Proceedings of the ASME 2013 Rail Transportation Division Fall Technical Conference
RTDF2013
October 15-17, 2013, Altoona, Pennsylvania, USA

RTDF2013-4711

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]:

$$S_{(i-1,i)} = R \times \frac{e^{-\left(\frac{N_{i-1}}{\beta}\right)^{\alpha}} - e^{-\left(\frac{N_{i-1}+X_i}{\beta}\right)^{\alpha}}}{1+\lambda\left(X_i-\mu\right)} \times \lambda\left(X_i-\mu\right) \quad (1)$$

Where:

$S_{(i-1,i)}$ = number of broken rails per track- mile between the $(i-1)^{th}$ and i^{th} inspection

R = number of rail segments per mile, 273 [14]

X_i =interval (MGT) between the $(i-1)^{th}$ and i^{th} inspection

α = Weibull shape factor, 3.1 [15]

β = Weibull scale factor, 2,150 [15]

λ = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval curve, 0.014 [14]

μ = minimum rail inspection frequency, 10 MGT [14]

N_i = rail age (cumulative tonnage on the rail) at the i^{th} 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.

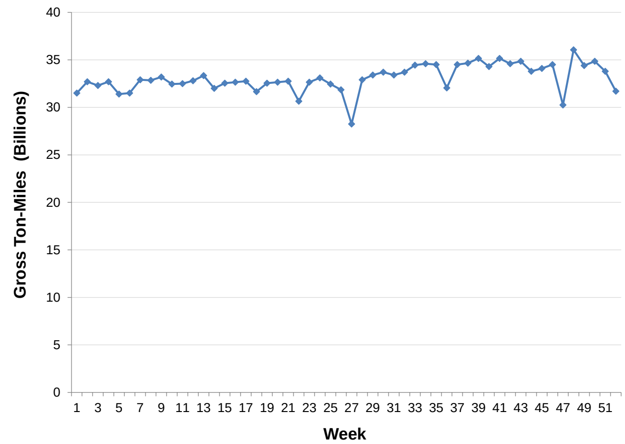

Figure 1 Weekly gross ton-miles on Class I mainlines, 2011 and 2012 average

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)

- λ_1 = 0.03 and μ_1 = 4 (inspection interval less than 20 MGT) [14]
- λ_1 = 0.05 and μ_1 = 10.4 (inspection interval between 20 MGT and 40 MGT) [14]

Warmer period (other weeks)

- λ_2 = 0.014 and μ_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].

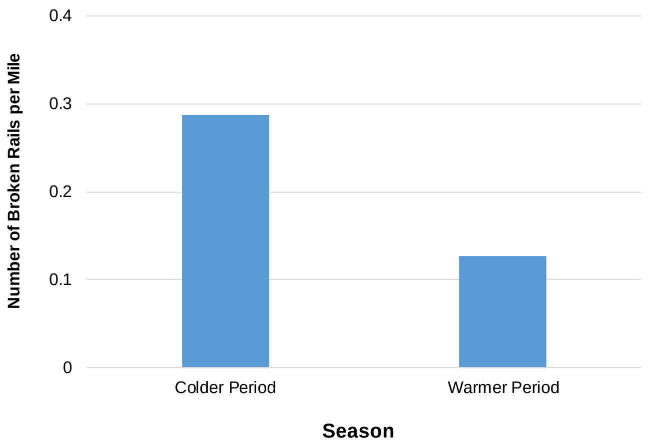

Figure 2 Number of broken rails per mile by season (rail age 500 MGT, 30 MGT inspection interval)

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).

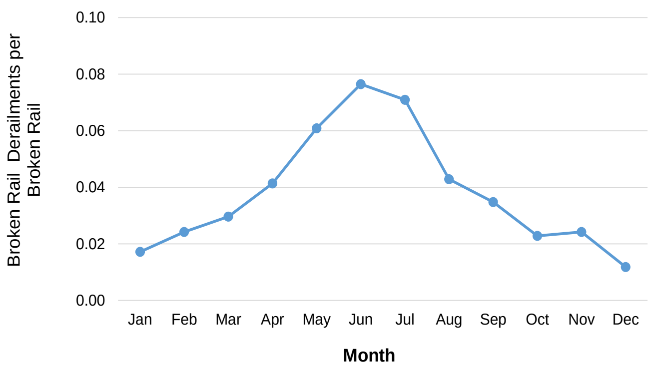

Figure 3 Average number of broken-rail-caused derailments per broken rail by month, adapted from Dick (2001) Table A-6 [2]

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.

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

Number of Rail Inspections in the Colder Period	Number of Rail Inspections in the Warmer Period	Total Number of Inspections per Year	Annual Number of Broken Rail Caused Derailments per Mile	Pareto Optimality
1	1	2	0.0227	Pareto
1	2	3	0.0138	Pareto
1	3	4	0.0094	Pareto
1	4	5	0.0068	Pareto
1	5	6	0.0051	Non-Pareto
2	1	3	0.0205	Non-Pareto
2	2	4	0.0116	Non-Pareto
2	3	5	0.0072	Non-Pareto
2	4	6	0.0046	Pareto
2	5	7	0.0029	Pareto
3	1	4	0.0196	Non-Pareto
3	2	5	0.0107	Non-Pareto
3	3	6	0.0063	Non-Pareto
3	4	7	0.0037	Non-Pareto
3	5	8	0.0020	Pareto
4	1	5	0.0190	Non-Pareto
4	2	6	0.0101	Non-Pareto
4	3	7	0.0058	Non-Pareto
4	4	8	0.0032	Non-Pareto
4	5	9	0.0014	Pareto
5	1	6	0.0187	Non-Pareto
5	2	7	0.0098	Non-Pareto
5	3	8	0.0054	Non-Pareto
5	4	9	0.0028	Non-Pareto
5	5	10	0.0011	Pareto

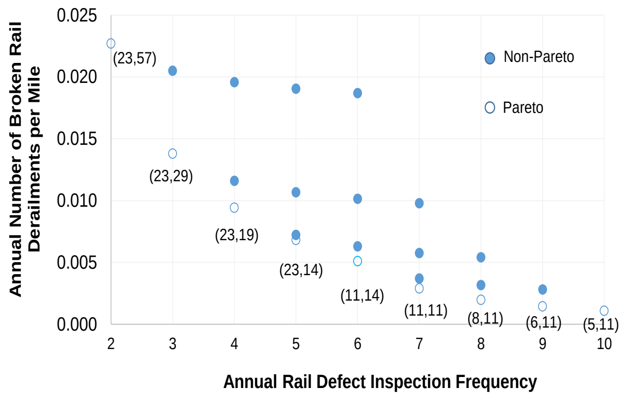

Figure 4 Optimization of rail inspection frequency (assuming rail age 500 MGT, annual traffic density 80 MGT)

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

Certain caveats should be taken into account when applying the method to a specific rail line. First, the model for estimating broken rail occurrence was developed based on data collected more than two decades ago. More up-to-date information should be used to update the model parameters. Second, there may be other factors affecting broken rail derailment risk in addition to those considered in this paper. Quantifying the effects of these factors would facilitate a better understanding of context-specific derailment risk and the corresponding rail inspection schedule. Third, this research focuses on risk-based rail inspection scheduling. Depending on questions to address and data available, cost and other factors can be included in the decision making process of infrastructure management. Finally, future research can be developed to account for the parameter uncertainties in rail inspection schedule using techniques such as Monte Carlo simulation [18]. This would facilitate a better understanding of the variation of outcomes under various circumstances.

CONCLUSION

This paper develops a model to optimize rail defect inspection frequency accounting for the seasonal effects of traffic, occurrence of broken rails and detection rate of broken rails by track circuits. On an industry-wide basis, there is no significant variation of weekly gross ton-miles. Tensile thermal stress increases the occurrence of broken rails in colder conditions but also improves the chance that a broken rail is identified by track circuits. This research can be incorporated into a larger framework of broken rail risk management to analyze and reduce accident risk due to broken rails.

ACKNOWLEDGEMENT

This research was partially funded by the Association of American Railroads, BNSF Railway, and the National University Rail (NURail) Center, a U.S. DOT University Transportation Center. The authors are grateful to Jose Manuel Martin Ramos for his assistance.

REFERENCES

[1] Liu, X., M.R. Saat and C.P.L. Barkan (2012). Analysis of causes of major train derailment and their effect on accident rates. Transportation Research Record 2289: 154-163.

[2] Dick, C.T. (2001). Factors affecting the frequency and location of broken railway rails and broken rail derailments. University of Illinois at Urbana-Champaign, IL, Urbana.

[3] Dick, C.T., C.P.L. Barkan, E. Chapman and M.P. Stehly (2002). Predicting the occurrence of broken rails: a quantitative approach. Proceedings of the 2002 Annual Conference, American Railway Engineering and Maintenance of Way Association (AREMA), Washington DC.

[4] Dick, C.T., C.P.L. Barkan, E. Chapman and M.P. Stehly (2003). A multivariate statistical model for predicting the occurrence and location of broken rails. Transportation Research Record 1825: 48-55.

[5] Barkan, C.P.L., C.T. Dick and R.T. Anderson (2003). Analysis of railroad derailment factors affecting hazardous materials transportation risk. Transportation Research Record 1825: 64-74.

[6] Palese, J.W. and T.W. Wright (2000). Risk based ultrasonic rail test scheduling on Burlington Northern Santa Fe. Proceedings of the 2000 Annual Conference, American Railway Engineering and Maintenance of Way Association (AREMA), Dallas, TX.

[7] Zarembski, A.M. and J.W. Palese (2005). Characterization of broken rail risk for freight and passenger railway operations. Proceedings of the 2005 Annual Conference, American Railway Engineering and Maintenance of Way Association (AREMA), Chicago, IL.

[8] Liu, X., C.P.L. Barkan, and M.R. Saat (2011). Analysis of derailments by accident cause: evaluating railroad

track upgrades to reduce transportation risk. Transportation Research Record 2261: 178-185.

[9] Liu, X., M.R. Saat and C.P.L. Barkan (2013a). Safety effectiveness of integrated risk reduction strategies for the transportation of hazardous materials by rail. Transportation Research Record (in press).

[10] Liu, X., M.R. Saat and C.P.L. Barkan (2013b). Integrated risk reduction framework to improve railway hazardous materials transportation safety. Journal of Hazardous Materials 260: 131-140.

[11] Liu, X. (2013c). Optimal strategies to improve railroad train safety and
reduce hazardous materials transportation risk. PhD Dissertation, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, IL.

[12] Jeong, D.Y. and G.E. Gordon (2009). Evaluation of rail test frequencies using risk analysis. Joint Rail Conference, ASME, Pueblo, Colorado, USA.

[13] Orringer, O. and M.W. Bush (1983). Applying modern fracture mechanics to improve the control of rail defects in track. American Railway Engineering Association Bulletin 689, 84: 19-53.

[14] Orringer, O. (1990). Control of rail integrity by self-adaptive scheduling of rail tests. Federal Railroad Administration DOT/FRA/ORD-90/05.

[15] Davis, D.D., M.J. Joerms, O. Orringer and R.K. Steele (1987). The economic consequences of rail integrity. Report No. R-656. Association of American Railroads, Chicago, IL.

[16] Association of American Railroads (2011, 2012). Weekly traffic summary.

https://www.aar.org/newsandevents/Freight-Rail-Traffic/Pages/2012.aspx#.UdoFi6Lz1v7

[17] Sinha, K., R. Krishnan, and D. Raghavendra (2007). Multi-objective robust optimisation for crashworthiness during side impact. International Journal of Vehicle Design, 43: 116-135.

[18] Orringer O., Y.H. Tang, D.Y. Jeong, and A.B. Perlman (1999). Risk/benefit assessment of delayed action concept for rail inspection. DOT-VNTSC-FRA-99-7, April 1999.