

Optimizing Ultrasonic Rail Defect Inspection to Improve Transportation Safety and Efficiency

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ABSTRACT

Preventing broken-rail-caused derailments is a high priority for the rail industry and government. The current practice is to periodically inspect rails using non-destructive technologies such as ultrasonic rail inspection. Determining the optimal inspection frequency is a critical decision in railway infrastructure management. The objective of this paper is to develop an analytical framework to address the trade-offs among various factors related to rail defect inspection frequency, in order to maximize rail transportation safety and efficiency.

Keywords: rail defect inspection, inspection frequency, broken rail, train derailment, train delay, optimization

1 Introduction

Derailments are the most common type of freight-train accident in the United States, accounting for 72% of accidents and 94% of cars derailed (Liu et al. 2012). Among all accident causes, broken rails or welds are among the most frequent cause of severe derailments (Dick et al. 2003; Barkan et al. 2003; Liu et al. 2012).

The importance of broken rail prevention has been recognized (Barkan et al. 2003; Zarembski and Palese 2005; Liu et al. 2011, 2012, 2013a, 2013b). Each broken-rail-caused derailment can be attributed to a particular type of rail break, described by the type and/or location of the initiating defect and the orientation of the fracture surface. A larger proportion of rail breaks are caused by rail fatigue due to cyclic loading of the rail by the passage of trains (Jeong and Gordon 2009). As rail fatigue fracture surfaces grow in size, they may be identified by non-destructive inspection methods, such as ultrasonic testing (Orringer et al. 1988; Orringer 1990; Cannon et al. 2003; Jeong and Gordon 2009).

The remainder of this paper will analyze the safety effectiveness and costs of ultrasonic rail inspection, and develop a model to optimize the inspection frequency.

2 Number of broken rails between two successive inspections

Equation (1) presents a general model to estimate the total number of rail breaks between two successive inspections assuming that no complementary broken rail

prevention technique (such as rail grinding or rail lubrication) is used in addition to ultrasonic rail testing (Orringer 1990).

$$S_{(i-1,i)} = \frac{R \times \frac{a(0.5N_{i-1} + 0.5N_i)^{a-1}}{b^a} e^{-[(0.5N_{i-1} + 0.5N_i)/b]^a}}{1 + \frac{1}{h(X_i - q)}} \times X_i \quad (1)$$

Where:

- $S_{(i-1,i)}$ = number of broken rails per track-mile between the (i-1)th and ith inspection
- R = rail segments per track-mile, 273 (Orringer et al. 1988)
- X_i = interval (MGT) between the (i-1)th and ith inspection
- a = Weibull shape factor, 3.1 (Davis et al. 1987)
- b = Weibull scale factor, 2,150 (Davis et al. 1987)
- h = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval curve, 0.014 (Orringer 1990)
- q = minimum rail inspection frequency, 10 MGT (Orringer 1990)
- N_i = rail age (cumulative tonnage on the rail) at the ith inspection, $N_i = N_{i-1} + X_i$

3 Costs of broken-rail-caused train derailments

This paper considers two consequence costs of freight-train derailments, including 1) infrastructure and rolling stock damage cost and 2) train delay cost. The infrastructure and rolling stock damage cost was multiplied by a factor of 1.65 to account for other loss and damage, wreck clearing, and unreported property damage costs that are not included in the FRA-reported costs (Kalay et al. 2011). However, some other possible costs related to casualties, hazardous materials release incidents, regulatory change, or impairment of business reputation are not specifically addressed in this paper. They may be incorporated into the safety decision making process in the future depending on which aspects the railroad would like to consider and the data they have available for the analysis.

3.1 Track and equipment cost per broken-rail-caused train derailment

Track and equipment damage costs of train accidents are recorded in the U.S. Federal Railroad Administration (FRA) Rail Equipment Accident (REA) database. An infrastructure index (MOW-RCR) was developed from components of the AAR Railroad Cost Recovery Index (AAR-RCR) using the methodology developed by Grimes and Barkan (2006). MOW-RCR was used to adjust maintenance costs incurred at various years in terms of base year prices (Liu et al. 2010). The average infrastructure and equipment damage cost is \$616,263 per broken-rail-caused train derailment, the cost of which may vary by the type of broken rail. Fortunately, only a small proportion, 0.5 to 1 percent, of rail breaks result in train derailments because most broken rails are identified by either visual track inspection or by track circuits (Davis et al. 1987; Dick 2001; Schaffer 2008). In this paper, we assume 0.84% of rail breaks may cause train derailments (Zaremski and Palese 2005).

3.2 Train delay cost due to derailments

In addition to infrastructure and equipment damage cost, a train derailment may result in costs due to train delay. It is assumed that 24 hours are required to return the track to service after a derailment, although they can take longer depending on the circumstances and location of the accident. Schaffer (2008) develops the following equation to estimate train delay time due to a derailment:

$$C_{DA} = Vx + \sum_{n=1}^m (V - nt)x \quad (2)$$

where,

C_{DA} = total train delay cost for multiple trains (\$)

V = total delay time for service interruption (hours)

x = cost of delay per train-hour (\$232/hour)

m = number of following trains delayed = V / t (rounded to the nearest integer)

t = hours per train arrival = $55.33 / T$ (T is annual traffic density)

The FRA regulations requires either immediate removal of rail defects or a prescribed remedial action until they are removed. In the next section, we analyze the cost of repairing a detected rail defect or a broken rail.

4 Costs of repairing detected rail defects and broken rails

There are three categories of costs associated with rail inspection activities and corresponding remedial actions regarding a detected defect or broken rail: 1) rail inspection cost, 2) repair cost for a detected defect or a broken rail, and 3) train delay cost due to repairing a detected defect or a broken rail. Note that the hi-rail inspection usually does not disrupt train operations, thereby the potential train delay due to inspection activities may be minimal, thus excluded in this analysis.

4.1 Rail inspection cost

The following equation is used to estimate rail inspection cost.

$$C_{insp} = \frac{L}{V} C_{hr} \quad (3)$$

Where:

C_{insp} = rail inspection cost (\$)

L = track length (miles)

V = average inspection vehicle speed (mph)

C_{hr} = inspection cost per hour per vehicle (\$/hour)

Communication with senior track engineers from a major railroad indicated that the speed of inspection (V) is generally between 15 to 20 mph and the average inspection cost per hour per vehicle (C_{hr}) is approximately \$300.

4.2 Cost for repairing a detected rail defect or broken rail

The Association of American Railroads (AAR) developed the following models to estimate the cost for repairing detected defects and broken rails (Wells and Gudiness 1981). We used the AAR's models with updated rail cost information.

$$DDC = \left[\frac{W_{replace} \times L_{replace} (P_{new} - 0.95P_{old})}{2000} + C_{drepair} \right] (1-t) \quad (4)$$

Where:

- DDC = cost for repairing a detected rail defect (\$)
 $W_{replace}$ = weight of replacement rail, in pounds per yard (141)
 $L_{replace}$ = length of replacement rail, in yards (3)
 P_{new} = price of new rail, in dollars per ton (\$800)
 P_{old} = price of scrap rail per net ton (\$200)
 $C_{drepair}$ = direct cost (labor, materials, equipment) for repairing a detected rail defect (\$1,070)
 t = federal and state marginal income tax rate (0.53)

Based on the information above, we estimated an average of \$601 to repair a rail defect. The actual cost will vary depending on infrastructure and operational circumstances. Some undetected rail defects could grow into rail breaks, a large number of which may be identified by either track circuits or by visual inspections (Dick 2001; Schaffer 2008). The AAR model for repairing broken rails is similar to the one for detected defects and is shown as follows (Wells and Gudiness 1981):

$$SDC = \left[\frac{W_{replace} \times L_{replace} (P_{new} - 0.95P_{old})}{2000} + C_{Srepair} \right] (1-t) \quad (5)$$

Where:

- SDC = cost for repairing a broken rail (\$)
 $C_{Srepair}$ = direct cost (labor, materials, equipment) for repairing a broken rail (\$1,640)

Other variables as defined above

Based on the model, we estimated an average of \$832 for repairing a broken rail.

4.3 Train delay cost due to repairing a detected defect or broken rail

The time required to repair a rail defect is dependent on the size, type and location of defect, and various other factors. Schlake et al. (2011) estimated train delay time by traffic density and the time to repair a rolling stock service failure using simulation tools. We adopt their delay functions for repairing a detected rail defect or broken rail.

Train delay cost due to repairing a detected rail defect

$$C_{DDT} = C_0 A_D \exp(B_D x) \quad (6)$$

Where:

- C_{DDT} = train delay cost due to fixing a detected rail defect (\$)
 C_0 = train delay cost per hour, \$232
 A_D = 1.503 (Schlake et al. 2011)
 B_D = 0.0811 (Schlake et al. 2011)
 x = number of trains per day ($T/0.006312/365$) (T : annual traffic density in MGT)

Train delay due to repairing a broken rail

$$C_{SDT} = C_0 A_S \exp(B_S x) \quad (7)$$

Where:

C_{SDT} = train delay cost due to fixing a broken rail (\$)

A_S = 3.559 (Schlake et al. 2011)

B_S = 0.0805 (Schlake et al. 2011)

Other variables are as defined above.

5 Optimization of ultrasonic rail inspection frequency

Given the total number of rail inspections per year (K), the total cost is (derivation is in Appendix A):

$$C_{total}(K) = \underbrace{\frac{KL}{V} C_{ins}}_{\text{Rail Inspection}} + \underbrace{\frac{S(K)L}{h(T/K - q)} (DDC + C_{DDT})}_{\text{Repair Rail Defect \& Train Delay}} + \underbrace{S(K)L(SDC + C_{SDT})}_{\text{Repair Rail Break \& Train Delay}} + \underbrace{S(K)Lw(pDA + C_{DA})}_{\text{Derailment Damage and Train Delay}}$$

(8)

Where:

C_{total} = total cost (\$)

K = annual rail inspection frequency

$S(K)$ = number of broken rails per track-mile by annual rail inspection frequency

w = proportion of broken rails causing train derailments, 0.84% (Zarembski and Palese 2005)

DA = average track and equipment damage cost per broken-rail-caused train derailment (\$616,263)

p = multiplier for including other related derailment costs, 1.65 (Kalay et al. 2011)

Other variables are as previously defined.

The optimal annual rail defect inspection frequency (K^*) is determined to minimize the total cost (C_{total}):

$$K^* = \arg \min_k [C_{total}(K)] \quad (9)$$

The total cost (rail inspection + repair rail defect+ repair broken rail + track and rolling stock damage cost) is minimized at a certain annual rail inspection frequency. For example, assuming that the route length is 200 miles, its average rail age is 300 MGT, annual traffic density on this segment is 90 MGT. The optimal annual rail inspection frequency in this hypothetical example is seven that minimizes the total cost (Figure 1 and Table 1).

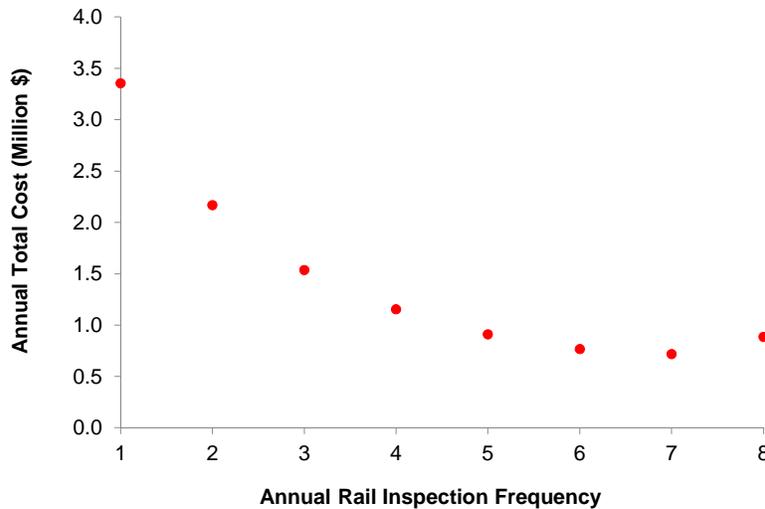


Figure 1. Total cost by annual rail inspection frequency

Note: Figure 1 shows the estimated total costs for all possible inspection frequencies. The FRA regulations and railroad engineering practice require a minimum annual rail inspection frequency.

Table 1 Annual total cost by rail inspection frequency (assuming the initial rail age is 300 MGT, annual traffic density is 90 MGT, 200-mile route)

Annual Rail Inspection Frequency	Breakdown of Total Cost (Million \$)				
	Total Cost (Million \$)	Rail Inspection & Train Delay	Rail Defect Repair & Train Delay	Rail Break Repair & Train Delay	Derailment Damage & Train Delay
1	3.36	0.0040	0.6794	1.7122	0.9606
2	2.17	0.0080	0.8808	0.9712	0.3091
3	1.54	0.0120	0.8743	0.5509	0.0994
4	1.15	0.0160	0.7935	0.3125	0.0320
5	0.91	0.0200	0.7033	0.1772	0.0103
6	0.77	0.0240	0.6383	0.1005	0.0033
7	0.72	0.0280	0.6336	0.0570	0.0011
8	0.89	0.0320	0.8214	0.0323	0.0003

The next step in this research is to evaluate the effect of input parameter uncertainty on the decision of optimal rail defect inspection frequency. It will enable a better understanding of the relationship between broken rail prevention, transportation safety and efficiency.

6 Conclusion

This research addresses the optimal rail defect inspection frequency to maximize train operational safety and efficiency. A model is developed to determine the optimal ultrasonic rail inspection frequency based on the trade-offs between transportation safety, cost and efficiency. The model in this paper can be further developed and

incorporated into a larger safety management system to efficiently mitigate transportation risk under limited resources.

7 Future work

Future research should be conducted to quantify the effect of various broken rail prevention strategies (such as rail inspection, rail grinding, and rail lubrication), alone and in combination. An industry-wide survey may be conducted to understand the current rail defect inspection practices. The ultimate goal is development of an integrated optimization approach to train safety improvement.

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Appendix A

Total Cost Related to Rail Defect Inspection (Equation 8)

The total costs related to rail defect inspection include:

- Costs for operating inspection vehicles
- Costs for repairing detected rail defects & train delay
- Costs for repairing broken rails & train delay
- Costs of broken-rail-caused derailment damage & train delay

For a track segment, the costs for operating inspection vehicles are:

$$C_{insp} = \frac{L}{V} C_{hr} \quad (A.1)$$

Where, L is segment length, V is the average speed of an inspection vehicle. C_{hr} is the operational cost per vehicle per hour.

The costs for repairing detected rail defects and corresponding train delay is a multiplication of the number of detected rail defects and repair & train delay cost per defect. Based on the model developed by (Orringer et al. 1988; Orringer 1990), the annual number of detected rail defects is:

$$N_{def} = \frac{S(K)L}{h(T/K - q)} \quad (A.2)$$

Where, N_{def} is the number of detected rail defects (note: current regulations require either immediate removal of rail defects or a prescribed remedial action until they are removed); $S(K)$ is the annual number of broken rails per mile by rail defect inspection frequency; L is segment length; T is annual traffic density in million gross tons, and K is annual rail defect inspection frequency; λ and θ are parameters related to inspection efficiency (Orringer 1990). The total rail defect repair & train delay cost (C_{def}) is:

$$C_{def} = \frac{S(K)L}{h(T/K - q)} (DDC + C_{DDT}) \quad (A.3)$$

Where, DDC is cost for repairing a detected rail and C_{DDT} is the corresponding train delay cost.

Similarly, total broken rail repair & train delay cost (C_{bre}) is:

$$C_{bre} = S(K)L(SDC + C_{SDT}) \quad (A.4)$$

Where, SDC is cost for repairing a broken rail and C_{SDT} is the corresponding train delay cost.

The number of broken-rail-caused freight-train derailment is estimated as a multiplication of the number of broken rails ($S(K) \times L$) and the proportion of rail breaks causing derailments (w). For each train derailment, the total consequence cost includes property damage cost ($p \times DA$) and train delay cost (C_{DA}). So train-derailment-related cost is:

$$C_{derail} = S(K)Lw(pDA + C_{DA}) \quad (A.5)$$

From (A.1) to (A.5), the total cost associated with rail inspection by rail inspection frequency is:

$$C_{total}(K) = \frac{KL}{V} C_{ins} + \frac{S(K)L}{h(T/K - q)} (DDC + C_{DDT}) + S(K)L(SDC + C_{SDT}) + S(K)Lw(pDA + C_{DA}) \quad (A.6)$$

Equation (8) is derived.