Feasibility Assessment for the Development of a Tie Condition Based Risk Index

October 2008

Submitted To

The Railway Tie Association (RTA)

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Table of Contents

1. Introduction

This report presents the results of a RTA sponsored project to utilize current tie condition data to determine the feasibility of utilizing this data to develop a tie condition based risk index associated with tie related derailments. Readily available data was collected from a Class I railroad and the FRA, and utilized for the analysis.

The focus of this activity was to use a broad population of recent in-track tie condition data to see if a correlation to tie related derailments existed. The data that was utilized was tie condition data, as collected by the *TieInspect* condition monitoring and recording system for a Class 1 railroad. The data consisted of tie conditions divided into four classes: Good, Marginal, Bad, and Failed. The condition is recorded for every tie in each inspected mile. Over 2,500 miles of data was utilized in this analysis. In addition to the *TieInspect* data, data from the railroad regarding traffic and track conditions, as well as current tie lives was utilized.

Derailment data was taken from publicly available data gathered from the Federal Railroad Administration website [1] for train accidents for the years 2005 – 2007. Specifically, derailments reported to the FRA associated with tie condition were downloaded. The specific FRA derailment codes are listed in Table 1, below.

Table 1. FRA Accident Cause Codes Associated with Wide Gage due to Tie Condition. [1]

Code	**Description**
T110	Wide gage (due to defective or missing crossties)
T111	Wide gage (due to defective or missing spikes or other rail fasteners)
T112	Wide gage (due to loose, broken, or defective gage rods)

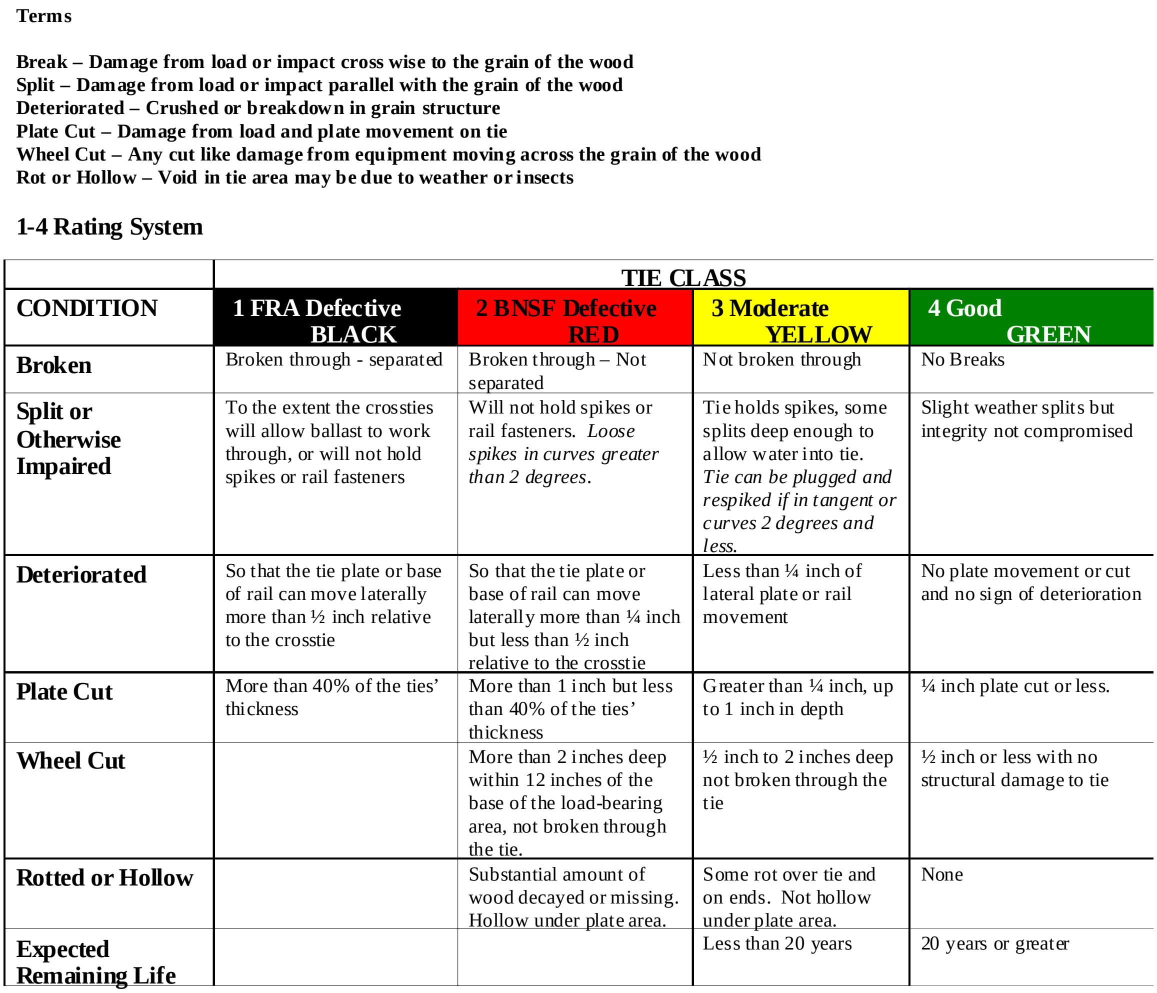
The data was analyzed and correlated to determine the significance of tie condition on tie related derailments. A preliminary correlation was found between a tie condition index and the derailment data and is presented in this report together with a sensitivity analysis.

While a preliminary correlation was found, the derailment data that was available was limited. Thus, the exact derailment location was not always known. In addition, the only derailments used were FRA reportable derailments. Since not all derailments are FRA reportable, the total derailment count is most probably different from that used. In addition, the data that was available for use was *TieInspect* data. GRMS data for these miles was not available, and may have impact on a final derailment index. The index developed here-in and the associated correlation suggests that the development of a risk based index is potentially feasible. However additional data is required to go beyond this preliminary validation stage.

2. Data Utilized

***TieInspect* Data**

Tie condition data as recorded by the *TieInspect* system was collected for the analysis from a Class 1 railroad. The *TieInspect* data contains individual tie condition data as rated by the tie inspector for four conditions: Good, Marginal, Bad, and Failed (as well as identifying bad joint ties). Additional *TieInspect* information includes, tie material, tie type, and curvature. The tie inspector walks the track and keys in the tie condition based on his visual inspection. The matrix of tie conditions is defined in Figure 1 below [2]:



Terms

Break – Damage from load or impact cross wise to the grain of the wood
Split – Damage from load or impact parallel with the grain of the wood
Deteriorated – Crushed or breakdown in grain structure
Plate Cut – Damage from load and plate movement on tie
Wheel Cut – Any cut like damage from equipment moving across the grain of the wood
Rot or Hollow – Void in tie area may be due to weather or insects

1-4 Rating System

	TIE CLASS			
CONDITION	**1 FRA Defective BLACK**	**2 BNSF Defective RED**	**3 Moderate YELLOW**	**4 Good GREEN**
Broken	Broken through - separated	Broken through – Not separated	Not broken through	No Breaks
Split or Otherwise Impaired	To the extent the crossties will allow ballast to work through, or will not hold spikes or rail fasteners	Will not hold spikes or rail fasteners. *Loose spikes in curves greater than 2 degrees.*	Tie holds spikes, some splits deep enough to allow water into tie. *Tie can be plugged and respiked if in tangent or curves 2 degrees and less.*	Slight weather splits but integrity not compromised
Deteriorated	So that the tie plate or base of rail can move laterally more than ½ inch relative to the crosstie	So that the tie plate or base of rail can move laterally more than ¼ inch but less than ½ inch relative to the crosstie	Less than ¼ inch of lateral plate or rail movement	No plate movement or cut and no sign of deterioration
Plate Cut	More than 40% of the ties' thickness	More than 1 inch but less than 40% of the ties' thickness	Greater than ¼ inch, up to 1 inch in depth	¼ inch plate cut or less.
Wheel Cut		More than 2 inches deep within 12 inches of the base of the load-bearing area, not broken through the tie.	½ inch to 2 inches deep not broken through the tie	½ inch or less with no structural damage to tie
Rotted or Hollow		Substantial amount of wood decayed or missing. Hollow under plate area.	Some rot over tie and on ends. Not hollow under plate area.	None
Expected Remaining Life			Less than 20 years	20 years or greater

Figure 1: BNSF Tie Condition Rating System [2]

While there were almost 39,000 miles of track inspected with *TieInspect* in the past six years, the data was reduced to approximately 11,000 miles of track that had at least two inspections more than one year apart. This data was then further filtered to remove any miles of track that had obvious tie work performed (e.g. Good ties increased significantly), and to eliminate sidings and any outlier data. This resulted in over 2,500 miles of track with tie condition data to be utilized for analysis purposes.

As an initial step, some statistical analyses were performed on the data. For the 2,500 miles of usable data, tie counts and percentages (by condition) were analyzed for the last two inspections. The results are presented in Table 2 below.

Table 2. Summary of Ties Used in Analyses

	Inspection 1		**Inspection 2**[1]	
Good	3,383,326	42%	2,513,520	31%
Marginal	2,907,784	36%	2,881,502	36%
Bad	1,693,076	21%	2,495,017	31%
Failed	86,697	1%	174,159	2%
Total	8,070,883		8,064,198	

In addition, it should be noted that the average expected life for the ties in a mile of track ranged from 14 to 68 years, with an average of 42 years. Note that tie lives were determined based on established tie life equations, which take into account the effects of tonnage, curvature, and climate, and were calibrated to match and satisfy the experiences of the Class 1 railroad. In order to correlate this data with the accident data, the average tie condition data (from the last two inspections) was broken down by division and is summarized in Table 3 below.

Table 3. Tie Condition Data by Division.

Division	Good Ties	Marginal Ties	Bad Ties	FRA Bad Ties	Avg Life	Miles
DIV 1	403688	320760	292068	18085	40.3	318.4
DIV 2	187148	157766	134193	11273	49.3	150.7
DIV 3	358295	354538	227124	11263	36.9	292.6
DIV 4	214488	294043	159351	13891	43.9	209.7
DIV 5	98014	101509	70823	3711	38.1	84.2
DIV 6	178291	161765	99287	9358	46.0	137.9
DIV 7	80528	132520	71549	2954	39.0	88.4
DIV 8	294451	345383	202553	5735	35.6	260.8
DIV 9	545010	491324	427883	28755	44.0	459.2
DIV 10	275735	264600	210193	14371	43.7	235.2
DIV 11	261679	204270	161014	9579	40.6	195.9
DIV 12	51099	66167	38011	1457	39.1	48.2

Derailment Data

Federal Railroad Administration safety data was utilized for the derailment side of the analysis and was gathered from the FRA safety database. Specifically, cause codes T110 – T112 for the years 2005 through 2007 were downloaded, as specified in Table 1.

Derailments for main line track only were isolated and were broken down by year and division and are presented below in Table 4.

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[1] Note that the tie totals are not exact as tie counts for each mile are not always equal

Table 4: FRA Tie Related Derailments.

	2005		2006		2007		2005-2007	
Division	**Total**	**Main**	**Total**	**Main**	**Total**	**Main**	**Total**	**Main**
DIV 1	2	0	7	1	6	1	15	2
DIV 2	1	0	5	1	8	3	14	4
DIV 3	3	1	0	0	9	3	12	4
DIV 4	0	0	1	1	1	0	2	1
DIV 5	0	0	2	0	3	1	5	1
DIV 6	3	2	7	3	4	0	14	5
DIV 7	3	1	0	0	1	1	4	2
DIV 8	2	1	1	0	3	0	6	1
DIV 9	3	1	4	1	9	2	16	4
DIV 10	1	0	2	0	2	0	5	0
DIV 11	1	1	3	1	4	1	8	3
DIV 12	5	0	1	0	3	1	9	1

The data presented above was utilized for the correlation analysis, presented in the next section.

3. Results of Data Analysis

The 2,500 miles of data was analyzed utilizing the tie condition counts for Good, Marginal, Bad, and Failed ties. This data was evaluated using several engineering and statistical techniques.

Initially, data was evaluated on a micro level, using a *TieInspect* Priority Index in and around the location of the derailment. The *TieInspect* Priority Index is based on the local tie condition and distribution, as well as track and traffic features (curvature and tonnage), and expected tie life in that area. Thus, the key relevant factors associated with tie related derailments are taken into account.

Figure 2 below shows a sample of a one mile plot of this index in the area of one derailment (occurring at MP 331.9). In the area of the derailment, the index is greater than 80, and appears to be one of the maximum points, well above the mean (below 40). However, while there are several locations where this occurs, the other locations did not exhibit this clear correlation. This is a phenomenon which has been found in other areas of derailment analysis; specifically since a derailment is a statistical occurrence, the derailment will not necessarily occur at every high risk location.

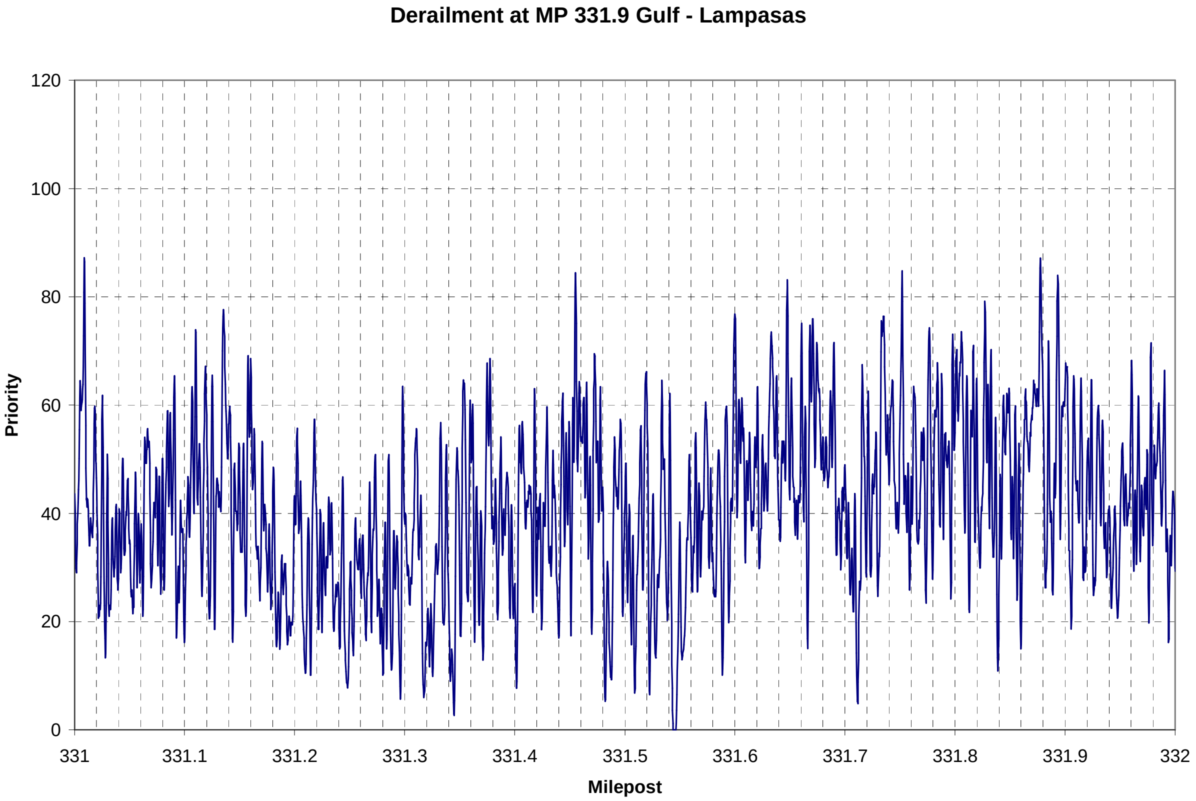

Figure 2. Sample Plot of *TieInspect* Priority Index by Milepost in Derailment Location.

Considering the above, and the fact that the accuracy of the location data available for many of the derailment events was questionable, a macro approach was investigated.

The macro approach utilized was to perform the correlation analysis on a divisional level using the distribution of TieInspect tie condition data, along with expected tie life and derailment occurrence. The first step was to normalize the data. This was done by determining average tie condition per mile for each of the four condition categories (Good, Marginal, Bad, and Failed), and derailment rate in terms of derailments per mile per year. This data is presented below in Table 5.

Table 5: Normalized Tie Condition and Derailment Data.

Division	Good Ties	Marginal Ties	Bad Ties	Failed Ties	Avg Life	2005-2007 Derail/Mi/Yr	
						Total	Main
DIV 1	1268	1007	917	57	40.3	0.016	0.002
DIV 2	1242	1047	891	75	49.3	0.031	0.009
DIV 3	1224	1212	776	38	36.9	0.014	0.005
DIV 4	1023	1402	760	66	43.9	0.003	0.002
DIV 5	1164	1206	841	44	38.1	0.020	0.004
DIV 6	1293	1173	720	68	46.0	0.034	0.012
DIV 7	911	1499	809	33	39.0	0.015	0.008
DIV 8	1129	1324	777	22	35.6	0.008	0.001
DIV 9	1187	1070	932	63	44.0	0.012	0.003
DIV 10	1172	1125	894	61	43.7	0.007	0.000
DIV 11	1336	1043	822	49	40.6	0.014	0.005
DIV 12	1059	1372	788	30	39.1	0.062	0.007

This data was then used as the basis for the risk analysis. Note, the analysis is based on Main Line derailment data only, and excludes all yard and industrial track derailments, since the tie condition data was available from main line track only.

The initial evaluation approach examined simple regression analyses attempting to correlate individual derailment occurrence with bad tie counts, FRA bad tie counts, combined tie counts, and other combinations of tie conditions with no significant overall correlation noted (though as Figure 2 shows, some individual derailments did have good correlation). Figure 3 below shows one such example for Failed and Bad ties combined versus Derailments per Mile per Year. Note that the trend line is forced through zero and that the R^2 value is negative, showing no correlation.

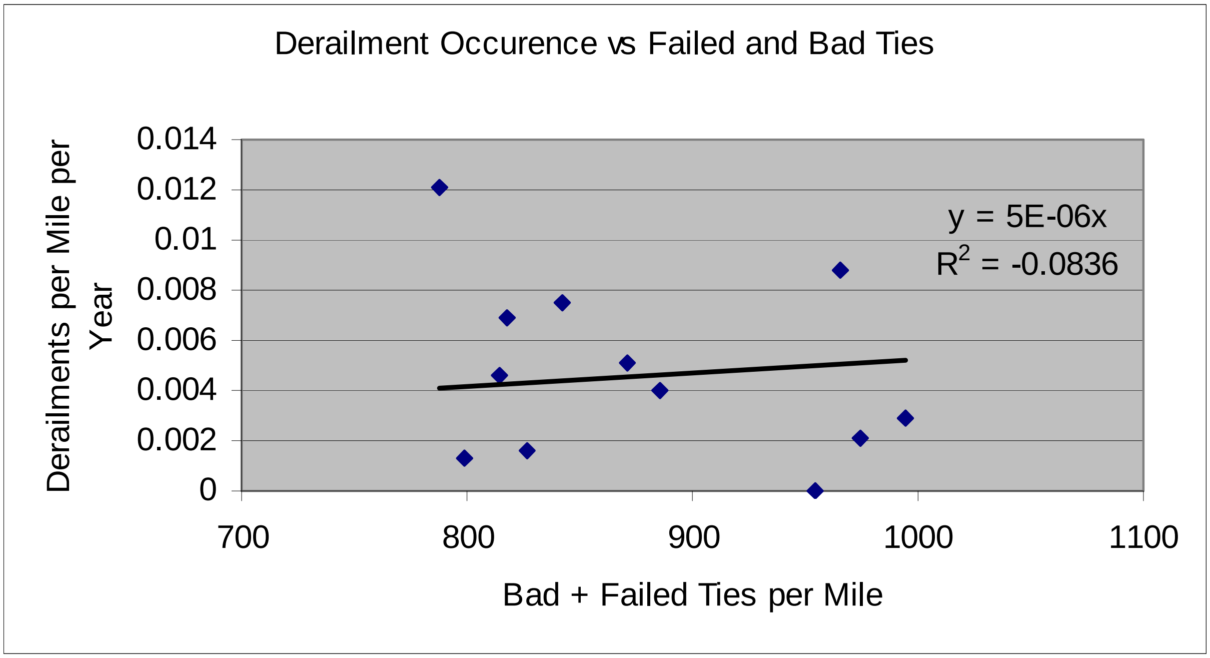

Figure 3. Derailments versus Bad + Failed Ties per Mile.

The second set of correlation analyses looked at derailment rate as a function of combinations of various tie condition counts together with the expected life of a tie in each geographic location (e.g. Division). Thus, a multivariate linear regression analysis was performed for several combinations of parameters and evaluated for significance[2]. While some correlation existed for several cases, the best case (i.e. best statistical correlation) will be presented here in detail.

Note: Some of these correlations are summarized below, but will not be presented in detail.

- Main line derailments vs. individual tie condition and expected tie life (Each tie condition considered an independent variable)
    - Good, Marginal, Bad, Failed
    - Marginal, Bad, Failed
    - Bad, Failed
    - Bad
- Failed Main line derailments vs. combined tie conditions and expected tie life (Combined tie conditions added considered an independent variable)
    - Good + Marginal, Bad + Failed
    - Good, Marginal, Bad + Failed
    - Bad + Failed

The combination that resulted in the best correlation and most reasonable results was main line derailments (derailment rate) as a function of the ratio of three parameters:

- Ratio of Failed to Bad ties (Failed/Bad)
- Ratio of Marginal to Good ties (Marginal/Good),
- Expected tie life.

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[2] Note that the DIV 10 was excluded from the analysis since it had no main line derailments, and thus was considered an outlier.

This correlation resulted in the following equation:

$$\textit{Expected Derailments/Mile/Year} = 0.00002813*(\textit{Marginal/Good}) + 0.03660*(\textit{Failed/Bad}) + 0.00007267*(\textit{Avg Expected Life})$$

The regression statistics are as follows:

Regression Statistics	
Multiple R	0.87
R Square	0.76
Adjusted R Square	0.58
Standard Error	0.0035
Observations	11

The R Square value of 0.76 represents a good statistical correlation. The physical meaning of the equation is of interest as well. The Failed/Bad ratio is a measure of how “bad” the track is, i.e. what percentage of the ties are allowed to go until complete failure before removal. Thus, the higher this ratio is, the greater the percentage of ties that are left in track until total failure. Conversely, the lower this ratio is, the earlier the bad ties are removed and the larger the margin of safety in the track. Similarly, the Marginal/Good ratio is a measure of how “good” the track is, with the lower the ratio, the “better” the track is. Finally, the average expected life (based on the tie life model) is a function of the local track and traffic conditions (curvature and tonnage), as is related to rate of tie degradation.

Table 6 below shows the actual derailments experienced for the three year period, along with the values predicted utilizing the equation presented above. Figure 4 presents this data graphically as a plot of the predicted versus actual derailments. Note, the correlation can be clearly seen, with some over and under prediction of actual values, as would be expected.

Table 6: Actual versus Predicted Derailments and Residuals.

					Derailments/Mile/Year		Derailments for 3 Year Period	
Division	M/G	F/B	Avg Life	Miles	Actual	Predicted	Actual	Predicted
DIV 1	0.79	0.06	40.3	318.4	0.002	0.005	2	5.0
DIV 2	0.84	0.08	49.3	150.7	0.009	0.007	4	3.0
DIV 3	0.99	0.05	36.9	292.6	0.005	0.005	4	4.0
DIV 4	1.37	0.09	43.9	209.7	0.002	0.006	1	4.0
DIV 5	1.04	0.05	38.1	84.2	0.004	0.005	1	1.2
DIV 6	0.91	0.09	46.0	137.9	0.012	0.007	5	2.8
DIV 7	1.65	0.04	39.0	88.4	0.008	0.004	2	1.2
DIV 8	1.17	0.03	35.6	260.8	0.001	0.004	1	2.9
DIV 9	0.90	0.07	44.0	459.2	0.003	0.006	4	7.8
DIV 11	0.78	0.06	40.6	195.9	0.005	0.005	3	3.0
DIV 12	1.29	0.04	39.1	48.2	0.007	0.004	1	0.6

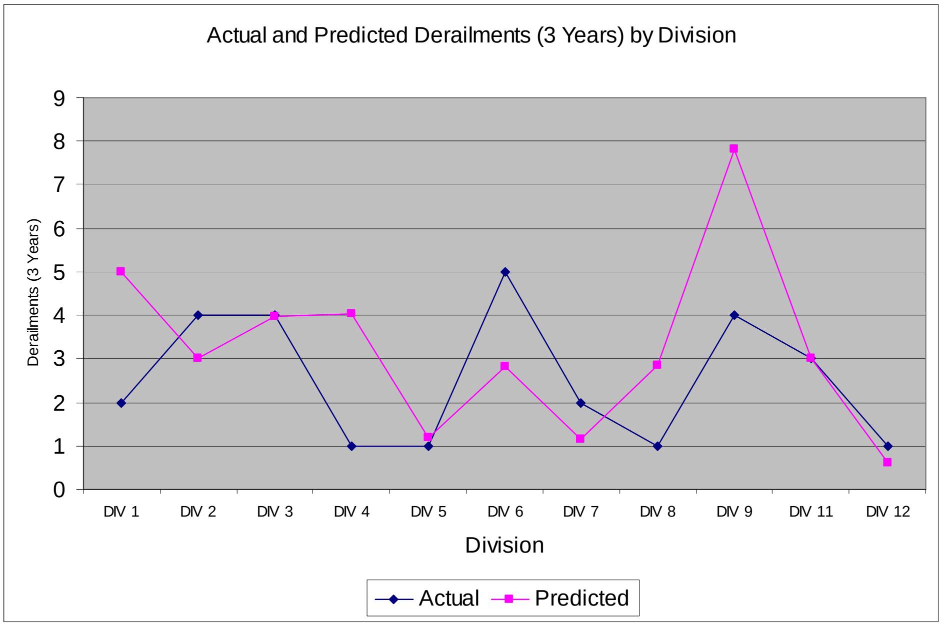


Figure 4. Plot of Actual versus Predicted Derailments.

In order to convert this relationship to a derailment prediction index, the predicted derailments per mile per year (from the equation presented above) is multiplied by 100. It is now possible to perform a sensitivity analysis of this tie derailment index with such key parameters as Failed Ties per Mile as shown in Figure 5 below.

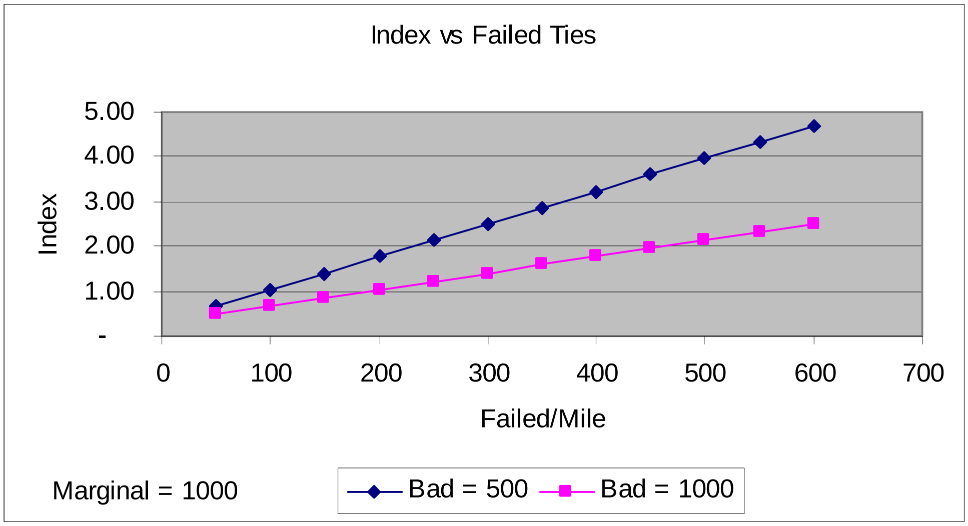
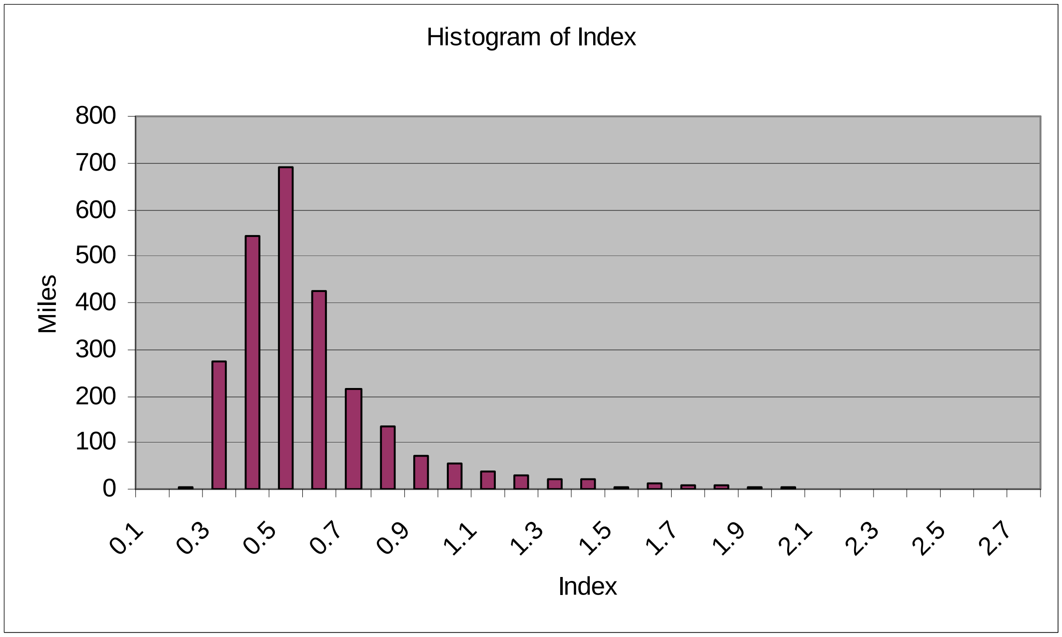


Figure 5. Index versus Failed Ties per Mile.

This sensitivity varies Failed Ties per mile and fixes Marginal ties at 1000 per mile and Bad ties per mile to either 500 or 1000 per mile (Good ties vary such that the total ties per mile is 3250).[3] Thus, as the ratio of Failed ties to Bad ties increases, corresponding to increasing "bad quality" of the track, the resulting Index (potential for derailment) increases. The higher the index, the higher the risk of a tie related derailment

To gain a better understanding of this derailment risk index, the model was applied to the 2,500 miles of track, on a mile by mile basis. The results of this application was 2,500 one mile segments of track with an individual index calculated for each segment based on the tie condition counts and expected average life. The minimum and maximum index values were 0.13 and 2.63 respectively, with an average of 0.53.

A histogram was developed for the data and is shown in Figure 6 below.



It can be seen from this figure that the majority of the occurrences of one mile track segments are at an index value of 0.4 to 0.5, a low derailment risk level. Of the 2,500 segments, 13.6% (340 miles) had an index greater than 0.75, and 6.1% (158 miles) had an index greater than 1.0. Based on the data in Table 6, this is approaching a measurable level of derailment risk. Thus, segments with a high risk index can be identified for further evaluation.

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[3] Expected average tie life if 42 years (the system average).

4. Summary and Conclusions

The focus of this study was to determine the feasibility of developing a risk based index of tie condition to predict the potential for tie related derailments. The analysis made use of recently collected tie condition data from a Class 1 railway. The data utilized was the tie condition data (Good, Marginal, Bad, Failed) collected using the *TieInspect* system of collecting tie condition data.

Over 2,500 miles of tie condition data was utilized together with tie related derailment data obtained from the FRA safety data base (public information on the FRA website). This data was correlated to determine the feasibility of developing a risk index that relates derailment risk with tie condition. Due to the limited nature of the data, a macro approach (segment basis) was taken, as opposed to a micro approach (location specific basis).

The study showed that it is feasible to calculate a risk index that associates tie condition and expected average tie life with the risk of a tie related derailment. Specifically, it was determined that tie related derailments correlate with three tie parameters:

- Ratio of Failed to Bad ties (Failed/Bad)
- Ratio of Marginal to Good ties (Marginal/Good),
- Expected tie life.

The calculated correlation or R Square value of 0.76 represents a good statistical correlation. The physical meaning of the equation is of interest as well. The Failed/Bad ratio is a measure of how “bad” the track is, i.e. what percentage of the ties are allowed to go until complete failure before removal. Thus, the higher this ratio is, the greater the percentage of ties that are left in track until total failure. Conversely, the lower this ratio is, the earlier the bad ties are removed and the larger the margin of safety in the track. Similarly, the Marginal/Good ratio is a measure of how “good” the track is, with the lower the ratio, the “better” the track is. Finally, the average expected life (based on the RTA tie life model) is a function of the local track and traffic conditions (curvature and tonnage), as is related to rate of tie degradation.

Using these correlation equations, a risk index was developed and a sensitivity analysis conducted to gain an understanding of how the index reacts to varying tie condition data.

Finally, an application of the index was performed for 2,500 miles of data on a mile by mile basis, showing the range of index values (0.13 to 2.63, with an average of 0.53) and a histogram of the index values. The majority of the occurrences were at an index value of 0.4 to 0.5, a low derailment risk level. However, 13.6% (340 miles) had an index greater than 0.75, and 6.1% (152.5) had an index greater than 1.0. Though not high risk values per se, these appear to represent potential derailment levels. By setting risk thresholds, it is possible to defining identify high risk segments for subsequent evaluation.

In conclusion, the study showed that the development and application of a risk index associating tie condition with tie related derailments is feasible. However, the study was based on a limited, defined set of data. By expanding this data set, to include additional (and more accurate) derailment information, as well as supplemental tie condition data (such as track strength or

GRMS values), it is expected that this study could be further developed and the risk index further refined.

References

1. Federal Railway Administration website for train accident data; http://safetydata.fra.dot.gov/OfficeofSafety/default.aspx
2. Zarembski, A.M., Parker, L.A., Palese, J.W., “Use of Comprehensive Tie Condition Data in Cross-Tie Maintenance Planning and Management on the BNSF”, **American Railway Engineering Maintenance Association Annual Technical Conference**, September 2002.