

Optimization of Ultrasonic Rail-Defect Inspection for Improving Railway Transportation Safety and Efficiency

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Abstract: Broken rails are the most frequent cause of freight-train derailments in the United States. Consequently, reducing their occurrence is a high priority for the rail industry and the U.S. Federal Railroad Administration. Current practice is to periodically inspect rails to detect defects using nondestructive technology such as ultrasonic inspection. Determining the optimal rail inspection frequency is critical to efficient use of infrastructure management resources and maximizing the beneficial impact on safety. Minimization of derailment risk, costs of inspection vehicle operation, rail defect repair, and corresponding train delay are all affected by rail inspection frequency. However, no prior research has incorporated all of these factors into a single integrated framework. The objective of this paper is to develop an analytical model to address the trade-offs among various factors related to rail defect inspection frequency, so as to maximize railroad safety and efficiency. The analysis shows that the optimal inspection frequency will vary with traffic density, rail age, inspection technology reliability, and other factors. The optimization model provides a tool that can be used to aid development of better-informed, more effective infrastructure management and accident prevention policies and practices. DOI: 10.1061/(ASCE)TE.1943-5436.0000697. © 2014 American Society of Civil Engineers.

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Introduction

Rail transportation is vital to the American economy, but as with any transport mode, there are attendant risks as well. In particular, train accidents pose safety risks to both the public and the railroads, so effective accident prevention practices are a critical element of their risk management practices. Although the rate of freight-train derailments in the United States reached an all-time low in 2012, they still resulted in approximately \$175 million in infrastructure and equipment damage costs, and releases from 42 cars transporting hazardous materials that were involved in these accidents. Consequently, prevention of train derailments continues to be a very high priority for the rail industry and the U.S. Federal Railroad Administration [FRA; Association of American Railroads (AAR 2014)].

The FRA categorizes accident causes into five major groups—track, equipment, human factors, signal, and miscellaneous. Within

each of these broad groupings, there are dozens of detailed causes that FRA further assigns to various subgroups of related causes, such as roadbed, track geometry, and several others within the track group. In this paper, a variation of the FRA subgroups developed by Arthur D. Little (ADL 1996) is used, in which related cause codes were combined into groups based on expert opinion. ADL's groupings are similar to the FRA's subgroups but are more fine-grained, thereby allowing greater resolution for certain causes (ADL 1996; Anderson 2005; Schafer 2008; Schafer and Barkan 2008; Liu et al. 2011, 2012). Different accident causes have different accident frequencies (Fig. 1). Among all accident causes, broken rails or welds are the most frequent derailment cause (Barkan et al. 2003; Liu et al. 2012).

The importance of broken rail prevention is recognized by industry and government (AAR 2014) and has been considered by a number of previous researchers (Shyr and Ben-Akiva 1996; Barkan et al. 2003; Dick et al. 2003; Zarembski and Palese 2005; Anderson 2005; Liu et al. 2011, 2012, 2013a, b). 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. From 2001 to 2010, two types of defect, transverse/compound fissures and detail fractures, accounted for over 65% of broken-rail-caused freight-train derailments, and this proportion increased to approximately 70% in the latter five years of the study period (Fig. 2). These types of rail breaks are typically caused by metal fatigue from cyclic loading on the rail from the passage of trains (Jeong and Gordon 2009). The mechanism of these types of rail failures has been described and discussed in a number of previous studies (Orringer et al. 1988, 1999; Orringer 1990; Jeong et al. 1997; Cannon et al. 2003; Jeong and Gordon 2009). In order to detect rail flaws before a rail breaks, railroads conduct periodic inspections of their rail using nondestructive technologies to find them. In this paper, the factors affecting formation and growth of rail defects are considered along with the safety effectiveness and cost of rail inspections. These factors are then used to develop a model to optimize rail defect inspection frequency.

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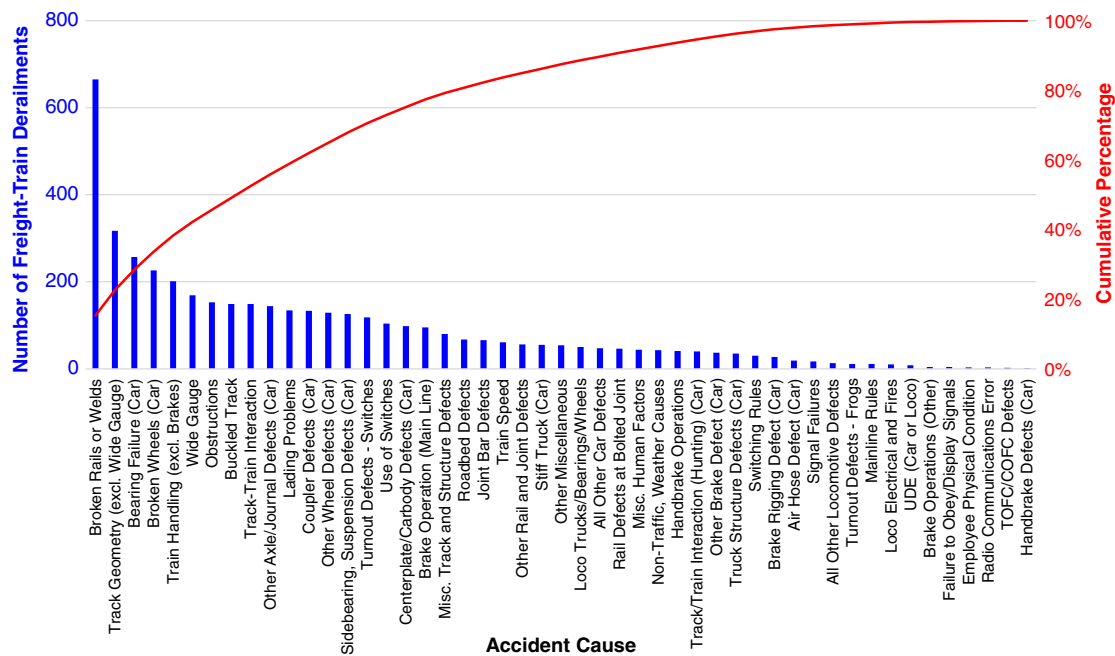


Fig. 1. Frequency of accident cause, Class I mainline freight train derailments, 2001–2010

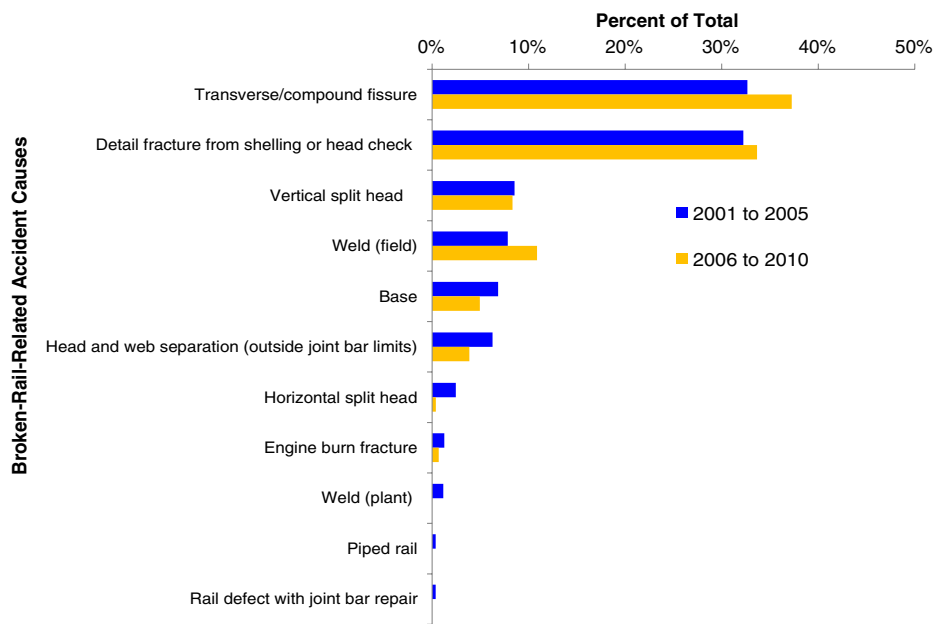


Fig. 2. Distribution of Class I railroad mainline freight train derailments by broken-rail-related accident causes, 2001–2010

Literature Review

Ultrasonic inspection is the principal technology used by North American railroads to identify certain types of rail defects before they grow large enough to cause a broken rail (FRA 2014). The occurrence and growth of rail flaws is a stochastic process, but the probability of defect formation is positively correlated with the cumulative tonnage passing over a rail (Orringer et al. 1988). Probabilistic estimation of the formation of rail fatigue defects is generally modeled using a Weibull distribution, which describes the probability that a rail has a defect at a given time or tonnage (Davis et al. 1987; Orringer 1990). Because of technological limitations of current ultrasonic inspection technology, defects of certain types, sizes, and locations may not be detected (Orringer 1990).

After a defect has formed, it will grow at a rate correlated with the number of loading cycles, axle load, track geometry, and environmental factors (Orringer 1990; Cannon et al. 2003). The number of broken rails is used as a proxy to measure broken-rail-caused derailment risk (Cannon et al. 2003; Zarembski and Palese 2005; Zhao et al. 2007; Jeong and Gordon 2009).

The U.S. Department of Transportation (U.S. DOT) Volpe Transportation Systems Center (hereinafter referred to as the Volpe Center) developed an engineering model to estimate the number of broken rails between two successive inspections given inspection interval and rail age (Orringer et al. 1988; Orringer 1990; Jeong and Gordon 2009). The model was further enhanced and implemented by ZETA-TECH Associates (Palese and Wright 2000). The model

recommends the frequency of rail defect inspections, and its use on at least one railroad is reported to have helped them reduce broken-rail-caused derailments (Zarembski and Palese 2005).

In addition to derailment risk, operational and train delay costs related to rail defect inspection are also important (Davis et al. 1987). The rail defect inspection cost model (INSPEC) developed by the Association of American Railroads (AAR) in the late 1980s predicted annual costs related to rail defect inspection, including derailment damage costs and costs for repairing a detected rail defects or broken rails (Davis et al. 1987). However, the data used in that model needed to be updated, in part because of changes in traffic volume, axle load, improved rail steel, and better rail maintenance practices. In addition, train delay costs (related to transportation efficiency) from derailments or repairing rail defects were not included in that model. In this paper, a model is developed to optimize rail defect inspection frequency accounting for both transportation safety and efficiency given specified operating characteristics.

Number of Broken Rails between Two Successive Inspections

Rail defect inspection should be scheduled such that the occurrence of broken rails is minimized. Inspection intervals are generally specified in terms of the accumulated traffic carried by a rail segment, measured in million gross tons (MGT; Orringer et al. 1988; Orringer 1990; Zarembski and Palese 2005). Eq. (1) presents a general model to estimate the total number of rail breaks between two successive rail defect inspections assuming that no complementary broken rail prevention technique (e.g., rail grinding or rail lubrication) is used [the derivation of Eq. (1) is presented in Appendix I]. Note that Eq. (1) was developed based on the Volpe Center model that used data from the 1980s, if more recent information is available, it could be used to update the model

$$S_{(i-1,i)} = R \times \frac{\frac{\alpha(0.5N_{i-1}+0.5N_i)^{\alpha-1}}{\beta^\alpha} e^{-[(0.5N_{i-1}+0.5N_i)/\beta]^\alpha}}{1 + \frac{1}{\lambda(X_i-\theta)}} \times X_i \quad (1)$$

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

Although the general form of the Volpe Center model may be applicable to all types of rail defects, the parameters they developed were primarily based on detail fractures. Given rail defect formation parameters (α , β), rail defect inspection efficiency parameters (λ , θ), and initial rail age at the first inspection, the number of broken rails between two successive ultrasonic rail inspections can be approximated by a nonlinear function of the inspection interval (Fig. 3). The analysis shows that as the inspection interval increases, the number of broken rails per mile is expected to increase at an accelerating rate.

The parameters in the broken rail risk model (N , R , α , β , λ , θ) are related to the mechanism of rail defect formation, accuracy of rail defect inspection, and track characteristics (Orringer 1990). A sensitivity analysis was conducted to understand the marginal effect of these parameters on the rate of broken rails (Table 1).

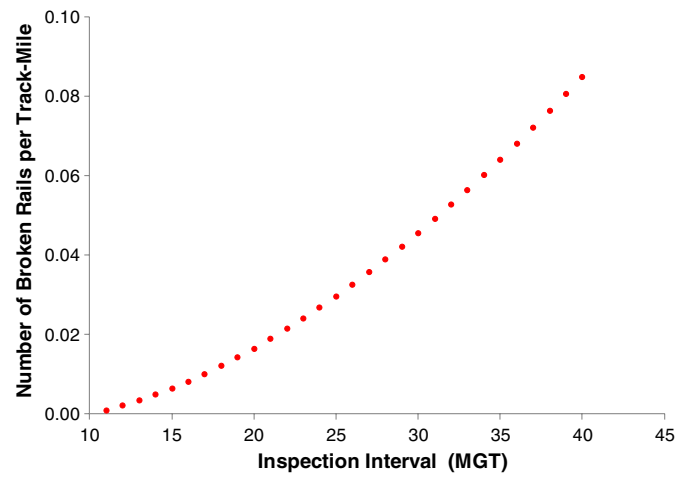


Fig. 3. Estimated number of broken rails by inspection interval ($\alpha = 3.10$; $\beta = 2,150$; $\lambda = 0.014$; $\theta = 10$; $N = 300$)

Table 1. Sensitivity Analysis of the Effect of the Input Parameters on the Expected Number of Broken Rails within an Inspection Interval

Variable	Minimum	Base	Maximum
Initial rail age (N) (MGT)	0	300	1,000
Rail segments per track-mile (R)	1	273	5,280
Weibull shape factor (α)	2.9	3.1	5.5
Weibull scale factor (β)	1,200	2,150	3,000
Slope of the S/D versus inspection interval curve (λ)	0.010	0.014	0.021
Minimum rail defect inspection interval (θ) (MGT)	1	10	40

The ranges were established based on published literature and discussion with railroad professionals.

The input values for each variable differ by orders of magnitude, so direct comparison of the output ranges of the sensitivity analysis could be misleading. Therefore, variability was normalized using the arc elasticity method (Allen and Lerner 1934). This consists of multiplying the ratio of the output range to the input range by the ratio of the base input to the base output and results in a measure that is independent of units. The output values are fairly sensitive to α and β (which are related to rail defect formation; Fig. 4), thereby underscoring the importance of understanding how defects develop

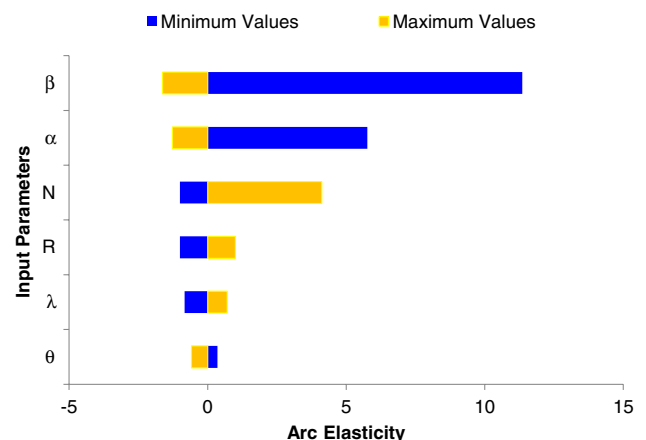


Fig. 4. Sensitivity analysis of input parameters

in the rail. The accumulated MGT (initial rail age) at the first inspection (N) is also a sensitive input, indicating the importance of accurately determining rail age when assessing broken rail risk.

Number of Broken Rails per Year

Some railroads in the United States plan their rail defect inspection on an annual basis, so the analysis in this paper is based on a one-year period; however, the model can also be adapted to a multiyear horizon. The number of broken rails per track-mile per year is dependent on the number of rail inspections per year, the accuracy and reliability of inspection technologies, and the timing of each inspection. An optimization model is developed to minimize the total number of broken rails given annual inspection frequency

$$\text{MINIMIZE} \left[\left(\sum_{i=2}^K S_{(i-1,i)} \right) + S_{(K,\text{end})} \right] \quad (2)$$

where

$$S_{(i-1,i)} = R \times \frac{\frac{\alpha(0.5N_{i-1}+0.5N_i)^{\alpha-1}}{\beta^\alpha} e^{-\{[0.5N_{i-1}+0.5N_i]/\beta\}^\alpha}}{1 + \frac{1}{\lambda(X_i-\theta)}} \times X_i$$

$$S_{(K,\text{end})} = R \times \frac{\frac{\alpha[0.5N_K+0.5(N_0+T)]^{\alpha-1}}{\beta^\alpha} e^{-\{[0.5N_K+0.5(N_0+T)]/\beta\}^\alpha}}{1 + \frac{1}{\lambda(T-\sum_{i=1}^K X_i-\theta)}} \times \left(T - \sum_{i=1}^K X_i \right)$$

Subject to

$$X_i \geq X_{\min} \quad (3)$$

$$X_i \leq \min(T, 30) \quad (4)$$

$$\sum_{i=2}^K X_i \leq T \quad (5)$$

where $S_{(i-1,i)}$ = number of broken rails between the $(i-1)$ th and i th inspection; $S_{(K,\text{end})}$ = number of broken rails between the K th inspection and the end of the year; X_i = inspection interval (MGT) between the $(i-1)$ th and i th inspection; T = annual traffic density (MGT); X_{\min} = minimum inspection interval (MGT); Other variables are previously defined.

The objective function is to minimize the annual frequency of rail defect inspection where the one-year cycle starts from the first inspection. The first constraint specifies the minimum inspection interval. The minimum inspection interval is determined based on the process of rail defect formation and growth and is also dependent on inspection vehicle allocation and logistics. In this paper, $X_{\min} = 10$ (Orringer et al. 1988) is assumed. The maximum inspection interval is determined by federal regulation. The FRA requires that the interval between internal rail inspections not exceed 30 MGT or 370 days—whichever is shorter—on Class 4 and 5 track, or Class 3 track that has regularly scheduled passenger trains or is a hazardous materials route (FRA 2014; Cerny 2014). In this paper, it was assumed that the maximum tonnage between two inspections is either the annual traffic density or 30 MGT, whichever is less. So there is at least one inspection per year, and the inspection interval complies with FRA regulations. This assumption was made to illustrate the methodology, but it can be adapted to account for other inspection intervals. The third constraint means that the sum of inspection intervals should not exceed annual traffic density. In addition to these three constraints, there may be various

other budgetary and operational constraints. The constraints considered in this study may represent the minimum set of considerations in optimizing rail defect inspection schedules.

To illustrate the model, a hypothetical example is presented below. The initial rail age is 300 MGT, and the annual traffic density is 80 MGT. Based on previous studies, α and β are assumed to be 3.1 and 2,150, respectively (Davis et al. 1987), and λ and θ are 0.014 and 10, respectively (Orringer 1990). Fig. 5 illustrates the optimal time for each rail defect inspection on the hypothetical route assuming that there are four rail defect inspections per year. Table 2 shows the optimal inspection spacing assuming three to seven inspections per year. The optimization model is solved by the general algebraic modeling system (GAMS) using its built-in solver MINOS.

The optimal inspection interval decreases as rail age increases (Table 2). For example, with three inspections per year, the second inspection is scheduled 29.96 MGT after the first inspection, while the third inspection is performed after only an additional 26.31 MGT. As rail age (cumulative tonnage over the rail) increases, the initiating micro manufacturing defects in the rail develop into detectable rail defects more rapidly, thereby increasing rail defect rate (Orringer 1990). Therefore, on average, achieving the same likelihood of detecting a defect before the rail breaks requires that the interval between inspections become shorter to compensate for the increasing rate of rail defect formation.

Given the total number of rail defect inspections per year, the optimization model can be used to determine the expected minimum number of broken rails with the optimal schedule for each inspection. In Fig. 6, each data point represents the estimated number of broken rails given the number of ultrasonic rail defect inspections per year using the optimization model. The number of broken rails per track-mile can be approximated by an exponential function of annual inspection frequency. This observation is consistent with prior work (Zhao et al. 2006, 2007).

There are diminishing returns in the safety benefit of additional rail defect inspection. For example, with four inspections per year, there are an estimated 0.08 broken rails per track-mile per year. Increasing the inspection frequency to five times per year is expected to result in 0.05 broken rails per track-mile, a 38% reduction; however, an additional annual inspection that increased the number to six per year, would result in 0.029 broken rails per track-mile, an incremental reduction of 26%. This diminishing marginal return is from the declining differences between inspection intervals as annual rail inspection frequencies increase. For example, using the optimal scheduling shown in Table 2, when there are three annual inspections the difference between the first two successive inspection intervals is 3.65 MGT (29.96 – 26.31 = 3.65); but this difference is reduced to 0.65 MGT when annual rail inspection frequency is increased to seven. The more frequent the rail is inspected, the shorter the intervals between inspections, leading to diminishing marginal returns in terms of safety benefit.

A sensitivity analysis was conducted for annual traffic density ranging from 60 to 90 MGT, in 10 MGT increments, and rail ages

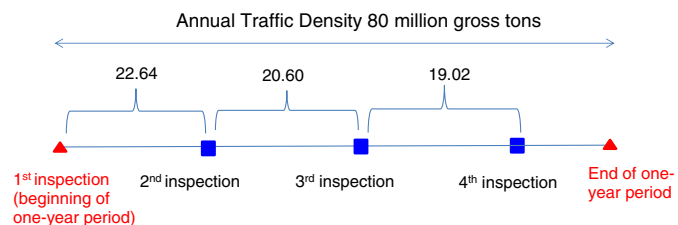
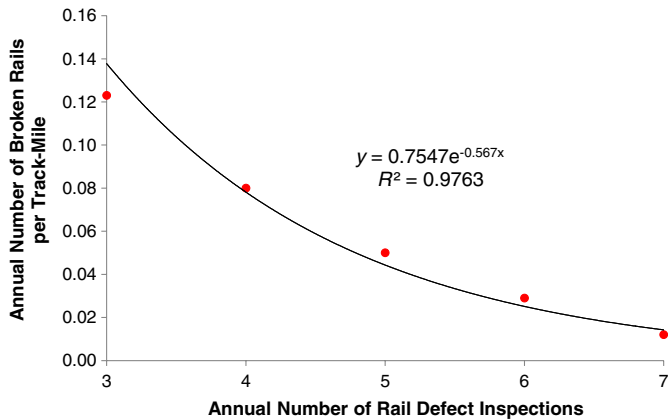


Fig. 5. Schematic illustration of ultrasonic rail defect inspection frequency (assuming that there are four inspections per year)

Table 2. Optimal Rail Defect Inspection Schedule for Different Inspection Frequencies ($T = 80$ MGT; $N_1 = 300$ MGT)

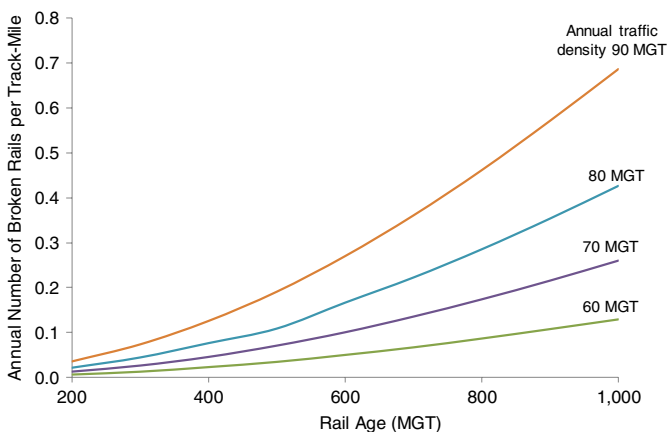
Inspection interval (MGT)	Annual rail defect inspection frequency				
	3	4	5	6	7
Between first inspection and second inspection	29.96	22.64	18.17	15.17	13.02
Between second inspection and third inspection	26.31	20.60	16.88	14.28	12.37
Between third inspection and fourth inspection	—	19.02	15.82	13.53	11.80
Between fourth inspection and fifth inspection	—	—	14.94	12.88	11.31
Between fifth inspection and sixth inspection	—	—	—	12.32	10.88
Between sixth inspection and seventh inspection	—	—	—	—	10.49

**Fig. 6.** Relationship between number of broken rails and annual rail defect inspection frequency (initial rail age is 300 MGT and annual traffic density is 80 MGT)

ranging from 200 to 1,000 MGT, in 100 MGT intervals. Each combination of annual traffic density and rail age was used to estimate the relationship between inspection-frequency and broken-rail occurrence. Fig. 7 illustrates the estimated number of broken rails per track-mile for different traffic densities and rail ages assuming four inspections per year. For each particular inspection frequency, the greater the rail age or annual traffic density, the more likely it is that a broken rail will occur.

Cost of Broken-Rail-Caused Train Derailments

Train derailments may result in damage to infrastructure and rolling stock, service disruptions, casualties, and harm to the environment.

**Fig. 7.** Estimated annual number of broken rails per track-mile by rail age and annual traffic density (assuming four inspections per year)

The U.S. FRA rail equipment accident/incident report (REAIR) form is used by railroads to report all accidents that exceed a monetary threshold of damages to infrastructure and rolling stock (FRA 2011). The FRA compiles these reports into the rail equipment accident (REA) database, which records rail equipment accident data back to 1975. This database was used to determine average damage cost per freight-train derailment from 2002 to 2011 on Class I railroad main tracks.

This paper considers two consequence costs of a freight-train derailment, 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, other possible costs related to casualties, hazardous materials release incidents, increased regulatory requirements, or other impacts on business are not specifically addressed in this paper. These factors could be incorporated into future model enhancements if they can be quantified.

Track and Equipment Cost per Broken-Rail-Caused Train Derailment

Several recent severe train accidents have been caused by broken rails. For example, a broken rail caused a freight-train derailment near Oneida, New York in 2007. This accident resulted in 29 derailed cars, of which six tank cars released hazardous materials. Estimated damages and environmental cleanup costs were \$6.73 million [National Transportation Safety Board (NTSB 2008)]. Track and equipment damage costs of train accidents are recorded in the FRA's REA database. An infrastructure index (MOW-RCR) was developed from components of the AAR Railroad Cost Recovery Index (AAR-RCR) using the methodology described by Grimes and Barkan (2006; discussed in more detail in Grimes 2004). The MOW-RCR index 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 was \$616,263 (adjusted to 2011 cost) per broken-rail-caused train derailment from 2002 to 2011. The accident-specific cost may vary by the type of broken rail and other circumstances. Fortunately, only a small proportion, approximately 0.5–1%, of broken rails result in train derailments because most broken rails are identified either by visual track inspection or by track circuits (Davis et al. 1987; Schafer 2008). In this paper, it was assumed that 0.84% of rail breaks cause train derailments (Zarembski and Palese 2005).

Train Delay Cost Because of Derailments

In addition to infrastructure and equipment damage, a train derailment may result in train delay cost. It was assumed that 24 h are required to return the track to service after a derailment, although it may take longer time depending on the circumstances and location of the accident. Schafer (2008) developed the following equation to estimate train delay time from a derailment on a single track line:

$$C_{DA} = Vx + \sum_{n=1}^m (V - nt)x \quad (6)$$

where C_{DA} = total train delay cost for multiple trains (\$); V = total delay time for service interruption (h); x = cost of delay per train-hour (\$232/h); 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).

Cost of Repairing Detected Rail Defects and Broken Rails

There are three categories of costs associated with rail defect inspection and the corresponding remedial actions regarding a detected defect or broken rail: (1) rail defect inspection cost, (2) repair cost for a detected defect or a broken rail, and (3) train delay cost from repairing a detected defect or a broken rail. Properly scheduled hi-rail rail defect inspection should not disrupt train operations because the hi-rail vehicle can get off the track to allow train traffic to pass. Thus the potential train delay from inspections is generally minimal, and therefore was not included in this analysis.

Rail Defect Inspection Cost

The following equation is used to estimate rail defect inspection cost:

$$C_{insp} = \frac{L}{V} C_{hr} \quad (7)$$

where C_{insp} = rail defect inspection cost (\$); L = track length (miles); V = average hi-rail vehicle speed (mph); C_{hr} = inspection cost per hour (\$/h).

Communication with senior track engineers from a major railroad indicated that the speed of inspection (V) is generally between 15 and 20 mph, although the speed may be lower based on the rail condition and meteorological conditions. The average inspection cost (C_{hr}) is approximately \$300 per hour per vehicle.

Cost for Repairing a Detected Rail Defect or Broken Rail

The AAR developed the following models to estimate the cost for repairing detected defects and broken rails (Wells and Gudiness 1981) that were used with updated rail cost information. The detected defect model is shown in Eq. (8)

$$DDC = \left[\frac{W_{replace} \times L_{replace} (P_{new} - 0.95P_{old})}{2000} + C_{drepair} \right] (1 - t) \quad (8)$$

where DDC = total cost for repairing a detected rail defect accounting for rail salvage value, tax, materials, equipment, and labor cost (\$); $W_{replace}$ = weight of replacement rail, in pounds per yard (e.g., 141); $L_{replace}$ = length of replacement rail, in yards (6); P_{new} = price of new rail, in dollars per ton (800); P_{old} = price of scrap rail, in dollars per ton (200); $C_{drepair}$ = expenses for labor, materials, equipment, and thermite welds for continuously welded rail; \$1,570); t = federal and state marginal income tax rate (0.53).

Based on the above model, an estimated \$859 is needed to repair a rail defect. The actual cost will vary depending on infrastructure and operational circumstances. Some undetected rail defects may grow large enough to cause a broken rail; however, most such breaks are identified by track inspection or track circuits before an accident occurs (Dick et al. 2003; Schafer 2008). The AAR model for repairing broken rails is similar to the one for detected rail

defects and is shown in Eq. (9), (Wells and Gudiness 1981), and results in an estimated cost of \$1,127 to repair a broken rail

$$SDC = \left[\frac{W_{replace} \times L_{replace} (P_{new} - 0.95P_{old})}{2000} + C_{Srepair} \right] (1 - t) \quad (9)$$

where SDC = total cost for repairing a broken rail accounting for rail salvage value, tax, materials, equipment, and labor cost (\$); $C_{Srepair}$ = expenses for labor, materials, equipment, and thermite welds for continuously welded rail (\$2,140); Other variables are defined previously.

Train Delay Cost for Repairing a Detected Rail Defect or Broken Rail

The time required to repair a rail defect is dependent on its size, type, location, and several other factors. Schlake et al. (2011) estimated train delay by traffic density and time to repair a rolling stock service failure using rail traffic simulation tools. This model was used because of its better accuracy for modeling short rail service disruptions (S. Sogin, personal communication, 2013). The authors adapted their delay functions for repair of a rail defect or broken rail, assuming 5 h to repair a broken rail, and 3 h to repair a detected rail defect, respectively. The actual repair time may often be less than this and will vary depending on circumstances. In addition, repair activities may not always delay trains because railroad dispatchers will grant maintenance-of-way personnel access to the track during intervals between trains. These uncertainties are not quantified in this paper because of data constraints, but may be accounted for in future work.

Train delay cost from repairing a detected rail defect

$$C_{DDT} = C_0 \alpha_D \exp(\beta_D x) \quad (10)$$

where C_{DDT} = train delay cost from fixing a detected rail defect (\$); C_0 = train delay cost per hour, \$232 (Schafer 2008); $\alpha_D = 1.503$ (Schlake et al. 2011); $\beta_D = 0.0811$ (Schlake et al. 2011); x = number of trains per day ($T/0.006312/365$) (T : annual traffic density in MGT) (Schafer 2008).

Train delay from repairing a broken rail

$$C_{SDT} = C_0 \alpha_S \exp(\beta_S x) \quad (11)$$

where C_{SDT} = train delay cost from fixing a broken rail (\$); $\alpha_S = 3.559$ (Schlake et al. 2011); $\beta_S = 0.0805$ (Schlake et al. 2011); Other variables are as defined above.

Optimization of Rail Defect Inspection Frequency

The authors developed a model to minimize the total cost related to ultrasonic rail inspection (model derivation presented in Appendix II)

$$C_{total}(K) = \frac{KL}{V} C_{ins} + \frac{S(K)L}{\lambda \left(\frac{T}{K} - \theta \right)} (DDC + C_{DDT}) + S(K)L (SDC + C_{SDT}) + S(K)L \Phi (\mu DA + C_{DA}) \quad (12)$$

where C_{total} = total cost related to rail defect inspection (\$); K = rail defect inspection frequency per year; $S(K)$ = number of broken rails per track-mile by annual rail defect inspection frequency; Φ = 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); μ = multiplier for accounting for other related derailment costs (excluding train delay cost), 1.65 (Kalay et al. 2011); Other variables are previously defined.

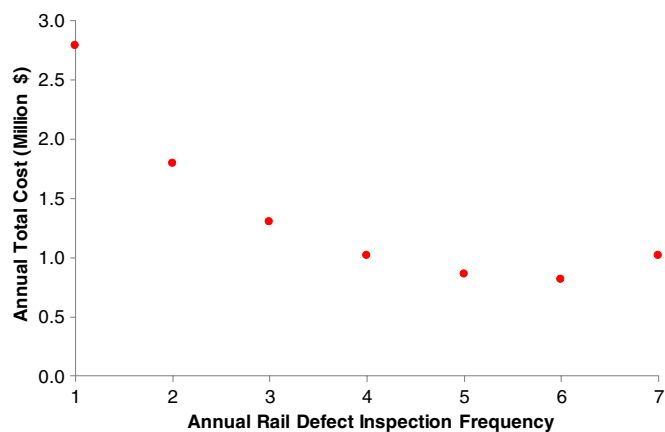


Fig. 8. Total cost by annual rail defect inspection frequency (assuming initial rail age is 300 MGT and annual traffic density is 80 MGT)

Table 3. Total Annual Total Cost for Different Rail Inspection Frequencies (Initial Rail Age is 300 MGT and Annual Traffic Density is 80 MGT, 200-Mile Route)

Annual rail inspection frequency	Total cost (million \$)	Cost category (million \$)			
		Rail inspection	Rail defect repair	Rail break repair	Derailment damage
1	2.79	0.004	0.584	1.254	0.951
2	1.80	0.008	0.773	0.711	0.306
3	1.30	0.012	0.789	0.403	0.098
4	1.02	0.016	0.746	0.229	0.032
5	0.87	0.020	0.705	0.130	0.010
6	0.82	0.024	0.720	0.074	0.003
7	1.02	0.028	0.953	0.042	0.001

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

$$K^* = \arg_k \min[C_{total}(K)] \quad (13)$$

The total cost (including rail defect inspection, rail defect or broken rail repair, track and rolling stock damage, and train delay because of derailments or repair activities) is minimized at a certain inspection frequency. For example, it is assumed that a 200-mi, single-track rail line has an initial rail age of 300 MGT at the first inspection in the study period, with annual traffic density of 80 MGT. The optimal annual rail inspection frequency that minimizes total cost is six per year (Fig. 8 and Table 3).

Table 4. Comparison of Broken Rail Risk with Different Inspection Schedules (Annual Traffic Density is 90 MGT and Initial Rail Age is 300 MGT)

Period	Decreasing interval		Constant interval	
	Inspection interval (MGT)	Number of rail breaks per mile within the interval	Inspection interval (MGT)	Number of rail breaks per mile within the interval
Between first inspection and second inspection	25.93	0.0325	22.5	0.0227
Between second inspection and third inspection	23.20	0.0291	22.5	0.0263
Between third inspection and fourth inspection	21.20	0.0264	22.5	0.0302
Between fourth inspection (last inspection this year) and the first inspection next year	19.67	0.0242	22.5	0.0343
Total	—	0.1121	—	0.1135

Discussion

Application of the models described in the previous sections requires at least the following practical considerations.

Constant Inspection Interval versus Varying Inspection Interval

Although the optimization model suggests decreasing inspection intervals, in practice it may be simpler to implement a constant inspection interval, an approach that is used by several U.S. railroads. To assess the effect of this, the estimated number of broken rails are compared if the risk-based optimization model presented here is used, compared with a constant inspection interval. Consider a rail line that has four inspections per year and a rail age of 300 MGT (Table 4). The reduction in broken rails using a decreasing-interval, versus a constant-interval schedule, is 0.0014 per mile per year (1.2% reduction). Assuming 1,000 track miles, this translates into a reduction of 1.4 broken rails per year or approximately 0.01176 broken-rail-caused train derailments per year. The difference between the two approaches is not very large because the traffic between each successive inspection is much less than the rail age (e.g., 22.5 MGT interval compared with 300 MGT initial rail age). If a constant inspection interval is simpler to implement and manage, the resultant difference from the optimal solution is small. The advantage of the varying inspection interval may be more substantial over larger-scale networks or multiperiod planning horizons. Railroads may adapt their annual rail inspection frequency based on previous inspection schedules, inspection and maintenance history, and safety goals. Either a constant or variable interval inspection plan could be incorporated into a network level optimization model for rail defect inspection and maintenance, similar to that developed by Peng (2011) and Peng et al. (2011).

Seasonal Effects

Another factor that will influence rail inspection schedule is seasonal variation in temperature. In summer, higher temperatures cause rails to expand, so broken rails may be less reliably detected. In the winter, lower temperatures cause rails to contract, which increases the possibility of a broken rail, but also tends to increase the likelihood of detection (Dick 2001). Such seasonal effects should be accounted for in an optimized rail defect inspection schedule (Liu et al. 2013a).

Special Routes (Hazardous Materials or Passenger Routes)

The FRA requires more stringent safety standards to manage broken rail risk on routes transporting hazardous materials and/or passengers. The optimal rail defect inspection frequency model,

when applied to these special routes, could be modified to take into account at least the following factors:

- Threshold for maximum allowable number of rail breaks. In FRA's final rule regarding track safety standards, it allows no more than 0.09 service failure per mile per year for a hazardous materials or passenger route and 0.08 service failure per mile per year for routes with both, for all Class 3, 4, and 5 track (FRA 2014).
- Consequences of a broken-rail-caused derailment. If a train derailment involves the release of hazardous materials or passenger casualties, some monetized proxy for these impacts could be factored into the model, in addition to economic loss (Liu et al. 2013b).

Proxy Variable for Rail Age

The optimization model in this paper uses rail age as an input variable. However, this information may not always be available or accurate. Therefore, the number of detected rail defects and rail breaks in the prior inspection has been used as a proxy variable for rail age when developing inspection schedules (Orringer 1990; Zarembski and Palese 2005). Further efforts might be useful to accurately measure and record rail age information and incorporate this into the decision making process to enable better-informed rail inspection schedule.

Conclusion

This research considers the optimal rail defect inspection frequency to maximize railroad operational safety and efficiency. An optimization model is developed to determine the optimal interval between inspections, given a specified annual inspection frequency. Next, an economic model is developed to determine the optimal rail defect inspection frequency based on the trade-offs between safety, cost, and transportation efficiency. The model in this paper can be further developed and incorporated into railroad-specific safety management systems to efficiently manage transportation risk under constrained resources.

Future Work

The information used in this paper was primarily related to detail fractures; further study should account for other types of rail defects. The model also does not account for other rail condition management techniques such as rail grinding, which has been found to reduce the occurrence of broken rails (Zarembski 2005; Zarembski and Palese 2011). Additional research should investigate the quantitative relationship between rail grinding, rail flaw growth, and broken rail risk reduction. Such work should be conducted in consideration of the potential effects of multiple rail maintenance and management strategies (such as rail defect inspection, rail grinding, and rail lubrication), alone and in combination. The ultimate goal is development of an integrated optimization approach to broken rail accident prevention and risk management.

Appendix I. Proof of Eq. (1)

From Eq. (14) of Orringer (1990)

$$\frac{S}{D} = \lambda(X - \theta) \quad (14)$$

where S = rate of broken rails per track-mile between tests; D = rate of detected rail defects per track-mile from the most recent test;

X = inspection interval; λ = slope of the number of rail breaks per detected rail defect (S/D) versus inspection interval curve, 0.014 (Orringer 1990); θ = minimum rail defect inspection interval, 10 MGT (Orringer 1990).

From Eq. (15) of Orringer (1990)

$$(S + D)X = Rf(N)X \quad (15)$$

where R = rail segments per track-mile, 273 (Orringer et al. 1988)

$$f(N) = \frac{\alpha N^{\alpha-1}}{\beta^\alpha} e^{-(N/\beta)^\alpha} \quad (16)$$

α = Weibull shape factor, 3.1 (Davis et al. 1987); β = Weibull scale factor, 2,150 (Davis et al. 1987); N = rail age (cumulative tonnage on the rail).

From (14)–(16)

$$SX = \frac{R \times \frac{\alpha N^{\alpha-1}}{\beta^\alpha} e^{-(N/\beta)^\alpha}}{1 + \frac{1}{\lambda(X-\theta)}} \times X \quad (17)$$

For the inspection interval (N_{i-1} , N_i), the average rail age is $0.5(N_{i-1} + N_i)$. As such, the expected number of broken rails within the inspection interval is

$$S_{(i-1,i)} = SX_i = \frac{R \times \frac{\alpha(0.5N_{i-1} + 0.5N_i)^{\alpha-1}}{\beta^\alpha} e^{-[(0.5N_{i-1} + 0.5N_i)/\beta]^\alpha}}{1 + \frac{1}{\lambda(X_i - \theta)}} \times X \quad (18)$$

Eq. (1) is proved.

Appendix II. Derivation of Eq. (12)

The total costs related to rail defect inspection include:

- Costs for operating inspection vehicles;
- Costs for repairing detected rail defects and the corresponding train delay cost; and
- Costs for repairing broken rails and the corresponding train delay cost.

For a track segment, the cost for operating inspection vehicles is estimated as

$$C_{\text{insp}} = \frac{L}{V} C_{hr} \quad (19)$$

where L = segment length, V = average speed of a high-rail vehicle. C_{hr} = operational cost per hour per vehicle.

The costs for repairing rail defects and the corresponding train delay cost is a multiplication of the number of detected rail defects and repair and train delay cost per defect. Based on the Volpe Center model (Orringer 1990), the annual number of detected rail defects is

$$N_{\text{def}} = \frac{S(K)L}{\lambda(\frac{T}{K} - \theta)} \quad (20)$$

where N_{def} is the number of detected rail defects. $S(K)$ is the annual number of broken rails per track-mile by rail defect inspection frequency using the optimization model. L is track length in miles, T is annual traffic density, K is annual rail defect inspection frequency, λ and θ are constants related to inspection efficiency (Orringer 1990). Based on this information, rail defect repair and train delay cost (C_{def}) is

$$C_{\text{def}} = \frac{S(K)L}{\lambda(\frac{T}{K} - \theta)} (\text{DDC} + C_{\text{DDT}}) \quad (21)$$

where DDC is the cost for repairing a detected rail defect [Eq. (8)] and C_{DDT} is the corresponding train delay cost [Eq. (10)].

Similarly, broken rail repair and train delay cost (C_{bro}) is

$$C_{bro} = S(K)L(SDC + C_{SDT}) \quad (22)$$

where SDC = cost for repairing a broken rail [Eq. (9)] and C_{SDT} = corresponding train delay cost [Eq. (11)].

The estimated number of broken-rail-caused freight-train derailment is a multiplication of the number of broken rails [$S(K) \times L$], and the proportion of broken rails causing derailments (Φ). For each train derailment, the total consequence cost includes damage cost (μDA) and train delay cost (C_{DA}). Train derailment-related cost (C_{derail}) is

$$C_{derail} = S(K)L\Phi(\mu DA + C_{DA}) \quad (23)$$

From Eqs. (19)–(23), the total cost as a function of rail defect inspection frequency is

$$C_{total}(K) = \frac{KL}{V}C_{ins} + \frac{S(K)L}{\lambda(\frac{T}{K} - \theta)}(DDC + C_{DDT}) + S(K)L(SDC + C_{SDT}) + S(K)L\Phi(\mu DA + C_{DA}) \quad (24)$$

Eq. (12) is derived.

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