Derailment Probability Analyses and Modeling of Mainline Freight Trains

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Summary: We conducted statistical analyses and used modeling techniques to develop derailment probabilities for freight trains and freight cars operating on North American railroads. Knowing the expected frequency of derailment and the conditional probabilities of derailment for individual cars enables estimation of the derailment risk as it is affected by train length, operating speed, and positioning of cars in the consist. These results can be used to quantify the benefit in terms of reduced accident probability and severity of various changes in railroad operating and safety practices.

Index Terms: safety, risk, accident rate, derailment probability

1 INTRODUCTION

The purpose of this research is to quantify the benefits in reduced derailment risk that can be achieved through various changes in railroad operating practices. We will consider the effects of train speed and train length on the probability of derailment for individual cars within a train consist. The probability that a train will be involved in a derailment is a function of the quality of track, the length of train, and the exposure in terms of miles traveled. The probability of derailment for individual cars within a derailed train consist is a function of the point-of-derailment (POD), train length, train speed, and the accident cause. Changes to any of these parameters can alter the risk level of particular shipments.

We will present methodologies to model the derailment potential to train consists and individual cars within the train. We will then present a derailment risk calculation for a specific shipping scenario, showing the effect of train length, train speed, and positioning on the overall derailment potential for various cars within the train consist.

The following analyses used accident data collected by the Federal Railroad Administration (FRA) in the Railroad Accident/Incident Reporting System (RAIRS) database [1]. This paper will focus on derailments of Class I railroad freight trains on mainline track that occurred in the tenyear period, 1992 to 2001.

2 SPEED & TRACK CLASS EFFECTS

It has been shown that the speed at which a derailment occurs can be a predictive measure of the severity of

derailment [2, 3]. To better understand the effect of speed on derailment severity, the accidents in our analysis are grouped by train speed, FRA track class, and number of cars derailed (Table 1). Track class is representative of track quality and minimum standards are specified by regulation for each class. The seven FRA track classes and associated freight train speed restrictions are as follows:

MAXIMUM	FRA TRACK CLASS					
SPEED	X/1	2	3	4	5	6
mph	10	25	40	60	80	110
km/h	16	40	64	97	129	177

The speed groups are associated with the maximum speed distinctions between levels of track class and are: 1-10, 11-25, 26-40, & >40 mph. The majority of freight trains are operated at speeds below 60 mph and there are few accidents at speeds above this; therefore, accidents occurring at speeds above 60 mph were grouped with those occurring at speeds between 41 and 60 mph. Due to the relatively small number of accidents occurring on excepted and class 6 track, accidents on class X track are combined with class 1 track and accidents on class 6 track are combined with class 5 track. The accidents are further divided into five bins based on the total number of cars derailed, as follows: 1-5, 6-10, 11-15, 16-20, 20-25, & >25 cars derailed.

For the ten-year study period, there were 4,661 train accident reports for Class I railroad freight train derailments on mainline track¹. The average speed of derailment was 24.8 mph.

 $^{^1}$ Of these, 66 have a speed of zero and 45 have zero cars derailed (11 have both) and 15 do not have a value for track class.

TABLE 1 Derailed Train Counts by Train Speed, Track Class, and Number of Cars Derailed

					D 7. 1				Total	Average
					ars Derailed				Cars	Cars
Speed (mph)	FRA Track Class	1-5	6-10	11-15	16-20	21-25	>25	Total	Derailed	Derailed
	X/1	353	154	55	11	4	2	583	3,230	5.6
	2	138	63	14	6	3	2	228	1,314	5.8
1-10	3	128	44	13	2	6	2	199	1,033	5.2
	4	150	42	12	3	1	3	216	1,032	4.8
_	5/6	41	7	3	0	0	0	51	189	3.7
	Total	815	312	98	22	14	9	1,285	6,845	5.3
	X/1	44	29	2	1	1	0	79	391	4.9
	2	260	187	112	32	18	12	622	4,853	7.8
11-25	3	162	75	30	22	5	3	300	1,925	6.4
	4	149	74	44	17	5	4	294	2,027	6.9
<u>-</u>	5/6	25	15	8	1	0	0	49	291	5.9
	Total	643	381	196	73	29	19	1,348	9,503	7.0
	X/1	3	0	1	0	0	0	4	25	6.3
	2	25	8	12	8	4	6	63	739	11.7
26-40	3	186	88	85	61	45	63	529	6,344	12.0
	4	163	59	66	44	28	31	394	4,032	10.2
_	5/6	37	13	8	8	3	2	71	515	7.3
	Total	414	169	172	121	80	102	1,062	11,663	11.0
	X/1	2	0	0	1	1	0	4	44	11.0
	2	1	1	1	0	0	5	8	299	37.4
>40	3	42	11	11	17	9	17	107	1,444	13.5
	4	275	67	69	55	42	109	621	7,720	12.4
	5/6	74	18	16	15	7	24	158	1,717	10.9
_	Total	394	97	98	89	59	155	890	11,251	12.5
	X/1	408	184	58	13	6	2	671	3,690	5.5
	2	429	259	139	46	25	25	923	7,205	7.8
Total	3	530	218	139	102	65	86	1,140	10,746	9.4
	4	752	243	191	120	77	151	1,534	14,811	9.7
	5/6	182	54	35	24	10	28	333	2,712	8.1
-	Total	2,309	962	564	306	183	292	4,661	39,747	8.5
** Note: Totals include those accident reports for which values of speed, track class, or total cars derailed were either zero or blank. **										

The following observations can be made regarding Table 1:

- Nearly half of all derailed train consists have five or fewer cars derailed.
- Only 6.3% of all trains derailed more than 25 cars; 90% of these were at speeds greater than 25 mph.
- One-third of all trains were derailed on class 4 track and nearly 25% derailed on class 3 track².
- 265 trains (5.7% of total) derailed at speeds exceeding the maximum allowable operating speed for the track class on which it was derailed. While the largest portion of these were low consequence derailments (1-5 cars derailed), these accidents still accounted for nearly 3,000 derailed cars.

Class I railroads [4].

 $^{2}\,$ Approximately 70% off all traffic is carried over these two track classes for

While it is apparent that more cars are derailed, on average, at higher speeds, it is not clear that more cars are derailed, on average, on higher track classes. This may be due to the fact that many of the derailments on higher class track occur at less than normal track speed or may be due to the differences in derailment severity for different accident causes, which is likely correlated with track quality (class).

3 TRAIN LENGTH EFFECTS

The likelihood that a train will be involved in an accident is a function of both train-miles (TM) and car-miles (CM) operated [5]. Car-mile related causes are those for which the likelihood of an accident is proportional to the number of car-miles operated. These include most equipment failures for which accident likelihood is directly proportional to the number of components (e.g. bearing failure) and also include most track component failures for which accident likelihood is proportional to the number of load cycles imposed on the track (e.g. broken rails or welds). Train-mile related causes are those for which accident likelihood is proportional to the number of trainmiles operated. These include most human error failures for which accident likelihood is independent of train length and depends only on exposure (e.g. grade crossing collisions).

Each FRA accident cause code has been grouped into 51 groups of related causes that share similar causal mechanisms based on a scheme developed for the IIRSTF hazardous materials risk model [5] and included in a 2001 unpublished report of the Association of American Railroads. Each cause group is categorized as either a CM or TM caused accident group. The probability that an accident will occur is then a summation of the number of train-miles multiplied by the train-mile accident rate and the number of car-miles multiplied by the car-mile accident rate. Thus, it follows that longer trains have an increased likelihood of having an accident due to a larger number of car-miles of exposure.

In 2001, the average number of cars per freight train of Class I freight railroads was 68.5 cars [6]. In the same year, the average length of derailed Class I freight trains was 78.6 cars [1]. These two statistics are consistent with the hypothesis that longer trains have a higher likelihood of derailment. Shorter trains may have a lower risk of derailment; however, more trains must be operated to ship the same number of cars. In light of the trade-off between car-mile and train-mile-caused derailments, there may be an optimal train length to minimize derailment occurrence.

4 POSITIONS OF DERAILED CARS

The first vehicle (lead locomotive) in the freight train is most frequently the first to derail. In one-quarter of all derailments, the point-of-derailment (POD) is located within the first ten positions of the train. Over 98% of all train consists analyzed had train lengths greater than ten cars. The large percentage of derailments with cars near the front of the train being first to derail is primarily due to the large proportion of track-related causes, many of which tend to derail the lead locomotive [1].

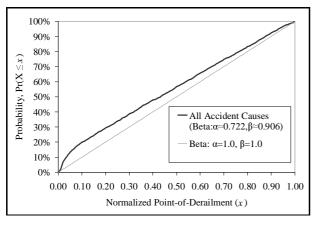


Figure 1 Point-of-Derailment Probabilities

The relationship between point-of-derailment (normalized by train length, NPOD) and position-in-train indicates that a large proportion of derailments initiate at the front of the train (Figure 1). This is often the case for track-caused derailments. We modeled NPOD probabilities by regression of the data against the beta distribution with parameters, α and β . The modeled NPOD distribution uses the beta distribution parameters that minimize the error sum of squares between the data and the beta distribution percentages. This allows for a smooth, continuous description of NPOD probabilities. The POD probabilities for various positions and train lengths can then be determined by discretizing the cumulative beta distribution.

The frequency of derailment for each position in the train (Figure 2) is obtained by counting the number of times vehicles in each position derailed (for all consist lengths). Although the first position most commonly derails first, it is not the position most frequently derailed. In absolute terms, the car in the eleventh position is derailed most frequently.

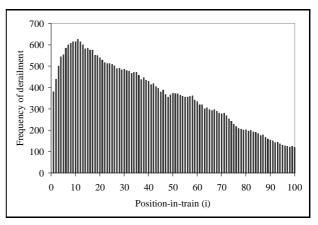


Figure 2 Frequency of Derailment by Position-in-Train

5 SEVERITY OF DERAILMENT

For all accident causes combined, the modal number of cars derailed is one, decreasing exponentially thereafter with about eight cars derailing on average. This distribution is not the same for all accident causes or accident speeds. For example, derailments caused by broken rail or welds tend to derail more than twice as many cars, on average, than bearing failure-caused derailments [3].

We have developed an analytical model for estimating the severity of derailment in terms of the number of cars derailed. Various factors considered include: accident cause, train speed, and residual train length (i.e. the number of cars behind the POD).

Prior work by Yang et al. [7, 8] analyzed the effects of several different variables on the severity of derailment. No explicit equations were given, but the relationships between the variables and the number of cars derailed were

determined by varying the parameters in the simulation model and observing the change in derailment severity. Nayak et al. [2] presented an equation for estimating the number of cars derailed as a function of the square root of train speed.

Saccomanno & El-Hage [9, 10] combined the effects of accident cause, train speed, and residual train length into a single equation based on a truncated geometric distribution for estimating the mean number of cars derailed (Appendix). Our investigations indicate that the equation for the mean of the truncated geometric distribution presented by Saccomanno & El-Hage was incorrect. The correct equation presented here (Eq. A.5) ensures that the number of cars derailed lies within the range $[1, L_r]$ where L_r is residual train length.

Using the correct equation for the mean of the truncated geometric distribution (Eq. A.5), we used nonlinear regression techniques to estimate the parameters of the response function (Eq. A.4) for all accident causes combined. The value for parameter a was estimated to be 0.56 with a standard error of 0.02. The results showed that the value estimated for parameter c was not statistically different than 0 (at the 95% confidence level) while the value for parameter b was estimated to be -0.97 with a standard error of 0.03. If parameter c is assigned a value of 0, the effect of residual train length is entirely accounted for by Eq. A.5 (i.e. the logistic function p remains constant for all positions). This model was able to account for 40% of the variation in the number of cars derailed when all accident causes are combined. If accidents are separated by cause group, the model accounts for more than 60% of the variation for certain accident causes [Anderson & Barkan, unpublished].

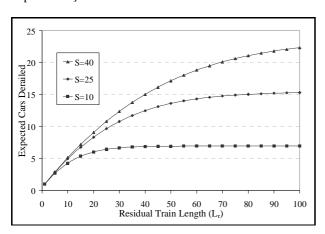


Figure 3 Cars Derailed by Residual Train Length & Speed (S)

The geometric model predicts that the number of cars derailed increases asymptotically with increases in the number of cars behind the POD and train speed (Figure 3).

6 PROBABILITIES OF DERAILMENT

In the following section, we consider the conditional probabilities of derailment for cars in a derailed train consist. The only analytical technique for determining the conditional probability of derailment that we are aware of is that of Saccomanno & El-Hage [9, 10]. Their equation (Eq. A.1) combines two probabilities: 1) the probability of a derailment initiating at the $k^{\rm th}$ position and 2) the probability of derailing x cars based on the point-of-derailment for a given train length.

Using the POD probabilities derived from Figure 1, and the parameters for the response function given above, we calculated the conditional derailment probabilities for all accident causes combined for different train lengths at 25 and 50 mph (Figure 4). The following observations can be made regarding this figure:

- The lowest derailment probabilities occur in the front and rear sections of the train
- As train length decreases or train speed increases, the probability of derailment increases for all positions (except i = 1), and most notably for those in the middle.

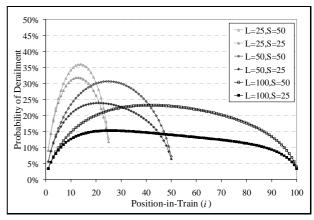


Figure 4 Derailment Probabilities by Position, Length (L) & Speed (S)

6.1 Empirical Validity

If we analyze the relative position of derailed cars (absolute position normalized by train length), the derailment probability is the number of cars derailed divided by the total number of cars derailed within the quantile of interest (Figure 5).

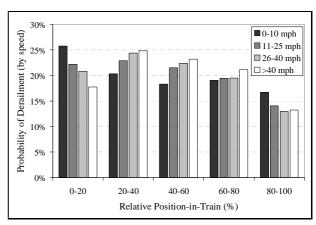


Figure 5 Derailment Probabilities by Relative Position-in-Train

Derailment probabilities by relative position sum to 100% (unlike those by absolute position, Figure 4). In general, cars within the second quintile have the highest probability of derailment while cars in the last quintile of the train have the lowest derailment probability. As train speed increases, the probability of derailment for cars in the front of train decreases in response to the increase in derailment probability for the second and third quintiles of the train.

7 RISK SENSITIVITY

In this section, we consider the effects of different operating practices on derailment probabilities. This analysis considers the shipment of one-thousand cars a distance of 1,000 miles over class 4 track. If train length is reduced, more train shipments will be required to haul the same number of cars—increasing the exposure to having an individual train consist derail. If train speed is increased, the expected derailment severity also increases. We consider the sensitivity to train length (25, 50, 100, 125, & 200 cars) and operating speed (25 & 50 mph) on the probability of derailment for various cars within the consist.

For class 4 track, estimated derailment rates are 7.8 derailments per billion freight car-miles (FCM) or 0.53 derailments per million freight train-miles (FTM) [4]. Using the grouping scheme mentioned above, approximately 75% of all Class I derailments can be classified as car-mile caused, while 25% are classified as train-mile caused³. Using these percentages, the corresponding derailment rates are 5.9 and 0.13 per billion FCM and million FTM, respectively.

The probability that an individual train of length L traveling on class 4 track a distance of M miles is involved in a derailment, $P_1(der)$, is as follows:

$$P_1(der) = 1 - e^{-M[5.9x10^{-9}(L) + 0.13x10^{-6}]}$$
 (Eq. 1a)

For $P_1(der) \ll 1$, Eq. 1a can be simplified to the following:

$$P_1(der) = M[5.9x10^{-9}(L) + 0.13x10^{-6}]$$
 (Eq. 1b)

The probability that one or more of S train shipments (with the same characteristics, i.e. train length and shipping distance) is involved in a derailment, $P_S(der)$, is as follows:

$$P_{S}(der) = 1 - [1 - P_{1}(der)]^{S}$$
 (Eq. 2)

The portion of $P_1(der)$ due to train-mile causes is constant for all train lengths, while the portion of $P_S(der)$ due to carmile causes is approximately constant for all train lengths⁴.

For the scenario considered of 1,000 cars shipped 1,000 miles, $P_{1-TM}(der) = 0.13 \times 10^{-3}$ and $P_{S-CM}(der) \approx 5.9 \times 10^{-3}$. Therefore, $P_I(der)$ is directly proportional to train length while $P_S(der)$ decreases asymptotically with increases in train length (Table 2).

We observe that longer trains have an increased likelihood of being involved in a derailment. For a fixed number of cars; however, fewer train shipments are required for longer trains, thereby decreasing the overall risk that one or more trains will be involved in a derailment.

TABLE 2 Probability of Derailment by Train Length

Train	Train	$P_1(der)$	$P_{S}(der)$
Length, L	Shipments, S	$(x 10^{-3})$	$(x 10^{-3})$
25	40	0.278	11.040
50	20	0.425	8.466
100	10	0.720	7.177
125	8	0.868	6.919
200	5	1.310	6.533

The risk of derailment for a car in the i^{th} position is a combination of the probability of derailment for the train consist, $P_I(der)$, and the conditional derailment probability for the car in a derailed consist, P(i|der). For S train shipments, the probability of derailment for a car in the i^{th} position, $P_S(i)$, is as follows⁵:

$$P_{s}(i) = 1 - [1 - P_{1}(der) \cdot P(i \mid der)]^{s}$$
 (Eq. 3)

Using the results from above, we calculated P(i|der) for the first, tenth, and last car for each of the five consist lengths at 25 and 50 mph, as well as for the position with highest derailment probability (Table 3).

TABLE 3 Conditional Derailment Probabilities by Length & Speed

Case	Train	Speed	P(i der)				
No.	Length	(mph)	i=1	i=10	i=L	$i=i_{\max}$	$i_{\rm max}$
0	25	25	9.07%	30.9%	11.78%	31.8%	13
1	25	50	9.07%	34.1%	12.87%	35.9%	14
2	50	25	5.49%	20.5%	6.31%	23.8%	21
3	50	50	5.49%	23.3%	7.18%	30.6%	25
4	100	25	3.33%	12.6%	3.31%	15.2%	26
5	100	50	3.33%	14.7%	3.84%	23.1%	42
6	125	25	2.83%	10.7%	2.69%	12.9%	26
7	125	50	2.83%	12.5%	3.12%	20.3%	47
8	200	25	2.02%	7.6%	1.75%	9.2%	26
9	200	50	2.02%	8.9%	2.02%	14.8%	51

From these results, we observe:

- The probability that the first car derails is simply the probability that the POD=1; this probability decreases with increased train length and is unaffected by speed.
- For i=10 and i=L (the last car), the probability of derailment is 13-17% higher at 50 mph than at 25 mph for each train length.
- The position with highest derailment probability (i_{max}) increases asymptotically with increased train speed and train length.

³ There is a slight tendency for a larger proportion of car-mile caused derailments on higher track classes (likely due to higher operating speeds).

⁴ As $P_1(der) << 1$, $P_5(der) \approx S \cdot P_1(der)$; therefore, $S \cdot M[5.9 \times 10^{-9} (L)]$ is constant for all train lengths as $S \cdot L = 1,000$ cars.

⁵ As $P_1(der) << 1$, $P_S(i) \approx P_S(der) \cdot P(i|der)$.

 Cars positioned in the middle sections of the train have the highest probabilities of derailment while the front and rear sections of a train have the lowest probabilities of derailment.

Applying Eq. 3 to the results in Tables 2 & 3, we derived derailment probabilities for each of the ten cases for each car position (Figure 6). For a given speed and car position, there appears to be a significant reduction in derailment probability as train length is increased up to 100-car trains and is largely due to the lower probability of derailment, $P_S(der)$. As train length is further increased to 125 and 200 cars, the reduction becomes much smaller. Again, for a given position and train length, the increase in risk by shipment at 50 mph is 13-17% higher than at 25 mph.

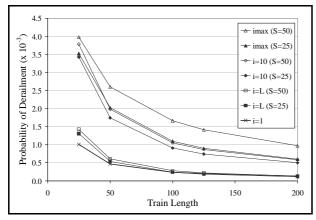


Figure 6 Derailment Risk by Length (L), Speed (S), & Position (i)

8 CONCLUSIONS

In this paper, we have examined the probabilities of derailment for freight trains and freight cars as affected by train length, train speed, and positioning of cars within the consist.

The probability of derailment for a single train is largely a function of track class, distance traveled, and train length. While a shorter train will have a lower probability of derailment, shipments of longer trains will have a lower probability that one or more trains will be derailed (for a fixed quantity of cars shipped).

The probability that a particular car will be derailed in a derailment is largely a function of train length, train speed, and positioning within the consist. More cars can be expected to derail with increases in train speed and residual train length. Cars positioned near the front or rear of a train have the lowest probability of being derailed in a derailment. As train length is decreased or train speed is increased, the conditional probability of derailment increases for all cars within the train consist.

As with any effective risk reduction option, the expected benefits from any changes in railroad operating practices must be compared with the costs associated with lowering the risk of derailment. For example, if train speed is reduced, the risk of derailment is lowered at the expense of increasing shipment time and possibly reducing traffic throughput. Physical constraints, such as siding lengths, may control the length of trains that can shipped over particular corridors. Other constraints, such as train handling procedures and train make-up regulations, may also affect the placement of cars within the consist. These and all other operational constraints must be considered before any change in operating procedure is implemented to reduce derailment risk. The optimal cost-effective configuration would allow for the necessary throughput at the lowest possible risk level.

9 APPENDIX

Saccomanno & El-Hage [9, 10] Equations:

$$P(i \mid der) = \sum_{k=1}^{i} \{ P_p(k) \times \sum_{x=i-k+1}^{L_r} P(x) \}$$
 (Eq. A.1)

- P(i|der) = conditional probability of derailment for car in the i^{th} position of a derailed train consist
- $P_p(k)$ = point-of-derailment probability for the car in the k^{th} position of a train
- P(x) = probability of derailing x cars in a train derailment (truncated geometric distribution)
- L_r = residual train length (i.e. number of cars behind the POD)

$$P(x) = \frac{p(1-p)^{x-1}}{1 - (1-p)^{L_r}}$$
 (Eq. A.2)

- p = logistic function of continuous "success" probability
- Range: $1 \le x \le L_r$

$$p = \frac{e^Z}{(1 + e^Z)} \tag{Eq. A.3}$$

• Z = response function based on the cause of derailment (C_d), train speed (S), and residual train length (L_r)

$$Z = a \mid C_d + b \times \ln(S) + c \times \ln(L_r)$$
 (Eq. A.4)

 Parameter a is dependent upon the cause of derailment (a|C_d)

$$D = \frac{1}{p} - \frac{L_r (1-p)^{L_r}}{1 - (1-p)^{L_r}}$$
 (Eq. A.5)

ullet D = the mean of the truncated geometric distribution (i.e. the estimated number of cars derailed)

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