Safety Effectiveness of Integrated Risk Reduction Strategies for Rail Transport of Hazardous Materials

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Railroad transportation plays a critical role in safely and economically moving hazardous materials throughout North America. Effective management of the risk of hazardous materials transportation is a high priority of both the American rail industry and government. A number of strategies and technologies have been implemented or are being developed to reduce this risk. Each risk reduction strategy has an effect on rail safety as well as a corresponding implementation cost. In addition, risk reduction strategies may have interactive effects. However, little prior research has addressed the interactive effects between different risk reduction strategies or how elements of them should be compared or combined, or both, to achieve the maximum risk reduction in the most cost-effective manner. A preliminary methodology was developed to estimate the reduction in the risk of the release of hazardous materials by implementing integrated risk reduction strategies, including accident prevention, tank car safety design enhancement, and changes in train operating practices such as train speed reduction. An analysis showed that risk reduction was affected in differing degrees by operating conditions, accident cause, effectiveness of accident prevention technologies, tank car safety design, percentage of tank car fleet requiring upgrade, and train speed. This study represents the first step in a systematic process of quantitative risk analysis of railroad freight transportation for local, regional, and systemwide safety improvement and is intended to assist decision makers in the development of an integrated cost-efficient risk reduction framework.

There are approximately 2 million rail shipments of hazardous materials (hazmat) in North America each year (*1*). Although the majority of these shipments reach their destination without incident, they still represent a safety concern for both the public and private sectors. Therefore, the release risk associated with these shipments should be minimized to the extent feasible. Improvements have focused on enhancing packaging and tank car safety design (*2–8*), deploying wayside defect detection technologies (*9–12*), upgrading track infrastructure (*13–16*), routing (*17–22*), reducing train speed (*22*), and improving emergency response practices (*23*). Each strategy has a direct effect on hazmat release risk, and different strategies may also have interactive effects. However, limited prior research has quantified the safety effect of integrated risk reduction strategies. In addition, there has been relatively little study of the variability in the effectiveness of risk reduction strategies under different operating conditions. This study represents the first step in a systematic process of quantitative risk analysis, with the ultimate goal of optimizing the integration of risk reduction strategies.

A generic framework for railroad hazmat transportation risk analysis is introduced. Next, basic strategies for reducing accident-caused hazmat release risk are identified. Then quantitative models are developed to estimate the effectiveness of various risk reduction strategies, individually and in combination, under different operating conditions.

RISK ANALYSIS MODEL

A generic risk analysis model for hazmat transportation by rail is expressed as the product of the derailment rate of a hazmat car, traffic exposure, the conditional probability of release of a derailed hazmat car, and the consequence of a car release (Equation 1). This basic risk model has been used by a number of previous researchers (*2, 3, 13, 14, 21, 22, 24, 25*).

$$R = Z \times M \times P \times C \tag{1}$$

where

R = risk of hazmat release (expected number of people affected),
Z = rate of hazmat car derailment per billion car miles,
M = traffic exposure (billion car miles),
P = conditional probability of release of derailed hazmat car, and
C = consequence of release from hazmat car (e.g., number of people affected).

Car derailment rate is defined as the number of cars derailed normalized by traffic exposure, such as car miles. Car derailment rates vary by track characteristics (*24, 26, 27*). The conditional probability of release (CPR) from a derailed tank car reflects its safety performance. The majority of railroad hazmat shipments (72%) is in tank cars (*1*); thus tank car safety design analysis and improvement is a priority in the rail industry and government. Treichel et al. developed a logistic regression model to predict the CPR of a derailed tank car given its safety design (*28*). Kawprasert and Barkan extended the model by accounting for the effect of derailment speed (*14*).

The consequences of a hazmat car release can be measured by several metrics, including property damage, disruption of service, environmental impact, human impact (e.g., number of people potentially exposed to a release), litigation, or other types of impacts (*22*). Among the consequence measures, population in the affected area of a release incident is often used (*7, 21, 22*). The hazard exposure

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model provided in the U.S. Department of Transportation *Emergency Response Guidebook 2012* includes recommended initial isolation, protective action (downwind) distances, or both. These can be used to estimate the affected area based on the material and scenario of release (fire, spill, daytime, nighttime) (*29*). Once the affected area is determined, the number of people affected can be estimated by multiplying the affected area of each segment by the corresponding average population density. Assessment of release consequences can be performed by using a Geographical Information System platform (*30*).

STRATEGIES TO REDUCE RATE OF HAZMAT RELEASE

Risk reduction strategies, individually and in combination, affect at least one of the risk factors. In this study, the focus is on reducing the likelihood of a hazmat release incident. Other strategies, which are intended to mitigate the release consequences, are beyond the scope of this paper. On a given hazmat route, it is assumed that the consequence of a release incident is constant. In terms of reducing the likelihood of a hazmat car release, two basic strategies are considered in this paper:

1. Reducing the car derailment rate by preventing certain accident causes and
2. Reducing the release probability of a derailed car by enhancing safety design of tank cars, reducing train speed, or both.

Accident Prevention

In terms of preventing accident causes to reduce the car derailment rate, it is first necessary to identify the distribution of derailment frequency by accident cause. The data used in this study are from the FRA rail equipment accident (REA) database, which is based on data from the rail equipment accident–incident report (*31*). The REA database contains information regarding all accidents that exceed a monetary threshold of damages to on-track equipment, signals, track, track structures, and roadbed. The reporting threshold increased from $7,700 in 2006 to $9,400 in 2011 (*32*). This study focuses on main-line releases of hazmat cars caused by accidents on Class I freight railroads, of which 87% occurred in train derailments from 2001 to 2010 as reported in the REA database. A railroad is classified as a Class I railroad if its operating revenue exceeded $378.8 million in 2009. Class I railroads accounted for approximately 68% of U.S. railroad route miles, 97% of total ton-miles transported, and 94% of the total freight rail revenue (*33*).

Figure 1 presents the number of freight cars derailed by primary accident cause for FRA-reportable freight train derailments on Class I mainlines from 2001 to 2010. The top 10 accident causes accounted for 62% of cars derailed. Broken rails or welds are the most common accident causes, accounting for 23% of cars derailed. Therefore, prevention of broken rails appears to be a promising risk reduction strategy.

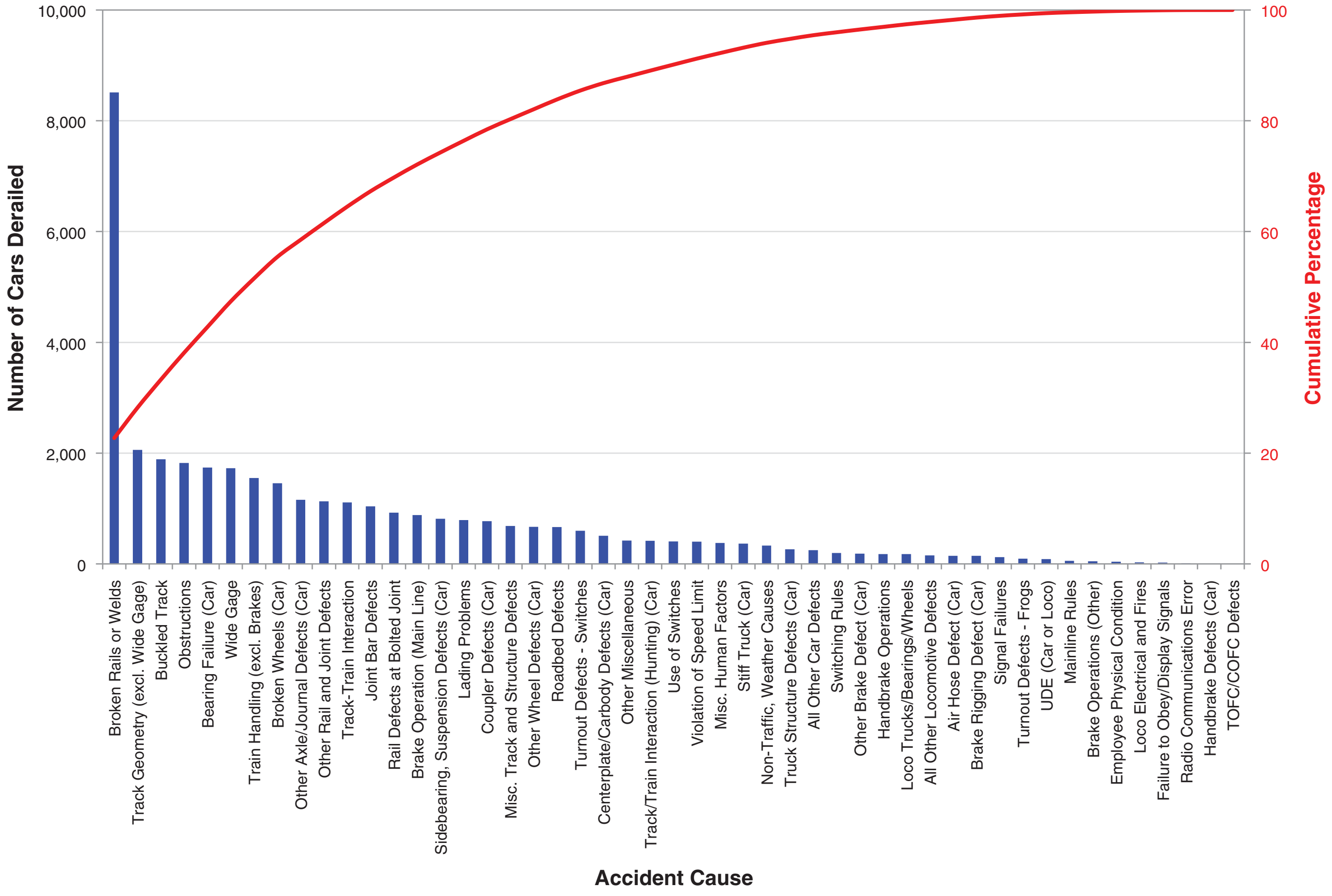

FIGURE 1 Frequency of car derailments by accident cause, FRA-reportable derailments of freight trains on Class I mainlines, 2001 to 2010 (excl. = excluding; misc. = miscellaneous; UDE = undesired emergency; TOFC = trailer on flatcar; COFC = container on flatcar).

Method of Operation and Its Effect on Derailments Caused by Broken Rails

In this study, prevention of broken rails is used as an example to illustrate the effectiveness of accident prevention on risk reduction. The methodology can be adapted to other accident causes. Typical preventive measures for broken rails include rail inspection for defects, rail grinding, and rail repair, replacement, and renewal. These measures not only reduce the likelihood of a broken rail's occurrence but also may improve the strength of the overall track structure (*34*). In railroad safety and risk analysis, it is of interest to understand the level of risk reduction if a proportion of derailments caused by broken rails were prevented. This understanding provides an initial assessment of the safety benefits that can be achieved with a strategy for the prevention of broken rails compared with other risk reduction strategies. Future study may need to quantify the safety effectiveness of a specific preventive measure for broken rails, such as rail grinding, increased inspection frequency, or an advanced rail inspection technology.

Statistical models are developed to estimate the proportion of derailments caused by broken rails under different track segment characteristics. The marginal and combined effects of three potential factors affecting the probability that a car derailment is due to broken rails are considered. These variables include method of operation, FRA track class, and annual traffic density. First, the effect of method of operation (nonsignaled versus signaled) on car derailments caused by broken rails is examined. Because a nonsignaled track has no track circuits that can detect broken rails, it is hypothesized that a nonsignaled track may have a greater proportion of car derailments caused by broken rails than signaled track, all else being equal. Figure 2 shows the distribution of car derailments caused by broken rails versus derailments not caused by broken rails by method of operation on Class I mainlines from 2001 to 2010. It shows that broken rails or welds accounted for 36% of cars derailed in nonsignaled track territories compared with 17% in signaled-track territories.

Multivariate Analysis

Multivariate analysis showed that there is a significant marginal association between the two variables method of operation (nonsignaled versus signaled) and the proportion of car derailments caused by broken rails. However, method of operation may be correlated with other railroad characteristics, such as FRA track class and annual traffic density. Therefore, it was investigated whether the effect of method of operation is a conditional association given other correlated factors such as variations in track class or traffic density. Considering that marginal association and conditional association may be different (*35*), a multivariate analysis was performed to examine whether nonsignaled track has a higher proportion of car derailments caused by broken rails given the same track class and annual traffic density level. Each train derailment is caused by either broken rails or other causes. The track segment on which a derailment occurs may have different characteristics, and these characteristics are used to estimate with a logistic regression model the likelihood that a derailment is caused by broken rails.

Two categories of annual traffic density were considered: trackage with more than 20 million gross tons (MGT) annually and trackage with less than this amount [20 MGT represents the average track traffic density on U.S. Class I railroads (*36*)]. FRA track safety standards require more frequent rail inspections on track Classes 4 and 5 than on lower track classes (*37*). In the logistic regression model, two categories of FRA track class were considered: lower track classes (Classes 1 to 3) and higher track classes (Classes 4 and 5). The likelihood ratio test (*38, 39*) was used to examine the effect of FRA track class, method of operation (nonsignaled versus signaled), and annual traffic density level (<20 MGT versus ≥20 MGT) on the probability that a car derailment is due to broken rails.

Variable	*Chi-Square*	*P-Value*
FRA track class	0.00	.95
Method of operation	123.30	<.0001
Annual traffic density	6.93	.01

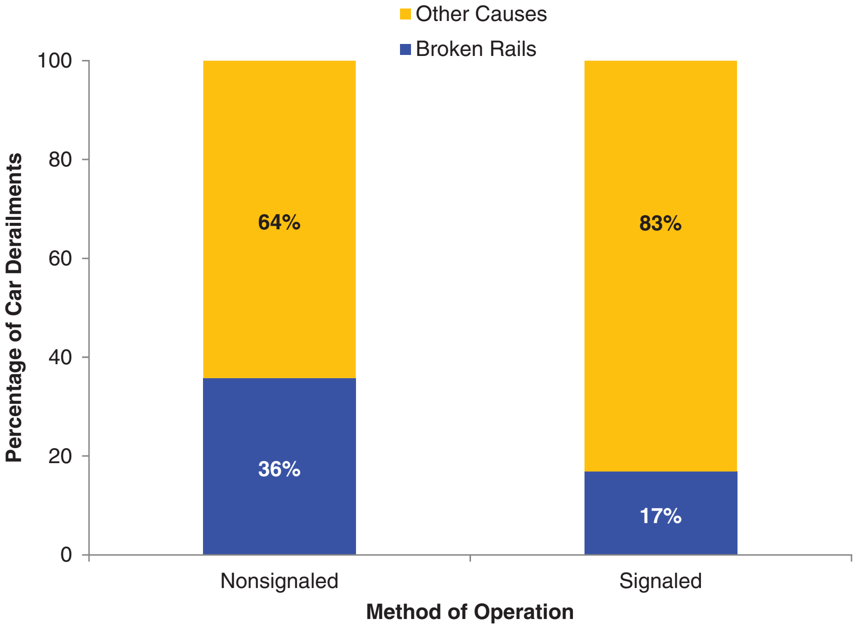

FIGURE 2 Proportion of car derailments by cause and method of operation, derailments of freight trains on Class I mainlines, 2001 to 2010.

TABLE 1 Estimated Proportion of Car Derailments Caused by Broken Rails by Method of Operation and Annual Traffic Density Level

Method of Operation	Mean	95% Confidence Interval by Bound	
		Lower	Upper
<20 MGT			
Nonsignaled	0.366	0.343	0.389
Signaled	0.204	0.183	0.227
≥20 MGT			
Nonsignaled	0.342	0.310	0.375
Signaled	0.157	0.146	0.169

The results, which show that the *P*-value for FRA track class is .95, indicate its insignificant contribution to the prediction given method of operation and annual traffic density level. Next, method of operation and annual traffic density are used to estimate the proportion of car derailments caused by broken rails.

Table 1 and Figure 3 present the predicted proportion of car derailments caused by broken rails. All else being equal, the following effects were evident:

- The effect of FRA track class is insignificant;
- Higher traffic density is associated with a lower proportion of car derailments caused by broken rails; this effect of traffic density is more significant in signaled track; and
- The proportion of car derailments caused by broken rails in signaled track territory is 50% lower than that in nonsignaled track territory.

Prevention of various accident causes differentially contributes to car derailment rate reduction, with corresponding effects on the risk. The proportion of risk reduction as a result of prevention of broken rails on a hazmat route can be estimated by the following equation:

$$\Delta R_{\text{rail}} = \frac{\sum_{i=1}^{N} Z_i M_i P_i C_i - \sum_{i=1}^{N} Z_i (1 - e_i \lambda_i) M_i P_i C_i}{\sum_{i=1}^{N} Z_i M_i P_i C_i} \qquad (2)$$

where

ΔR_{rail} = percentage of risk reduction on route by reducing car derailments caused by broken rails,
Z_i = car derailment rate on *i*th track segment,
M_i = traffic exposure on *i*th track segment,
P_i = conditional probability of release of derailed tank car on *i*th track segment,
C_i = release consequence on *i*th track segment,
e_i = effectiveness of broken-rail prevention (proportion of car derailments caused by broken rails that could be prevented) on *i*th track segment,
λ_i = proportion of car derailments on *i*th track segment that are caused by broken rails, and
N = number of track segments on route.

In Equation 2, the effectiveness of prevention of broken rails (e_i) is defined as the proportion of car derailments caused by broken rails that could be prevented by certain preventive measures for broken rails, such as grinding, more frequent rail inspection and maintenance, or both. This 0% effectiveness means that no car derailments caused by broken rails would be prevented, and 100% effectiveness means that all derailments caused by broken rails could be eliminated. The effectiveness of a specific measure for broken rails is dependent on technology, operations, extent of implementation, and many other factors. Quantification of the effectiveness of accident prevention strategies requires extensive further analysis and is beyond the scope of this paper.

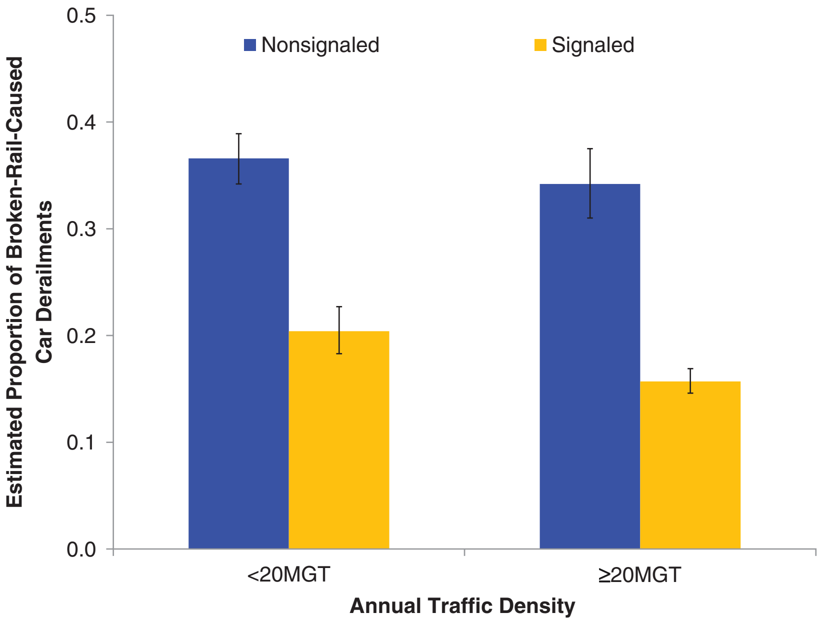

FIGURE 3 Estimated proportion of car derailments caused by broken rails by method of operation and annual traffic density (error bars represent 95% confidence interval).

Also not considered is the possible interaction between different accident causes. The effects of different accident prevention strategies may not necessarily be independent of one another. For example, improved wheel condition may reduce the impact load on the track, thereby reducing track defects, and vice versa. The interactive damage forces between track and equipment were discussed by Resor and Zarembski (*9*). With their model, it was estimated that a 1% reduction in the impact load would result in a 1.3% reduction in damage to track and a 0.6% reduction in damage to wheels and axles. Further research is needed to understand better what the possible interactive effects are, how to quantify them where they exist, and their effects on accident rate estimation and safety policy evaluation (*40*).

Reducing Release Probability of Derailed Tank Car

Another risk reduction strategy is to reduce the probability that a derailed tank car releases its contents. Reduction of release probability can be achieved by improving tank car safety design (*2–8, 13*), reducing train speed (*14*), or both. Kawprasert and Barkan developed an approach to estimate the CPR of a derailed tank car given its design specification and derailment speed (*14*). Kawprasert presented the estimated speed-dependent CPR for various tank car design specifications (*22*). These results were used to develop a linear regression model in which the release probability is approximated by a linear function of derailment speed. The linear regression has zero intercept because it is assumed that zero train speed does not cause accident-caused hazmat releases (*22*). In the linear regression, slope parameter A represents the change of CPR with respect to unit change of train speed. For example, for Tank Car 111A100W1, the speed-dependent CPR function would be $0.0096S$ (S is derailment speed). If derailment speed is 25 mph, the CPR of this tank car is $0.0096 \times 25 = 0.24$. This calculation means that the probability that a derailed 111A100W1 tank car will have a hazmat release is 0.24. When speed is reduced from 25 mph to 24 mph, the CPR is expected to decrease from 0.24 to 0.2304 ($0.0096 \times 24 = 0.2304$). The reduction of CPR ($0.24 - 0.2304 = 0.0096$) is equal to the slope parameter A (0.0096).

Table 2 presents the estimated speed-dependent CPR for the top 10 tank car specifications used to transport hazmat in 2011. These tank cars accounted for 93% of the tank car fleet used in railroad hazmat transportation in 2011 (*1*). Nonpressurized tank cars (111A- and 211A-) have a higher CPR than pressurized tank cars at the same derailment speed.

TABLE 2 Estimated Speed-Dependent CPR by Tank Car Specification and Grouped by CPR Function

Stenciled Specification	Speed-Dependent CPR ($A \times S$)[a]	Percentage in Fleet
111A100W1	$0.0096S$	51.04
111A100W3	$0.0096S$	5.72
111A100W2	$0.0096S$	4.51
211A100W1	$0.0096S$	4.17
111A100W5	$0.0096S$	3.35
112J340W	$0.0018S$	13.54
105J300W	$0.0018S$	4.25
112J400W	$0.0018S$	1.92
105J400W	$0.0018S$	1.84
105J500W	$0.0012S$	2.77
Other	na	6.90
Total	na	100.00

NOTE: na = not applicable.
[a] A = slope parameter; S = derailment speed.

Both tank car safety design enhancement and train speed reduction can reduce the probability of a tank car's releasing in a derailment, thereby reducing hazmat release risk. However, their combined effect has not been studied before. For example, if it is assumed that a certain proportion, β ($0 \le \beta \le 1$), of existing tank cars is replaced with upgraded tank cars associated with a lower CPR and that train speed is reduced by θ ($0 \le \theta \le 1$), given a constant car derailment rate, the estimated proportional risk reduction on a hazmat route is

$$\Delta R_{\text{tank}} = \frac{\sum_{i=1}^{N} Z_i M_i A_b S_i C_i - \sum_{i=1}^{N} Z_i M_i \left[A_b(1-\beta) + A_u\beta\right] S_i (1-\theta_i) C_i}{\sum_{i=1}^{N} Z_i M_i A_b S_i C_i} \tag{3}$$

where

ΔR_{tank} = percentage of risk reduction on route as a result of reduction in CPR and derailment speed;
A_b = change of CPR with respect to speed for baseline car (if speed is reduced by 1 mph, CPR for baseline tank car is reduced by A_b);
A_u = change of CPR with respect to speed for upgraded car (when speed is reduced by 1 mph, CPR for upgraded tank car is reduced by A_u);
β = percentage of tank car fleet requiring upgrade (assuming it is constant on route);
S_i = derailment speed (mph); and
θ_i = percentage of train speed reduction on ith track segment.

All other terms are as defined previously.

EFFECTIVENESS OF INTEGRATED STRATEGIES FOR RISK REDUCTION

Model Formulation

Equations 4 and 5 present the methodology for estimating the proportional risk reduction on each track segment and on the route, respectively, by implementation of integrated risk reduction strategies (e.g., accident prevention, tank car safety design enhancement, and train speed reduction):

$$\begin{aligned}\Delta R_{\text{seg}i} &= \frac{Z_i M_i A_b S_i C_i - Z_i (1 - e_i\lambda_i) M_i \left[A_b(1-\beta) + A_u\beta\right] S_i (1-\theta_i) C_i}{Z_i M_i A_b S_i C_i} \\ &= 1 - (1 - e_i\lambda_i)\left(1 - \frac{A_b - A_u}{A_b}\beta\right)(1-\theta_i)\end{aligned} \tag{4}$$

$$\Delta R_{\text{route}} = \frac{\sum_{i=1}^{N} Z_i M_i A_b S_i C_i - \sum_{i=1}^{N} Z_i (1 - e_i\lambda_i) M_i \left[A_b(1-\beta) + A_u\beta\right] S_i (1-\theta_i) C_i}{\sum_{i=1}^{N} Z_i M_i A_b S_i C_i} \tag{5}$$

where

$\Delta R_{\text{seg}i}$ = segment-specific percentage of risk reduction,
ΔR_{route} = route-specific percentage of risk reduction,
e_i = effectiveness of prevention of broken rails (proportion of car derailments caused by broken rails that can be prevented) on ith track segment, and
λ_i = percentage of car derailment caused by broken rails on ith track segment.

All other terms are as defined previously.

On each segment, the proportional reduction in risk is affected by the impact of the prevention of broken rails, the proportion of car derailments caused by broken rails, the proportion of the tank car fleet requiring upgrade, and the reduction of train speed. All else being equal, the marginal safety effectiveness of an individual risk reduction strategy is

- Rail: $e\lambda$,
- Tank car safety design improvement: $A_b - A_u/A_b\beta$, and
- Speed reduction: θ.

The marginal safety effectiveness of the prevention of broken rails is subject to the proportion of car derailments caused by broken rails (λ) and the proportion of these derailments that could be prevented (e). For tank car safety design improvement, the larger the CPR reduction ($A_b - A_u/A_b$) and the larger the proportion of the tank car fleet (β) requiring upgrade, the more effective this strategy is for reducing the risk. Finally, a certain percentage of train speed reduction (θ) results in an equal proportion of risk reduction. Which risk reduction strategy is more effective is dependent on the extent of implementation, interactions with other strategies, and segment characteristics.

For the route, in addition to these factors, risk reduction is affected by car derailment rate, traffic exposure, and affected population on each segment. Traffic exposure on each segment is a product of number of carloads transported multiplied by segment length. Affected population is a product of population density along each segment and the affected area.

Numerical Example

Table 3 summarizes segment-specific track information on a hypothetical hazmat route. The following risk reduction strategies and effectiveness are assumed to apply to this route:

1. Rail grinding was reported to result in more than 50% reduction of the rail defect rate (*41*). A prevention strategy for broken rails is assumed to reduce the train derailment rate by 50%. The effectiveness of the prevention of broken rails depends on the techniques used, the extent of the implementation, and the operating conditions.
2. Forty percent of the tank car fleet is upgraded from 105J400W to 105J500W.
3. Train speed is reduced on certain track segments.

Risk reduction as a result of the strategies for integrated risk reduction on each segment (Equation 4) and on the route (Equation 5) is presented in Table 4.

The route-based risk is estimated to decline by approximately 32.5% from implementation of integrated risk reduction strategies. Technologies or practices for the prevention of broken rails, proportional tank car fleet replacement, and train speed reduction all affect risk reduction on a specific hazmat route. The optimal combination of

TABLE 3 Information on Hypothetical Hazmat Route

Segment Number	FRA Track Class	Method of Operation	Annual Traffic Density (MGT)	Speed (mph)	Car Derailment Rate per Billion Car Miles	Segment Length (mi)	Population Affected
1	3	Signaled	≥20	30	89	0.41	531
2	3	Signaled	≥20	30	89	0.33	141
3	3	Signaled	≥20	30	89	0.53	111
4	3	Signaled	≥20	30	89	1.09	104
5	4	Signaled	≥20	40	50	0.25	84
6	4	Signaled	≥20	40	50	0.72	54
7	4	Signaled	≥20	40	50	0.73	154
8	4	Signaled	≥20	40	50	2.85	351
9	3	Signaled	≥20	40	89	0.49	572
10	3	Signaled	≥20	40	89	1.25	2,430
11	3	Signaled	≥20	40	89	0.28	1,767
12	3	Signaled	≥20	40	89	0.13	1,271
13	3	Nonsignaled	≥20	30	125	0.18	882
14	3	Nonsignaled	≥20	30	125	0.12	441
15	3	Nonsignaled	≥20	30	125	0.07	98
16	3	Nonsignaled	≥20	30	125	0.09	79
17	3	Nonsignaled	≥20	30	125	0.07	90
18	3	Nonsignaled	≥20	30	125	0.06	111
19	3	Nonsignaled	≥20	30	125	0.17	154
20	3	Nonsignaled	≥20	30	125	0.33	763

TABLE 4 Reduction of Risk of Hazmat Release on Segment and Route

Segment Number	Input				Output			
	Percentage of Car Derailments Caused by Broken Rails	Effectiveness of Broken Rail Prevention[a] (%)	Percentage of Tank Car Fleet Upgrade	Percentage of Train Speed Reduction	Baseline Risk per Carload	Reduced Risk per Carload	Amount for Risk Reduction	Percentage of Risk Reduction
1	15.7	50	40	0	1.04 E–06	8.31 E–07	2.10 E–07	20.1
2	15.7	50	40	0	2.27 E–07	1.81 E–07	4.58 E–08	20.1
3	15.7	50	40	0	2.82 E–07	2.25 E–07	5.67 E–08	20.1
4	15.7	50	40	0	5.45 E–07	4.35 E–07	1.10 E–07	20.1
5	15.7	50	40	0	7.75 E–08	6.19 E–08	1.56 E–08	20.1
6	15.7	50	40	20	1.40 E–07	8.92 E–08	5.04 E–08	36.1
7	15.7	50	40	20	4.02 E–07	2.57 E–07	1.45 E–07	36.1
8	15.7	50	40	20	3.60 E–06	2.30 E–06	1.30 E–06	36.1
9	15.7	50	40	15	1.78 E–06	1.21 E–06	5.73 E–07	32.1
10	15.7	50	40	15	1.95 E–05	1.33 E–05	6.27 E–06	32.1
11	15.7	50	40	15	3.19 E–06	2.16 E–06	1.02 E–06	32.1
12	15.7	50	40	15	1.08 E–06	7.31 E–07	3.46 E–07	32.1
13	34.2	50	40	15	1.07 E–06	6.56 E–07	4.18 E–07	38.9
14	34.2	50	40	15	3.68 E–07	2.25 E–07	1.43 E–07	38.9
15	34.2	50	40	15	4.47 E–08	2.73 E–08	1.74 E–08	38.9
16	34.2	50	40	15	4.84 E–08	2.96 E–08	1.88 E–08	38.9
17	34.2	50	40	15	4.39 E–08	2.68 E–08	1.71 E–08	38.9
18	34.2	50	40	15	4.78 E–08	2.92 E–08	1.86 E–08	38.9
19	34.2	50	40	15	1.73 E–07	1.05 E–07	6.72 E–08	38.9
20	34.2	50	40	15	1.69 E–06	1.03 E–06	6.58 E–07	38.9
Route summary	na	na	na	na	3.54 E–05	2.39 E–05	1.15 E–05	32.5

[a] Fifty percent of car derailments caused by broken rail are assumed to be preventable.

these strategies can be determined with a mathematical programming model:

Objective function:

$$\text{maximize}\left\{\frac{\sum_{i=1}^{N} Z_i M_i A_b S_i C_i - \sum_{i=1}^{N} Z_i (1-e_i\lambda_i) M_i [A_b(1-\beta)+A_u\beta] S_i (1-\theta_i) C_i}{\sum_{i=1}^{N} Z_i M_i A_b S_i C_i}\right\}$$

Constraints:

$$\sum_{i=1}^{N}\sum_{j=1}^{J} \text{cost}_{ij} \le \text{budget} \qquad (6)$$

$$0 \le e_i \le 1 \qquad (7)$$

$$0 \le \beta \le 1 \qquad (8)$$

$$0 \le \theta_i \le 1 \qquad (9)$$

where cost_{ij} is the implementation cost of the *j*th risk reduction strategy on the *i*th track segment, and the other terms are as defined previously.

The objective function is to maximize the proportional risk reduction on a hazmat route. The decision variables are the proportion of car derailments caused by broken rails that it is feasible to prevent (*e*), the proportion of baseline tank car fleet requiring upgrade (β), and the proportion of reduction in train speed (θ). The first constraint is that total implementation cannot exceed the budget. The other three constraints require that the decision variables be between 0 and 1. Depending on the questions to address and data available, the optimization model can be adapted to account for multiple objectives and their trade-offs, such as benefit and cost. Solving this optimization problem requires information regarding the implementation cost of a specific risk reduction measure. Understanding the cost-effectiveness of integrated risk reduction strategies and the corresponding policy implications is the next step of this research. Ultimately, this understanding will aid development of an optimized integration of strategies to reduce hazmat transportation risk (*42*).

CONCLUSIONS

An analytical framework is presented to evaluate risk reduction by implementing three risk reduction strategies, including broken-rail prevention, tank car fleet upgrade, and train speed reduction. Prevention of broken rails represents an accident prevention strategy to reduce the probability of a tank car derailment, whereas tank car upgrade and speed reduction affect the probability of a derailed-car release. The interactive effects among the risk reduction strategies are taken into account in evaluating the combined safety effectiveness of these strategies. The preliminary methodology presented here is the first step of a larger integrated risk management framework under development. The method can be further developed and applied to a broader set of risk reduction strategies. It can be used to demonstrate how to properly analyze the combined effectiveness of multiple approaches to reduce risk.

FUTURE RESEARCH

The next steps in this research include

- Quantification of the interactive effects of accident causes; for example, it is necessary to understand the reduction of track-related causes by preventing mechanical defects, particularly wheel defects, and vice versa;
- Consideration of the effectiveness of preventing other accident causes (e.g., mechanical failures or human factors);
- Consideration of additional risk reduction strategies (routing, placement of tank cars in the train, etc.) to address a broader set of risk management problems;
- Analysis of cost-effectiveness of each risk reduction strategy and its integration to facilitate better-informed decision making and more efficient allocation of safety resources;
- Application of the methodology to representative hazmat routes on the national rail network; and
- Analysis of the implications of train safety policy and practice.

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