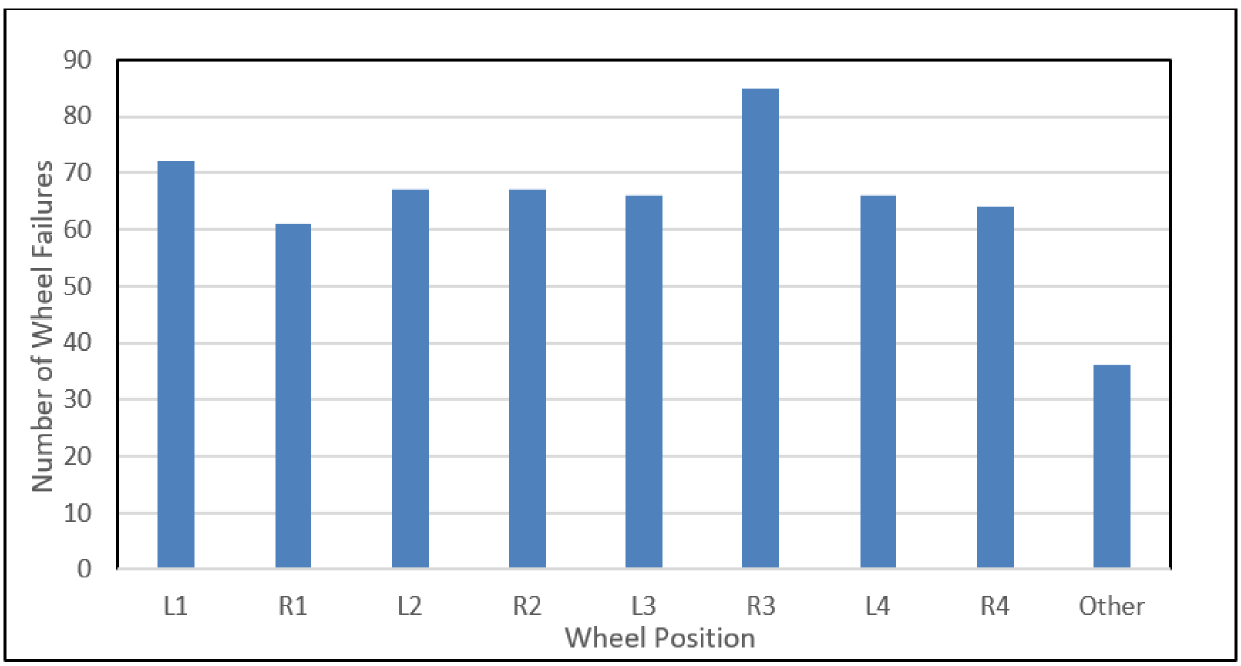


Figure 32. Shattered Rim Failures with Respect to Wheel Position

The position of wheels with shattered rims was assessed for different vehicle types. As shown in Table 3, 42 of 78 WM71 failures occurred on covered hoppers and the failures were evenly distributed throughout the car. This contrasts with the observation that VSR failures had a greater tendency to be found on the B-end of the covered hoppers.

Table 3. Shattered Rim Failure Rate for a Combination of Vehicle Type and Wheel Position

Car Type	L1	R1	L2	R2	L3	R3	L4	R4	Other	Total Per Car
Box Car	3	0	5	8	1	2	1	0	0	20
Covered Hopper	12	7	11	12	5	15	9	7	0	78
Gondola	10	8	9	4	8	14	12	9	0	74
Flat Car	4	6	2	4	1	1	2	5	0	25
Open Hopper	6	6	5	5	2	5	6	7	0	42
Stack Car	4	2	5	3	4	1	1	1	10	31
Tank Car	4	3	2	2	5	2	2	2	0	22

As observed with VSR failures, shattered rim failures are more prevalent during the winter months as shown in Figure 33.

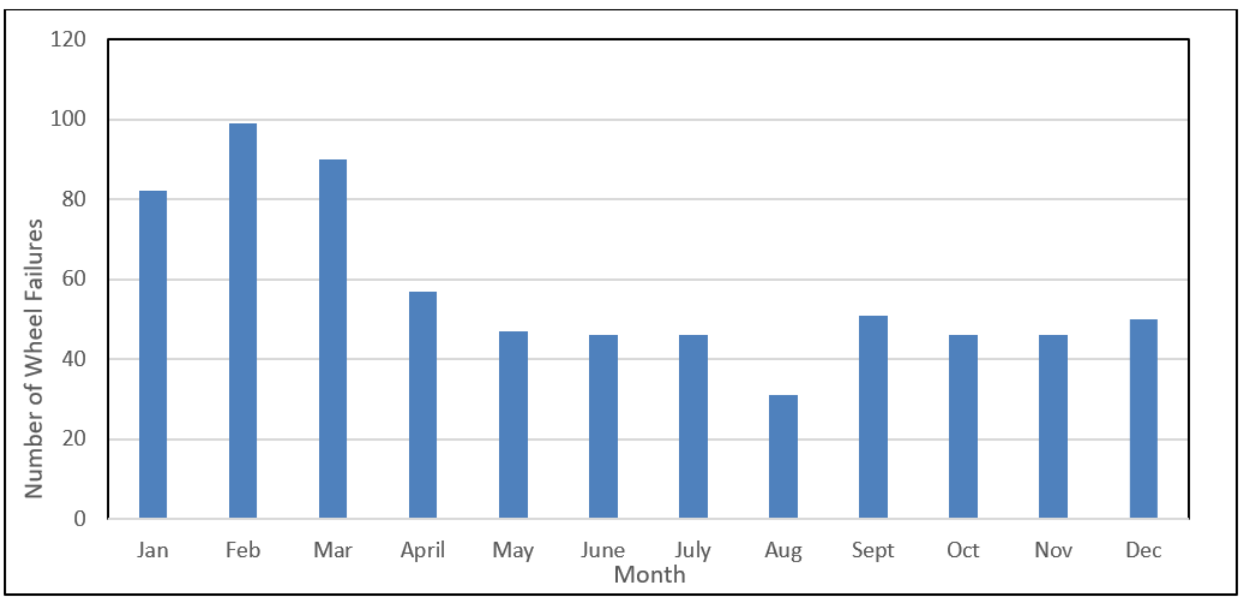


Figure 33. Shattered Rim Failures per Month of the Year

Several other shattered rim characteristics were analyzed using the MD-115 database including the manufacturer of the failed wheel and age of wheel before failure and manufacturing year of failed wheel. It should be noted that shattered rim failure numbers are based on the whole database ranging from 1995–2015 unlike the VSR failure statistics which were based on confirmed failures. Shattered rim wheel failures were separated per the MD-115 database manufacturer code in Figure 34. This distribution is like the general population distribution shown in Figure 12, indicating that there does not appear to be a correlation between shattered rim failures and wheels from specific manufacturers at this stage of analysis. The distribution of manufacturing year for shattered rim failures is shown in Figure 35. The highest number of shattered rim failures occurred on wheels manufactured in 1995; this is thought to be associated with wheels manufactured by Southern Wheels. It is interesting to note that the highest failure rate for VSRs occurred for wheels manufactured in 2005. Additional efforts should be made to understand this difference including normalization of the data with respect to several factors, including number of wheels manufactured in that year, mileage, and loading if available.

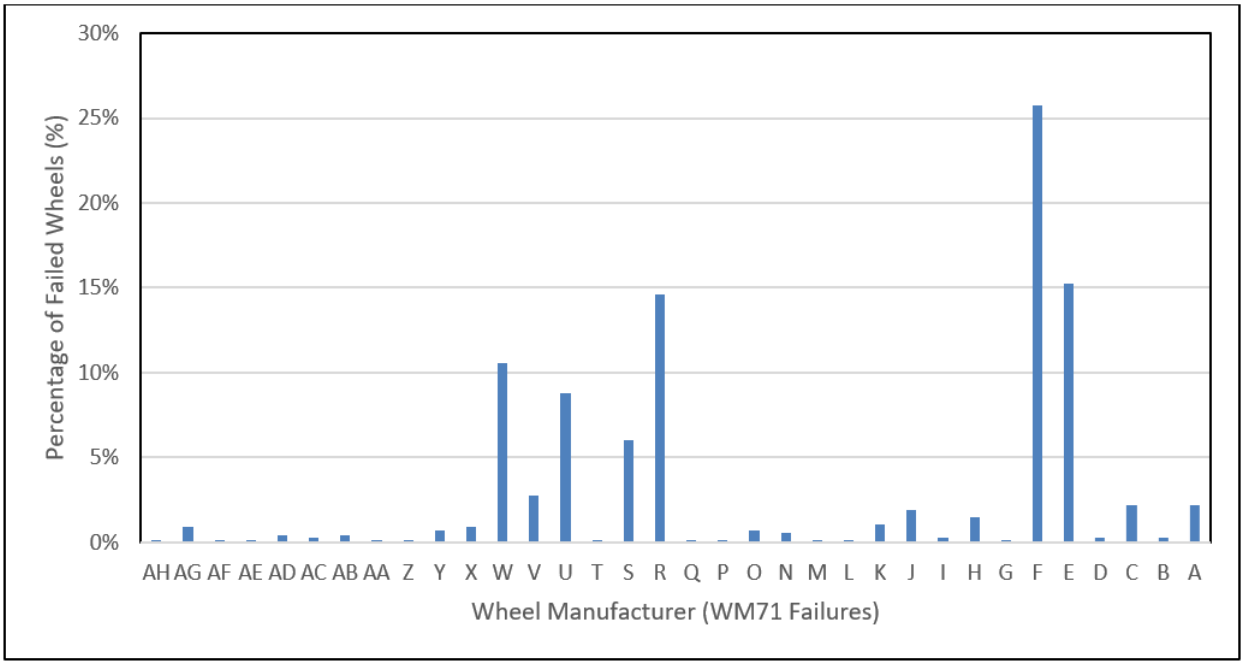


Figure 34. Shattered Rim Failures with Respect to Manufacturer

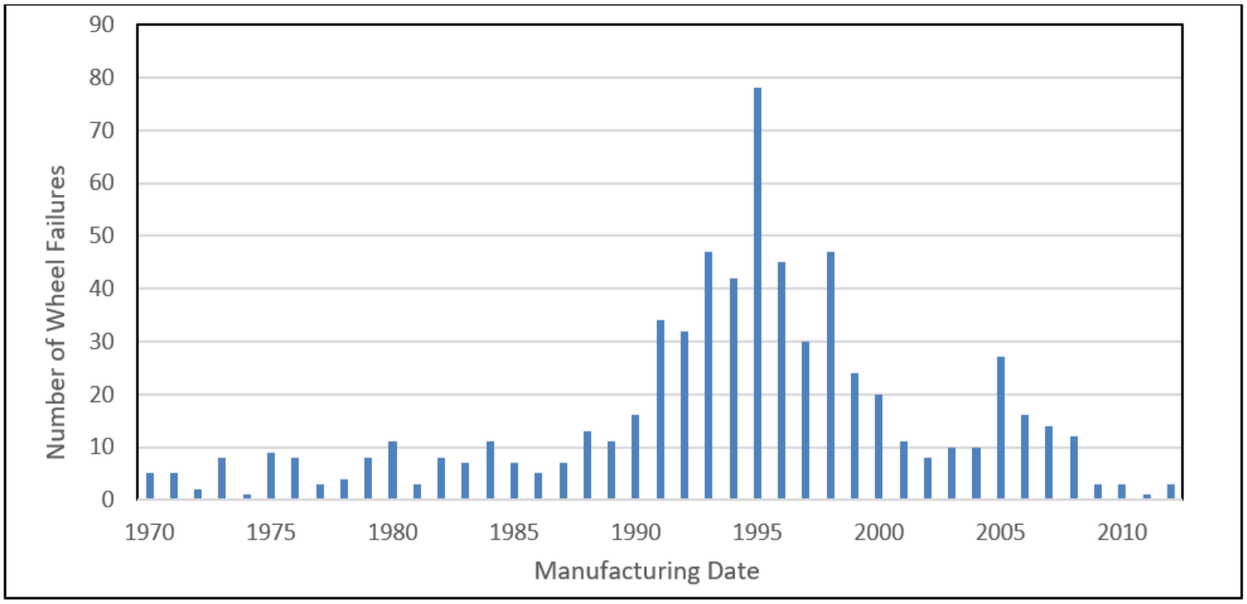


Figure 35. Shattered Rim Failures with Respect to Manufactured Year

Analysis of service life shown in Figure 36 confirms that shattered rim failures occur in wheels with an average life of 10 years which is comparable to that associated with VSR failures. The service life analysis done in this report is preliminary and ultimately needs to be compared to service life of the general wheel population. This analysis should also be expanded to consider mileage and load combinations to arrive at a metric to normalize service with respect to operational parameters.

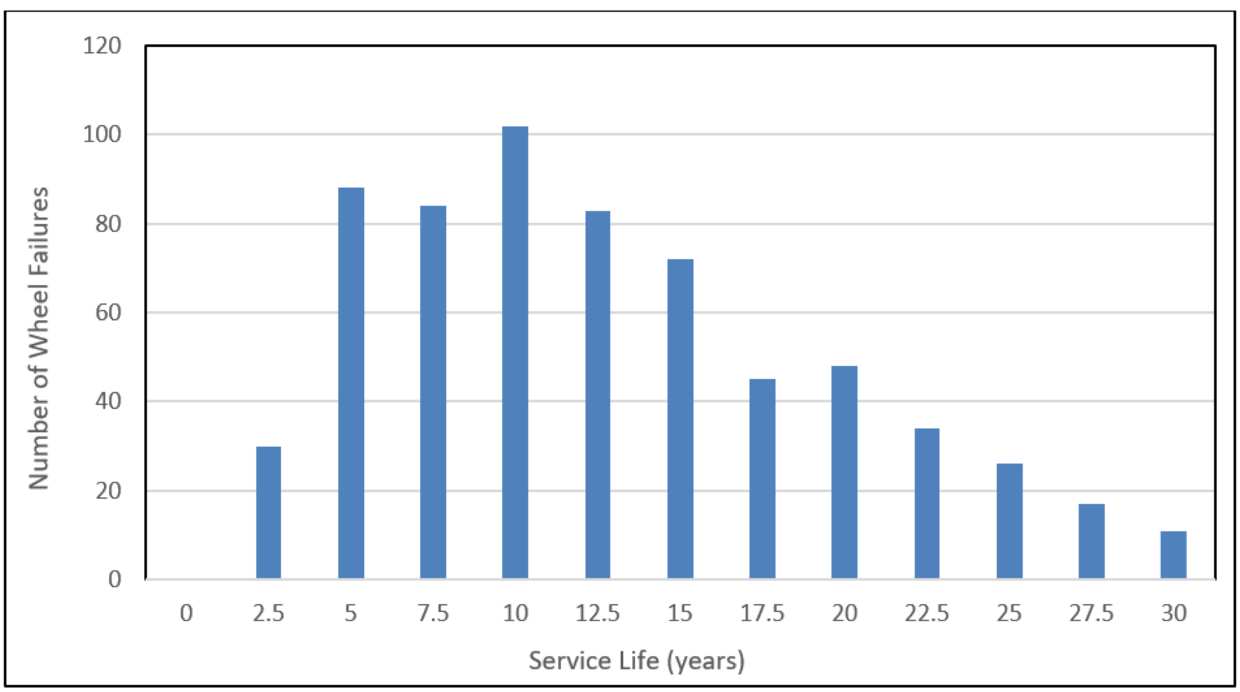


Figure 36. Shattered Rim Failures with Respect to Service Life

Rim thickness has been shown to be a factor for VSR failures but has not been attributed to shattered rim failures. Analysis conducted under this effort shows the average rim thickness of shattered rim failures is lower than the general population of in-service wheels as shown in Figure 37. Normalization of the failure rim thickness data with respect to mileage on the failed wheels should be considered by using rim thickness population data from wheels with a similar mileage distribution.

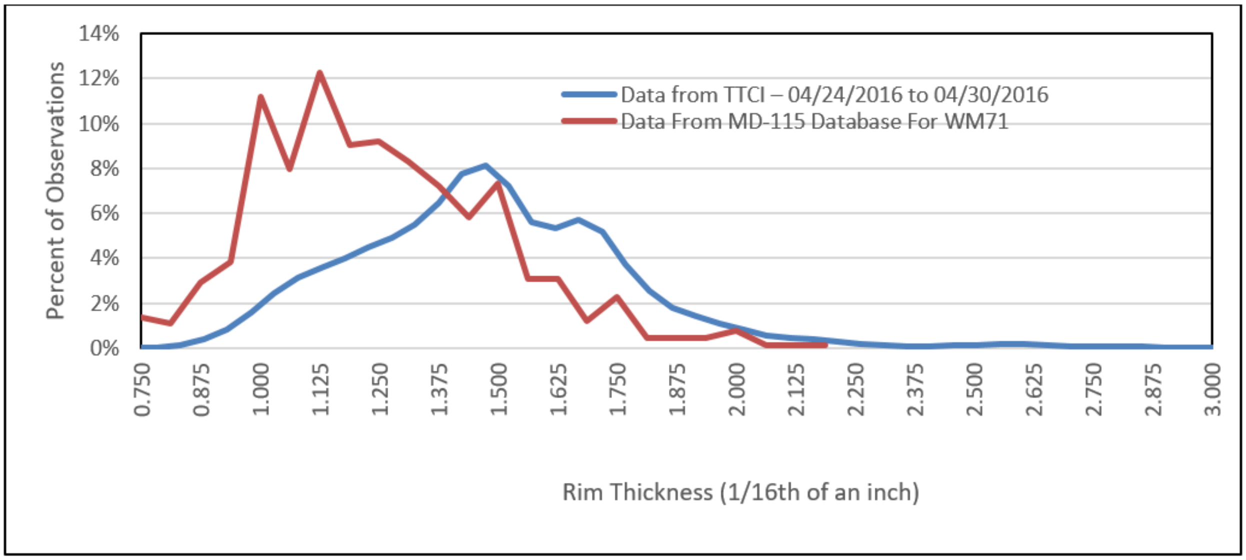


Figure 37. Rim Thickness for Shattered Rim Wheels Compared to the General North American Freight Population

As was done for the VSR failed wheels, researchers analyzed the wayside data included in the 47 available railroad laboratory reports for shattered rims. In this analysis, data from failed wheels were used to identify trends and effects of:

- Wheel impacts measured at WILD sites prior to wheel failure
- Tread wear on the failed and mate wheels
- Rim and flange thickness measurements of the failed and the mate wheels

WILD impact data was available for 21 of the 47 (45%) laboratory-assessed wheels. As seen in Figure 38, no maximum impact values greater than 100 kips were observed on these wheels. This is to be contrasted with VSR failures analyzed during this effort using railroad-provided laboratory reports which identified impacts of 144 kips measured by WILD detectors. It should be noted that the shattered rim population analyzed using the laboratory assessed reports was a relatively small subset of the shattered rim data contained within the MD-115 database.

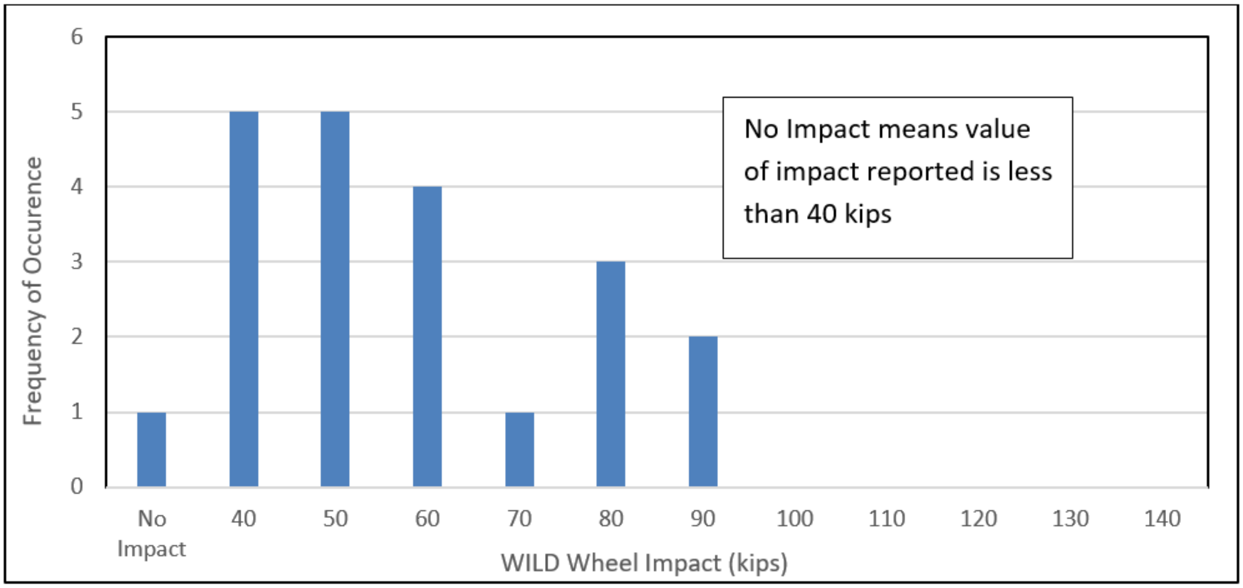


Figure 38. Maximum WILD Impact Values for Failed Wheels with Shattered Rims

Railroad reports indicated that 55 percent of shattered rim failures had hollow wear. As shown in Figure 39, an analysis of the uneven hollow wear observed that shattered rims tend to be more worn on the mate wheel as compared to the failed wheel, however the small sample size makes drawing definitive conclusions difficult.

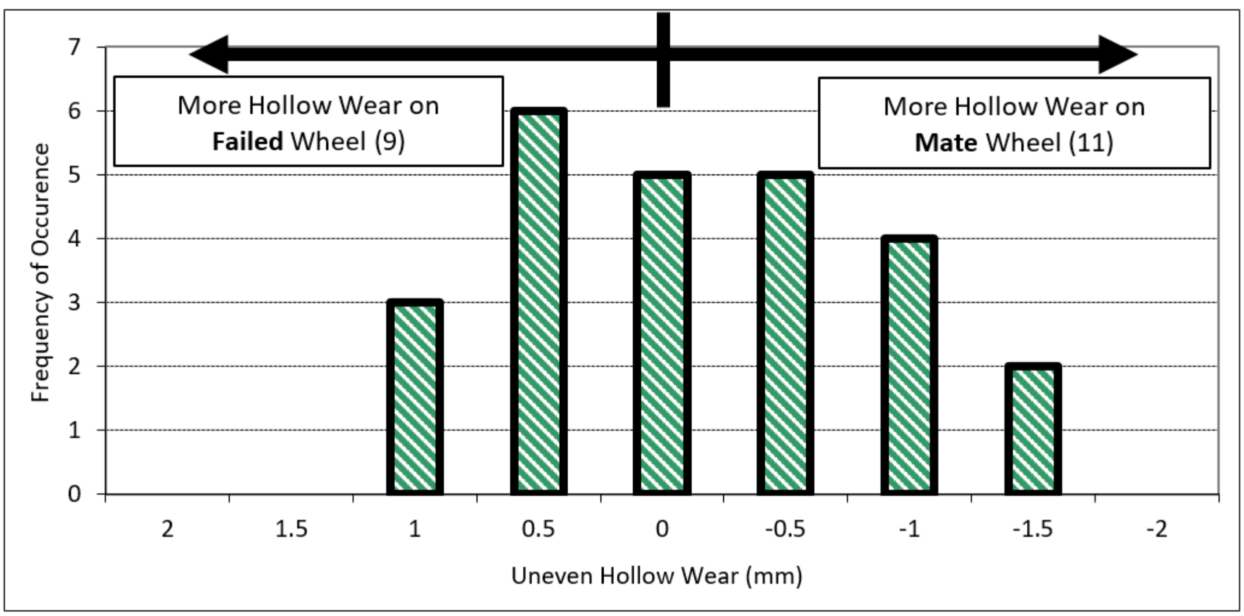


Figure 39. Uneven Hollow Wear Measurements on Shattered Rim Failed Wheelsets

A similar assessment of the rim thickness values for 31 out of 47 wheelsets with shattered rim failures, shown in Figure 40, indicates that the mate wheel generally has more rim wear than the failed wheel on the same wheelset. This contrasts with the VSR failure characteristics.

Figure 40. Uneven Rim Thickness on Shattered Rim Failed Wheelset

Evaluation of flange thickness measurements for 31 of the 47 wheelsets with shattered rim failures indicates that there is a slight tendency of higher flange wear on the mate wheel as compared to the failed wheel, seen in Figure 41.

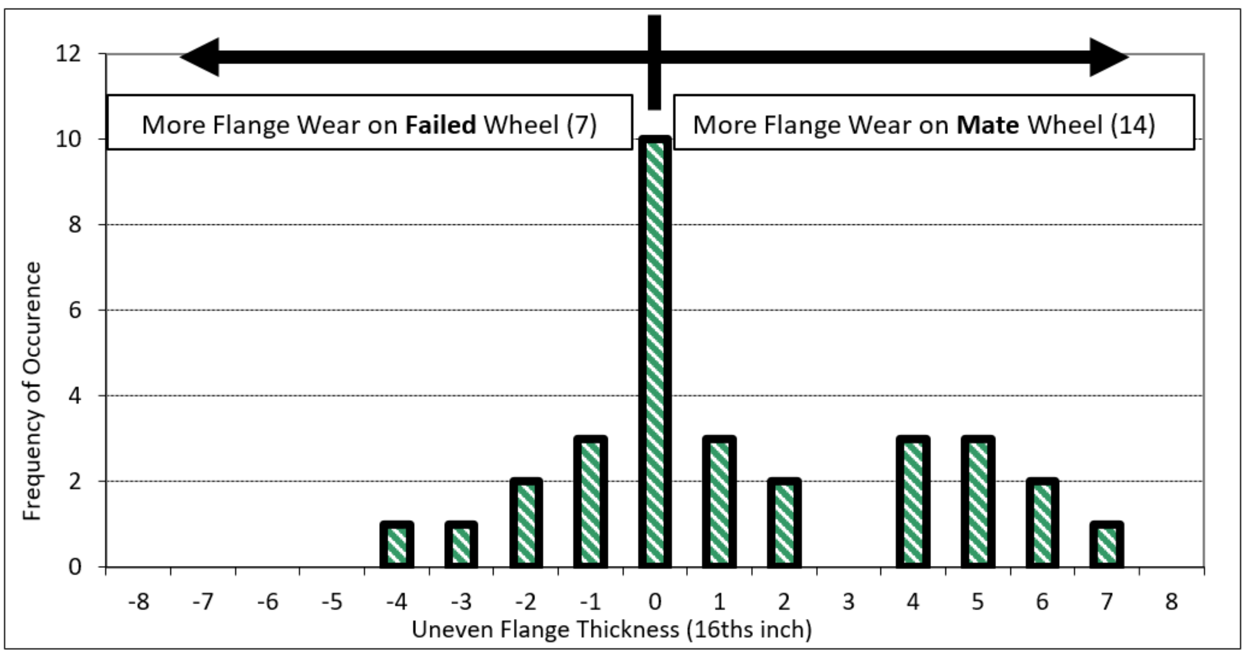


Figure 41. Uneven Flange Wear on Shattered Rim Failed Wheelsets

As recommended for further analysis of VSR failure trends, normalization of wheel data using information from non-failed wheels with similar accumulated service life as the failed wheels should be considered in subsequent analysis.

4.2 Current Industry Understanding of Failure Mechanism

Shattered rim failures have been on the decline due to improvements to manufacturing processes. For cast wheels, improvement was made to reduce the porosity experienced at the transition area between the plate and rim by adjusting dimensions in that area and modifying the design of the reservoir built into wheel casting molds, or risers, to prevent cavities due to shrinkage. For wrought wheels, improvements were made to reduce relatively large inclusions. For both cast and wrought wheels, ultrasonic testing has aided in finding at-risk porosity and inclusions. Lastly, the industry has proactively removed high risk wheels that had the above problems before manufacturing changes were made. Most notably were cast wheels manufactured by Southern Wheel, which triggered AAR Field Manual Rule 41 A.2.j to allow for their removal.

Although shattered rim failures are on the decline, there are still a sizable number of failures each year. This begs the question of what further research is required to virtually eliminate shattered rim failures. The following are areas of shattered rim research that have not yet been investigated:

- Stone (2001) discovered that WILD impact conditions have a correlation with shattered rims. Further research should be conducted to determine the WILD value and number of impacts is required to initiate a shattered rim.
- Stone (2000) initially found that shattered rims failed prematurely due to a manufacturing condition. These early failures occurred when the rim was thick. Stone also found that when the rim thickness approached the condemning limit, shattered rim failures increased. When the wheels are new, any significant porosity or inclusions are deep within the rim and relatively distant from the Hertzian contact stress effects. However, as the wheel wears and is turned, this distance is reduced, putting the porosity/inclusions in the zone of the Hertzian contact stress. Results from the MD-115 data analysis indicated shattered rims now have a stronger correlation to thin rim conditions than Stone previously reported. Further research should be conducted to evaluate the current state of the industry and if there is a growing correlation of thin rim conditions to shattered rims.
- Residual stress creation during service was found to be a significant factor in VSRs. It is currently unknown if this residual stress has an effect on shattered rim creation or not.

5. Future Research and Recommended Actions

As a result of the initial analysis of MD-115 data and railroad-provided laboratory reports described in previous sections, the researchers along with the FRA and SWG have developed an expanded data collection and analysis plan that is currently underway:

1. Researchers will complete a compilation of a comprehensive database using the MD-115 data, railroad laboratory reports, FRA derailment database and Universal Machine Language Equipment Register (Umler) car identification information by adding any additional railroad provided laboratory reports. The intent of this step is to document as much characteristic information about each wheel failure as possible from all available data sources.
2. For each failed wheel, researchers will acquire the following data:
   a. Installation date of each wheelset of interest by correlating information with car repair billing data maintained by the railroads
   b. Wheel profile (e.g., rim thickness, etc.) from the failed wheel as well as its mate prior to failure
   c. The history of wheel impacts as reported by WILD sites for both the failed wheel and its mate wheel prior to failure
   d. Hot wheel measurement history of the failed wheel and its mate prior to failure
3. Build histograms of each characteristic of failed wheels to identify commonalities
4. Build the same histograms of non-failed wheels in the population
5. Compare results for the failed and non-failed wheels to identify outlier characteristics
6. Gather data to understand the increase number of broken flange failures under WM66
7. Conduct analysis to understand the major contributors of the non VSR/VSF WM68 failures which make approximately 60 percent of the failures under this category

Data will be provided by the railroads as well as Railinc, the host of the North American railroad's data repository. In addition, this information will be compared to the general wheel counts in the industry to ensure that all results are put in perspective to the overall wheel population. Members of the SWG have identified alternative data elements that may be of interest, such as individual wheel impact histories through WILD sites in lieu of maximum wheel impacts, in the event that data identified in the analysis plan does not prove as valuable as anticipated. Researchers and data analysts will be sharing interim results with FRA and SWG members throughout the analysis effort to identify potential modifications to the plan.

<u>Preliminary Hypothesis of Vertical Split Rim Creation</u>

To help guide the data analysis efforts, researchers have developed several hypotheses regarding the development of wheel failures, particularly VSRs. It is hoped that these hypotheses will either be proven or refuted during the execution of the analysis plan. Either outcome is expected to advance the understanding of the development of conditions that lead to wheel failures.

a. The tensile axial residual stress is generated according to the Lonsdale theory (see Section 2), which involves plastic deformation of the wheel tread surface creating residual compression on the tread surface and residual tension below the surface. This plastic tread deformation can be created by:

i. Rolling contact (which is quantified wear identified by rim thickness and hollow wear measurements)

ii. Wear (which is quantified by rim thickness and hollow wear)

iii. Elevated wheel/rail contact stress (which is quantified by undesired wheel profile characteristics such as hollow wear)

iv. Wheel impact load severity and duration (which is quantified by WILD data)

v. Tread braking during rolling, elevated wheel/rail contact stress, and/or wheel impacting (which can be assessed with wheel characteristics along with previous wheel stress research and/or modeling efforts that can be conducted in subsequent phases of the research program).

b. It is hypothesized the axial residual stress is not created from a sole source, but can be created by various combinations of the above contributors. This would explain the general trends of having a thin rim, hollow wear, and WILD history, but having variability of those three parameters in VSR wheels. Theoretically, there may be a relationship that proportionally combines the above parameters to correlate to residual stress generation. The existence of this relationship can be explored once the data cited in the analysis plan has been compiled.

c. A horizontal crack is needed to turn downward and enter the axial residual stress zone.

d. The vertical crack occurs due to an external load applied to a sufficiently sized and oriented horizontal crack in combination with the tensile axial residual stress. Additionally, reduced fracture toughness may also play a role.

<u>Preliminary Hypothesis of Vertical Split Rim Characteristics Explanation</u>

a. As discussed above, there are many different factors that can work in combination to create a VSR. Because of all the various combinations of these factors, VSRs have a relatively broad range of common characteristics.

b. Based on initial data assessments and discussions with SWG members, western U.S. and Canadian freight railroads have higher VSR failure rates than the eastern freight railroads. A hypothesis for explaining this is summarized by the following:

i. Western U.S. and Canadian railroads run higher train speeds for longer periods of time as compared to the eastern railroads. This means that high-impact wheels are in service for longer periods of time.

ii. Western U.S. and Canadian railroads have a significant number of concrete ties while the eastern railroads have virtually none. Concrete ties are known to be stiffer, which would cause an impacting wheel to impact harder.

iii. Western U.S. and Canadian railroads have longer, steeper grades which require longer periods of tread braking as compared to the eastern railroads.

ii. Canadian railroads have a higher rate of WILD impacting wheels. It has been hypothesized that icy conditions and less adhesion leads to wheel slip and slide creating flats and ultimately impacting wheels. It has also been shown that ice formation in the cracks leads to accelerated growth of existing cracks which leads to higher failure rates in northern railroads (Dedmon, S., Stone, D., & Snyder, T., 2009).

This hypothesis and potential contributing factors will be assessed with WILD data and expanded information regarding wheel histories.

c. Based on data analysis conducted to date, it is observed that VSRs are more common in the winter/spring than summer/fall. This is potentially explained by frozen ballast being stiffer than ballast at other times of the year. As a result, an impacting wheel will experience higher impacts in the winter/spring. This explanation may be more viable than temperature effects on wheel material properties as a contributing factor.

d. VSRs were predominantly in Class C wheels while Class U wheels did not incur many VSR failures. It is not believed that the rim quenching itself is introducing a direct problem, but rather the Class C wheels are harder and last longer as compared to the Class U wheels. This allows the Class C wheels to have more time to generate an impacting condition and generate tensile axial residual stress. Interestingly, rim quenching was first instituted in 1989. VSR failures were noted to occur after 1990 with a significant increase after 2000. The most common service life of a VSR wheel was found to be 10 years.

e. VSR research conducted in the late 2000s, noted that shelling/spalling was the primary mechanism for the horizontal cracking (Stone, D., Tournay, H., & Cummings, S., 2009) (Stone, D., Dedmon, S., Pilch, J., & Cummings, S., 2010) (Kristan, Elkins, & Stone, 2004) (Dick, M., Snyder, T., Iwand, H., McConnell, D., & Magner, J., 2008). Later research conducted by Tournay et. al. (2016) and Dedmon et. al. (2016) noted a third mechanism called "delamination." Figure 4 highlights that there was a spike in VSR failures in wheels manufactured in 2005 and Figure 14 highlights that the service life is commonly 10 years. Further research is needed to determine what happened in 2005 and if those wheels are an explanation for the discrepancy between the pre-2000 and post-2000 research work in terms of proposed failure mechanisms.

It is important to note that the hypothesis described in this section does not represent the outcome of the effort that researchers are driving towards. The hypothesis serves as a guide to the investigation. Any results from the data analysis that confirm or refute any aspect of the hypothesis will be shared with FRA and SWG participants for assessment of the results as well as any necessary changes to the research and analysis plan.

As researchers have developed and initiated the analysis plan, several recommendations for future activities have been formulated for FRA's consideration. The following sections highlight these potential efforts.

5.1 Vertical Split Rim Wayside Detector Combination Criteria

A short term, high reward strategy to reduce VSR failures is to determine a combination criterion employing wayside detector data that correlates to a high probability of the wheel having a VSR. It is envisioned that this criterion may include a combination of rim thickness, hollow wear, WILD history and potentially hot wheel history. Combination criterion can target a relatively small amount of the wheel population for removal, which is palatable to the railroads. Some of the railroad stakeholders have already voiced their support of this effort. Sultana (2015) investigated this concept and identified a combination rule using WILD and thin rim which was later implemented as *AAR Field Manual* Rule 41 A.1.h.3. Feedback from the SWG indicated that the rule did not remove many wheels that would not have been removed anyways and that the WILD impacts or rim thickness individually would have condemned the wheel. Cummings (2011) proposed that the kip-miles may be a useful metric to correlate impacting conditions to VSR failures. Further investigations should be conducted in this area.

A combination criterion is not anticipated to completely remove VSR failures, but it should reduce them. The wheels that are removed can be further analyzed to help understand the underlying root cause(s) of the failures.

5.2 Thin Rim Practices

A common characteristic of VSR and shattered rim failures is that they have thinner rims than the general wheel population.

For shattered rims, it is well understood that a thin rim creates risk because the Hertzian contact stress field is closer to inclusions or voids deep within the rim. When the rim is thick, the Hertzian contract stress is sufficiently far away from these inclusions/voids that they do not cause concern.

For VSRs the effect of a thin rim is less understood. It is theorized that a thin rim implies more residual stress due to more plastic deformation/wear on the tread surface. Additionally, it is unknown at this point if delamination is associated with thin rim conditions or not. Further research should be conducted to investigate the correlation of thin rim and VSR failures.

A statistical and economic analysis should be performed to investigate changing CFR § 215.103(c)–Defective wheel. Questions that should be evaluated are:

- How many wheels would be removed when increasing the FRA limit up in increments of 1/16th of an inch?
- What is the economic impact of making this change?
- What is the safety/risk improvement of making this change?

Some SWG members expressed concern that failed wheelsets comprise an extremely small fraction of the wheelset population (less than 0.0035%), whereas increasing the minimum rim thickness would shorten the average service life wheels by a certain percentage governed by the threshold that would be used to flag wheels for removal. Other aspects that should be researched in anticipation of this response include:

- Economic and safety/risk improvement of applying a more conservative rim thickness criteria to hazardous materials and crude oil tank cars
- Evaluation of current UT or current use of the technology to determine if inclusions/voids which can cause a shattered rim can be better detected
- Investigation of the benefits of turning a wheel to remove surface defects and reduce VSR residual stress. In addition to removing any initiated cracks, turning a wheel removes the compressive axial stress on the tread surface which will result in a reduction of subsurface axial tensile stress, which is the driving stress for VSRs. If these practices

are found to be beneficial, investigate the economics and safety/risk improvement of requiring wheel turning and UT testing on non-new wheels before they are returned to service and/or testing while the car is shopped.

5.3 Residual Stress

Unfortunately, residual stress research has stalled in recent years. There are still many unanswered questions that should be researched:

- How to determine the peak tensile axial residual stress within a wheel, regardless of the location tested and accounting for relaxation caused by fracture?
- What is the correlation of WILD values to axial residual stress values?
- What is the correlation of braking temperature and time to axial residual stress values?
- Do WILD impacting conditions and tread braking at the same time cause an effect on the axial residual stress?
- What is the axial residual stress after a turned wheel has been in service for ~3,700 miles or more? Is it the same as a new wheel after that same service duration?
- What is the growth rate of axial residual stress during normal rolling contact and WILD impacting conditions over long distances?

A test program should be created to further the residual stress research to answer these questions.

5.4 Rim Quenching

Rim quenching is a key heat treatment process to induce beneficial compressive hoop residual stress in the rim. However untreated Class U wheels have a lower VSR rate and incur less tensile axial residual stress as compared to heat treated Class C wheels. This begs the question what role rim quenching plays in VSRs. It is not believed that the rim quenching itself is introducing a direct problem, but rather the heat treated Class C wheels are harder and last longer as compared to the untreated Class U wheels. This allows the Class C wheels to have more time to generate an impacting condition and generate axial residual stress. Further research should be conducted to investigate the role that rim quenching plays in VSRs using analysis and/or experimentation to determine if modifications to the rim quenching can be made to still retain the beneficial compressive hoop residual stress, but reduce the tendency for Class C wheels to generate tensile axial residual stress during service.

5.5 Delamination

Further research is needed to determine the root cause of delamination. The first task is to determine the percentage of VSR failures initiated by delamination. This will help determine the overall priority of the delamination failure mechanism. Secondly, delamination appears to be a classic subsurface fatigue crack similar to a shattered rim, but much shallower. Additionally, the delamination cracking appears to have restricted growth in the axial direction (up to 0.5 ~ 1.0-inch-wide cracks), but unrestricted growth in the circumferential direction. This gives the delamination a unique “cigar” shape. The initiation of the delamination should be investigated to determine if it is caused by manufacturing issues associated with inclusion/voids and whether the "cigar" shaped crack growth is defined by residual stress, brake application location, wheel/rail contact conditions or some combination thereof.

5.6 VRS Causes Data Analytics and VSR Recreation in Lab/Field Testing

It is believed that VSRs are caused by a combination of factors working together. A data analytics analysis is proposed to determine the underlying relationship between the factors to create an equation to be used to predict VSR failure risk. It is anticipated that this equation would highlight many combinations that can yield VSR failure. Once this equation is developed and validated using past VSR failure data, it can be used to aid in recreating a VSR in the laboratory or field testing. By being able to recreate VSRs in the laboratory, it will greatly accelerate identification of preventative measures.

5.7 Wheel Turning Economic Analysis

As previously discussed, VSRs are extremely rare—if not non-existent—in domestic and international passenger wheels, and international freight wheels, including Australian mining railroads which operate at higher axle loads than the North American freights. The aforementioned railroads generally utilize multi-wear wheels and routinely turn their wheels. However, the North American freight railroads use single wear wheels which typically have zero or one turn before end of life. It appears that the U.S. freight railroads are an outlier in the world for not utilizing multi-wear wheels and routinely turning the wheels.

If the North American freight railroads were to consider adopting the practice of multi-wear wheels with routine turning, a cost-benefit analysis will need to be performed to evaluate the benefit of attempting to maximize the wheel's life through turning as opposed to use of single-wear wheels as is currently done. Interestingly, the North American track maintainers have already adopted the practice of grinding to remove rail surface defects/cracks and promoting a more favorable profile. This practice has shown that it can extend rail life instead of reducing it. A similar practice applied to wheel maintenance would clean the wheel surface and remove any surface cracks which could help reduce shell creation on wheels.

Key aspects that would need to be evaluated in a cost-benefit analysis would include:

- Why the North American freight market adopted the single-wear wheel practice in the first place?
- What criteria should be used for turning wheels?
- What are the anticipated intervals for turns and work load for wheel shops?
- What is the current state of wheel shop infrastructure and what infrastructure would be needed to achieve the goal?
- Does wheel turning technology need to be developed/improved to achieve the goal?
- What wheel profile templates are required to remove the minimum amount of material to achieve the economic and safety goals?

An analysis of this nature should consider the economic impact of extended wheel life on rail life and rail grinding. It is anticipated that the economic benefits of preventive wheel truing on the wheels themselves will be modest. However, the economic benefits on prevented derailments, extending rail life and reducing rail grinding could be significant. Questions that should be answered in this research are:

- Do the international heavy haul railroads that routinely turn their wheels have to grind their rail as often as the North American freight railroads?
- What effect would less impacting wheels and worn wheel profiles have on rail life, rail breaks, and rail grinding?

5.8 Roadmap for Shattered Rim Failure Extinction

Shattered rim failures have significantly reduced over the past decades. However, they have not experienced a virtual extinction like thermal cracking. Thermal cracking in wheels was extremely common, but is now very rare. Shattered rims were extremely common, but are now somewhat uncommon. Further research work should be performed to determine the roadmap to reduce shattered rim failures to the levels of modern thermal crack failures. Elements that should be investigated include:

- Are there wheels from a manufacturer or year in the general wheel population that are at high risk of generating a shattered rim that can be preventively removed? If this were the case, can modern machine vision technology be used to read the wheel markings like the year of manufacture or manufacturer to identify these wheels?
- Can adjustments to rim thickness and ultrasonic practices for non-new wheels be adjusted to make a greater impact in removing at risk wheels?
- What effect do WILD impacting conditions and residual stress have on shattered rims?

5.9 MD-115 Database

Review of the MD-115 data and the railroad-provided laboratory data led to identification of gaps between these two data sources. SWG members confirmed that railroads consider completion of the MD-115 form mandatory but compliance can be difficult to enforce. To mitigate some of the concerns, the AAR's WABL Committee is already working on change to the MD-115 database including refinement of cause codes to eliminate two different failures being captured with the Why Made 68 code. An electronic database is also being created which is intended to improve record accuracy. These changes are expected to go into effect in the end of 2017. It was also suggested by the SWG that several of the following key improvements to MD-115 record keeping could be made:

- More photos included with each wheel report and a clearer definition of photos that need to be included
- A mechanism to audit the entries
- Including wayside data such as WILD history and hollow wear measurements
- Matching information on the mate wheel

6. Conclusion

Researchers working with FRA and the SWG identified the following wheel failures to consider in this study: VSR; shattered rims; broken flange; plate cracking; thermal cracking in flanges; and thin rim overloads. A general understanding of VSRs is provided in Section 1.1. Hypotheses have been proposed for both the initiation and characteristics of VSRs along with an analysis plan that will allow for answering questions. SWG members stressed the importance of considering wheel measurements at or just prior to removal when looking at measurements from the general wheel population for comparison to measurements from broken wheels.

Shattered rim failures are characterized as a large subsurface fatigue crack created by Hertzian contact stress resulting in a characteristic "bullseye" fatigue fracture roughly parallel to the tread surface. Eventually the bullseye fatigue fracture grows large enough to cause a final overload fracture which removes a large portion of the rim.

The following should be conducted for shattered rim failures:

- Further research to determine if maximum wheel impact values and number of impacts reported by WILDs can be correlated to identify an early warning for shattered rim failures
- Additional research to evaluate the current state of the industry and if there is a growing correlation of thin rims and shattered rim failures
- Determine whether residual stress effects the creation of shattered rims

Researchers proposed several recommendations for FRA's consideration provided in Section 5. It is likely that the railroads will state that failed wheels comprise an extremely small amount of the wheel population, and changing the rim thickness threshold would remove too many good wheels. Other aspects that should be researched in anticipation of this response are noted in Section 5.2. Section 5.3 notes many unanswered questions that still require research. It is recommended that a test and/or analysis program be created to further the residual stress research to answer these questions.

7. References

Cummings, S. (2011). *AAR Strategic Research - Wheel Failures.* Pueblo, CO: Transportation Technology Center, Inc.

Cummings, S. (2011). Inspection Results and Impact Load History of Vertical Split Rim Wheels . *Technology Digest TD-11-020.* Pueblo, CO.

Cummings, S. (2014). *Broken Rims in Railroad Wheels*. Washington, DC: U.S. Department of Transportation, Federal Railroad Adminstration.

Cummings, S. (2016). Wheel Life and Maintenance Practices of Heavy Haul Railways,. *TTCI Technology Digest TD-16-004.* Pueblo, CO.

Cummings, S., Oliver, J., & Lonsdale, C. (2011). Axial Residual Stresses in Vertical Split Rim Wheels. *TTCI Technology Digest TD-11-040.* Pueblo, CO.

Cummings, S., Sura, V., Mahadevan, S., & Oliver, J. (2010). Modeling the Vertical Split Rim Failure of Wheels. *TTCI Technology Digest TD-10-028.* Pueblo, CO.

Dedmon, S., & Guzel, H. (2011). Crack Initiation in Railway Wheels Resulting from Rolling Contacts. *Proceedings of the 2011 ASME/ASCE/IEEE Joint Rail Conference.* Pueblo, CO.

Dedmon, S., Kato, T., & Pilch, J. (2016). Effect on Temperature on Hardening and Residual Stress Development During Wheel-Rail Rolling Contact. *Proceedings of the 2016 Joint Rail Conference.* Columbia, SC.

Dedmon, S., Pilch, J., Hiramatsu, S., Yamamoto, Y., & Kato, T. (2016). Finite Element Analysis of Vertical Split Rim Cracks and Prediction of Wheel Failure Mode(s). *Proceedings of the 11th World Congress of Railway Research.* Milan, Italy.

Dedmon, S., Stone, D., & Snyder, T. (2009). A Proposed Mechanism for Accelerated Shelling of Railroad Wheels Induced by the Hyperbaric Transformation of Ice. *8th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, *CM2009.* Firenze, Italy.

Dick, M., Snyder, T.; Iwand, H., McConnell, D., & Magner, J. (2008). *Characterization of Vertical Split Rim Wheel Failures.* BNSF Wheel Shelling & Failure Study Group.

Kristan, J., Elkins, J., & Stone, D. (2004). Effect of Wheel Loading on the Occurence of Vertical Split Rim Wheel Failures. *ASME International Mechanical Engineering Congress and Exposition.* Anaheim, CA.

Lonsdale, C., & Oliver, J. (2011). Wheel Rim Axial Residual Stress and a Proposed Mechanism for Vertical Split Rim Formation. *Proceedings of the ASME 2011 Rail Transportation Division Fall Technical Conference.* Minneapolis, MN.

Lonsdale, C., & Oliver, J. (2013). Effect of Wheel Truing on Wheel Rim Axial Residual Stress. *Proceedings of the ASME/ASCE/IEEE 2011 Joint Rail Conference.* Knoxville, TN.

Lonsdale, C., Oliver, J., Bitner, A., & Guzel, H. (2013). Vertical Split Rim Wheel Failures and the Role of Axial Residual Stress. *Proceedings of the 17th International Wheelset Congress.* Kiev, Ukraine.

Lonsdale, C., Oliver, J., Maram, R., & Cummings, S. (2013). Development Of Railroad Wheel Rim Axial Residual Stress In Heavy Axle Load Service. *Proceedings of the ASME 2013 Rail Transportation Division Fall Technical Conference.* Altoona, PA.

Lonsdale, C., Rusin, T., & Hay, T. (2009). Research to Understand the Effects of Wheel Impact Loads on Wheel Stress Levels. *Proceedings of the 2009 ASME Joint Rail Conference.* Pueblo, CO.

Lonsdale, C., Rusin, T., & Pilch, J. (2007). Wheel Rim Residual Stress Research Using Finite Element Analysis Computer Simulations. *Proceedings of the 15th International Wheelset Congress.* Prague, Czech Republic.

Meddah, A., & Stone, D. (2013). A Neural Network Analysis of the Causes of Vertical Split Rim Wheel Rim Failure. *Proceedings of the 17th International Wheelset Congress.* Kiev, Ukraine.

Railinc. (2015). The North American Freight Railcar Review. *Railinc.* Cary, NC.

Stone, D. (2000). Shattered Rim Defects in Wheels. *Wheels and Axles, Cost Effective Engineering, I MECH E Seminar.* London, UK: Institution of Mechanical Engineers.

Stone, D., & Koch, K. (2005). *Estimation of Residual Stress at Root Shell Crack that Initates a Vertical Split Rim.*

Stone, D., Dedmon, S., Pilch, J., & Cummings, S. (2010). A Neutral Network Analysis Of The Causes Of Vertical Split Rim Wheel Rim Failure. *Proceedings of the 16th International Wheelset Congress.* Cape Town, South Africa.

Stone, D., Dedmon, S., Pilch, J., & Cummings, S. (2010). Vertical Split Rim Wheels. *Proceedings of the 16th International Wheelset Congress.* Cape Town, South Africa.

Stone, D., Lonsdale, C., & Kalay, S. (2001). *Effect of Wheel Impact on Shattered Rim*. Retrieved from Standard Steel Technical Technical Papers.

Stone, D., Tournay, H., & Cummings, S. (2009). Broken Wheel Inspections. *TTCI Technology Digest.* Pueblo, CO.

Stratman, B. (2007). Reliability and Clustering Techniques for Inspection Optimization of Large Populations. *Dissertation - Graduate School of Vanderbilt University.* Nashville, TN.

Sultana, T. (2015). High Impact and Thin Rims Broken Wheel Analysis. Pueblo, CO: Transportation Technology Center, Inc.

Sura, V., & Mahadevan, S. (2010). Shattered Rim Failure Modeling in Railroad Wheels. *Proceedings of the ASME 2010 Rail Transportation Division Fall Technical Conference.* Roanoke, VA.

Sura, V., & Mahadevan, S. (2010). Vertical Split Rim Failure Analysis in Railroad Wheels. *Proceedings of the 2010 Joint Rail Conference.* Urbana-Champaign, IL.

Tournay, H. (2010). A Root Cause For Thermal Mechanical Fatigue Resulting In High Impact Wheels. *Proceedings of the 16th International Wheelset Congress.* Cape Town, South Africa.

Tournay, H., & Jones, K. (2016). Investigation: Root Causes of Vertical Split Rim Wheel Failures. *Association of American Railroads 21st Annual Research Review.* Pueblo, CO.

Transportation Technology Center, Inc. (2015). 20th Annual Research Review. *TTCI.* Pueblo, CO.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	Association of American Railroads
BNSF	Burlington Northern Santa Fe Railway
CN	Canadian National Railway
CP	Canadian Pacific Railway
CRB	Car Repair Billing
CFR	Code of Federal Regulations
CSX	CSX Transportation
ESI	Engineering Systems, Inc.
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
FEA	Finite Element Analysis
GATX	GATX Corporation
GRL	Gross Rail Load
NS	Norfolk Southern Corporation
RRS	Office of Railroad Safety
RD&T	Office of Research, Development and Technology
RCF	Rolling Contact Fatigue
SWG	Stakeholder Working Group
TTCI	Transportation Technology Center, Inc.
UT	Ultrasonic Technology
UP	Union Pacific Railroad
VSF	Vertical Split Flange
VSRs	Vertical Split Rims
WABL	Wheel, Axle, and Bearing Lubrication
WILD	Wheel Impact Load Detectors
WM68	Why Made 68