Integrated Risk Management Framework for Improving the Safety of Hazardous Materials Transportation by Rail

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ABSTRACT

Millions of carloads of hazardous materials are transported annually throughout the North American railway network. The risk of hazardous materials release incidents makes railway transportation safety a high priority. A number of strategies have been implemented or are in development to reduce the risk. Each risk reduction strategy has a particular effect on safety and different risk reduction strategies may have interactive effects. Little prior research has addressed these interactive effects among different risk reduction strategies, nor how elements of them should be compared and/or combined to achieve the maximum risk reduction in the most cost-effective manner. This paper develops an integrated risk management framework to estimate the levels of risk reduction due to prevention of major accident causes, modification of tank car safety design or/and changes in operational practices such as train speed reduction. The model has the potential to be implemented into railways' risk management system for local, regional and system-wide safety improvement.

1. Introduction

Hazardous materials (hazmat) transportation is important for the American economy and a major source of revenue for railways. There is interest in optimization of various approaches to reduce the risk of hazmat release incidents from train accidents. There are a number of risk reduction strategies that have been implemented or are under development. Evaluating which strategy to apply under which circumstances in an integrated, optimized manner requires understanding their respective cost-effectiveness and context-dependent efficacy.

The primary objective of this paper is to identify promising risk reduction strategies, and evaluate their risk reduction benefits, individually and in combination. The exposition of this paper is as follows. First, a railway hazmat transportation risk analysis model is introduced. Then, several promising risk reduction strategies are identified and evaluated. Then, a model is developed to estimate the levels of risk reduction by implementing multiple risk reduction strategies. Finally, the methodology is illustrated by a numerical example.

2. Railway Hazmat Transportation Release Risk

In the context of rail transport of hazardous materials, release risk is defined as the product of tank car derailment rate, traffic exposure, conditional probability of release (CPR) of a derailed tank car, and release consequence (Saat 2009, Kawprasert and Barkan 2008, 2010, Kawprasert 2010):

$$R = Z \times M \times P \times C \quad (1)$$

where:

- R = hazmat release risk
- Z = hazmat car derailment rate per billion hazmat-car-miles
- M = billion hazmat-car-miles
- P = conditional probability of release (CPR) of a derailed hazmat car
- C = release consequence (e.g., number of persons in the affected area)

There are two basic strategies to reduce the risk: 1) reduce the likelihood of a hazmat release incident; and/or 2) reduce release consequences (Liu et al. 2013a, 2013b). This paper focuses on the first term in this expression – reducing the likelihood of a hazmat car release. Tank cars transported 72% of North American railroad hazmat shipments in 2012 (BOE 2013), including the majority of the most hazardous products, so they are used as an example in this paper. Reducing the likelihood of a hazmat car release incident can be achieved by reducing tank car derailment likelihood and/or reducing the release probability of a derailed tank car. Specifically, this paper considers the following risk reduction strategies:

<u>Reducing tank car derailment rate</u>

- Broken rail prevention

<u>Reducing release probability of a derailed tank car</u>

- Tank car safety design enhancement
- Train speed reduction

3. Risk Reduction Strategies

3.1 Broken Rail Prevention

Broken rails are among the most common causes of major freight-train derailments on U.S. railroads (Dick 2001, Barkan et al. 2003, Liu et al. 2012). A large proportion of broken rails are caused by rail fatigue due to cyclic loading on the rail by passage of trains (Orringer 1990). Ultrasonic inspection is the primary rail defect detection technology used by American railroads (FRA 2012). However, no feasible detection technology is capable of detecting all types of rail defects, consequently, some remain undetected until growing to critical size and cause a broken rail. Fortunately, the majority of broken rails can be identified by visual inspection or track circuits (Dick 2001). Consequently, only a small percentage of broken rails result in train derailments (ca. one derailment per 100 broken rails) (Orringer and Bush 1983, Zarembski and Palese 2005).

There are two basic approaches to reduce broken-rail-caused train derailments: 1) reduce the occurrence of broken rails, and/or 2) better identify broken rails before they cause derailments. Some of the possible approaches to broken rail prevention include:

- Increasing rail defect inspection frequency to reduce the occurrence of broken rails (Orringer 1990)
- Increasing detection accuracy to reduce the number of undetected rail defects, thus reducing broken rail occurrence (Orringer 1990)
- Improving detection of broken rails in non-signaled territories, such as by adding track circuits (Bowden 2010)

3.2 Train Speed Reduction

The greater the derailment speed, the more likely that a derailed tank car releases (Kawprasert and Barkan, 2010). Therefore, reducing train speed is expected to reduce the conditional probability release for a derailed tank car, thereby reducing release risk (Kawprasert and Barkan 2010, Kawprasert 2010).

3.3 Tank Car Safety Design Improvement

Improving tank car safety design is a well-recognized risk reduction strategy (Barkan et al. 2007, Barkan 2008, Saat 2009, Saat and Barkan 2011). Improvement in tank car safety design is expected to reduce the release probability of a derailed tank car, thereby reducing risk.

Each of these risk reduction strategies has a direct safety effect on hazmat transportation risk. Furthermore, they may also have interactive effects (Liu et al. 2013a, 2013b). In the next section, a mathematical model is developed to analyze the integrated safety benefits of multiple risk reduction measures on a hazmat route.

4. Integrated Risk Reduction

In this paper, the following risk reduction strategies are considered:

1) Increase rail defect inspection frequency
2) Improve the accuracy of rail defect detection technologies
3) Add track circuits to non-signaled territories
4) Reduce train speed
5) Improve tank car safety design

Without implementation of any of these risk reduction strategies, the baseline risk on the route is denoted as R_0. Using Equation (1), the baseline risk is calculated as follows:

$$R_0 = \sum_{i=1}^{N} Z_{0i} M_{0i} P_{0i} C_{0i} \quad (2)$$

where:

- Z_{0i} = tank car derailment rate per traffic exposure in the baseline scenario
- M_{0i} = traffic exposure in the baseline scenario
- P_{0i} = conditional probability of release of a derailed tank car in the baseline scenario
- C_{0i} = consequence of a tank car release in the baseline scenario

Given constant traffic exposure and release consequence, the five risk reduction approaches affect either tank car derailment rate or the conditional probability of release of a derailed tank car. For simplicity, the risk is presented on a per-carload basis. The following model is used to estimate the route risk after implementing some (or all) of these risk reduction strategies:

$$R = \sum_{i=1}^{N} \left[(Z_{0i} - \Delta Z_i) \times (A_b(1-\beta) + A_u \beta) \times V_i (1-\mu_i) \times C_i \right] L_i \quad (3)$$

where:

- R = risk after implementation of integrated risk reduction strategies
- ΔZ_i = reduction of broken-rail-caused tank car derailment rate
- A_b = rate of CPR change in response to 1mph speed change for baseline tank car

A_u	=	rate of CPR change in response to 1mph speed change for enhanced tank car
β	=	percent baseline tank cars to upgrade
V_i	=	train speed (mph)
μ_i	=	percent speed reduction on the i^{th} segment
C_i	=	release consequence (e.g., number of persons in the affected area)
L_i	=	segment length (miles)
N	=	total number of track segments on the route

The reduction of tank car derailment rate by increasing rail defect inspection frequency, improving rail defect detection accuracy and improving the detection of broken rails in non-signaled track territories is estimated as follows:

$$\Delta Z_i = \frac{S(K_i)\phi_i D_i - S(K_{0i})\phi_{0i} D_i}{T} \times \theta \tag{4}$$

where:

S(K)	=	number of rail breaks per mile by annual rail inspection frequency
K_i	=	annual rail inspection frequency on the i^{th} segment
K_{0i}	=	baseline annual rail inspection frequency on the i^{th} segment
Φ_i	=	percent broken rails causing derailments
Φ_{0i}	=	baseline percent broken rails causing derailments
D_i	=	average number of cars derailed per broken-rail-caused derailment (8.9 for track classes 1 to 2, and 16.4 for track classes 3 to 5)
T	=	annual traffic density (MGT)
θ	=	average tonnage (including loading) of a car (this factor is used to convert car derailment rate per ton-mile to per car-mile)

The number of broken rails per mile can be estimated using the engineering model developed by the Volpe Transportation System Center of U.S. Department of Transportation (U.S DOT) (Orringer 1990):

$$S(K_i) = \sum_{j=1}^{K_i} \left\{ R \times \frac{e^{-\left(\frac{N_{j-1}}{\beta}\right)^{\alpha}} - e^{-\left(\frac{N_{j-1}+\frac{T}{K_i}}{\beta}\right)^{\alpha}}}{1+\lambda\left(\frac{T}{K_i}-\mu\right)} \times \lambda\left(\frac{T}{K_i}-\mu\right) \right\} \tag{5}$$

$$S(K_{0i}) = \sum_{j=1}^{K_{0i}} \left\{ R \times \frac{e^{-\left(\frac{N_{j-1}}{\beta}\right)^{\alpha}} - e^{-\left(\frac{N_{j-1}+\frac{T}{K_{0i}}}{\beta}\right)^{\alpha}}}{1+\lambda_0\left(\frac{T}{K_{0i}}-\mu\right)} \times \lambda_0\left(\frac{T}{K_{0i}}-\mu\right) \right\} \tag{6}$$

where:

R	=	273 (Orringer 1990)
α	=	Weibull shape factor, 3.1 (Davis et al. 1987)
β	=	Weibull scale factor, 2,150 (Davis et al. 1987)
λ_0	=	0.014 for baseline inspection accuracy (Orringer 1990)
λ	=	0.011 for improved inspection accuracy (Orringer 1990)
μ	=	minimum rail inspection interval, 10 MGT (Orringer 1990)
N_{j-1}	=	rail age (cumulative tonnage on the rail) at the $(j-1)^{th}$ inspection, where N_0 is the rail age at the last inspection in the last year

Adding track circuits to non-signaled track territories could reduce Φ_{0i}, the percentage of broken-rail-caused derailments. In this paper, we assume that 0.5% of broken rails cause derailments in signaled territory, compared to 1% of broken-rail-caused derailments in non-signaled territory. The actual proportion of broken-rail-caused derailments may vary dependent on a number of factors such as climate, track maintenance schedule and other factors. This paper does not attempt to quantify the effects of these factors.

Train speed reduction and tank car safety design improvement could reduce the probability that a derailed tank car releases (Kawprasert 2010). Treichel et al. (2006) developed logistic regression models to estimate the conditional probability of release and lading loss of a derailed tank car of almost any common or hypothetical configuration incorporating existing design features (Treichel et al. 2006). Kawprasert and Barkan (2010) extended Treichel et al's analysis by accounting for the effect of train speed.

5. Numerical Example

5.1 Baseline Risk

It is assumed that annual traffic density on a hypothetical route is 80 million gross tons (MGT) and the average rail age is 500 MGT. The baseline annual rail inspection frequency is three times per year. The U.S. Federal Railroad Administration (FRA) specifies track quality standards or "track classes" required to operate freight and passenger trains at different maximum speeds (FRA 2003). These classes include specifications for track structure, geometry, and inspection frequency and method, with more stringent requirements for higher track classes, thereby having greater maximum allowable train speeds. Additionally, railroads may maintain their infrastructure to a higher standard than the minimum required by the FRA (Liu et al. 2011). Tank car derailment rates decline on higher track classes (Anderson and Barkan 2004). Table 1 presents the basic route information.

Table 1
Hazardous Materials Route Information

	Value
Total Length (Miles)	2,273
Number of Segments	1,194
Distribution of Track Class (%)	
Class 1	1.1%
Class 2	2.2%
Class 3	14.2%
Class 4	46.1%
Class 5	36.4%
Method of Operation (%)	
Non-Signaled	6.9%
Signaled	93.1%
Average Population Density per Squared Miles	349

The baseline risk per carload is 0.0117. It is interpreted as the expected number of persons affected (to be protected or evacuated) per tank car shipment on this route. For every 100 carloads, there is an average of 1 person affected by potential hazmat release incidents (0.0117×100=1.17).

5.2 Risk Reduction

The amount of risk reduction by implementing multiple risk reduction strategies is evaluated. Although some decision variables (such as percent speed reduction) are continuous, for illustration, this paper considers that all decision variables are binary (no implementation or implemented at a specified level). For example, we consider two annual rail defect inspection frequencies (3 for the baseline scenario, and 5 is the increased frequency). Similarly, the track segment either has no speed reduction or reduces train speed by 20%. Because there are five risk reduction strategies considered and the implementation of each is a binary variable, there is a total of 32 possible scenarios (2^5=32). Table 2 shows the estimated route risk given each scenario.

Table 2
Route Risk by Implementing Integrated Risk Reduction (Descending Order by Risk)

Scenario	Increase Rail Inspection Frequency	Improve Detection Accuracy	Add Track Circuits to Dark Track Territories	Speed Reduction	Tank Car Enhancement	Route Risk	Percent Risk Reduction
1 (baseline)						0.01167	0%
2			X			0.01121	4%
3		X				0.01076	8%
4		X	X			0.01038	11%
5				X		0.00934	20%
6			X	X		0.00896	23%
7					X	0.00883	24%
8		X		X		0.00861	26%
9			X		X	0.00847	27%
10		X	X	X		0.00830	29%
11	X					0.00820	30%
12		X			X	0.00814	30%
13	X		X			0.00804	31%
14		X	X		X	0.00785	33%
15	X	X				0.00783	33%
16	X	X	X			0.00769	34%
17				X	X	0.00706	39%
18			X	X	X	0.00678	42%
19	X			X		0.00656	44%
20		X		X	X	0.00651	44%
21	X		X	X		0.00643	45%
22		X	X	X	X	0.00628	46%
23	X	X		X		0.00626	46%
24	X				X	0.00620	47%
25	X	X	X	X		0.00615	47%
26	X		X		X	0.00608	48%
27	X	X			X	0.00592	49%
28	X	X	X		X	0.00582	50%
29	X			X	X	0.00496	57%
30	X		X	X	X	0.00486	58%
31	X	X		X	X	0.00473	59%
32	X	X	X	X	X	0.00465	60%

"X" means implementation of a specific risk reduction approach

Notes: the following risk reduction strategies are considered:

1. *Increasing annual rail defect inspection frequency from 3 to 5*
2. *Improve detection accuracy to reduce undetected defects. Detection accuracy parameters are from Orringer (1990)*
3. *Add track circuits to non-signaled tracks*
4. *Reduce train speed by 20%*
5. *Upgrade 30% baseline tank car (111A100W1) to enhanced type (112J340W)*

Table 2 illustrates the estimated route risk after implementing a specific set of risk reduction strategies. For example, when all five strategies are applied, the route risk is expected to reduce from 0.0117 to 0.0047, a reduction of 60%. Adding track circuits to non-signaled territories has limited safety benefit for this specific hypothetical example because of the small proportion (<7%) of non-signaled track miles on the route. Improving rail defect inspection accuracy could reduce the risk by 8%. Compared with these two broken rail prevention approaches, increasing rail inspection frequency reduces the route risk to a greater extent (30%). In addition, tank car safety design improvement and speed reduction result in 20%-30% risk reduction, both of which affect the release probability of a derailed tank car.

Note that the effectiveness of these risk reduction strategies is dependent on route characteristics and the implementation level of each strategy. The conclusions based on the example in this paper may not apply to other routes with different infrastructure features and operating characteristics. The decision maker should use the methodology developed in this paper based on the most appropriate information related to the operations on their rail networks.

6. Conclusion

This research provides a decision support tool to quantify the amount of risk reduction by implementing various types of risk reduction strategies, including broken rail prevention, train speed reduction and tank car upgrade. The model takes into account the marginal safety benefit of each risk reduction strategy and their interactive effects. The framework model developed in this paper can be further developed to achieve the ultimate goal of optimizing the portfolio of risk reduction strategies at any level of resources available.

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