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Reducing the threat of in-transit derailments involving dangerous goods through effective placement along the train consist

Morteza Bagheri[a,*], Frank Saccomanno[b], Shojaeddin Chenouri[c], Liping Fu[b]

[a] Desautels Faculty of Management, McGill University, Montreal, Quebec H3A 1G5, Canada
[b] Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
[c] Department of Statistics and Actuarial Science, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

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ABSTRACT

Train derailments are important safety concerns, and they become increasingly so when dangerous goods (DG) are involved. One way to reduce the risk of DG derailments is through effective DG railway car placement along the train consist. This paper investigates the relationship between DG railway car placement and derailment for different route attributes and DG shipments. A model is presented for estimating the probability of derailment by position, based on the estimated point of derailment (POD) and the number of cars derailing. A DG placement model that considers in-transit derailment risk is shown to provide a sound scientific basis for effective DG marshalling in conventional rail hump yard operations.

1. Introduction

US railroads carry approximately 1.8 million carloads of DG annually, representing over 5% of total rail freight movement nationally (Association of American Railroads, 2006a). In Canada, approximately 500,000 carloads of DG are shipped annually, or 12% of total freight is shipped by rail (Transportation Safety Board of Canada, 2004).

Over half of all train derailments in both countries involved DG during the last ten years (Fig. 1). The US Federal Railroad Administration (FRA) database reported that between 1997 and 2006, DG derailments with subsequent releases produced average per derailment damages of about $500,000 to rolling stock and track, and the value is five times higher when compared to derailments when DG releases do not take place (Federal Railroad Administration). The reduction of DG car derailments has recently been recognized as an important safety objective by a number of industry and government agencies in North America (Transport Canada, 2007; Association of American Railroads, 2006b, 2007). One way this objective can be achieved in a conventional train assembly process is by formally considering the potential for derailment directly in the DG car placement strategy. In the US, the 1994 Hazardous Materials Transportation Act recommended an investigation into the placement of DG cars in mixed freight trains to reduce their potential involvement in derailments along a given route. Section 111 of this Act (P.L. 103-311) explicitly states:

> "The Secretary of Transportation shall conduct a study of existing practices regarding the placement of cars on trains, with particular attention to the placement of cars that carry hazardous materials. In conducting the study, the Secretary shall consider whether such placement practices increase the risk of derailment, hazardous materials spills, or tank ruptures or have any other adverse effect on safety. . ."

This research has two major objectives:

1. Develop a DG car placement strategy that minimizes the risk of in-transit DG derailments for a given route and shipment attributes.
2. Integrate this DG risk minimum strategy into a conventional hump yard marshalling operation and demonstrate its practical relevance through a case study application.

DG risk in this paper refers to a potential derailment of cars carrying some type of DG along a given route or route segment. Subsequent events such as releases, fires, explosions, etc. are not within the scope of this analysis. Furthermore, it is assumed that the effect on total risk resulting from the interaction of incompatible DG materials derailing in proximity to one another can be ignored, such that all derailing DG cars are treated equally in terms of the

* Corresponding author at: School of Railway Engineering, Iran University of Science and Technology (IUST), Tehran 16846-13114, Iran.
Tel.: +1 514 398 4000x089746.
E-mail address: morteza.bagheri@mail.mcgill.ca (M. Bagheri).

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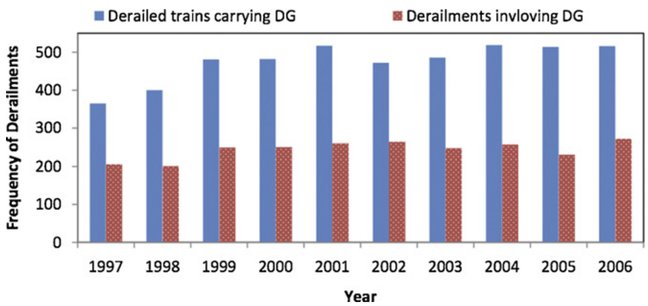

Fig. 1. Share of car derailments involving DG from FRA 1997–2006.

potential threat they pose to population and property. It should also be noted that the additional risk due to marshaling operation at the rail yard is not considered in this paper. A further discussion on the reason for the assumption and possible implications is provided in Section 2.

2. DG car placement framework

The DG car placement framework considered in this paper consists of two major models: (i) an in-transit risk model and (ii) a rail yard marshalling model. The in-transit risk model provides an estimate of the risk of derailment by position along a route segment for a given mix of DG and non-DG cars making up the train consist. The rail yard marshalling model estimates the rail yard train assembly risks and costs (or processing time) for each train and DG placement strategy or plan.

Several researchers believe that although in-transit risks are important, risks associated with marshaling cars in rail yards cannot be ignored (CCPS, 1995; Glickman and Erkut, 2007). Developing a comprehensive risk model requires considering both in-transit and rail yards risks that recognizes that additional marshaling operations to reduce in-transit risks could lead to increased risk in rail yards due to increased yard engine operations. Based on literature review, some studies have been conducted to analyze risks in rail yards, in particular, those associated with DG. Importance of risk associated with transportation of DG cars through marshalling yards has been raised by Christou (1999) which found that hazards associated with DG cars at rail yard depends on DG materials, the volume, duration of presence in the yard, the marshalling operation, and the distance of population centers to these facilities. Recently, Cozzania et al. (2007) conducted a quantitative risk analysis to evaluate risk from DG materials at rail yards in Italy. In their study, three hazardous events were considered: 1) in-transit-accident-induced releases, 2) shunting-accident-induced releases and 3) non-accident-induced releases. Bagheri (2009) compared the average cost per accident for mainline and yards (FRA 2002–2006). As a result, it is necessary to make a tradeoff by considering the increased risk due to marshalling operations in classification area and the potential benefit of reduced in-transit risk through placement of DG cars in a train consist. This paper focuses on the later with the potential contribution of making such trade-off analysis possible in future work. The model framework is illustrated in Fig. 2.

This framework begins with the arrival of a train at the hump yard with DG and non-DG cars tagged for specific destinations. These cars are disengaged and humped to the classification track on a first-come, first-served (FCFS) basis. Each classification track contains cars that are coupled together based on a common destination point (a block) along the route. Once a block has been completed with the desired number of cars, a yard engine shunts it to the departure track, where it is combined with other blocks to make up a train, and which is subsequently inspected prior to departure. The

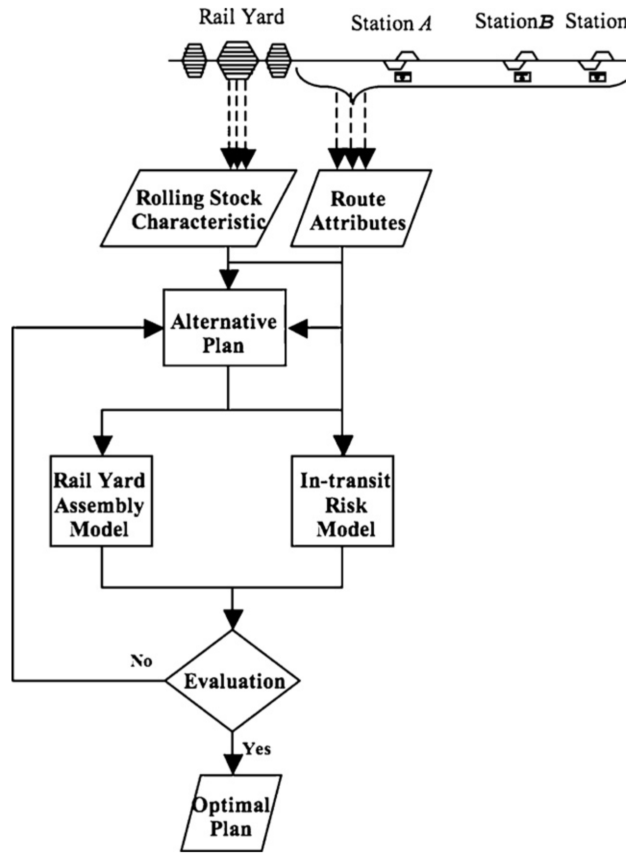

Fig. 2. DG car placement framework.

order of blocks on a given train is set with respect to the sequence of intermediate destination points along a route, such that the block assigned to the closest destination is shunted to the front of the train, followed by the block assigned to the next closest destination, and so on until the final destination block is connected to the train.

The order of cars in the classification track is currently set on an FCFS basis that does not explicitly consider DG derailment risk from position along the route. In consequence, DG cars may not be excluded from those positions that are more prone to derailment. Under current regulations (Transport Canada; U.S. Department of Transportation), a yard engine may be used to insert a designated number of non-DG buffer cars to separate DG cars from train operating personnel in, for instance the locomotive or caboose. Current regulations may also take into account possible train instability problems caused by locating loaded and empty cars near one another.

The DG car placement framework considered in this research envisions the introduction of an in-transit risk model that assigns DG cars to those positions along the train that have the lowest probability of derailing along the different route segments. This strategy serves to modify the FCFS approach currently in use at the interface between the hump and the classification track. The modified DG placement strategy is implemented by the yard engine on instruction from the hump controller. It is proposed that this strategy be introduced at the interface between the hump and the classification track prior to these cars being shunted to the departure track.

As illustrated in Fig. 2, the DG car placement strategy receives input from two sources: (i) DG and non-DG shipment volumes by intermediate and final destination points along a given route and (ii) route attributes and operating and design features by segment. The first input is used to estimate the number of DG and non-DG

Table 1
Estimated accident rates by FRA track class: 1992–2001.

FRA track class	X and 1	2	3	4	5 and 6
Derailments per million freight train miles	48.54	6.06	2.04	0.53	0.32
Derailments per billion freight car miles	720.1	92.7	31.5	7.8	4.9

cars traversing a given segment of track, while the second input is used to estimate car derailment probabilities by position for each route segment. Presumably, the yard engine plan will include the full set of marshalling instructions required to modify DG car placement based on minimizing in-transit derailment risk. The in-transit risk model in Fig. 2 estimates three specific probabilities: train derailment, point of derailment (POD) by position, and number of cars derailing for different PODs. Within the scope of this study, the number of cars derailing reflects the basic unit of “in-transit risk”, such that, the risk consequence is 1 for every DG car derailing and 0 otherwise.

A number of DG placement strategies (car and block combinations) are possible for every train and all route attributes, including the current FCFS option. The in-transit risks and rail yard assembly risks and costs associated with each DG car placement strategy can be assessed with respect to the existing FCFS procedure. The in-transit risk minimization strategy proposed in this paper takes the position that the given DG placement strategy is cost effective if the risk reduction exceeds extra rail yard marshalling costs. Within the scope of the proposed framework, an evaluation of the cost-effective DG placement strategies can be undertaken prior to implementation of the plan by the yard engine.

3. In-transit route risk formulation

In-transit risk requires the estimation of two constituent components, POD and number of cars derailing. The aim of the DG placement model is to position DG cars along the train so that the route segment risk of derailment is minimized. For a given train and route segment, this risk is summed over all positions, that is $\sum_{i=1}^{n} R_i$, where the risk of derailment for position i is given by

$$R_i = P_i \times C_i, \tag{1}$$

and where

$$P_i = P_r(\mathrm{TD}) \times P_r(i|\mathrm{TD}). \tag{2}$$

Note that $P_r(\mathrm{TD})$ is the probability of train derailment on a given route and $P_r(i|\mathrm{TD})$ is the conditional probability that a car in the ith position derails.

As noted above,

$$C_i = \begin{cases} 1 & \text{if a DG car occupies the position } i \\ 0 & \text{otherwise.} \end{cases}$$

The conditional probability of a car in position ith derailing given that the train has derailed can be expressed as

$$P_r(i|\mathrm{TD}) = \sum_{j=1}^{i} \left[P_r(\text{POD at position } j) \sum_{x=i-j+1}^{n-j+1} P_r(x \text{ cars derailing}|\text{POD at position } j) \right]. \tag{3}$$

Eq. (3) yields the probability of the ith position derailing for an n car train given that the POD is position j. This expression applies to a given train traversing a uniform track segment with similar derailment-cause profiles.

Thus the risk associated with each position i (as in Eq. (1)) is simply the product between Eq. (2) and the placement of DG cars in this position, i.e.,

$$R_i = P_r(\mathrm{TD}) \times P_r(i|\mathrm{TD}) \times C_i. \tag{4}$$

For a given route segment and an n car train, the risk associated with all positions of the train is estimated by summing in Eq. (4) for $i = 1, \ldots, n$. As we have noted, only those positions occupied by DG cars contribute to this risk.

In this exercise, the total train segment risk serves as the objective function that will need to be minimized with respect to each DG placement strategy being considered.

4. Analysis of train derailments

Anderson and Barkan (2004) show that the probability of a freight train derailing is a function of exposure (distance traveled), train length, and track class (which indicates track quality). Their resultant expression is given in Eq. (5).

$$P_r(\mathrm{TD}) = 1 - e^{-\text{distance} \times (\mathrm{RC} \times (\text{train length}) + \mathrm{RT})}, \tag{5}$$

where, $P_r(\mathrm{TD})$ is derailment probability; RC is derailment rate per billion freight car-miles; and RT is derailment rate per million freight train-miles.

Their model is based on aggregate data for accident rates for several track classes in terms of the number of derailments per billion freight car-miles and number of derailments per million freight train-miles. Table 1 summarizes several train derailment rates for different track classes. These rates are given in both train and car-mile measures of exposure. This model (Eq. (5)) is used as the probability of a train derailment in this paper.

5. Point of derailment analyses and modeling

A car occupying a given position along the train can be involved in a derailment in one of two ways: either by initiating the derailment (reflecting the POD) or by being involved in the derailed cars following the POD. In this paper we have assumed that only cars “following” the POD can be derailed.

5.1. Factors affecting POD

In this section of the paper, several factors explaining POD are explored, based on historical train derailments reported by the FRA for the period 1997–2006. Out of 4148 derailments in this database (after data cleaning), over 18% were found to take place at the front of the train, and only 3% were found to take place beyond the 100th car position. One of the major problems with using these observations to establish POD rates is that they do not take train-length distribution into account. The distribution of train lengths in the FRA database indicates that over 30% of trains are in the 0–50 car-length range. Hence, there appears to be an over-representation of front-end positions in the distribution, which leads to an over-representation of front-of-train POD in the database.

To adjust for train length, a number of studies (El-Hage, 1988; Anderson, 2005) have expressed POD in a normalized form (NPOD) that reflects a standard 100-car train. While the NPOD accounts for absolute train length, it fails to reflect dynamic forces acting on the train with respect to POD that cause car-track instability leading to derailments. This failure requires specification of actual positions along a train in lieu of standardized measures. For example the 50th percentile position in a 10-car train is subjected to different dynamic forces along a sharp curve than those for the 50th percentile position in a 100-car train.

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To account for limitations in NPOD, FRA train derailments in this study have been classified into short (<40 cars), medium (40–120 cars), and long (>120 cars) trains, and analyzed separately with respect to their NPOD. The nonparametric Kruskal–Wallis test, a one-way analysis of variance by ranks, was applied to determine whether train length (short, medium, and long) provides a statistically significant explanation for median POD.

Using the Minitab 14.0 software package, the Kruskal–Wallis test examines the validity of the null hypothesis that the median NPOD does not differ according to train length, against its alternative assertion that median NPOD differs for at least two out of the three train length groups. The sample NPOD medians for the three groups were estimated to be 0.33 for short trains, 0.57 for medium trains, and 0.47 for long trains. The Kruskal–Wallis test yielded a test statistic value of 239.5 well above its critical value of $\chi^2_{0.05,2} = 5.99$. Hence, there is sufficient evidence to reject the null hypothesis H_0 that there is no difference in NPOD medians for different groupins of train length. It can also be stated that the absolute train length has a significant effect on POD.

The next factor possibly affecting POD is derailment cause. The underlying assumption is that different causes are likely to lead to different POD profiles. For example, it is expected that the front of a train would be more likely to derail if a track-related problem causes the derailment, since it is the front of a train that first encounters any track faults as the train traverses a segment. Rolling stock defects, on the other hand, can take place at different points. A previous study Saccomanno and El-Hage (1991) used ANOVA to confirm the relationship between cause and POD empirically by analyzing derailment data from Canada (years 1983–1985). Another study Anderson (2005) presented a methodology to estimate the probability of POD for different causes and train lengths.

In this paper, the Kruskal–Wallis test was applied to confirm the relationship between NPOD and cause of derailment for the FRA (1997–2006) data. The sample medians for the three cause groups (track related, track geometry and car related)were estimated to be 0.40, 0.64, and 0.50, respectively. The value of the test statistic, 130.27, exceeded its critical value of $\chi^2_{0.05,2} = 5.99$ at the 5% level of significance. Hence, there is sufficient evidence to reject the null hypothesis H_0 (no cause effect) and conclude that the causes have a statistically significant effect on POD when trains are adjusted for length. The above test provides some statistical evidence that the probability of POD along a given route segment depends on train length and primary cause of derailment.

5.2. Estimating POD probability by position

The primary aim of this section is to develop expressions for estimating POD probability for different derailment causes and train lengths. The first step in estimating POD for each track segment is obtaining the probability of different derailment causes along each route segment. In this paper, it is assumed that the probability of derailment causes is a function of route attributes and rolling stock characteristics. Developing the derailment cause model is beyond the scope of this paper but will be investigated in a future paper.

A number of distributions were explored to explain NPOD by train length and cause (C). The best-fit distribution for each of the nine groupings of train length (short, medium, and long) and derailment cause (C1: track, roadbed, and structure, excluding track geometry, C2: track-geometry related and C3: causes related to each car (such as mechanical and electrical causes) was established for the FRA data using BestFit software developed by Palisade (Palisade Corporation). FRA derailment data by position was initially classified into three train length groups (short, medium and long) and subsequently into three causes. An example of the distribution for track-related causes for medium length trains is illustrated in Fig. 3. Three different types of distribution (beta, triangle, and uniform) have been fitted to POD frequency for medium-train length and track-related causes.

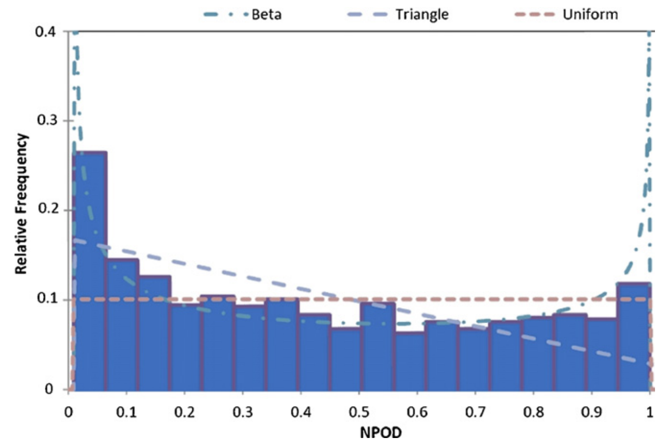

Fig. 3. Three distributions for track-related derailments involving medium trains.

Table 2
Values of the χ^2 goodness of fit statistic for distributions for track-related derailments involving medium trains.

Distribution	χ^2 statistic
Beta	75.15
Triangle	154.6
Uniform	243.4

Comparison of observed POD frequency from the FRA data with expected values from the underlying distribution provided χ^2 statistic. Table 2 summarizes these Chi-Square values of the three distributions considered. For this combination of derailment cause and train length, the Beta distribution yielded the lowest Chi-Square value and, hence, the best-fit result.

In a similar fashion, best-fit distributions were obtained for all nine train length/cause combinations or groupings (Table 3).

To illustrate how these results can be used, we consider the probability of derailment for the 10th position of a 39-car train (at the top of the short-train class). The best-fit distribution for track-related causes is $U(0.03, 1)$, and this finding yields a probability of 0.10 for the 10th position for a short-train membership. On the other hand, for the same 10th position and cause on a 41 car train, a $Beta(0.58, 0.66)$ distribution is used for a medium-train length membership. This distribution yields a probability of 0.09 for the same 10th-car position. The difference between these estimates can be explained by the uncertainty associated with assigned train length membership of between 39 and 41 cars (i.e., short versus medium).

To incorporate this uncertainty, we consider a membership expression Tsouklas and Uhrig (1997) of the form

$$P_r(\text{POD at position } j) = \frac{f_1(j) \cdot m_1(k) + f_2(j) \cdot m_2(k)}{m_1(k) + m_2(k)}, \quad (6)$$

where $f_1(j)$ and $f_2(j)$ are estimated from probabilities of NPOD from Table 3 for a given position j, train length, and cause group. The membership values m_1 and m_2 are obtained for a given train length k, from Fig. 4.

Table 3
Best fit POD distributions (U = Uniform, T = Triangle, Beta = General Beta) for all derailment causes and train lengths.

	Short train	Medium train	Long train
Cause Group 1	U(0.03,1)	Beta(0.575,0.6579)	Beta(0.602,0.745)
Cause Group 2	T(−0.094,1,1)	Beta(0.782,0.504)	Beta(0.646,0.59)
Cause Group 3	U(0.031,1)	U(0.008,1)	Beta(0.763,0.799)

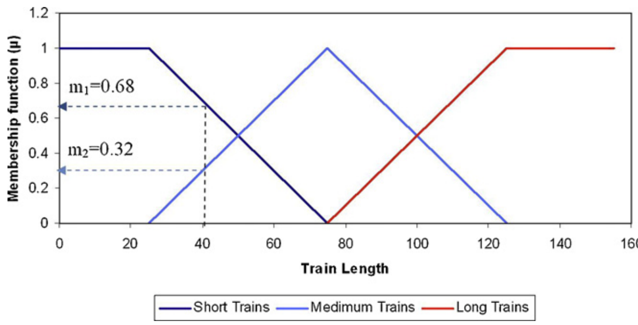

Fig. 4. Membership function for different classes of train length.

As shown in Fig. 4, assuming a 41-car train over a segment of track subject to cause group 2 (track-geometry related), it is obtained a membership factor of $m_1 = 0.68$ for a short-train classification and $m_2 = 0.32$ for a medium-train classification. Since a 41-car train is considerably shorter than the 80-car minimum for long train classification, the membership function associated with long trains is assumed to be zero.

The probability of derailment for the 10th position (in a train with 41 cars) with a cause-2 derailment (track-geometry related) is obtained by applying the following four steps:

i) For the 41 car train Fig. 4 suggests the membership factors $m_1 = 0.68$ and $m_2 = 0.32$ for short and medium trains, respectively.
ii) The ratio of NPOD is calculated as 10/41 = 0.244.
iii) From Table 3, we obtain the corresponding derailment probabilities, $f_1 = 0.033$ and $f_2 = 0.07$.
   Assuming a short-train membership, f_1 is established from the Triangle distribution from Table 3, $T(-0.094, 1, 1)$. The resultant derailment probability for position 10 on this 41 car train is estimated to be 0.0133.
   Assuming a medium-train membership, f_2 is established from the Beta distribution, $Beta(0.782, 0.504)$, the derailment probability for position 10 becomes 0.0165, a difference of about 20%.
iv) The probability of initiating a derailment per position is obtained by combining the fuzzy function memberships with the underlying NPOD distribution values as per the above membership expression, such that

$$P_r(\text{POD at position } 10) = \frac{f_1(10) \cdot m_1(41) + f_2(10) \cdot m_2(41)}{m_1(41) + m_2(41)} = 0.014.$$

In a similar fashion, the probabilities for each position on the 41-car train can be obtained. A similar set of values can be obtained for the other cause groups for the 41-car train (these have not been included in this paper).

6. Analysis of number of cars derailed

As the number of cars in the derailment increases so does the severity of the train derailment. A.D. Little Inc. (1983) has suggested a non-linear relationship between the mean number of cars derailing and train speed (in mph), such that

$$M_{nd} = 1.7(\text{Speed})^{0.5}. \quad (7)$$

where M_{nd} is the mean number of cars derailing and the train speed is in miles per hour.

In the above expression, the speed reflects the amount of kinetic energy that is generated by the derailment that needs to be dissipated before car-track stability can be re-established. For a given speed, distance to POD affects the amount of residual kinetic energy available to cause further cars to derail. As the distance increases, lower forces of instability act on the remaining cars and no further derailment takes place.

A number of studies (Saccomanno and El-Hage, 1991; Anderson and Barkan, 2005) have suggested that the number of cars derailing is also affected by residual train length and cause of derailment. The longer the residual length of the train (post POD), the higher the potential number of cars derailing. The link between cars derailing and train length is affected by the cause of derailment, such that, for example, causes that have a more pronounced effect on lateral instability result in more cars jumping the track following the initial derailment.

Using data reported by the Canadian Transport Commission (CTC) for the period 1983–1985, Saccomanno and El-Hage (1989) explored the relationship between the probability of a specific number of cars derailing and the residual train length (L_r), speed and cause of derailment. For a train length L, and position j, they introduced a truncated geometric distribution for the probability of x cars derailing, such that

$$P_r(x \text{ cars derailing} | \text{POD at position } j) = \begin{cases} \dfrac{p(1-p)^{(x-1)}}{1-(1-p)^{L_r}} & \text{if } x = 1, \ldots, L_r \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

where, $L_r = L - j + 1$ is the residual length or simply the number of cars after POD, and $1 - p$ is the probability of derailment for a position after POD.

The probability, p, is assumed to be related to the factors/covariates through the logit link function

$$p = \frac{1}{1+e^{-z}},$$

where z is a linear function of speed, L_r, and causes. As a standard approach for categorical variables, considering the cause "railbar" as a baseline, the other causes are entered into this model as binary variables (i.e., 0 or 1 for the absence or presence of a specific cause, respectively). Thus, for a typical train

$$z = \beta_0 + \beta_1(\text{speed}) + \beta_2 L_r + \beta_3(\text{roadbed}) + \ldots + \beta_8(\text{allother}).$$

The results from fitting a logit expression to derailment data from the CTC are summarized in Table 4. With the exception of switching causes, all factors have a statistically significant effect in explaining the mean number of cars derailed.

Similar to the previous study, in this research, the distribution in Eq. (8) is linked to the covariates through the logit function. This truncated geometric logistic model is fitted to the FRA data (instead of the CTC data) for the period of 1997–2006. Parameter values were estimated by maximizing a likelihood function of the form

$$L(\beta_o, \beta_1, \ldots, \beta_8) = \prod_{i=1}^{n} \frac{p_i(1-p_i)^{(x_i-1)}}{1-(1-p_i)^{L_r}} \quad (9)$$

using statistical software R (http://cran.r-project.org/). The results of this calibration are summarized in Table 5.

With the possible exception of residual train length and track geometry, all input factors were found to provide a significant explanation for the mean number of cars derailing at the 5% level. Track geometry and residual train length were found to be significant at the 10% level. Table 5 also gives a 95% confidence interval for each of the factors considered. Note that since the cause railbar is considered as a baseline, no parameter is associated in the above tables. This table also shows that increasing the train speed would reduce the z value and subsequently increase the derailment probability. In addition, the effect of axles/wheels defects on the

Table 4
Summary statistics for POD logit expression from CTC derailment data.

Parameters	Estimates	Std. Error	Student *T*-test	Lower (95% interval)	Upper (95% interval)
Intercept	1.674	0.334	5.01	1.017	2.331
Residual length	−0.638	0.053	11.855	−0.744	−0.532
Speed effect	−0.575	0.082	7.036	−0.736	−0.414
Roadbed	0.648	0.143	4.505	0.365	0.931
Track geometry	0.382	0.094	4.060	1.197	0.577
Railbar	NA				
Switches	0.470	1.425	0.330	−2.33	3.270
General car	1.672	0.323	5.181	1.308	2.306
Axles/wheels	1.510	0.128	11.771	1.258	1.763
All other	1.329	0.261	5.091	0.816	1.842

Table 5
Summary statistics for estimates with the FRA database (1997–2006).

Parameters	Estimates	Std. Error	*Z* statistics	Lower (95% interval)	Upper (95% interval)
Intercept	−2.013	0.082	−24.465	−1.850	−2.170
Residual length	0.001	0.001	1.266	0.002	−0.001
Speed effect	−0.032	0.002	−17.075	−0.029	−0.036
Roadbed	0.419	0.018	2.367	0.766	0.072
Track geometry	0.171	0.089	1.921	0.346	−0.003
Railbar	NA				
Switches	0.715	0.119	6.013	0.949	0.482
General car	0.841	0.085	10.132	1.030	0.697
Axles/wheels	1.108	0.077	14.404	1.260	0.958
All other	0.444	0.073	6.056	0.587	0.300

Table 6
Car shipments along the case study corridor.

Station	Distance from rail yard (mile)	Total number of cars	Number of DG cars
A	600	25	15
B	900	30	20
C	1000	55	10

probability of derailment would be less compare to track geometry defect.

7. Case study application

The proposed model is applied to a hypothetical railway corridor to illustrate how risks along a route can be used to guide cost-effective DG placement strategies at the rail yard. The case study corridor consists of a rail yard (train origin point) and three subsequent stations along a given route. Stations A, B, and C are situated at a distance of 600, 900, and 1000 miles from the rail yard, respectively. Car shipments to each intermediate station consist of a given mix of DG and non-DG cars, as summarized in Table 6.

In this application, information is needed concerning train derailment rates and causes along each route segment. The route being considered consists of six separate uniform segments: three segments between the rail yard and station A of lengths 300, 200, and 100 miles; two segments between stations A and B of lengths 200, and 100 miles; and one segment of 100 mile between stations B, and C. Table 7 summarizes the train and car derailment rates as well as the expected number of train derailments for the different route segments. Table 7 can be obtained by using the train and car derailment rates from Table 1 and assuming that approximately 25% of all derailments can be classified as train-mile caused while 75% are classified as car-mile caused. For example, in Table 7 for station A, segment 1, using Table 1, RC and RT are calculated as following:

$$RC = 31.5 \times 0.75 = 23.62, \quad \text{and} \quad RT = 2.04 \times 0.25 = 0.51.$$

The values in the last column of Table 7 are calculated by utilizing the formula in Eq. (5). These values are basic estimates of the probability of train derailment along different route segments which provide estimates of $P_r(\mathrm{TD})$ in Eq. (2).

$P_r(i|\mathrm{TD})$ for a given segment is obtained from Eq. (3), based on POD and probability of number of cars derailing. As discussed before, this calculation requires information concerning the expected causes of derailment along the segment and various train operating characteristics.

It is assumed that the main cause of derailments associated with individual/specific segments can be predicted based on route attributes and rolling stock characteristics(Table 8).

To estimate $P_r(\mathrm{POD\ at\ position}\ j)$ in Eq. (6), Table 3 and Fuzzy function are used. The parameters m_1 and m_2 can be obtained from Fig. 4 for each segment (Table 9).

Table 7
Expectation of train derailment along the case study corridor.

Station	Segments	Distance (mile)	Track class	Train derailment rate		Train length	Expectation of train derailment
				RC($\times 10^{-9}$)	RT($\times 10^{-6}$)		
A	1	300	3	23.62	0.51	110	0.0093
	2	200	5	3.67	0.08	110	0.001
	3	100	3	23.62	0.51	110	0.0031
B	1	200	3	23.62	0.51	85	0.005
	2	100	5	3.67	0.08	85	0.0004
C	1	100	4	5.85	0.132	55	0.0005

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Table 8
Main cause of derailment for different segments along the case study corridor.

Station	Segments	Main cause	Cause group of derailment	Train speed (mph)
A	1	Roadbed	1	40
	2	Axels/wheels	3	80
	3	Switches	1	40
B	1	Roadbed	1	40
	2	General car	3	80
C	1	Track geometry	2	60

Table 9
Membership functions of distributions based on the train length.

Station	Segment	m_1	m_2
A	1 2 3	0.3	0.7
B	1 2	0.8	0.2
C	1	0.4	0.6

To estimate $P_r(x\,\text{cars derailing}|\text{POD at position}\,j)$, Eq. (8) and Table 5 are used. Finally, by applying Eq. (2) the probability of derailment by position for a given train and track segment (P_i) can be yielded.

The involvement of DG cars in derailment depends on the DG car placement strategy. A block is introduced as a number of cars which have one destination. In this exercise, six possible block placement strategies are considered. For instance CBA means that the first block after the engine is block A, and the last block is C.

CBA^0: Do nothing, current operation when the order of blocks is based on intermediate and final destinations, and the order of cars is based on FCFS.
CBA*: Same as CBA^0 but with the order of cars in each block determined from application of the minimum in-transit risk principle.
CAB, ACB, ABC, BAC, and BCA are five other block arrangements along a train with the order of cars determined from the application of the minimum in-transit risk principle.

We need to assume the order of blocks when calculating the probability of derailment for each position. With this assumption, the best combination of cars within each block can be identified by minimizing the total risk. This step repeats for the next assumed order of blocks. More details can be found in the study by Bagheri et al. (2010).

For each block placement, the risk of DG placement is obtained by applying Eq. (1) to all train positions over the entire route. From Table 6 only those positions that are relevant for a given route segment with respect to the assumed shipment profile are considered in the estimation of risk. For example, cars destined for station A (the first station along the route) will not be considered for segments beyond this station. Thus, the train length varies over the route, from 110 cars traveling from the rail yard to A, 85 cars to B, and 55 cars to C.

The results can be represented in terms of percent reduction in risk with respect to the Do-nothing (CBA^0 strategy).To estimate the total risk value for current operation (CBA^0), the order of DG (1) and non-DG (0) cars are allocated randomly to reflect an FCFS operation. For the case study the results can be illustrated as in Fig. 5.

The results suggest a 20% reduction in risk can be realized over the entire route if the existing block order is maintained (i.e., CBA),

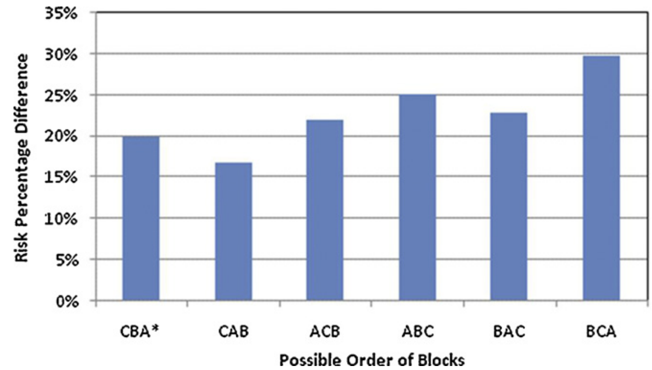

Fig. 5. The comparison of risk percentage difference for six possible combinations of blocks.

while individual DG car placement within each block reflects the in-transit risk minimizing principle introduced in this paper. The strategy that yields the lowest route risk corresponds to a BCA block order and minimum risk DG placement within each respective block. The benefit of the risk-minimum strategy (BCA) over the base case is 28% reduction in risk. Given the rather modest risk safety gains associated with the BCA block order over the CBA order with restricted DG placement, it may be advisable for this corridor application to continue with the existing CBA (first station at front) order for blocks and only restrict DG placement within their respective blocks to the lowest risk slots.

8. Conclusions

This paper has introduced a new framework for considering in-transit risk for placement of DG railway cars along a train. Derailment probabilities for different railway car positions along the train have been used to obtain this risk. These probabilities are combinations of probability of POD and number of cars derailing. It has been shown that train length and cause of derailment affect POD. Causes of derailment are assumed to depend on route attributes and rolling stock characteristics.

The proposed model has been applied to a hypothetical rail corridor. The results indicate that the current first-come first-serve strategy perhaps is not the best way to make-up freight trains for shipment of DG cars.

It should be noted that in this research we consider the in-transit risk only without examining the potential implications of increased risk due to additional marshalling operations at the classification yard. Future research should therefore develop more realistic models considering operating risks and costs associated with marshaling and switching. A comprehensive risk model is required to determine the optimum marshaling operations considering the trade-off between the benefits of lower in-transit risk and increased rail yard risk.

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