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PRELIMINARY RISK ANALYSIS OF FREIGHT-TRAIN DERAILMENT CAUSED BY TRACK GEOMETRY DEFECT

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ABSTRACT

This paper develops an analytical framework for analyzing freight-train derailment risk due to track geometry failures. First, track geometry degradation is estimated based on a previous study that uses data from one Class I railroad. Then, the frequency of expected number of track-geometry-defect-caused derailment on mainlines is estimated. After that, the derailment severity (measured by the number of railcars derailed) can be predicted based on FRA-reportable track-geometry-failure-caused freight-train derailments. Due to data limitations, several simplifying assumptions were made to illustrate model structure and implementation procedure. The model can be adapted to specific carriers and locations for normative risk management of track geometry defects.

INTRODUCTION

Track geometry defect is a common cause of track-related derailments on freight railroads in the United States. There are various types of track geometry defects, such as profile, alignment, crosslevel and wide gauge (Figure 1).

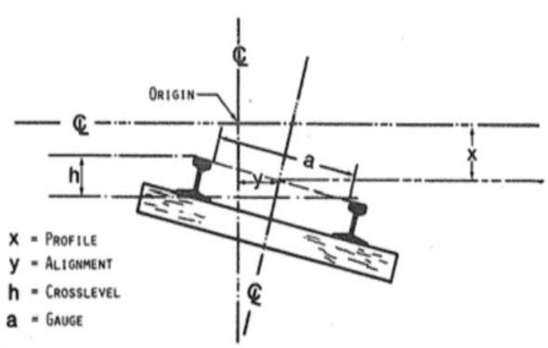

Figure 1 Track geometry defects [1]

Profile and alignment describe track geometry in both surface and line uniformity against the vertical and horizontal plane [2]. Cross-Level, also called XLEVEL, is the difference in elevation between the top surfaces of the rails at a single point in a tangent track segment [3]. Track gauge is the distance between the inner faces of each side of rails.

The Federal Railroad Administration (FRA) of the US Department of Transportation (USDOT) collects reports on all the accidents that exceed a specified monetary threshold from the railroads operating in the United States every year. The FRA compiles the submitted accident reports into a Rail Equipment Accident (REA) database. Based on this database, we analyzed the number of freight-train derailments due to track-geometry-related accident causes from 2000 to 2014 on mainlines.

Table 1
Freight-train mainline derailments from 2000-2014

FRA Cause Code	Description	Number of Freight-Train Derailments
T101	Cross level of track irregular (at joints)	269
T102	Cross level of track irregular (not at joints)	296
T103	Deviation from uniform top of rail profile	20
T104	Disturbed ballast section	5
T105	Insufficient ballast section	6
T106	Superelevation improper, excessive, or insufficient	54
T107	Superelevation runoff improper	6
T108	Track alignment irregular (other than buckled/sunkink)	148
Total		**804**

Because crosslevel defects caused more derailments than other track geometry defects, this paper focuses on the derailments due to this specific track geometry defect. The methodology could be adapted to other cause codes as well.

LITERATURE REVIEW

Table 2 presents a review of relevant studies regarding railroad infrastructure risk management.

Table 2
Selected track infrastructure management studies

Scope	Author	Key Words
Rail Life	Zarembski 2006; Joy & Tournay 2012;	Extend Rail Life
Track Geometry Condition	IMRT 2005; Berawi at al. 2010	TQI; Traffic; Maintenance
Track Degradation	Vale & Lurdes 2013; Andrade & Teixeira 2012; Zarembski 2006	Stochastic & Bayesian Model; Track Geometry; Rail and Joint Bars; Frogs and Switches
Track Buckling	Kish & Clark 2009	Compressive Longitudinal Force; Probabilistic Model
Maintenance & Renewal	Andrade at al. 2013	Standard Deviations; Horizontal Alignment Defects

Some studies focused on extending rail life, through management of rail temperature, rail lubrication, grinding or change of wheel profile [4,5]. Regarding track geometry defects, the prior research has discovered that the track geometry condition is influenced by TQIs (Track Quality Indices), traffic, and maintenance [6]. TQI methodology is developed to evaluate track geometry conditions by different track features. Profile, alignment, crosslevel and gauge are considered as TQI parameters that constitute the important performance indicators for track quality in relation to track classifications. Traffic is a key affecting factor of track geometry defect rate. As traffic volume and axle load increase, periodic inspection and repair play a more critical role in extending the service life of a track system [7]. Vale and Lurdes found that the initial track quality affects track degradation rate [8]. Andrade & Teixeira analyzed the uncertainties in track degradation processes using a Bayesian model [9]. Kish and Clark developed a probabilistic model to understand buckling risk by lateral resistance, misalignments and the rail neutral temperature [10].

METHODOLOGY

This paper develops a five-step methodological framework to evaluate the derailment risk due to track geometry defect, with a focus on crosslevel defects (Figure 2).

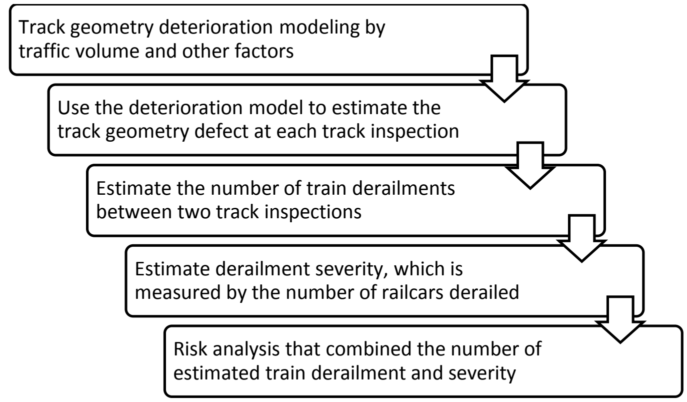

Figure 2 Analytical procedure of track geometry derailment risk analysis

Step 1: Track degradation modeling

He et al. (2014) developed the following equation to estimate the amplitude of track geometry degradation:

$$z = \log\left(\frac{y_k(t+\Delta t) - y_k(t)}{\Delta t y_k(t)}\right) = \alpha_0 + \alpha_1 X_{1k}(t) + \cdots + \alpha_p X_{pk}(t) + \varepsilon_k(t);\ \forall k = 1 \ldots N \quad (1)$$

Where:
$y_k(t)$ = The amplitude of a specific type of track geometry defect at track segment k and inspection time t
k = Track section (each track section is 0.02 miles)
t = Inspection time
Δt = Interval between inspections
$X_{pk}(t)$ = The p^{th} influencing factor
N = The total number of track sections

The parameter coefficients in Equation 1 were developed by He et al. (2014) based on infrastructure data from one Class I railroad.

Table 3 Parameter coefficients for track geometry degradation model (source: He et al. 2014)

Defect type	*α_0-intercept*	*α_1-Traffic (MGT)*	*α_2-Traffic (number of cars)*	*α_3-Traffic (number of trains)*	*α_4-Sequence number*	*Mean squared error (MSE)*
CANT	−7.66	−7.01E-02	6.05E-06	6.52E-04	0.067	0.242
DIP	−7.58	7.21E-02	—	—	—	0.099
GAGE_C	−8.53	8.62E-02	—	—	0.113	0.046
GAGE_W1	−7.19	3.55E-02	4.59E-06	—	0.068	0.021
GAGE_W2	−8.08	1.90E-02	—	2.05E-04	0.080	0.061
OVERELEV	−7.58	2.45E-01	—	—	0.699	0.102
SURF	−6.99	2.00E-01	—	−1.33E-03	0.044	0.007
WEAR	−8.22	2.95E-02	—	4.73E-04	0.075	0.080
XLEVEL	−7.66	—	2.64E-06	3.23E-04	0.092	0.019

'—' means that the coefficient is not significant.

Based on Table 3, a parametric track degradation model is as follows:

$$z = -7.66 + 2.64 * 10^{-6} X_{2k}(t) + 3.23 * 10^{-4} X_{3k}(t) + 0.092 X_{4k}(t) \quad (2)$$

For example, assuming that the interval between two inspections is 90 days ($\Delta t = 90$), if there is one train per day, there will be a total of 90 days between two inspections ($X_{3k}(t) = 90$). If each train has 95 cars, the total number of railcars between two inspections would be 8,550 ($X_{2k}(t) = 8{,}550$). At the first inspection ($X_{4k}(t) = 1$), we have

$$z = \log\left(\frac{y_k(t+\Delta t) - y_k(t)}{\Delta t y_k(t)}\right) = \alpha_0 + \alpha_1 X_{1k}(t) + \cdots + \alpha_p X_{pk}(t) + \varepsilon_k(t) = -7.66 + 2.64 * 10^{-6} * 8550 + 3.23 * 10^{-4} * 90 + 0.092 * 1 = -7.516358 \quad (3)$$

Assuming that the initial cross level value is 0.625 (inch), based on Equation (3), at the first inspection, the rate of change is:

$$\frac{y_k(t+\Delta t) - y_k(t)}{\Delta t} = e^{-7.516358} * \frac{1.25}{2} = 3.40069 * 10^{-4}$$

$$\begin{aligned} y_k(t+\Delta t) &= 3.40069 * 10^{-4} * \Delta t + y_k(t) \\ &= 3.40069 * 10^{-4} * 90 + 0.625 \\ &\approx 0.656 \text{ (inch)} \end{aligned}$$

This means that 90 days later, the cross level value increased from 0.625 inch to 0.656 inch, if there is one train per day within the interval. Using a similar approach, the estimated cross level amplitudes for the first 10 inspections are presented as follows.

Table 4 Estimated cross level amplitudes (assuming 90 days inspection interval, one train per day, each train has 95 cars, initial cross level is 0.625 inch)

Inspection	# of Trains	# of Cars	Log (Change Rate)	Deterioration Rate	Cross Level (Inch)
0	0	0			0.6250
1	90	8550	-7.5164	0.0003	0.6556
2	90	8550	-7.4244	0.0004	0.6908
3	90	8550	-7.3324	0.0005	0.7315
4	90	8550	-7.2404	0.0005	0.7787
5	90	8550	-7.1484	0.0006	0.8338
6	90	8550	-7.0564	0.0007	0.8984
7	90	8550	-6.9644	0.0008	0.9749
8	90	8550	-6.8724	0.0010	1.0658
9	90	8550	-6.7804	0.0012	1.1747
10	90	8550	-6.6884	0.0015	1.3064

It is assumed that when the crosslevel is above 1.25 inch, the defect must be repaired immediately. This assumption is based on the FRA Track Standards of the maximum crosslevel for FRA track class 4 [11]. The railroads may have more stringent maintenance standards than the minimum required by the FRA [12]. In the example above, at the 10th inspection, the crosslevel has exceeded the maximum allowable threshold and the track geometry will be adjusted. For illustration, we assume that the initial allowable cross level is 0.625 inch. The analyst may choose to let cross-level be zero or other values as the initial level and the method can be adapted accordingly.

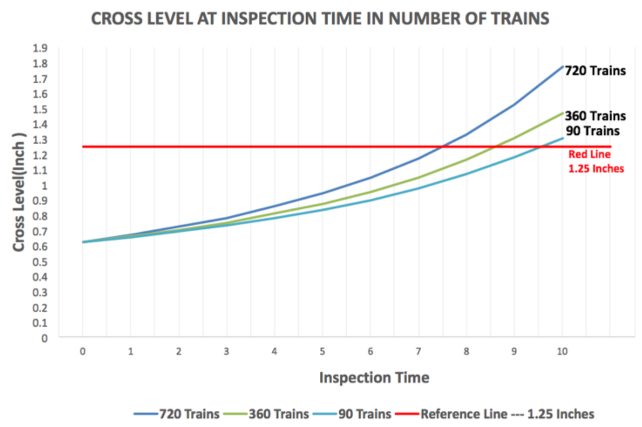

Figure 3 Estimated cross level by traffic

Figure 2 presents estimated cross level values at different traffic volumes. A higher traffic volume will accelerate track geometry degradation.

Step 3: Track geometry caused derailments

Due to data limitations, this paper assumed that derailment probability is linearly correlated with the amplitude of a track geometry defect. Without detailed information at hand, it is assumed that when crosslevel is 1.25 inch, the derailment probability is 0.0005 per car-mile. When crosslevel is 0, the derailment probability is 0. Based on these assumptions, the extrapolated derailment probability given a specified cross-level is:

P(x) = [(0.0005-0)/(1.25-0)]x (4)

Where:

P(x) = probability of a crosslevel-caused train derailment per car-mile

x = crosslevel amplitude

For example, if the crosslevel is 0.625, its corresponding derailment probability is 0.00025. Note that the probability values here are for illustrating the methodological framework. Further research is needed to better understand the probability of a derailment given specified track geometry defect values.

Between any two inspections, the number of train derailments due to crosslevel can be estimated as:

$$N(t-1,t) = \frac{P_{t-1}(x) + P_t(x)}{2} \times M \quad (5)$$

Where:

N(t-1,t) = estimated number of crosslevel-caused train derailments

M = number of car-miles

Step 4: Derailment severity analysis

Speed was found to be a significant factor that affects derailment severity, which is measured by the number of railcars derailed [13,14]. Liu et al. (2011) developed a nonlinear function to estimate the average number of railcars derailed by derailment speed:

$S = A \times V^B$ (6)

Where:
S = average number of railcars derailed per FRA-reportable mainline train derailment
A, B = model coefficients by accident cause (A=2.952; B = 0.257 for track geometry defects)
V = train speed in mph

For example, if train speed is 40 mph, the average number of railcars derailed per derailment is:

$$N_c = A_c * S^{B_c} = 2.952 * 40^{0.257} = 7.62 \quad (7)$$

Step 5: Derailment risk

$R(t-1,t) = N(t-1,t) \times S$ (8)

Where:
R(t-1,t) = derailment risk due to track geometry failures between two inspections (expected total number of railcars derailed)
N= Number of track-geometry-defect-caused train derailments
S = Average number of railcars derailed per derailment

NUMERICAL EXAMPLE

This section presents a numerical example to illustrate model application. The results hereafter were based on a set of simplifying assumptions and can only be used for illustrating the methodology. The example results shall not be used for any commercial or legal purposes. Figure 4 shows crosslevel-caused derailment risk between two track inspections. The horizontal axis (X axis) represents the inspection sequence. For example, "2" represents the interval between the 2nd inspection and the 1st inspection. The vertical axis (Y axis) represents the estimated derailment risk, measured by the number of railcars derailed, within the two inspections. It is assumed that the inspection interval is 90 days. Each day has one train. Each train has 95 railcars. The operating speed is 40 mph, and its corresponding derailment severity is 7.62 cars derailed (Equation 7).

The average crosslevel value between the 1st and 2nd inspection is (0.6556+0.6908)/2 = 0.6732 inch. Using Equation (4), the corresponding derailment probability per car-mile is 0.00027. Within the 90-day interval, there are 8,550 railcars on each 0.02-mile track section. The total traffic volume is 171 car-miles. The estimated number of train derailments is 0.046. On average, each train derailment results in 7.62 cars derailed, so the total number of railcars derailed is 0.351. Using a similar approach, the derailment risk between any other two inspections can be estimated (Figure 4).

It shows that, given all else being equal, derailment risk increases by inspection sequence, when there is no track rectification. This phenomenon was also found by He et al. (2014) based on data from one Class I railroad. As traffic cumulates, the marginal change of derailment risk also increases. It appears that an exponential function fits the relationship between the derailment risk and inspection sequence, in this particular hypothetical example.

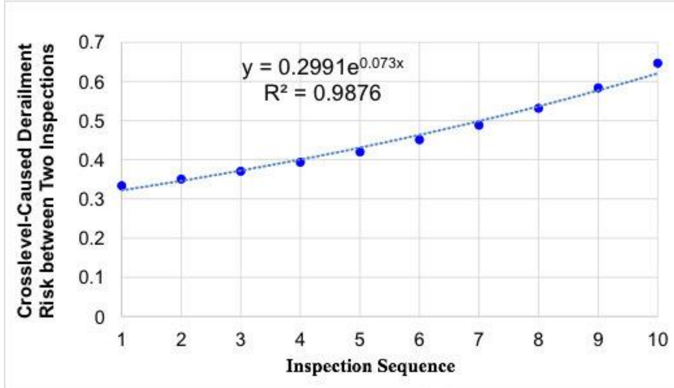

Figure 4 Track geometry caused derailment risk by traffic volume

Figure 4 is based on an assumption of 90 trains within the 90-day inspection interval (one train per day). Figure 5 shows a sensitivity analysis in which the risk was computed when traffic volume increased to 360 trains (4 trains per day) and 720 trains (8 trains per day). The analysis shows that a higher traffic volume is associated with a higher derailment risk.

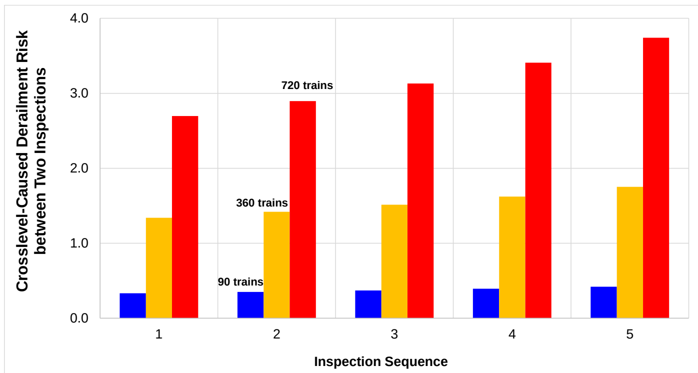

Figure 5 Derailment risk by traffic volume

CONCLUSION

Track geometry defect is one common cause of track-related freight-train derailments. This paper develops a practical analytical framework for evaluating track geometry caused derailment risk, accounting for track geometry degradation, the derailment likelihood at a given track geometry defect amplitude, and the average number of cars derailed per derailment. The analysis shows that, given all else being equal, the higher traffic volume, the faster the track deteriorates within an interval, and correspondingly more frequent inspection and maintenance may be needed to rectify track geometry and assure operational safety.

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