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Optimizing Rail Defect Inspection Frequency to Reduce the Risk of Hazardous Materials Transportation by Rail

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SUMMARY

Rail defects are the most frequent cause of freight train derailments and a major hazard to the transportation of hazardous materials in the United States. Railroads periodically inspect their rails using ultrasonic technologies to prevent train derailments, thereby mitigating transportation risk. This research quantifies the relationship between ultrasonic rail defect inspection frequency and railroad hazardous materials transportation risk. A Pareto optimization model is developed to determine optimal annual inspection frequencies on different track segments with different risk levels. The model provides an evaluation of segment-specific hazardous materials transportation risk due to rail failures, as well as an assessment of risk-based prioritization of rail defect inspection. The model can be adapted to other types of hazardous materials or account for other accident causes in the future.

KEY WORDS: Ultrasonic Rail Defect Inspection, Train Derailment, Railroad Safety, Pareto-Optimization, Hazardous Materials

1. INTRODUCTION AND MOVITATION OF STUDY

Railway is a safe and efficiency way of transporting large quantities of hazardous materials (hazmat) over long distances. In 2014, 2.2 million carloads (176 million tons) of hazardous materials were transported by rail in the United States. Hazardous materials account for seven percent of railroads' total carloads and 14 percent of total gross revenue (behind coal and intermodal) [1]. Although over 99.99 percent of railroad hazmat carloads safely reach their destinations without a release incident [2], hazmat transportation still represents a significant safety concern given the potential impact of a release on human health, property and the environment. A notable example is the Lac-Mégantic crude oil train accident in Canada in July 2013, which caused 47 fatalities and resulted in thousands of evacuees and millions of dollars in damages [3].

According to the author's analysis of the U.S. Federal Railroad Administration (FRA) railroad accident database, between 2000 and 2014, there were 1,032 hazardous materials cars derailed or damaged in broken-rail-caused derailments, accounting for 24 percent of derailments among all derailment causes, more than any other cause (Figure 1). In 2016 alone, broken-rail-caused freight train derailments caused $ 22 million track and rolling stock damage costs.
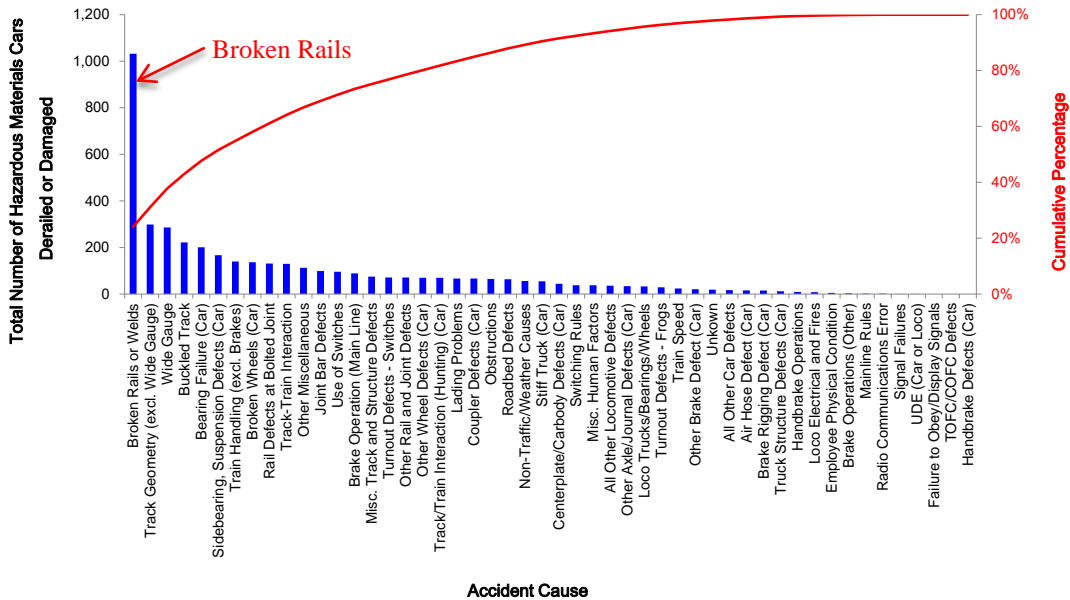

**Figure 1 hazardous materials cars derailed by accident cause
on mainlines in the U.S., 2000 to 2014**

Broken rails have caused a number of recent hazardous materials train derailments. For example, a CSX train was carrying 3 million gallons of crude oil when it derailed on Feb. 16, 2015 in Mount Carbon, West Virginia. Twenty-seven of the train's 109 cars derailed. Twenty cars leaked crude oil. The FRA said the broken rail resulted from a rail crack that was missed during two inspections in December 2014 and in January 2015 [4]. In fact, inspection for rail defects is an important issue for track infrastructure health. According to Schafer and Barkan [5], the U.S. railroad industry spends over $850 million annually for inspecting and repairing rail defects. In the context of hazmat transportation, the considerable investment in track safety requires a better understanding of what the risk is, how it is spatially distributed, and how to prioritize the resources for minimizing the total risk in the most cost-justified manner.

To address these questions, this paper develops a probabilistic risk analysis (PRA) model specific to broken-rail-caused hazardous materials release incidents. The remainder of this paper is as follows. Section 2 reviews the previous literature, identifies knowledge gaps and clarifies the scope and objectives of this paper. Sections 3 and 4 explain a methodological framework for quantifying broken-rail-caused hazardous materials transportation risk, and the parameters needed to implement the risk model. Section 5 applies the methodology to a numerical case study. Section 6 presents a sensitivity

analysis to evaluate risk inspection frequency optimization given different inspection technology reliability and tank car placement scenarios. Although this paper focuses exclusively on broken rails, the risk analysis framework developed herein can be adapted to other types of accident causes (e.g., track geometry failures, broken wheels, human errors) in future research.

2. LITERATURE REVIEW

This section reviews the occurrence of broken rails, broken-rail-caused derailments and the number of tank cars derailing or releasing contents in a train derailment, as well as the consequences of a release.

2.1. Occurrence of broken rails

There are several types of rail defects, such as longitudinal defects, transverse defects, base defects and others [6]. Transverse defects related to metal fatigue are one of the more common severe defects leading to rail service failures and train derailments [7,8]. Previous studies found that rail design, rolling stock characteristics, inspection and maintenance schedules all affect the risk of broken rails. The mechanism of rail crack formation and growth through theoretical modeling and laboratory testing has been extensively studied in the literature. For example, Farris et al. [9] studied the effect of service loading on shell growth using a two-dimensional linear elastic fracture mechanics model combined with a fatigue crack path stability model. Orringer et al. [10] developed a comprehensive study of the crack propagation behavior of detail fractures based on full-scale crack growth experiments in a test track, similar field tests, and observations on revenue tracks. Aglan & Gan [11] examined the fatigue crack growth behavior of head-hardened premium rail steel under load. This study found that cleavage facets initiated from the grain boundaries led to instability in the third stage of crack growth. Skyttebol et al. [12] studied the effect of residual stresses on fatigue crack growth in rail welds. The authors found that fatigue is strongly dependent on ambient temperature, time before failure depends on axle load, and that surface cracks are more dangerous than an embedded crack in the rail. Zumpano and Meo [13] studied new detection techniques for a rail damage alternative to ultrasonic inspection.

Another group of researchers modeled the occurrence of broken rails using statistical approaches. Shry and Ben-Akiva [14] established a relationship between fatigue failures of rail and factors affecting fatigue. The authors developed both a survival function and a hazard function for the condition of the rail. Dick [15] evaluated the factors affecting broken rail service failures and derailments using a multivariate analysis of predictor variables. Dick et al. [16] developed a broken rail prediction model to estimate broken rail risk given rail age, rail weight, degree of curvature, speed, average tons per car, average dynamic tons per car, percent grade, annual gross tonnage, annual wheel passes, presence of insulated joints, and presence of mainline turnouts. Sourget and Riollet [17] developed two models for prediction of broken rails: logistic regression and decision trees. Liu et al. [8] developed an exponential model to correlate broken rail rate with inspection frequency. The authors found that more frequent rail defect inspections could

reduce broken rail risk.

Based on the mechanistic and statistical models, some researchers developed studies to optimize the risk management of rail breaks. For example, Palese and Zarembski [18] and Zarembski and Palese [19] described the risk-based ultrasonic inspection program currently implemented by the BNSF railway company. They considered a risk-based approach to scheduling inspections based on three factors: defect initiation, defect growth, and detection reliability. Some of the risk factors developed for specific BNSF track segments were passenger-carrying-miles, dark territory, single-track territory, and BNSF-defined key routes. The authors determined that both the service failure rate and the service-failure-to-detected-defect ratio have decreased significantly with use of the risk-based inspection scheduling. They used risk-based approaches to optimize the locations for rail inspection. Zhao et al. [20] studied the risk of derailment of railway vehicles due to rail defects and broken rails. Four models were developed in this study, specifically for thermite weld defects, imperfect inspections, fatigue defects, and the impact of grinding on reducing defects, respectively.

2.2. *Broken-rail-caused derailment*

Many broken rails can be detected visually by track inspectors or other staff. In addition, broken rails can be detected by electrical track circuits - a portion of which are composed of rails [21, 22]. Previous studies reported that around 0.5% to 1% of broken rails caused train derailments [23, 19, 7]. After a train is derailed, a number of locomotives or railcars could derail from the train. Although the total damage costs of a train accident are sometimes used as a metric of accident severity, the number of locomotives or railcars derailed is appropriate for analysis of railroad safety risk, because of its relationship with accident kinetic energy [24, 25]. The total number of cars derailed is affected by accident cause [26, 27, 28, 29, 30, 31], accident speed [32, 26, 27, 31], train length [26, 27, 31] and point of derailment [26, 27, 31]. Based on the derailment severity model, train position-dependent car derailment probability can be estimated.

2.3. *Tank car derailment and release*

Depending on derailment severity and the number and placement of hazardous materials in a train, a train derailment may result in a number of tank cars derailed and possibly releasing contents. For each derailed tank car, its release can be viewed through a Bernoulli process. The Bernoulli probability represents the conditional probability of tank car derailment. This probability is affected by tank car safety design features, accident speed, and other accident circumstances [25]. If a train carries more than one type of tank car, each tank car will have its own release probability. If these release probabilities are independent, a Poisson binomial model can be used to predict the number of tank cars releasing contents given the total number of tank cars derailed [25]. If the release probabilities among different tank cars are dependent, a generalized binomial model can be used to calculate the probability of multiple cars releasing content [33].

2.4. Release consequence

The release consequence can be evaluated by several metrics, such as the number of casualties and evacuees, property damage, traffic delays, environmental impact, litigation, business loss and other factors. The affected area is subject to many variables, including chemical properties, quantity released, rate of release, meteorological conditions and local terrain [34]. The USDOT Emergency Response Guidebook (ERG) recommends that emergency responders determine initial isolation and protective action distances for specific chemicals and scenarios of release [35]. According to the recommended evacuation distance, geographical information system (GIS) techniques were used to estimate the affected population, which is widely used as a metric for release consequence [36, 37].

2.5. Knowledge gaps in railroad hazmat transportation risk management

Previous studies have identified various risk reduction strategies to improve the safety of rail transport of hazardous materials. Some risk reduction options include tank car upgrade [38, 39]; speed reduction [40]; routing [41, 42]; tank car placement [28, 43, 44] and rail defect inspection [45] (Table 1).

Table 1 Selected railroad hazmat transportation risk reduction strategies

Risk Reduction Strategy	Selected Publications
Tank Car Enhancement	Barkan et al. (2008); Saat and Barkan (2011); Liu (2016)
Speed Reduction	Kawprasert and Barkan (2010); Liu et al. (2014)
Routing	Glickman et al. (2007); Kawprasert and Barkan (2008)
Tank Car Placement	Bagheri et al. (2011, 2012, 2014)
Rail Defect Inspection	Liu and Dick (2016)

As seen in Table 1, regarding rail defect inspection for hazmat transportation risk management, the only published paper is developed by Liu and Dick [45]. In that paper, the authors proposed a model to estimate broken-rail-caused hazmat transportation risk for a particular train type called a "unit-train," in which all the railcars contain the same commodity. However, their study does not account for a more general scenario in which a train could contain some hazmat cars and some non-hazmat cars (this type of train is called a mixed train or a manifest train). Unit hazmat train operation is a special type of the mixed train in which the number of non-hazmat cars is zero. Previous studies haven't shown that train configurations can affect hazmat transportation risk [28, 43, 44, 47]. Therefore, it is necessary to extend the prior research by accounting for a generalized train configuration consisting of any types of hazmat cars at any positions. This paper is developed to fulfill this research need.

2.6. *Contributions of this research*

The purpose of this research is to develop a generalized model to optimize rail defect inspection frequencies by track segment, accounting for rail condition, hazmat train configuration, reliability of inspection technology, tank car safety design, the number of and placement of tank cars in a train and adjacent population density along a rail route. The model can be further adapted to identify and prioritize cost-effective strategies for mitigating the risk associated with the rail transport of hazardous materials. This research aims to bring three-fold contributions to the literature and practice:

1) Quantify the complex relationship between rail defect inspection frequency and railroad hazmat transportation risk, accounting for any hazmat train configuration.
2) Develop a Pareto optimization model to determine risk-based rail defect inspection frequencies at different segments, under specified circumstances (e.g., considering tank car placement or the reliability of inspection technology).
3) The model can be used to inform decision makers to prioritize the allocation of limited safety resources to improve the safety of hazmat transportation by rail.

3. BROKEN RAIL CAUSED HAZMAT TRAIN TRANSPORTATION RISK ANALYSIS

The largest majority of railroad hazardous materials release incidents occur in train derailments [24]. Therefore, this paper focuses on train derailments. Train collisions and grade crossing incidents were not considered herein when modeling hazmat transportation risk. Risk is generally defined as the probability distribution of the (negative) consequence [48]. In the context of hazmat transportation, expected consequence (i.e., probability multiplied by consequence) has been used as a risk measure [4, 50, 42, 40 28, 43, 44]. The expected consequence model assumes risk neutrality. To account for risk aversion towards catastrophic consequences, researches also developed a disutility based risk model [51]. Although risk-aversion-based risk analysis model is theoretically sound, it is more difficult to develop and interpret for practical risk planning purpose in the industry. For practicality, this paper uses the expected consequence to represent the risk. If the population in the evacuation zone (affected population) measures the release consequence, the risk can be interpreted as the expected number of affected persons.

Note that a broken-rail-caused release incident can occur on any segment of a route. For example, for one train shipment, if a release occurs on the second segment, it indicates that there is no release on the first segment. So the probability of release is $(1-P_1)P_2$. The consequence of release on the second segment is C_2. Therefore, in this particular case, the expected consequence (aka. risk) is $(1-P_1)P_2C_2$. Similarly, if a release occurs on the ith segment, it means that there is no release incident on all the prior segments (1, 2, 3,…, i-1). An original train shipment will terminate if a derailment occurs [64]. It is possible that some of the unaffected railcars will continue the trip on the route as a new shipment. Route-specific railroad hazmat transportation risk per shipment is calculated as follows:

$$R = \sum_{i=1}^{N} P_i C_i \tag{1}$$

Where

R   = hazardous materials transportation risk

P_i = the probability of a release incident on the ith segment, due to a broken rail

C_i = consequence of a release (e.g., affected population) on the ith segment

Segment-specific release probability (P_i) is further estimated as a product of train derailment probability ($P_i(TD)$) and the conditional probability that a train derailment causes a release ($P_i(X_R|TD)$):

$$P_i = P_i(TD) \times P_i(X_R \mid TD) \tag{2}$$

Where

$P_i(TD)$ = probability of a hazmat train derailment when this train traverses the ith track segment

$P_i(X_R|TD)$ = probability of a release incident after a hazmat train is derailed

Train derailment rate (Z_i) is sufficiently small. Based on these conditions, derailment probability on a segment is approximately equal to the product of derailment rate and segment length:

$$P_i(TD) = Z_i L_i \exp(-Z_i L_i) \approx Z_i L_i \tag{3}$$

where:

Z_i = broken-rail-caused hazmat train derailment rate per mile per shipment

L_i = segment mileage

The U.S. railroads typically arrange their rail inspection and maintenance schedules on an annual basis. Given multiple hazmat train shipments each year (B), the annual frequency of broken-rail-caused hazmat train derailments per mile is:

$$F_i(TD) = B \times P_i(TD) = B \times Z_i \times Li = BZ_i \times L_i \tag{4}$$

Where:

$F_i(TD)$ = annual frequency of broken-rail-caused hazmat train derailments on the ith segment

BZ_i = annual broken-rail-caused hazmat train derailment rate per mile ($B \times Z_i$)

The estimated annual broken-rail-caused train derailment rate per mile (BZ_i) can be estimated as a multiplication of annual number of broken rails per mile (S_i), and the proportion of broken rails causing hazmat train derailments ($P_i(D|B)$).

$$BZ_i = S_i \times P_i(D|B) \tag{5}$$

Where:

S_i = annual number of broken rails per mile

$P_i(D|B)$ = proportion of broken rails causing hazmat train derailments

Broken-rail-caused train accident probability, $P_i(D|B)$, can be estimated as a product of the percentage of hazmat trains among all rail traffic and the percentage of broken rails causing accidents (there is presumably no difference in the probability that a broken rail causes a hazmat train accident versus other types of freight trains), therefore,

$$P_i(D|B) = \theta_i \times Q_i \tag{6}$$

Where:
θ_i = probability that a broken rail that would cause derailments, regardless of whether it is a hazmat train (assuming 1% in this paper, based on an engineering study from Zarembski & Palese [19]).
Q_i = proportion of hazmat trains on a particular segment (this proportion could vary by route and traffic composition)

The probability that a hazmat train derailment would cause at least one tank car to release contents, denoted as $P_i(X_R|TD)$, can be modeled as follows using Equation (7). This equation considers heterogeneous tank car derailment and release probabilities at different train positions. For example, suppose that a tank car is located at the jth position of a train. If this train is derailed on the ith track segment, the probability of derailing for this tank car is denoted as $PD_i(j)$. After this tank car is derailed, its release probability is represented by $CPR_i(j)$. Assuming that the releases of different tank cars are independent of each other, the probability of at least one tank car release in a train derailment is equal to one minus the total probability that none of the derailed tank cars release contents (complementary probability):

$$P_i\left(X_R | TD\right) = 1 - \prod_{j=1}^{J}[1 - PD_i(j) \times CPR_i(j)] \tag{7}$$

Where:
$PD_i(j)$ = derailment probability of a tank car at the jth position of a train, when this train is derailed on the ith track segment
$CPR_i(j)$ = conditional probability of release of a derailed tank car
J = total number of tank cars in a train

Furthermore, position-dependent car derailment probability can be estimated as follows [26, 27]:

$$PD_i(j) = \sum_{g=1}^{L}\left\{POD_i(g) \times \sum_{x=j-g+1}^{L-g+1} PN_i(x)\right\} \tag{8}$$

where:
$POD_i(g)$ = point-of-derailment probability for the gth position of a train if a train is derailed on the ith track segment
$PN_i(x)$ = probability of derailing x cars in a train derailment on the ith segment
L = train length (total number of cars in a train, including locomotives)

Finally, based on Equations (1) to (8), route-specific railroad hazmat transportation risk can be expanded as follows:

$$R_{route} \approx \sum_{i=1}^{N} \left[S_i L_i \theta_i Q_i \left\{ 1 - \prod_{j=1}^{J} [1 - \sum_{g=1}^{L} \{POD_i(g) \times \sum_{x=j-k+1}^{L-g+1} PN_i(x)\} \times CPR_i(j)] \right\} C_i \right]$$

$$(9)$$

The next section will introduce the estimation of the parameters used in the risk model (Equation 9).

4. PARAMETER ESTIMATION

Implementation of the risk model relies on the estimation of a number of parameters, including number of broken rails per mile (S), point of derailment (POD(g)), number of cars derailed per derailment (PN(x)), tank car release probability (CPR(j)) and release consequence (C). These parameters have been studied, to some extent, in previous studies. However, the integration of these parameters using the latest information in a broken-rail-caused railroad hazmat transportation risk modeling and optimization is not available. In the following subsections, I will briefly explain the approaches to estimating these principal risk parameters based on up-to-date data. I do not duplicate the effort to explain the detailed methods for estimating these risk parameters. Readers can refer to the cited references for more technical details.

4.1. Number of broken rails per mile, S

The annual number of broken rails per mile (S_i) can be estimated using an engineering model originally developed by USDOT Volpe Transportation Systems Center [10,52]. This model represents a comprehensive mechanistic study of rail defect formation and growth. Note that this model was developed based on both field tests and in-service tests at the Association of American Railroads and several railroads almost two decades ago. We are unaware of any updated model to reflect the latest railroad operational and infrastructural conditions. Also, there might be alternative models for estimating rail break occurrence. My intent is to provide an illustrative risk analysis methodology that offers the flexibility for industry practitioners to use other valid models. When new data becomes available, the model can be modified accordingly risk factor for broken rails. Rail age is an important risk factor for broken rails [10]. Rail age is measured by cumulative tonnage on the rail. When a new rail is laid, its initial rail age is set to be zero. As traffic accumulates, its rail age increases. We can estimate rail age at a given inspection time, based on inspection interval and number of inspections per year.

$$S_i = \sum_{m=1}^{K_i} \left\{ A \times \frac{e^{\left(\frac{N_{i,m-1}}{\beta}\right)^{\alpha}} - e^{\left(\frac{N_{i,m-1} \mid X_{i,m}}{\beta}\right)^{\alpha}}}{1 + \lambda\left(\frac{T_i}{K_i} - \mu\right)} \times \lambda\left(\frac{T_i}{K_i} - \mu\right) \right\}$$

(10)

Where,

S_i = Annual number of broken rails per mile on the ith segment

A = number of 39-foot rail sections per track-mile, 273

α = Weibull shape factor, 3.1 [23]

β = Weibull scale factor, 2150 [23]

λ = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval curve, 0.014 [52]

μ = minimum rail inspection interval, 10 MGT

$N_{i,m-1}$ = rail age (cumulative gross tonnage on the rail) at the $(m-1)^{th}$ inspection on the ith track segment, $N_{i,m} = N_{i,m-1} + X_{i,m}$

$X_{i,m}$ = traffic volume (measured by million gross tons) between the $(m-1)^{th}$ and m^{th} inspection on the ith track segment

T_i = annual traffic density (million gross tons) on the ith segment

K_i = annual ultrasonic rail defect inspection frequency on the ith segment

4.2. Point of Derailment, POD(g)

Point of derailment (POD) is the position where the vehicle (locomotive or railcar) is initially derailed. The first vehicle (generally the lead locomotive) is frequently the POD in a train derailment. Previous studies have found that the POD affects the number of vehicles derailed, holding other factors constant [26, 27, 53, 28, 43, 44 31, 25]. To account for different train lengths, the normalized POD (NPOD) was calculated by dividing POD by train length. Using the FRA train derailment data between 2002 and 2011, we found that the "best-fit" for the NPOD distribution (all accident causes combined) is a Beta distribution, Beta (0.6793, 0.8999) (P = 0.48 using the Kolmogorov-Smirnov Test). Given a train length L, the probability that the POD is at the gth position, POD(g), can be estimated using the following equation:

$$POD(g) = F\left(\frac{g}{L}\right) - F\left(\frac{g-1}{L}\right)$$

(11)

Where:

POD(g) = POD probability at the gth position of a train

F() = cumulative density distribution of the fitted normalized POD distribution

L = train length (total number of cars in a train)

For example, for a 100-car train (L=100), the estimated POD (g=1) is 0.040, and POD (g=2) is 0.024 from the fitted Beta distribution. It is interpreted that there is 4.0 percent chance that the derailment initiates from the first unit in a train (i.e., lead locomotive), and a 2.4 percent chance that the derailment initiates from the second car. Each car may be the POD, though with differing probabilities.

4.3. Number of Cars Derailed, PN(x)

The number of locomotives or railcars derailed is frequently used in railroad safety analysis because of its relationship with accident kinetic energy [24]. The total number of cars (including locomotives thereafter) derailed is affected by accident cause [26, 27, 28, 31], accident speed [32, 26, 27, 31], train length [26,27, 31] and point of derailment [26, 27, 31]. The statistical model for estimating train accident severity was first developed by Saccomanno and El-Hage [26,27], and subsequently modified by Anderson [53] and Bagheri et al. [28], respectively. The probability distribution of the number of cars derailed given the POD can be estimated as:

$$PN_i(x) = \frac{\dfrac{\exp(z)}{1+\exp(z)}\left[\dfrac{1}{1+\exp(z)}\right]^{x-1}}{1-\left[\dfrac{1}{1+\exp(z)}\right]^{L-g+1}} \tag{12}$$

$$Z = a + b \times \ln(V) + c \times \ln(Lr) + d \times I(POD) \tag{13}$$

Where:
$PN_i(x)$ = the probability that x cars derailed given the POD on the ith segment
V = accident speed (mph)
L = train length (total number of cars in a train, including locomotives)
L_r = residual train length, defined as the number of cars between the POD and the train end ($L_r = L - g + 1$)
I(POD) = 1 if the POD is a loaded car, 0 otherwise
a = 1.215 (U.S. freight train derailment data from 2002 to 2011, the same data for other parameters)
b = -1.206
c = 0.004
d = -0.312

4.4. Tank Car Release Probability

The conditional probability of release (CPR) of a derailed tank car reflects its safety performance in accidents. The Association of American Railroads (AAR) and Railway Supply Institute (RSI) maintained an industry-wide tank car safety database since the 1970s. This database records detailed information regarding the design, accident speed and release status of each derailed or damaged tank car in a train accident. Although this proprietary database is not publicly available, the AAR-RSI periodically publishes average tank car release probabilities (Table 2). For example, USDOT [54] specifies a new tank car design (DOT-117) for transporting flammable liquids. This type of tank car has head and shell thickness of 0.5625 inch, with jacket, full height head shields and top fitting protection. According to the Treichel [47], its release probability is 0.029. It means

that an average of 3 tank cars of this type are expected to release contents given 100 tank cars are derailed or damaged.

Table 2 Tank car design specifications and conditional probability of release

Tank Car Design	Head Thickness (inch)	Shell Thickness (inch)	Jacket	Head Shields	Top Fittings Protection	Conditional Probability of Release (CPR)*
Conventional, Non-Jacketed	0.4375	0.4375	No	None	No	0.196
Conventional, Jacketed	0.4375	0.4375	Yes	None	No	0.085
Non-Jacketed CPC 1232	0.5000	0.5000	No	Half Height	Yes	0.103
Jacketed CPC 1232	0.4375	0.4375	Yes	Full Height	Yes	0.046
DOT-117	0.5625	0.5625	Yes	Full Height	Yes	0.029

Notes: The CPR values are from Treichel [47]. The CPR of a tank car in Table 2 is for a release of more than 100 gallons according to current practice in the U.S. railroad industry

Note that the AAR published CPR statistics were based on 26 mph train derailment speed [55]. To the author's best knowledge, the only published speed-dependent CPR was estimated by Kawprasert and Barkan (2010) based on tank car accident data provided by the Association of American Railroads (AAR) and Railway Supply Institute (RSI). These results were used to develop a linear regression model in which the release probability is approximated by a linear function of derailment speed given tank car safety design ($R^2 >$ 0.95). The RSI and AAR are anticipated to publish updated speed-dependent CPRs in the near future, at which time their forthcoming tank car safety statistics will be used in a revised risk model. Future research should be directed towards a better understanding of tank car safety performance under specified accident characteristics." There might be uncertainty regarding tank car release probability under different accident conditions. Future research should be directed towards a better understanding of tank car safety performance under specified accident characteristics.

4.5. Consequence of a tank car release incident, C

Population in the affected area (to be protected or evacuated) was often used in previous studies [49, 50] as a measure of consequence. The hazard exposure model provided in the U.S. DOT Emergency Response Guidebook (ERG) includes recommendations for the calculation of affected areas [35]. Therefore, in this paper, the affected area is a 0.5-mile-radius circle based on the ERG recommendation for a fire caused by flammable hazardous material releases [35]. Once the affected area is determined, the number of people affected can be estimated by multiplying the size of the affected area by the average population density within the affected area. In addition to affected population, environmental impact, infrastructure and rolling stock damage, train delay, loss of productivity may also be among the consequences of a release incident. Quantifying these consequences would require a case-by-case detailed assessment based on infrastructure and operating characteristics. To illustrate the methodology, this paper focuses on the risk measured in terms of the number of persons that would potentially be evacuated or protected. Use of this risk measure is aligned with the current evacuation

practices in the wake of a hazmat release. Future research can adapt the methodology to account for other types of consequences, such as traffic delay, environmental impact and property damage cost.

5. RAIL DEFECT INSPECTION FREQUENCY OPTIMIZATION

The U.S. Railroads often use a road–rail vehicle (also called high-rail vehicle) that can operate both on railway tracks and on conventional roadways to inspect rail defects. This type of inspection method allows for different inspection frequencies on different track segments. Skipping inspection of certain lower-risk segments might enable more frequent inspection of higher-risk track segment, thereby maximizing the magnitude of total risk reduction.

Generally, optimal ultrasonic rail defect inspection frequency can be formulated through a Pareto-optimization model under various engineering and operational constraints. When only the total risk and total mileage inspected are considered, a general optimization model is conceptually described as follows:

Minimize	$R(K_1, K_2, \ldots, K_N)$
Subject to	$L(K_1, K_2, \ldots, K_N) <= L_{max}$
	$K_i \leq K_{max}$
Decision variables	$K_1, K_2, \ldots, K_N$ are integers

Where:
R = total hazardous materials transportation risk on a route
L = total miles inspected
L_{max} = maximum amount of miles inspected (resource constraint)
K_{max} = maximum annual inspection frequency (a minimum of 10 MGT between two consecutive inspections, as per [52])
K_i = annual inspection frequency on the ith track segment

Given a certain level of inspection resource (L_{max}), the optimal segment-specific inspection frequency can be determined so as to minimize total route risk. At different levels of inspection resources (L_{max} changes), the varying optimal solutions construct a "Pareto frontier". The Pareto frontier represents the optimal scheduling of rail defect inspection frequency given a total mileage to inspect. For a finite number of inspection schedules, the Pareto frontier can be developed using the following algorithm:
1) Compute R and L for all possible inspection schedules; set i = 0 (base case); initialize the set of Pareto-optimal solutions, S = {∅}
2) From the ith schedule, find the schedule with the closest L and lower R than the current R(i)
3) Insert solution schedule (i+1) that has the minimum R among schedules identified in step 2 to the set of Pareto-optimal solutions
4) Repeat steps 2 and 3 until i = total number of schedules minus 1

In this research, I did not account for the logistical considerations (e.g., crew traveling) when skipping certain segments to achieve the minimum route risk. Instead, this research focuses on understanding the feasibility of risk-based approaches for scheduling ultrasonic rail defect inspection. The next step can be to adapt it based on railroad-specific business needs and data availability. In the next section, a numerical example is developed below to illustrate the application of the methodology.

6. CASE STUDY

The methodology developed above can be used for any type of hazardous material. In this paper, I focus on crude oil, which is currently the top traffic volume commodity, transported by rail, in the United States. The number of carloads of crude oil by rail has increased from 6,000 in 2005 to 500,000 in 2014, or an 80-fold increase [56]. Crude oil by rail represents a significant safety concern for both the public and private sectors given the potential impact of a release on human health, property and the environment.

6.1. Route Information

Hazardous materials routing is security sensitive. In this section, I used a real hazardous materials rail shipment route (made anonymous for this paper). The purpose is to illustrate the implementation and implications of the risk and Pareto optimization models. The route information was analyzed on a geographic information system (GIS) platform. The population density along each track segment was estimated by linking U.S. Census data to route data based on geographic information. The GIS analysis divided the 2,273-mile-long route into 1,164 track segments. The majority of the route segments are in signaled territories and are maintained to meet FRA Class 4 and Class 5 standards (the higher the track class, the more stringent safety standards apply, and allow for a higher operating speed). The average speeds by FRA track class are used in the numerical examples, which are 7.5 mph (FRA track class 1), 16.1 mph (class 2), 24.1 mph (class 3), 31.9 mph (class 4) and 37.1 mph (class 5). Using U.S. Census data, the average population density along this route is 349 people per square mile. For a crude oil release, it is assumed that the affected area is a 0.5-mile-radius circle based on the USDOT recommendation [35].

6.2. Baseline Risk

In this paper, we used the following input parameters for an illustrative case study. The model can be adapted to any other infrastructure and operational characteristics. For example, on one hypothetical route, the average rail age (in terms of cumulative tonnage on the rail) is 600 million gross tons, annual traffic density is 80 million gross tons, and the crude oil is shipped in DOT 117 tank cars. It is also assumed that 25 percent of the trains on this corridor are crude oil trains. It is also assumed that all segments on this route are currently inspected three times per year. In terms of train configuration, it is assumed that the train has 100 units (including locomotives), among which 10 tank cars

are fully loaded with crude oil. Without knowing the positions of the 10 crude oil tank cars, we conservatively assume that all of them are placed in the positions that are the most prone to derailment (worst case tank car placement scenario). Based on these assumptions, the segment-specific crude oil transportation risk due to broken rails is calculated and tallied into a route risk. The baseline annual risk on this route is 16, which means that annually, 16 people are expected to be affected by a crude oil hazmat train release incident caused by broken rails on this particular corridor.

6.3. Risk Hot Spot Identification

In the segment risk calculation process, I found that the risk is not equally distributed on the segment. For practical considerations, we delineate the segment-specific risk into three categories (i.e., low risk, medium risk, high risk) and require the same inspection frequencies on the segments within the same risk category. Jenks optimization algorithm is used to delineate risk categories. This optimization algorithm minimizes the variance within the same category and maximizes the variance between different categories [57]. This classification algorithm is widely used and implemented into ESRI's ArcGIS software. Table 3 illustrates the number of segments, mileage and risk within each risk category. A particular note is that 31 track segments with the highest annual risk accounts for only 6 percent of the route length but 36 percent of the total route risk. These high-risk segments are located in highly populated areas, with population density above 1,000 persons per square mile.

TABLE 3 Segment risk classification

Annual Risk Category on the Segment	Number of Segments	Percentage of Total Mileage	Percentage of Total Risk
Low (0 to 0.04)	1,065	86%	35%
Medium (0.04 to 0.12)	68	9%	29%
High (0.12 to 0.494)	31	6%	36%
Total	1,164	100%	100%

Due to rounding errors, the sum of rounded percentages is not equal to 100%

6.4. Pareto Optimization of Rail Defect Inspection Frequency

The current railroad practice involves inspecting all track segments of the same route at equal frequencies. In the context of rail transport of hazardous materials, the analysis above identifies that certain segments may have much higher risks than others. Therefore, we propose use of the hazardous materials transportation risk as a metric to prioritize the inspection of rail defects. The risk modeling accounts for broken rail rate, train derailment probability, number of tank cars derailing and releasing as well as the affected population. For illustration, within each risk category specified above, consider six

possible annual inspection frequencies on those segments, ranging from 2 to 7 inspections per year. For example, five inspections per year correspond to an inspection interval around 75 days (365/5). If there are three risk categories and each risk category has six possible annual inspection frequencies, there is a total of 6^3 (216) possible combinations of rail inspection schedules. For instance, consider one schedule where all track segments are inspected five times per year, denoted as (5, 5, 5). An alternative inspection schedule may be as follows: the low-risk track segments are inspected four times per year, medium-risk tracks receive six inspections per year and high-risk tracks are inspected seven times per year. This example scenario is denoted as (4, 6, 7). Compared to the first scenario in which all tracks are inspected five times per year, using an alternative schedule will lead to 18 percent risk reduction on the route, while the total inspected mileage is also reduced by 13 percent. This example indicates that risk-based ultrasonic rail defect inspection prioritization may achieve a substantial risk reduction with equal or fewer miles of track inspected. The estimated broken-rail-caused crude oil transportation risk and total mileage inspected for each possible rail inspection schedule are illustrated in Figure 2.
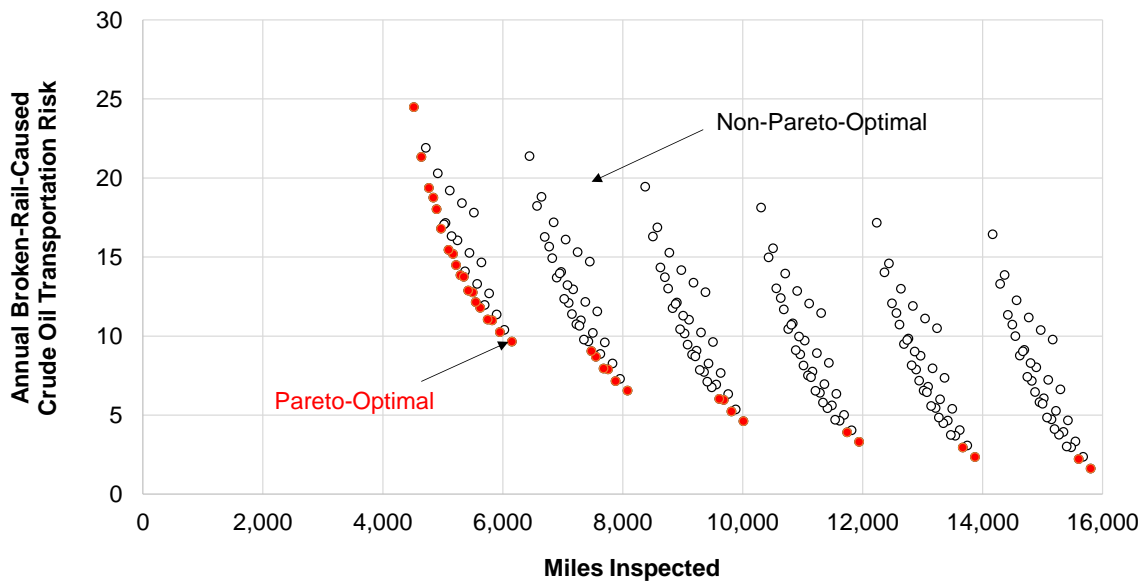

Figure 2 Pareto-optimization of broken-rail-caused hazmat transportation risk by total miles to inspect (three risk categories, 100 cars in a train in which there are 10 tank cars in the positions that are the most prone to derailment)

Notes: Due to the limited number of inspection scenarios, the Pareto-frontier is discontinuous hereafter.

7. SENSITIVITY ANALYSIS

Railroad engineering safety and risk analysis is a complex process that is dependent on various input parameters. The sensitivity of the risk with respect to each parameter

provides insights into the relative importance of each risk factor. Due to data limitation, this paper focuses on two potential risk reduction strategies for mitigating rail-failure-caused hazardous material transportation risk. The first strategy is to enhance the reliability of inspection technology, thereby improving the probability of identifying the defect and removing it before it causes a derailment. Another strategy is to reduce the probability of a crude oil tank car derailment by placing them at the positions which are less prone to derailment. The model can be adapted to other risk reduction strategies as well in future research.

7.1. Improving Defect Detection Reliability

The rail defect risk model in the paper is based on the current ultrasonic inspection technology. Considering that the industry has been improving the ultrasonic inspection technology, the paper considers baseline ultrasonic rail testing technology versus more advanced technology. The prior research uses the ratio of broken rails to detect rail defects (S/D) as a proxy variable to measure the effectiveness of ultrasonic rail defect inspection technology. The lower the ratio, the more reliable the technology is in identifying a defect [10]. This ratio has been used in developing the guidelines for rail testing schedules in the American railroad industry [58]. Besides this, inspection interval also affects the occurrence of broken rails. Orringer [58] depicts the relationship between the S/D ratio and the inspection interval (million gross tons) by a linear approximation. Orringer found that in general, 10 MGT is the minimum economically feasible inspection interval based on an engineering study of the growth rate of rail defect [52]. He also proposed the new linear relationship when using an improved inspection technology. Figure 3 compares the effectiveness of a baseline inspection technology (used in previously mentioned analyses) and the effectiveness of an improved technology. For example, at a 30 MGT inspection interval, using improved detection technology would reduce the broken rail ratio by approximately 20 percent (the S/D ratio for 30 MGT is 0.28 for the base detection, versus 0.22 for the improved detection).
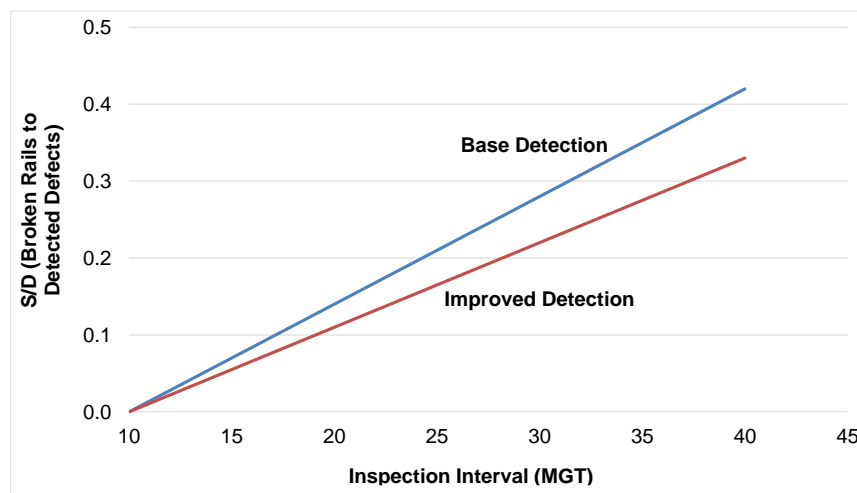

Figure 3 Base versus improved detection (adapted from Orringer 1990)

Figure 4 shows the two Pareto-optimal inspection scheduling solutions (for simplicity, non-Pareto-optimal solutions are not displayed herein) for improved detection, compared to the baseline inspection. It shows that improved inspection will reduce the risk given the same amount of mileage inspected. For example, using the improved detection technology, at 6,000 miles of total inspection mileage, the minimum risk level is 8.9 by using risk-based scheduling. By contrast, if using the baseline detection technology, the rail industry needs to inspect 7,500 miles for retaining the same level of risk. Equivalently, choosing an improving technology could equal inspecting 1,500 more miles per year. Depending on the technology cost and inspection cost, the rail industry can weigh the associated respective benefits and costs and make their optimal decisions on the selection of inspection technology and the total miles of inspection.
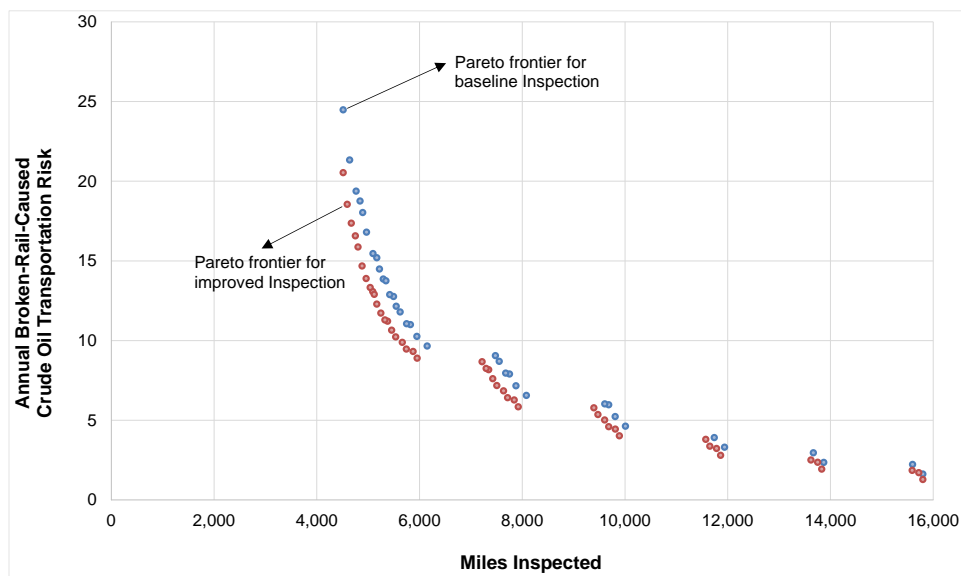

**Figure 4 Broken rail caused hazmat transportation risk
by baseline inspection versus improved inspection**

7.2. *Change of Tank Car Placement*

Bagheri et al. (28, 43, 44) demonstrate that tank car placement is a promising risk reduction strategy. After a train derailment occurs, tank cars at different positions have different derailment probabilities. For a mixed train, detailed train configuration information is generally not available to researchers. In this sensitivity analysis, I consider two extreme scenarios: all ten crude oil tank cars are in positions which are the most prone to derailment (worst scenario) or the least prone to derailment (best scenario). For each tank car placement scenario, I use risk-based scheduling to prioritize the segments for more inspections (Pareto frontier). Figure 5 shows the Pareto-optimal solutions (non-Pareto-optimal solutions are not shown here for simplicity).

The analysis shows that there is a large risk difference between the two alternative tank car place scenarios. When all of the tank cars are in the positions that are the least prone to derailment, the risk decreases by a factor of ten. This indicates that hazardous materials

transportation risk could be sensitive to tank car placement. When the railroad evaluates hazmat transportation risk, knowing the positions of tank cars in a train could be important. When the railroads have limited resources for improving the safety, they should understand the reduction of the risk due to infrastructure improvement versus change of operational practices. Given hazmat train configuration and rail defect detection reliability, the model developed in this paper can be used to prioritize the locations for more frequent rail defect inspections.
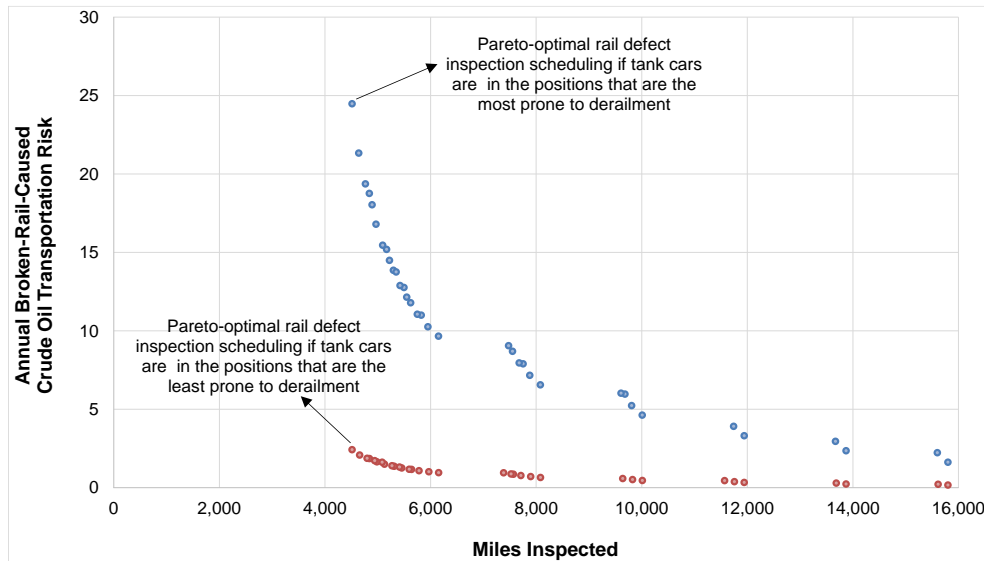

Figure 5 Risk-based rail defect inspection scheduling by tank car placement

The risk associated with a specific tank car placement is between the two extreme scenarios. The actual tank car placement can be affected by various operational and engineering constraints on main corridors and in yard marshalling [43].

7.3   *Contributions to the Literature and Practice*
The examples above demonstrate the feasibility of modeling the risk of transporting hazardous material due to rail failures. This research develops a generalized risk analysis model that accounts for principal factors affecting rail failures, train derailment likelihood, tank car derailment & release probability, as well as release consequences. To the author's knowledge, this is the first comprehensive model that can explicitly analyze broken-rail-caused hazmat transportation risk. In future research, the risk model can be adapted to other accident causes (e.g., track geometry failures, bearing failures), and ultimately aiding with the evaluation of various railroad hazmat risk reduction alternatives.

In terms of practice, this research identifies risk-based approaches to prioritize rail defect inspection frequencies on different segments, given specified train and track characteristics. The research shows that inspecting more trackage may result in an equivalent risk reduction, compared to other risk reduction options, such as increasing inspection reliability or changing tank car placement. The risk equivalency concept can

potentially be implemented by railroads to determine their most appropriate actions for risk management, given resource availability.

8. CONCLUSION

This research develops a model to evaluate the relationship between rail failures and hazardous materials transportation risk, accounting for any train configurations and track characteristics. The model is used on an example route to demonstrate the safety effectiveness of optimizing rail inspection frequency for risk reduction. The analysis shows that increased inspection frequency on a small number of high-risk segments may significantly reduce the overall route risk with a minimal increase in required resources. The research also shows that improving rail defect detection and changing tank car placement could lead to additional risk reduction, given an inspection schedule. The model can be further developed and incorporated into a larger risk management framework for improving railroad safety in a cost-efficient manner.

9. FUTURE RESEARCH

This paper focuses on broken-rail-caused hazardous materials transportation risk. The next step should consider a variety of other factors affecting railroad transportation risk, such as other track geometry defects [59, 60, 61], rolling stock condition sensing [62], speed reduction, routing [63], and emergency response. Also, future research can account for additional factors that may affect the safety effectiveness of rail defect inspection, such as the speed of the inspection vehicle, axle load and other factors. In addition to physical impacts in a derailment, future research should account for tank car releases due to thermal tear [56]. For example, in a crude oil train derailment, a fire frequently ensues due to the flammability of crude oil. These fires can engulf other derailed tank cars that had not failed during the initial derailment. Heat from a fire weakens the tank structure, potentially resulting in a sudden release of large quantities of product. Additionally, effective crew scheduling [60] should also be considered in the future to implement optimal inspection frequencies identified in this paper. Ultimately, an integrated risk management framework can be developed to optimize the allocation of resources to minimize the risk in the most cost-efficient manner.

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