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of Transportation
**Federal Railroad
Administration**

ECONOMIC ANALYSIS OF THE USE OF THE ELECTROMAGNETIC ACOUSTIC TRANSDUCER (EMAT) FOR WHEEL STRESS MEASUREMENT

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16. Abstract

Transportation Technology Center, Inc. (TTCI) has analyzed the economics of using Electromagnetic Acoustic Transducer (EMAT) technology to inspect freight car wheels. EMATs are designed to nondestructively determine the residual hoop stresses of a freight car wheel at the rim. Braking irregularities that generate heat above the upper transformation temperature of the steel causes residual hoop stresses in freight car wheels. Residual hoop stresses in freight car wheels may lead to brittle fractures of the rim, which may contribute to the propagation of cracks and potentially to wheel failure.

The objective of this report is to provide technical, as well as operational information by conducting a feasibility study of the EMAT systems potential benefits and cost in today's railway operating environment.

The report concludes that EMAT technology is not a fully developed wheel inspection system and it requires further testing to prove its accuracy and reliability. Accuracy and reliability drive the economics of EMATs. Under optimal conditions (100 percent service accuracy and reliability), and with every AAR certified wheel shop using EMATs to test for residual hoop stresses, the feasibility study shows a benefit to the railway industry. However, any deviation from these optimal conditions show a significant loss due primarily to false positive measures, which would cause a potentially good wheel to be scrapped. Therefore, additional resources required for further development of the EMAT system must be carefully reviewed in order to justify its development for in-shop wheel inspection.

Additionally, freight car wheels and braking technologies have improved to a point that wheel failures in service are considered an infrequent event, which was the primary reason for EMATs development. New wheel designs, improved metallurgy, and heat-treated wheels have played an important part in decreasing wheel failure accidents over the last three decades. Therefore, because of the small number of wheel failures in the railway industry today EMATs continued development is not warranted as an in-shop wheel measurement device under the scope of this study.

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Electromagnetic Acoustic Transducer (EMAT), Residual Hoop Stress, Wheel Detection Technology

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	m^2
mi^2	square miles	2.60	square kilometers	km^2
	acres	0.40	hectares	ha

MASS (weight)

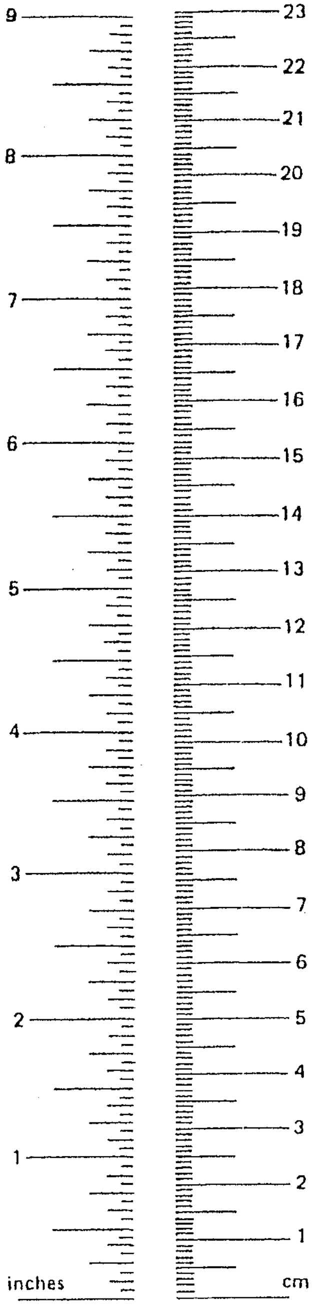
Symbol	When You Know	Multiply by	To Find	Symbol
oz	ounces	28.00	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.90	tonnes	t

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
tsp	teaspoons	5.00	milliliters	ml
Tbsp	tablespoons	15.00	milliliters	ml
fl oz	fluid ounces	30.00	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.80	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0 76	cubic meters	m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
mm	millimeters	0.04	inches	in
cm	centimeters	0.40	inches	in
m	meters	3.30	feet	ft
m	meters	1.10	yards	yd
km	kilometers	0.60	miles	mi

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
cm^2	square centim.	0.16	square inches	in^2
m^2	square meters	1.20	square yards	yd^2
km^2	square kilom.	0.40	square miles	mi^2
ha	hectares ($10{,}000\ \text{m}^2$)	2.50	acres	

MASS (weight)

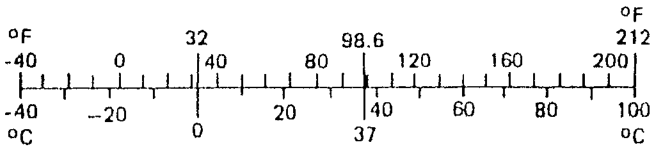
Symbol	When You Know	Multiply by	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2 2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.10	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36.00	cubic feet	ft^3
m^3	cubic meters	1.30	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32	Fahrenheit temperature	°F



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* 1 in = 2.54 cm (exactly)

EXECUTIVE SUMMARY

The Transportation Technology Center, Inc. (TTCI) has analyzed the economics of using Electromagnetic Acoustic Transducer (EMAT) technology to inspect freight car wheels. EMATs are designed to nondestructively determine the residual hoop stresses of a freight car wheel at the rim. Braking irregularities that generate heat above the upper transformation temperature of the steel causes residual hoop stresses in freight car wheels. Residual hoop stresses in freight car wheels may lead to brittle fractures of the rim, which may contribute to the propagation of cracks and potentially to wheel failure.

Accuracy and reliability drive the economics of EMAT technology. Under optimal conditions, assuming the EMAT system operates with 100 percent accuracy and reliability, and with every AAR certified wheel shop using EMATs to test for residual hoop stresses, the feasibility study shows a benefit to the railway industry. However, any deviation from these optimal conditions show a significant loss due primarily to false positive measures, which would cause a potentially good wheel to be scrapped. Therefore, additional resources required for further development of the EMAT system must be carefully reviewed in order to justify its development as an in-shop wheel inspection system.

Freight car wheels and braking technologies have improved to a point that wheel failures in service are an infrequent event, which was the primary reason for EMATs development. New wheel designs, improved metallurgy, and heat-treated wheels have played an important part in decreasing wheel failure accidents over the last three decades. Therefore, because of the small number of wheel failures in the railway industry today EMATs continued developed is not warranted under the scope of this study as an in-shop wheel measurement device.

In addition to the findings of this report a similar study conducted by the Burlington Northern (BN) in 1990, which analyzed the Barkhausen noise analysis system (BNA) reported similar results. Under their current operating conditions the BNA technology, also designed to measure residual stress in freight car wheels, conclusions indicated that it was unlikely that a non-destructive wheel inspection technology could be developed that would be economical. Therefore, the BNA was not a recommended alterative for decreasing their wheel failure accidents.

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Figures and Tables

1.0 INTRODUCTION

Various factors determine the life of a railroad wheel. One is thermal damage caused by abnormally heavy braking. A visual effect of a thermally damaged wheel is thermal cracking on the tread surface or flange. However, many thermally damaged wheels show no sign of being damaged but have lost the compressive stresses that are built into the wheel during the manufacturing process. When a wheel loses its manufactured compressive stress because of thermal damage, it may take on a state of residual tensile stress (hoop stress) causing the wheel to become less resistant to fracture. Development of tensile hoop stresses in a freight wheel while in service may lead to the propagation of thermal cracks. Research has shown that high levels of residual tensile stresses developing in the rim of some wheels may result in wheel thermal failure if a crack is present. Wheel thermal failure means rapid fracture of the wheel as an extreme consequence of excessive thermal damage. Nondestructive identification of a thermally abused wheel in service is complex and difficult. Electromagnetic Acoustic Transducers (EMAT) are designed to nondestructively determine the residual stress of a freight car wheel at the rim.

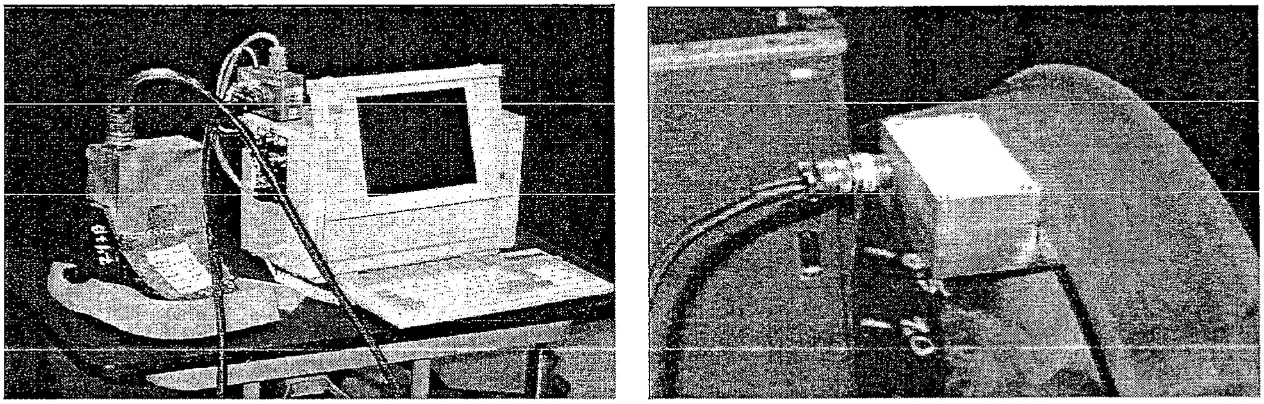
Wheel accidents have been decreasing consistently over the past 20 years. In 1979, the Federal Railroad Administration (FRA) reported 110 wheel failure accidents. Today, using a five-year average, (1993-1997) FRA data shows there are approximately 20 wheel failure accidents per year. Derailments caused by wheel thermal failure are an infrequent occurrence as a result of recent improvements in operating procedure and wheel technology. For example, there are approximately 10 million wheels in revenue service, and 20 failures represent a probability of failure of less than 0.0000002 (2×10^{-7}) or two failures per million wheels annually.

1.1 BACKGROUND

Thermal cracking is believed to result from tensile stresses occurring within the rim area of a wheel that has been heated above the upper transformation temperature of the steel. To improve detection of these stresses, the Federal Railroad Administration sponsored the development and evaluation of an EMAT system. EMATs are quantitative nondestructive testing tools designed to determine the residual stress state of both new and in-service cast railroad wheels. A laboratory evaluation has demonstrated that the system can consistently measure the average residual hoop stress through the rim thickness of Class C cast railroad wheels to ± 60 MPa

(±9ksi). The estimated accuracy of the system was determined by comparing EMAT results with destructive saw cut measurements and the commercially available DEBRO-30 system.

The EMAT system (Figure 1) was developed by the National Institute of Standards and Technology (NIST) in Boulder, Colorado. The system's performance has been evaluated by the Transportation Technology Center Inc.,(TTCI) a wholly owned subsidiary of the Association of American Railroads (AAR). The Griffin Wheel Company provided test facilities and equipment used to thermally damage the test wheels.



a. Lunchbox Computer with Transducer **b. Example of Transducer Connected to Wheel**

Figure 1. EMAT System

2.0 EMAT TEST PROGRAM

The prototype EMAT system is a compact, lightweight unit manufactured almost totally with commercially available parts for ease of replacement and maintenance. The equipment consists of a portable computer, a transducer housing that is held to the wheel with strong magnets, two commercial plug-in computer cards, and one specialty part containing a pre-amplifier and a polarization switch.

2.1 LABORATORY TEST PROGRAM

The accuracy of the EMAT system was assessed by taking ultrasonic measurements using both the EMAT and a piezo-electric based European system known as DEBRO-30, and comparing them with the results from saw-cutting, which allows the material adjacent to the cut to "relax." These cuts are made by a bandsaw from the outer edge of the wheel toward the center while monitoring the displacement (opening or closing, depending on the residual stress state) at the cut with a clip gage.

Wheels evaluated by the systems include:

- Two as-manufactured wheels
- Eight induction-heated wheels
- Twenty dynamometer drag-braked wheels

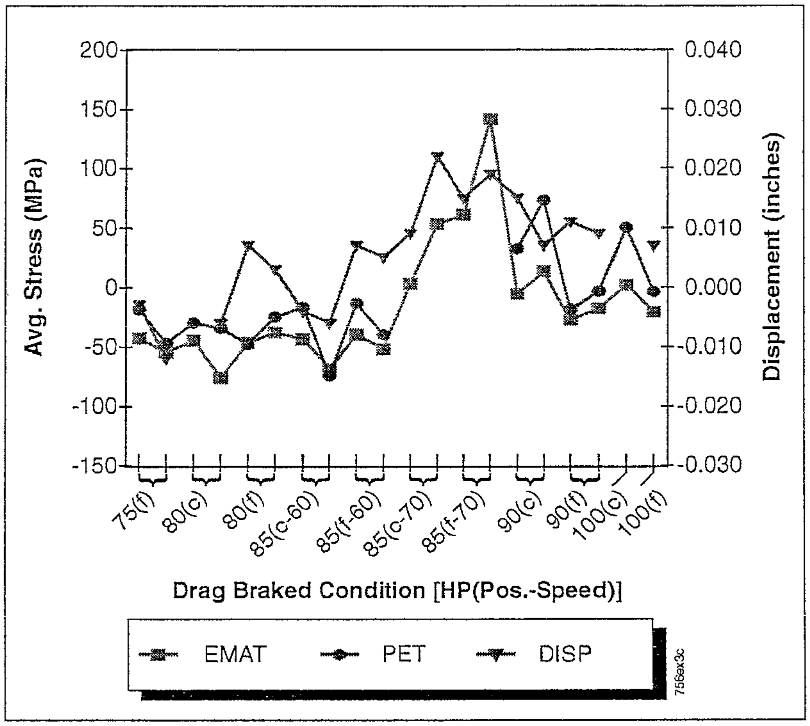
All wheels investigated were 36-inch Class C cast railroad wheels. The ultrasonic values from the two systems for the induction-heated wheels were also compared with finite element analysis (FEA) models, in which temperature-dependent material properties of the wheel steel were the basis for estimating the residual stress distribution caused by the heat input.

The drag-braked wheels were subsequently saw cut while measuring the material displacement around the saw cut caused by residual hoop stresses imparted by the drag braking. The residual stress of each wheel was then calculated by an FEA model that basically reversed the effects of the saw cuts ("unsaw-cuts"'or reversed cut opening/closing) to calculate the residual hoop stress. The hoop stress was then compared with the ultrasonic measurements taken prior to cutting.

2.2 ACCURACY AND RELIABILITY

The EMAT nondestructive testing system has demonstrated both accuracy and reliability in a laboratory environment to determine the residual hoop stress in as-manufactured, induction-heated, and drag-braked Class C cast Griffin railroad wheels to within approximately ±60 MPa (±9 ksi). This resolution is adequate for reliably and consistently determining the residual stress state of in-service railroad wheels and discerning damaged from undamaged wheels. However, the accuracy of the system in a less controlled wheel shop environment has not been quantified.

Comparison with the DEBRO-30 ultrasonic system showed excellent correlation in measurement trends with a maximum offset of approximately 40 MPa (6 ksi) or less. Destructive results from saw cutting, correlate with the ultrasonic data shown in Figure 2. The saw-cut displacements showing compression agreed with ultrasonic measurements showing that the wheel was in compression and conversely for residual tension. Comparisons between ultrasonic data and finite element analysis for induction-heated wheels also show a correlation to theoretical residual hoop stress estimates and ultrasonic measurements. An offset of -80 MPa (-12 ksi) was applied to the FEA heat model results shown in Figure 3 to compensate for the compressively stressed wheel condition produced as part of the manufacturing process.



Brake Position Identified Indicates f=Flange-Crowded or c=Tread-Centered.
All Test Speeds are 60 mph unless otherwise Stated.

Figure 2. Average Ultrasonic Residual Stress Measurements Correlated with Saw-Cut Displacements

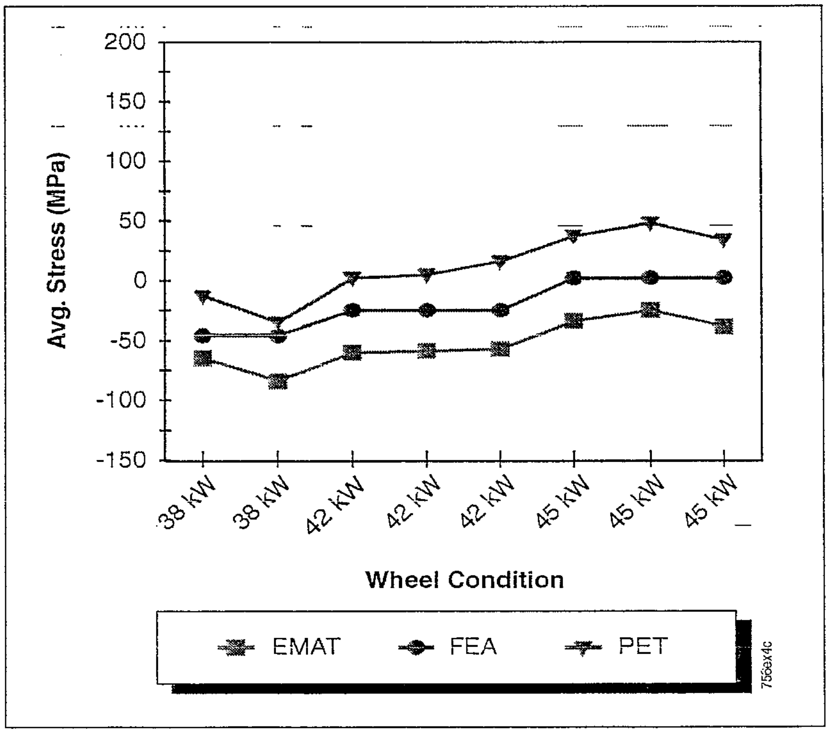


Figure 3. Correlation Between Ultrasonic Testing and FEA Heat Model Results for Induction-Heated Wheels

3.0 WHEEL DATA

North American freight car wheels function as brake drums and are therefore subject to heating. When the wheel is being braked, the temperature of the tread and rim increase while the plate and hub remain at a relatively low temperature. Because of this steep temperature gradient, the cool plate and hub restrain the expansion of the hot rim. This restraint between rim and plate produces stresses in the wheel which, under normal railway operations, are elastic and the stresses and deformations which occur return to their original state when the wheel cools. However, if the wheel is subjected to some unusual braking condition, such as a stuck brake, the thermal stresses produced may cause the wheel rim to deform beyond the elastic limit of the steel, leaving circumferential residual tensile stresses in the rim of the wheel upon cooling. The presence of circumferential residual tensile stresses in the rim defines a thermally damaged wheel.

A thermally damaged wheel must have other conditions present to result in a wheel failure. A crack of critical size must also be present. Wheel failure then can occur instantaneously when a sharp crack of critical length is subjected to a tensile stress at or above the critical level.

3.1 WHEEL POPULATION DATA

AAR data shows that approximately 6 percent of the system wheel population are straight plate wheels (Figure 4). Previous studies have shown that straight plate wheels have a disproportionally high wheel breakage-to-population ratio. Broken straight plate non-heat treated wheels have shown to be the most numerous, followed by straight plate heat treated, curved plate non-heat treated, and finally curved plate heat treated wheels. Data confirms that straight plate wheels fail more often than curved plate wheels in service. Therefore, Rule 41 Section A of the AAR Interchange Rules require straight plate wheels to be replaced (with the exception of some A-28 and A-30 wheels) by wheels with curved plate designs. This number of straight plate wheels in the system will decline, improving the industry accident ratio.

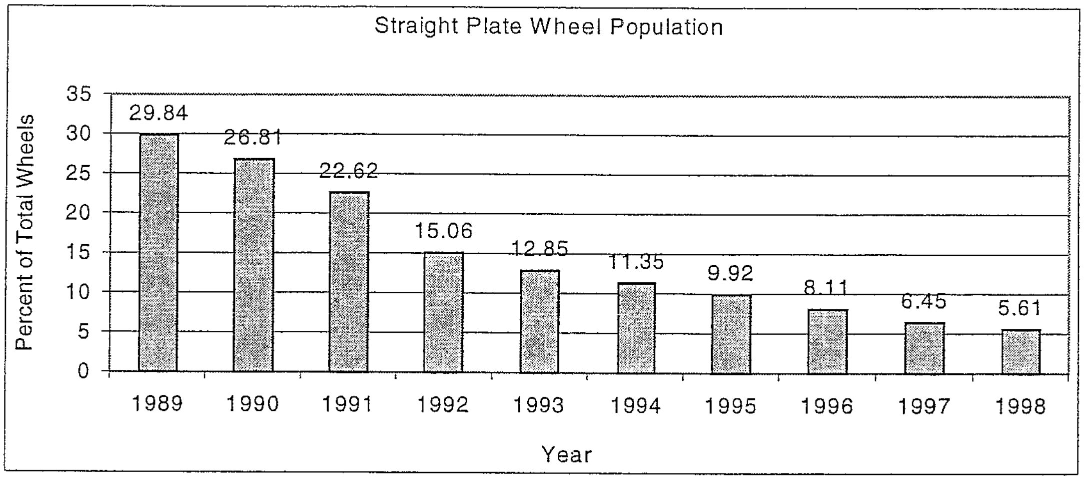


Figure 4. Straight Plate Wheel Population

3.2 BROKEN WHEEL ACCIDENTS

The train accident data used in this analysis were compiled by the FRA based on reports from all U.S. railroads (Figures 5, 6, and 7). Property damage for each year is adjusted to 1999 dollars using the Railroad Cost Recovery index (RCR). The accident/incident reporting threshold for calendar year 1995-1996 is $6,300, and changing to $6,500 for 1997. Reportable costs of property damage represent only a portion of the total cost of train accidents. Reportable costs include the cost of direct labor and damage to on-track equipment, track, track structures, and roadbed. Other direct accident costs, such as wreck clearing, third party property damage, lost lading, environmental damage, and train delay are not included in reportable damages.

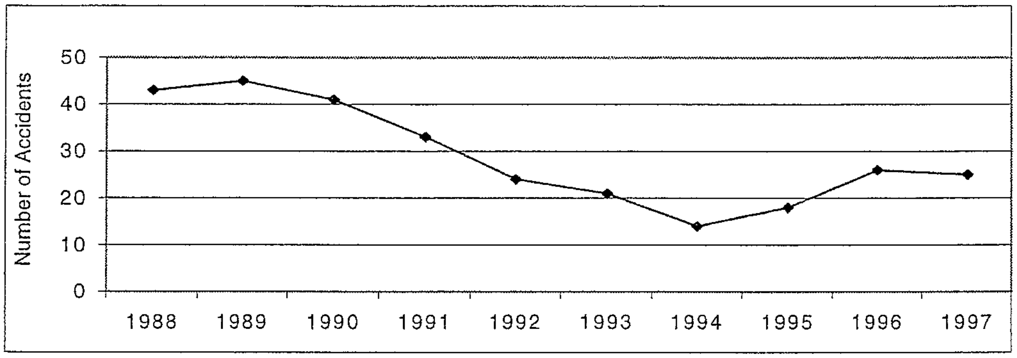


Figure 5. Accidents Related to Broken or Cracked Wheels

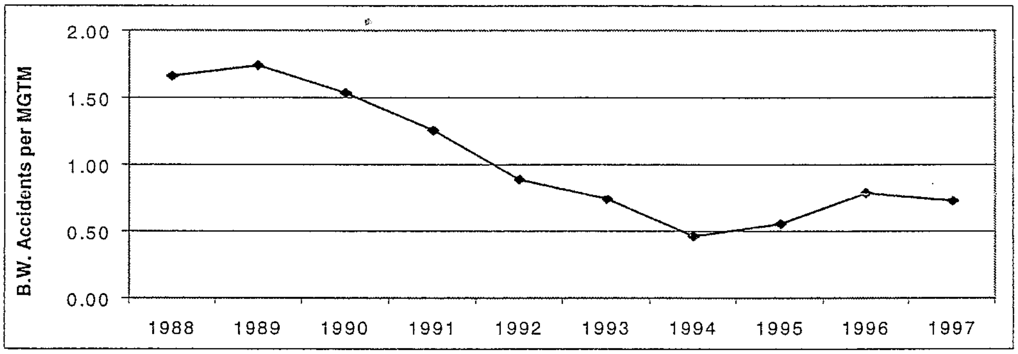


Figure 6. Occurrences of Broken or Cracked Wheel Accidents with MGT per Mile

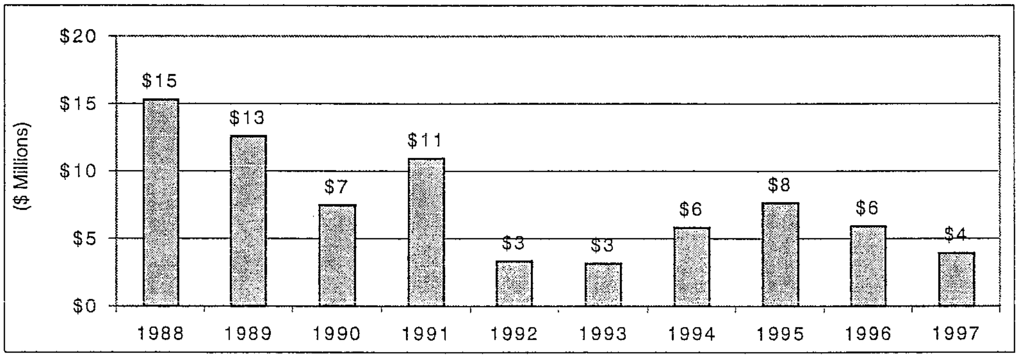


Figure 7. Property Damage due to Broken or Cracked Wheels

4.0 IDENTIFYING THE PROBLEM

The problem of circumferential residual tensile stresses in the rim is a result of thermally damaged wheels. Development of residual tensile stress in a freight wheel may lead to the propagation of cracks and potentially a wheel failure accident. Research has shown that some wheels may develop high levels of residual tensile stresses in the rim, which may result in wheel failure accidents. Accidents/incidents resulting from thermally damaged wheels are represented by six FRA cause codes (Appendix A). Although, the problem of wheel failure is rare, the consequences remain a sensitive issue for U.S. railroads and the FRA.

4.1 THERMALLY DAMAGED WHEELS IN POPULATION

In 1997, the Car Repair Billing database (CRBD) reported 10,375 cracked wheels were removed from service (Appendix B). The CRBD reports only foreign (not owned by the maintenance shop providing the service) wheel removals, which represent approximately 50 percent of all equipment removals. From the data, the number of wheels removed with "thermal cracks" is estimated to be 20,750 annually. The U.S. car fleet currently contains approximately 10,000,000 wheels in revenue service. Therefore, the probability of a wheel having the presence of a "thermal crack" is 20,750/10,000,000 or 0.002075 (2.075×10^{-3}).

FRA accident/incident data show there were 25 wheel failures in 1997 (Appendix A). Consequently, the probability of wheel failure is estimated to be 25/10,0000,00 or 0.0000025 (2.5×10^{-6}).

Cracks in wheels that lead to failure occurs as a result of fatigue cracks, scrapes and gouges from mechanical damage, stamping used to identify the wheel, or thermal events that create brittle martensite that easily cracks on application of mechanical or thermal stress. The growth of these cracks occurs as a consequence of sufficiently high loads to cause the crack to progress.

Low stress wheels in particular fail almost exclusively because of cracks that initiate at a sharp point on the top of the wheel flange caused by planing of the inner surface of the wheel flange. The present low failure rate of low stress wheels is determined primarily by cracks that initiate at a sharp point on top of the wheel flange, caused by rail planing of the inner flange surface, and residual stresses caused by unusually high brake forces, are the other condition necessary for wheel failure. Therefore, based on the available variables used to estimate thermally damaged wheels in the population, it should be understood that reported wheel failures and wheels with the presence of thermal cracks are considered to be independent variables when calculating probabilities in this section.

The following equation is used to determine the number of thermally damaged wheels in the population:

$$P_{wf} = P_c \chi P_{tdw}$$

where:

P_c = Probability of wheels in the population having the presence of thermal cracks
P_{wf} = Probability of a wheel failure accident
P_{tdw} = Probability of thermally damaged wheels relative to the total wheel population

Inserting the values for P_{wf} and $P_{c,}$ P_{tdw} is estimated to be 0.0012048 (.0000025/.002075), and it follows that there were approximately 12,048 (.0012048 × 10,000,000) thermally damaged wheels in service during the year.

4.2 THERMALLY DAMAGED WHEELS INSPECTED

In order to determine the number of thermally damaged wheels that may be inspected during routine wheel shop maintenance, the probability of finding thermally damaged wheels must be determined. According to an industry survey conducted by TTCI, and supported by the Car Repair Billing database, U.S. wheel shops inspect approximately 1,200,000 wheels each year. If there are 12,048 thermally damaged wheels in service during the year and 1,200,000 wheels are inspected each year from the total population of 10,000,000, the probability of finding a thermally damaged wheel is, 1,200,000/10,000,000, or 0.1200:

$$P_{tdw} = P_i \chi P_\sigma$$

P_{tdw} = Probability of thermally damaged wheels in the wheel population
P_i = Probability of wheel population inspected by U.S. wheel shops
P_σ = Total number of thermally damaged wheels inspected annually

Inserting the value P_{tdw} and P_i, P_σ is estimated to be 0.1200. It follows that 1,446 (.1200 × 12,048) thermally damaged wheels will be inspected during annual routine wheel shop maintenance.

A TTCI survey of major U.S. wheel shops also suggests that out of the total number of wheels inspected during routine wheel shop maintenance each year, approximately 60 percent or

720,000 wheels are scrapped. The remaining 480,000 wheels are reconditioned and returned to railway freight service. Only the remaining 40 percent or 480,000 would potentially be inspected by the proposed EMAT system. Therefore, the potential number of damaged wheels found by using an EMAT wheel detection system is (480,000/1,200,000) or .40.

Of the estimated 1,446 thermally damaged wheels inspected annually, assuming a normal distribution, 60 percent will be scrapped leaving 40 percent or 578 (1,446 x .40) wheels that may potentially be returned to revenue service. If the EMAT systems accuracy is 100 percent, 578 wheels will be found to have thermal damage or a condemnable degree of residual stress. Those 578 wheels will be scrapped and are then considered a cost to the industry to decrease wheel failure accidents.

4.3 WHEEL ACCIDENTS PREVENTED

In 1997, there were 25 accidents related to thermally damage wheels. The number of thermally damaged wheels in the fleet population is estimated to be 12,048. Therefore, the probability of a thermally damaged wheel reaching a failure state or derailment is 25/12,048 or .0020750 using:

$$P_{\sigma} = P_{wf} \chi P_{i}$$

P_i = Probability of wheels inspected relative to the total wheel population
P_{wf} = Probability of a wheel failure accident relative to thermally damaged wheels in service
P_{σ} = Total number of wheel failure accidents prevented

Inserting the values for P_{wf} and P_i, P_{σ} is estimated to be 0.0002490 (.002750 × .1200). It follows that the incremental benefit of EMAT technology is estimated to prevent approximately three (.0002490 × 12,048) thermally damaged wheel related failures per year. It should be emphasized that this is the optimal scenario, because the assumption is based on all U.S. wheel shops using EMAT technology in their routine wheel maintenance process. Additionally, this scenario is based on a 100 percent confidence of accuracy in identifying thermally damaged wheels. The implications for various confidence sensitivities will be analyzed relative to false positive and false negatives in the next section.

5.0 RELIABILITY SCENARIOS

Current data and analyses available from the EMAT system and saw-cutting rim responses are insufficient with observation sample sizes too small to provide confidence in forecasting the accuracy of the EMAT system in a wheel shop environment. Therefore, reliability scenarios are based on a statistical method referred to as the empirical rule. The assumption is that the population from which wheel data is collected would theoretically maintain a normal or bell-shaped distribution; that is, it is symmetric and tapers off smoothly into each tail, i.e.; the population of wheels inspected is considered to come from a normal population.

5.1 WHEELSET REPLACEMENT COST

The cost of replacing wheelsets are calculated based on the costs associated with wheel labor, roller bearing, axle, and wheel costs. Labor and material costs are based on information extracted from the *Field Manual of the AAR Interchange Rules*, the *Office Manual of the AAR Interchange Rules*, and Circular Letters pertaining to Car Repair Billing.

The total cost to replace a wheelset depends on the type of wheel used, as well as the wheel removal policy. Case 1 represents the cost of repairing a wheelset at an owners wheel shop, and Case 2 represents the cost of a wheelset repair at a foreign wheel shop. These costs are presented in Tables 1, 2, and 3.

Table 1. Cost to Replace a Wheelset: 1-Wear Wheels

Wheelset Removal Cost		
Cost Driver	(Case 1) Owner's Workshop	(Case 2) Foreign Workshop
Wheel Labor	$103.94	$284.64
Axles	$78.64	$78.64
Wheels	$579.24	$579.24
Total	$761.82	$942.52
NPV Wheelset Replacement	**$469.99**	**$581.47**

Table 2. Cost to Replace a Wheelset: 2-Wear Wheels

Wheelset Removal Cost		
Cost Driver	(Case 1) Owner's Workshop	(Case 2) Foreign Workshop
Wheel Labor	$103.94	$284.64
Axles	$78.64	$78.64
Wheels	$618.46	$618.46
Total	$801.04	$981.74
NPV Wheelset Replacement	**$494.19**	**$605.67**

Table 3. Cost to Replace a Wheelset: Multi -Wear Wheels

Wheelset Removal Cost		
Cost Driver	(Case 1) Owner's Workshop	(Case 2) Foreign Workshop
Wheel Labor	$103.94	$284.64
Axles	$78.64	$78.64
Wheels	$573.00	$573.00
Total	$755.58	$936.28
NPV Wheelset Replacement	**$466.14**	**$577.62**

5.1.1 Incremental Wheel Replacement Cost

The estimated incremental cost to replace a wheel is based on the cost of replacing a wheelset at the time of detection instead of leaving it in service until it reaches its normal life in *N* years. The net present value (NPV) of the incremental wheel replacement cost is equal to the difference between the NPV of wheel replacement costs at a normal cycle of ***T*** years throughout the infinite time period beginning at **X** years from the time of detection, and the NPV of wheel replacement costs beginning at the time of detection (or X years earlier than the normal replacement cycle year) and then following the ***T*** years normal cycle of wheel replacement throughout the infinite time period.

For example, a typical case for a 1-wear wheel: 250,000-mile wheel life, 50 percent life remaining, 25,000 miles/year usage, and 10 percent discount rate. This results in a typical NPV of the incremental wheel replacement cost of $469.99 for Case 1 and $581.47 for Case 2 (T=250,000/25,000 = 10 years, and X = 10 *0.5 = 5 years). For the purpose of planning at the industry level, Tables 1, 2, and 3 will be utilized.

Incremental wheel replacement cost Formula:

$$\Delta C = C_o\, A/P(T,i)\;\; P/A(X,i) = C_o\left[\frac{i(1+i)^T}{(1+i)^T-1}\right]\left[\frac{(1+i)^X-1}{i(1+i)^X}\right]$$

ΔC	The incremental wheel replacement cost in NPV
C_0	Average wheelset replacement cost to the car owner (from Tables 1, 2, 3)
$A/P\,(T,i)$	The capital recovery factor over a period of ***T*** years for discount rate i
P/A (X,i)	Present worth factor of a uniform series over a period of **X** for discount rate i
T	The normal wheel replacement cycle in years (equals the wheel life in miles divided by the annual usage in miles per year)
X	The remaining normal life of the detected high impact wheel in years (equals the remaining wheel life in miles divided by the annual usage in miles per year)

5.1.2 Car Repair Billing Database

Car Repair Billing Data is reported by repair shops that service foreign-owned equipment (any equipment not owned by the company providing the service). It is an accountability process for billing for repair cost of service of foreign equipment. Based on a sample of interchange rule services, approximately 50 percent of repairs are provided by foreign repair shops. Therefore, the number of wheels removed will consider both the owners cost of repair (Case 1) and repairs made at foreign wheel shops (Case 2) in Tables 4, 5, and 6.

Additionally, the number of wheels removed during routine maintenance by a wheel detection system should reflect the population of wheel types in freight service. A sample from the Car Repair Billing Database estimates a percentage distribution by wheel type. Therefore, the number of wheels removed from service should be reflected by wheel type in Table 4.

Table 4. Wheel Distributions

Wheel Type	Total Wheels In Sample	Percent Total
1-Wear	447,526	83.2%
2-Wear	89,900	16.7%
Multi-Wear	298	.06%

Car Repair Billing Database-Wheel types removed from service.

5.2 FINANCIAL SENSITIVITY ANALYSIS

The assumption used for the sensitivity is that the population from which wheel data is collected would theoretically maintain a normal distribution; that is, it is symmetric and tapers off smoothly into each tail. Therefore, the number of wheels inspected by an EMAT system is considered to come from a normal population.

"False positive" readings indicate a wheel is thermally damaged when in fact the wheel is not. A "false negative" occurs when a wheel is thermally damaged and is not detected as being a damaged wheel. The former will result in scrapping a good wheel and the latter will decrease the chances of finding a potentially dangerous wheel. The cost of removing thermally damaged wheels relative to the occurrence of false positives and false negatives will be estimated in the sensitivity analysis. Assuming an even distribution of false positives and false negatives, Table 5, reflects the empirical rule sensitivities for EMAT technology benefits and cost.

Table 5. Confidence Sensitivity Analysis

Between	Actual Percentage	Thermally Damaged Wheels	False Positive	False Negative	Accidents Prevented	Empirical Rule Percentage
$\mu - 3\sigma$ and $\mu + 3\sigma$	100 % (480,000 out of 480,000)	578	0	0	3.0	≈ 100 %
$\mu - 2\sigma$ and $\mu + 2\sigma$	98 % (470,400 out of 480,000)	566	4,800	14	2.94	≈ 95%
$\mu - \sigma$ and $\mu + \sigma$	66 % (316,800 out of 480,000)	381	81,600	156	2.0	≈ 68%

Using the 100-percent confidence scenario as an example, this implies that 578 thermally damaged wheels will be found during routine wheel maintenance inspection. It is also implied that with the 100-percent confidence scenario, there are no false positives or false negatives and three accidents will be prevented.

To estimate cost per accident, three-year averages using adjusted dollars are $269,371 per accident. A railroad study suggested that FRA-reported property damage costs understate the true cost of an accident by an estimated factor of 1.5. Therefore, an accident multiplier of 1.5 is added to the three-year average, which results in average cost per accident of $404,057.

The number of EMAT systems required to provide maximum inspection coverage at U.S wheel shops is estimated to be 70 units. The number of EMAT units required were determined by an AAR circular letter (c-8953), listing the number of quality assurance certified companies providing routine wheel shop maintenance. Cost per unit for an EMAT system is estimated be to $30,000, as shown in Appendix C. Intell Tech, Inc., a potential supplier of EMAT systems, provided cost estimates for the EMAT system. Cost for maintenance and calibration of the EMAT system was also estimated by Intell Tech, Inc., to be $1,500 per year per unit. The equivalent uniform annual cost (EUAC) is estimated using a five-year useful life and 10 percent cost of capital. The EMAT system sensitivity scenarios are shown in Tables 6, 7, and 8.

Table 6. Net Annual Saving/Loss- 100 Percent Confidence

Cost/Benefit Category	Cost/Benefit (units)	Cost/Benefit ($)
Number of Accidents Prevented	3.0	$1,212,171
Wheels Removed	575	($368,723)
EMAT Units	70	($427,000)
EMAT Calibration/Maintenance	70	($105,000)
Net Annual Savings/(Loss)		**$311,448**

Table 7. Net Annual Saving/Loss- 95 Percent Confidence

Cost/Benefit Category	Cost/Benefit (units)	Cost/Benefit ($)
Number of Accidents Prevented	2.97	$1,187,928
Wheels Removed	5,366	($2,842,766)
EMAT Units	70	($427,000)
EMAT Calibration/Maintenance	70	($105,000)
Net Annual Savings/(Loss)		**($2,186,838)**

Table 8. Net Annual Saving/Loss- 68 Percent Confidence

Cost/Benefit Category	Cost/Benefit (units)	Cost/Benefit ($)
Number of Accidents Prevented	2.0	$808,114
Wheels Removed	81,981	($43,431,384)
EMAT Units	70	($427,000)
EMAT Calibration/Maintenance	70	($105,000)
Net Annual Savings/(Loss)		**($43,155,270)**

6.0 SUMMARY OF CONCLUSIONS

EMAT technology was driven by safety concerns over the disproportionately high number of wheel failure accidents in the mid to late 1970's. Since that time railroads and manufacturers have decreased wheel failure accident trends significantly by improving the quality of wheels in service. As a result, the number of wheel failure accidents EMAT technology is designed to prevent is small and is expected to decrease further with continued wheel, brake design, and operating improvements. Although the problem of wheel failure is rare, the consequences remain a sensitive issue for U.S. railroads and the FRA.

The EMAT system is shown only to be economically feasible at the 100 percent accuracy and reliability scenario. It should be emphasized that this is the optimal scenario, because the assumption is based on all U.S. wheel shops using EMAT technology in their routine wheel maintenance process. Additionally, this scenario is based on a 100 percent confidence of accuracy in identifying thermally damaged wheels. The 95 percent confidence scenario shows a loss, primarily due to the false positive readings that would require scraping good wheels because of an inaccurate reading. The 68 percent confidence scenario shows a significant loss and illustrates the importance of accurately identifying wheel conditions.

Because of the few wheel failure accidents reported, and the unproven accuracy and reliability of the system in service, EMAT would have to prove its value, first, by evaluation of the EMAT system in a maintenance/inspection environment, and second, by designing a system to inspect a larger percentage of the wheel population. Additionally, the current EMAT system is calibrated to inspect 36-inch Class C Griffin-type wheels. Although these wheel types represent a significant part of the wheel population, additional development and testing is required to accurately inspect all wheel types in service with an EMAT system.

Although investment in EMAT technology thus far is significant it should not be considered in determining the optimal course of action, only the future economic benefits relative to the additional investment in development and testing. Therefore, from an economic perspective, the opportunity cost or forgone value associated with additional investment in EMAT technology rather than the next best use of available assets is not warranted.

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APPENDIX A

Table A-1. FRA Reported Accident/Incident Data for Broken or Cracked Wheels

Cause code	Cause	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
E60C	Broken Flange	5	4	6	5	2	0	2	0	3	1
		$885,020	$413,200	$594,026	$1,317,689	$587,950	$0	$92,704	$0	$948,563	$25,500
E61C	Broken Rim	19	19	9	9	8	1	4	1	3	3
		$4,501,378	$3,496,054	$1,060,656	$3,400,590	$568,822	$173,750	$278,137	$20,500	$105,185	$476,877
E62C	Broken Plate	15	12	17	14	1	6	5	8	11	8
		$4,681,731	$2,520,997	$1,733,837	$2,649,960	$1,596,101	$1,070,526	$4,474,400	$1,519,350	$2,526,354	$1,631,252
E63C	Broken Hub	2	4	3	2	1	11	1	9	7	8
		$752,159	$104,212	$274,459	$1,010,646	$17,200	$1,088,172	$18,700	$5,312,791	$1,026,222	$692,650
E6AC	Thermal Crack	2	3	3	2	0	3	1	0	1	2
		$110,258	$111,218	$88,705	$419,131	$0	$335,007	$8,400	$0	$6,840	$96,052
E69C	Wheel Defects	0	3	3	1	2	0	1	0	1	3
		$0	$2,736,427	$2,097,001	$148,600	$17,200	$0	$112,600	$0	$904,839	$803,099
Wheel Accidents		43	45	41	33	24	21	14	18	26	25
Reported Damage		$10,930,546	$9,382,108	$5,848,684	$8,946,616	$2,787,273	$2,667,455	$4,984,941	$6,852,641	$5,518,003	$3,725,430
Adjusted Damage		$15,296,706	$12,577,750	$7,465,299	$10,942,403	$3,322,572	$3,154,474	$5,806,636	$7,628,873	$5,907,349	$3,927,080
Average Adjusted Cost per Accident		$355,737	$279,505	$182,080	$331,588	$138,440	$150,213	$414,760	$423,826	$227,205	$157,083

APPENDIX B

Table B-1. Wheel Removal Why Made Codes

Wheel Removal Why Made Code	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
66 Flange Cracked or Broken	526	444	495	436	280	274	269	223	176	194
68 Rim Cracked or Broken	3,241	0	9,036	127	90	1,013	1,091	751	545	583
69 Thermal Crack Extending into Plate	19	1,740	95	3,337	16,581	127	273	257	168	69
71 Rim Shattered	312	289	371	320	295	276	258	185	169	163
74 Thermal Cracks	**3,125**	**6,834**	**8,586**	**10,951**	**8,277**	**5,533**	**7,725**	**7,205**	**8,363**	**10,375**
83 Cracked or Broken Plate	163	166	155	141	78	72	68	35	55	0
Total Broken or Cracked Wheels Removed	7,386	9,473	18,738	15,312	25,601	7,295	9,684	8,656	9,476	11,384
Total Wheels Removed	511,206	519,168	547,806	525,604	527,805	516,253	535,643	522,504	537,724	555,586
Percent of Broken or Cracked Wheels Removed	1.4%	1.8%	3.4%	2.9%	4.9%	1.4%	1.8%	1.7%	1.8%	2.0%

EMAT Process Targets

APPENDIX C

Table C-1. EMAT Unit Cost

EMAT System Component Cost	
Component	**Cost**
Lunchbox Computer	$5,000
Plug-ins	$10,000
Gage A/D	$1000
Preamp/relay Box	$1000
EMAT and Cable	$1500
Total Component Cost	***$18,500***
Development & Labor Cost/Mark-up	***$11,500***
Estimated Cost Per Unit	**$30,000**

Estimate cost per unit – Ray Schramm-Intell Tech, Inc.