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Integrated risk reduction framework to improve railway hazardous materials transportation safety

Xiang Liu*, M. Rapik Saat[1], Christopher P.L. Barkan[2]

Rail Transportation and Engineering Center, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801, United States

HIGHLIGHTS

- An integrated framework is developed to optimize risk reduction.
- A negative binomial regression model is developed to analyze accident-cause-specific railcar derailment probability.
- A Pareto-optimality technique is applied to determine the lowest risk given any level of resource.
- A multi-attribute decision model is developed to determine the optimal amount of investment for risk reduction.
- The models could aid the government and rail industry in developing cost-efficient risk reduction policy and practice.

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ABSTRACT

Rail transportation plays a critical role to safely and efficiently transport hazardous materials. A number of strategies have been implemented or are being developed to reduce the risk of hazardous materials release from train accidents. Each of these risk reduction strategies has its safety benefit and corresponding implementation cost. However, the cost effectiveness of the integration of different risk reduction strategies is not well understood. Meanwhile, there has been growing interest in the U.S. rail industry and government to best allocate resources for improving hazardous materials transportation safety. This paper presents an optimization model that considers the combination of two types of risk reduction strategies, broken rail prevention and tank car safety design enhancement. A Pareto-optimality technique is used to maximize risk reduction at a given level of investment. The framework presented in this paper can be adapted to address a broader set of risk reduction strategies and is intended to assist decision makers for local, regional and system-wide risk management of rail hazardous materials transportation.

1. Introduction

There are approximately two million annual rail carloads of hazardous materials (hazmat) in North America [1]. Although the majority of these shipments (99.996% in 2011) safely reach their destinations [1], the potential severe consequence of a hazmat release incident remains a major safety concern to the rail industry, government and public in the U.S. For example, the consequent release of chlorine gas from a train collision in Graniteville, South Carolina in January 2005 resulted in 9 fatalities, hundreds of injuries, an evacuation of about 5400 people and economic loss exceeding $6.9 million [2]. There has been growing interest and intensifying regulatory requirement in the U.S. to improve the safety of railway hazmat transportation. Improvements have focused on enhancing packaging and tank car safety design [3–9], deploying wayside defect detection technologies [10–13], upgrading track infrastructure [14–16], routing [17–22], reducing train speed [22] and improving emergency response practices [23]. Each strategy has a direct effect on the hazmat release risk, and different strategies may also have interactive effects.

However, how to optimize the integration of different risk reduction strategies in the most cost-efficient manner is not well understood. In order to facilitate a risk-based decision, this paper develops an integrated risk reduction framework, accounting for the cost-effectiveness of an individual risk reduction strategy, their interactive effects and optimal integration. The paper is structured as follows. First, we formulate hazmat risk management as a multi-attribute decision analysis problem. Then, we develop a Pareto-optimality approach to determine the lowest risk that can be achieved at a specific level of investment. Understanding the risk-and-cost relationship leads to development of a decision

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* Corresponding author. Tel.: +1 217 244 6063; fax: +1 217 244 6063.
E-mail addresses: liu94@illinois.edu (X. Liu), mohdsaat@illinois.edu (M.R. Saat), cbarkan@illinois.edu (C.P.L. Barkan).

[1] Tel.: +1 217 333 6974; fax: +1 217 333 6974.

[2] Tel.: +1 217 244 6338; fax: +1 217 244 6338.

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model to determine the “optimal” investment. To illustrate the methodology, we analyze cost-effectiveness of broken rail prevention, tank car safety design enhancement and their optimal combination under budgetary constraint. Although the model implementation is based on U.S. data, the methodology may be adapted to the rail systems in other regions.

2. Multi-attribute decision model for hazmat transportation risk management

Hazmat transportation risk management can be formulated as a multi-attribute decision problem. It is assumed that certain risk reduction strategies are implemented to reduce the baseline risk (R_0) to a lower level (R). The associated implementation cost is I. Given a specific investment I_i, there is an optimal combination of risk reduction strategies so as to achieve the lowest risk. Let $R^*(\mathrm{I}_i)$ define the lowest risk given investment I_i. For a rational decision making, additional investment should not worsen the system safety, that is:

$$\text{If } I_j > I_i, \quad \text{then } R^*(I_j) \le R^*(I_i) \tag{1}$$

In Eq. (1), the equality holds when the additional investment ($I_j - I_i$) does not result in additional safety benefit. Fig. 1 illustrates the relationship between $R^*(I)$ and I. This relationship is called Pareto-optimality in economics [24]. In the context of hazmat risk management, Pareto-optimality means that the safety cannot be further improved without additional investment. When Pareto-optimality is used in a multi-attribute decision analysis model, the “optimal” investment (I^{**}) and the corresponding risk (R^{**}) can be determined.

In decision analysis, the value function is a general approach to account for the decision maker’s preference and trade-off between multiple attributes (such as the risk and cost) [25]. The linear form of value function has been used in previous studies and it has practical convenience [26,27]. A value function $V(R,I)$ is defined based on the risk and corresponding investment to reduce the baseline risk to a lower level of risk.

$$V(R, I) = W_R R + W_I I \tag{2}$$

where $V(R,I)$ = value function of risk and investment, R = proportion of baseline risk (R = 100% for baseline risk), I = investment for reducing the baseline risk (R_0) to a lower level of risk R, W_R = first-order partial derivative of the value function with respect to risk, W_I = first-order partial derivative of the value function with respect to investment.

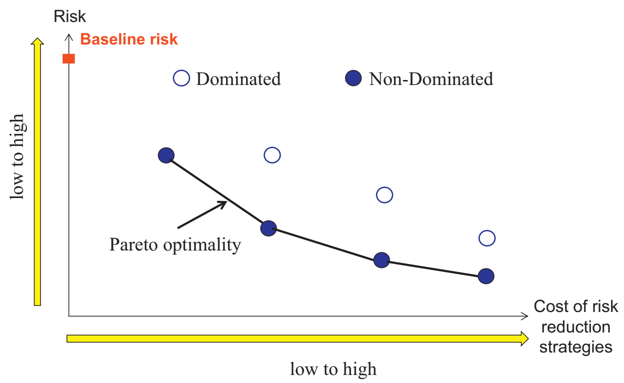

Fig. 1. Schematic illustration of Pareto-optimality in hazardous materials transportation risk management.

On the Pareto-optimality frontier, the minimum risk can be estimated as a function of investment, denoted as $R = g(I)$. Eq. (2) can be re-written as:

$$V(R, I) = W_R g(I) + W_I I \tag{3}$$

The optimal investment (I^{**}) is determined by solving the following equation:

$$\frac{\partial V(R, I^{**})}{\partial I^{**}} = W_R \frac{\partial g(I^{**})}{\partial I^{**}} + W_I = 0 \tag{4}$$

Eq. (4) can be simplified as:

$$\frac{\partial g(I^{**})}{\partial I^{**}} = -\frac{W_I}{W_R} \tag{5}$$

If the optimal investment (I^{**}) exceeds the budgetary constraint ($I_{\max}$), the optimal decision may be either no investment ($I^{**} = 0$) or using all the budgets ($I^{**} = I_{\max}$), depending on the value function. In order to optimize the allocation of investment, we need to estimate the safety effectiveness and cost of a risk reduction strategy. In the next section, we introduce a railway hazmat transportation risk model.

3. Railroad hazmat transportation risk analysis model

In rail transport of hazardous materials, risk is generally defined as a multiplication of derailment rate of a hazmat car, traffic exposure, conditional probability of release (CPR) of a derailed hazmat car and the consequence of a car release (Eq. (6)) [14,15,22,23,28,29].

$$R = Z \times M \times P \times C \tag{6}$$

where R = hazardous materials release risk (e.g., expected affected population), Z = hazmat car derailment rate per billion car-miles, M = traffic exposure (e.g., billion car-miles), P = CPR of a derailed hazmat car, C = consequence of a car release (e.g., number of people affected).

Hazmat car derailment rate is defined as the number of cars derailed by traffic exposure (e.g., train-miles, car-miles or ton-miles). Car derailment rates vary by track characteristics [28,30,31]. The CPR of a hazmat car reflects its safety performance. The majority of railroad hazardous materials shipments (72%) and the greatest quantity are in tank cars [1], thus tank car safety design analysis and improvement has been a priority in the U.S. rail industry and government. Treichel et al. developed a logistic regression model to estimate the CPR of a derailed tank car given its configuration [32]. Kawprasert and Barkan extended Treichel et al.’s model by accounting for 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 [8,22,23]. The hazard exposure model provided in the U.S. Department of Transportation (U.S. DOT) Emergency Response Guidebook (ERG) can be used to estimate the affected area based on the material and scenario of release (fire, spill, daytime, nighttime) [33]. 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. The assessment of release consequence could be performed using Geographical Information System (GIS) [22].

Fig. 2 illustrates two basic strategies to reduce tank car release risk: (1) reduce the likelihood of a hazmat release incident; (2) reduce release consequences. This study focuses on the former – reducing the likelihood of a hazmat release incident.