SEASONAL EFFECT ON THE OPTIMIZATION OF RAIL DEFECT INSPECTION FREQUENCY

Xiang Liu
Rail Transportation and Engineering Center
University of Illinois at Urbana-Champaign
Urbana, IL, USA

C. Tyler Dick
Rail Transportation and Engineering Center
University of Illinois at Urbana-Champaign
Urbana, IL, USA

Alexander Lovett
Rail Transportation and Engineering Center
University of Illinois at Urbana-Champaign
Urbana, IL, USA

Mohd Rapik Saat
Rail Transportation and Engineering Center
University of Illinois at Urbana-Champaign
Urbana, IL, USA

Christopher P. L. Barkan
Rail Transportation and Engineering Center
University of Illinois at Urbana-Champaign
Urbana, IL, USA

ABSTRACT
Broken rails are the most common cause of severe freight-train derailments on American railroads. Reducing the occurrence of broken-rail-caused derailments is an important safety objective for the railroad industry. The current practice is to periodically inspect rails using non-destructive technologies such as ultrasonic inspection. Determining the optimal rail defect inspection frequency is a critical decision in railway infrastructure management. There is a seasonal variation in the occurrence of broken rails that result in train derailments. This paper quantifies the effect of this seasonal variation on the risk-based optimization of rail inspection frequency. This research can be incorporated into a larger framework of broken rail risk management to improve railroad transportation safety.

INTRODUCTION
Derailments are the most common type of freight-train accidents in the U.S., accounting for 60% of accidents and correspondingly 68% of cars derailed [1]. Broken rails are the most frequent cause of severe derailments [1-5]. The importance of broken rail prevention has been widely recognized [3-11]. The majority of broken rails are caused by fatigue growth of internal rail defects due to cyclic loading by the passage of trains [12]. Ultrasonic inspection is the primary rail defect detection technology used by American railroads. However, no feasible detection technology is capable of detecting all types and sizes of rail defects. Consequently, some defects remain undetected until growing to a critical size where thermal and applied stresses result in a broken rail. Fortunately, the majority of broken rails can be identified by visual inspection or track circuits before the passage of a train [2]. Consequently, only a small percentage of broken rails, approximately on the order of one in 100, result in train derailments [13].

The risk of broken rails and corresponding train derailments may vary by season [2, 14]. However, limited prior research has been conducted to understand the seasonal effects on the optimization of rail inspection frequency. The primary objective of this paper is to identify and quantify this effect and develop season-specific rail inspection schedules to minimize train derailment risk in a cost-efficient manner. To meet this objective, we first review an engineering model to estimate the number of broken rails. Next, we analyze the three-fold seasonal effects in terms of traffic, broken rail occurrence and the corresponding train derailment likelihood. Finally, a Pareto-optimality model is developed to optimize the rail defect inspection schedule within different seasons.

BROKEN RAIL RISK MODEL
The U.S. Department of Transportation (U.S. DOT) Volpe Transportation Systems Center developed an engineering model to estimate the number of broken rails between two successive inspections given inspection interval and rail age [14]:
\[ S_{(i-1,i)} = R \times e^{\left( \frac{N_{i-1}}{\beta} \right) - e^{\left( \frac{N_{i-1} \times X_i}{\beta} \right)}} \times \lambda \left( X_i - \mu \right) \] (1)

Where:
- \( S_{(i-1,i)} \) = number of broken rails per track-mile between the (i-1)th and ith inspection
- \( R \) = number of rail segments per mile, 273 [14]
- \( X_i \) = interval (MGT) between the (i-1)th and ith inspection
- \( \alpha \) = Weibull shape factor, 3.1 [15]
- \( \beta \) = Weibull scale factor, 2,150 [15]
- \( \lambda \) = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval curve, 0.014 [14]
- \( \mu \) = minimum rail inspection frequency, 10 MGT [14]
- \( N_i \) = rail age (cumulative tonnage on the rail) at the ith inspection, \( N_i = N_{i-1} + X_i \)

### Seasonal Effect on Broken-Rail-Caused Derailment Likelihood

There are three compounding seasonal effects on broken-rail-caused derailment likelihood. First, there may be seasonal variation in traffic, thereby affecting the cumulative tonnage on the rail during inspection intervals of equal calendar length. Second, there may be a greater number of broken rails in winter than in summer because small rail defects are more likely to grow into a rail break under tensile thermal stresses in colder climates [2]. Third, although a broken rail may be more likely to occur in winter than in summer, the probability that the break is identified by track circuits increases (and the conditional probability of the broken rail causing a derailment correspondingly decreases) in the winter because the fractures are further pulled apart due to thermal contraction [2]. All three of these effects are considered in this paper to develop an optimal rail defect inspection schedule by season. This paper considers the 15-week colder period to be from late November to mid-March and the warmer period in other weeks. This demarcation is based on a previous study regarding the effect of cold weather on broken rail occurrence [14]. However, the methodology is applicable to other demarcation of seasons as well.

### Seasonal Variation in Rail Traffic

Traffic distribution in terms of gross ton-miles is estimated using weekly rail traffic data published by the Association of American Railroads [16]. There is no industry-wide significant seasonal variation of traffic (Figure 1). On average, 28.7% of gross ton-miles were in the colder period (late November to mid-March). Based on this, this paper assumes 28.7% of annual traffic density (MGT) occurs from late November to mid-March, and the other 71.3% traffic in other weeks. However, the framework presented here can account for particular rail line segments that exhibit greater seasonal variation.

### Seasonal Variation in Number of Broken Rails

Equation (1) is used to estimate the number of broken rails per mile. Orringer (1990) presented representative values in severe colder climate [14]. Without up-to-date and season-specific information, we assume the following parameter values as provided by Orringer [14] in the broken rail risk model:

- Colder period (late November to mid-March)
  - \( \lambda_1 = 0.03 \) and \( \mu_1 = 4 \) (inspection interval less than 20 MGT) [14]
  - \( \lambda_1 = 0.05 \) and \( \mu_1 = 10.4 \) (inspection interval between 20 MGT and 40 MGT) [14]

- Warmer period (other weeks)
  - \( \lambda_2 = 0.014 \) and \( \mu_2 = 10 \) [14]

The estimated number of broken rails per mile in the colder period is more than two times greater than that in the warmer period during a 30 MGT inspection interval given an initial rail age of 500 MGT (Figure 2). As described earlier, this difference accounts for the propensity of rail defects to fracture in colder conditions due to tensile thermal stress [2].

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**Figure 1** Weekly gross ton-miles on Class I mainlines, 2011 and 2012 average

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Seasonal Variation in Detection of Broken Rails

Although a broken rail is more likely to occur in the colder months due to tensile thermal stresses, this effect improves the detectability of broken rails in winter over summer months because the rail breaks are pulled apart so they can be detected by track circuits [2]. Figure 3 illustrates the proportion of broken rails causing derailments [2]. There is an average of 0.04 derailments per broken rail in the warmer period, compared to an average of 0.02 derailments per broken rail in the colder period (late November to mid-March).

Although railroads may know that there is an increased risk of a rail break in the colder months, there may be operational constraints associated with the ability of railroads to fix all detected defects in a timely manner. It should also be noted that the thermal contraction would not be the primary force in the rail break, but it would accelerate the crack growth.

Figure 2 Number of broken rails per mile by season (rail age 500 MGT, 30 MGT inspection interval)

Figure 3 Average number of broken-rail-caused derailments per broken rail by month, adapted from Dick (2001) Table A-6 [2]

OPTIMIZATION OF RAIL DEFECT INSPECTION FREQUENCY BY SEASON

In order to determine the optimal rail defect inspection frequency in different seasons, we calculate broken-rail-caused train derailments per mile by using different combinations of season-specific inspection frequency. It is assumed that there is at least one inspection in each period. Based on the calculated risk for each combination of inspection frequency, we applied the Pareto-optimality technique to determine the optimal rail inspection schedule. The Pareto-optimality technique is widely used to address the decisions involving multiple (conflicting) objectives [17]. It optimize one objective given certain values of the other objectives. For example, given the total number of inspections per year, the rail testing schedule yielding the lowest train derailment rate per mile is a Pareto solution and preferred to other schedules with the same total number of inspections (Table 1). For example, if a railroad plans to inspect a track segment six times per year, to minimize the risk of a derailment due to a broken rail, the railroad should inspect the rails two times (average inspection interval 11.5 MGT or 7.5 weeks) from late November to mid-March and four times in the warmer period (average inspection interval 14.3 MGT or 9.3 weeks). Figure 4 shows the optimal season-specific inspection frequency based on the Pareto-optimality analysis for the example line with annual traffic of 80 MGT. As total annual inspections increases, broken-rail-caused train derailment likelihood decreases, at a diminishing rate.

Table 1 Season-specific rail defect inspection frequency

<table>
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<tr>
<th>Number of Rail Inspections in the Colder Period</th>
<th>Number of Rail Inspections in the Warmer Period</th>
<th>Total Number of Inspections per Year</th>
<th>Annual Number of Broken Rail Caused Derailments per Mile</th>
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Optimization of rail inspection frequency (assuming rail age 500 MGT, annual traffic density 80 MGT)

Note: (11,14) means 11 MGT average inspection interval from late November to mid-March and 14 MGT inspection interval in the warmer period.

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REFERENCES


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