Risk-Based Optimization of Rail Defect Inspection Frequency for Petroleum Crude Oil Transportation

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ABSTRACT

The rapid expansion of North American petroleum crude oil production from shale has led to a significant increase in rail transport of crude oil. Broken rails are frequent causes of train accidents. Ultrasonic rail defect inspection is widely used to prevent broken-rail-caused train accidents, thereby reducing hazardous materials transportation risk. This paper describes a new methodology to estimate unit-train crude oil transportation risk by location-specific rail defect inspection frequency. The risk model is used to develop a Pareto optimization model that determines segment-specific rail defect inspection frequency in order to reduce the total route risk in a cost-effective manner. A numerical case study is developed to illustrate the application of the risk analysis and optimization models. This research is intended to provide new methods and information to assist the railroad industry in optimizing investment in infrastructure improvement, thereby mitigating the risk of rail transport of crude oil and other hazardous materials.

1 INTRODUCTION

North America is experiencing significant growth in the production of petroleum crude oil from shale, driven by technological advancements in hydraulic fracturing and horizontal drilling. This has consequently led to a dramatic increase in crude oil transported by rail. In 2005, there were only 6,000 tank carloads of petroleum crude oil shipped in the U.S. By 2014, this number had increased to over 500,000, an 80-fold increase (*1*). Although over 99.99 percent of railroad crude oil carloads safely reach their destinations without a release incident (*2*), they still represent a significant safety concern for both the public and private sectors due to the potential impact of a release on human health, property and the environment. Recently, a spate of crude oil train accidents in North America attracted more intense attention to the safety of rail transport of crude oil and other hazardous materials. There are two basic strategies to reduce railroad crude oil (and hazardous materials in general) transportation risk: 1) reduce the likelihood of a release incident; and/or 2) reduce release consequences (*3*, *4*). This study focuses on the former – reducing the likelihood of hazmat release incidents by preventing train accidents.

In terms of accident prevention, it is first necessary to identify major causes of hazardous materials train accidents. All railroads operating in the U.S. are required to submit detailed reports on all accidents exceeding a monetary threshold of damage to on-track equipment, signals and track infrastructure (*5*). The Federal Railroad Administration (FRA) of the U.S. Department of Transportation (USDOT) compiles the submitted accident reports into their Rail Equipment Accident (REA) database. This database contains useful information regarding the time, location, circumstance, cause and consequence of each train accident. Analysis of the REA database shows that broken rails are the leading causes of hazardous materials cars releasing lading (Figure 1).

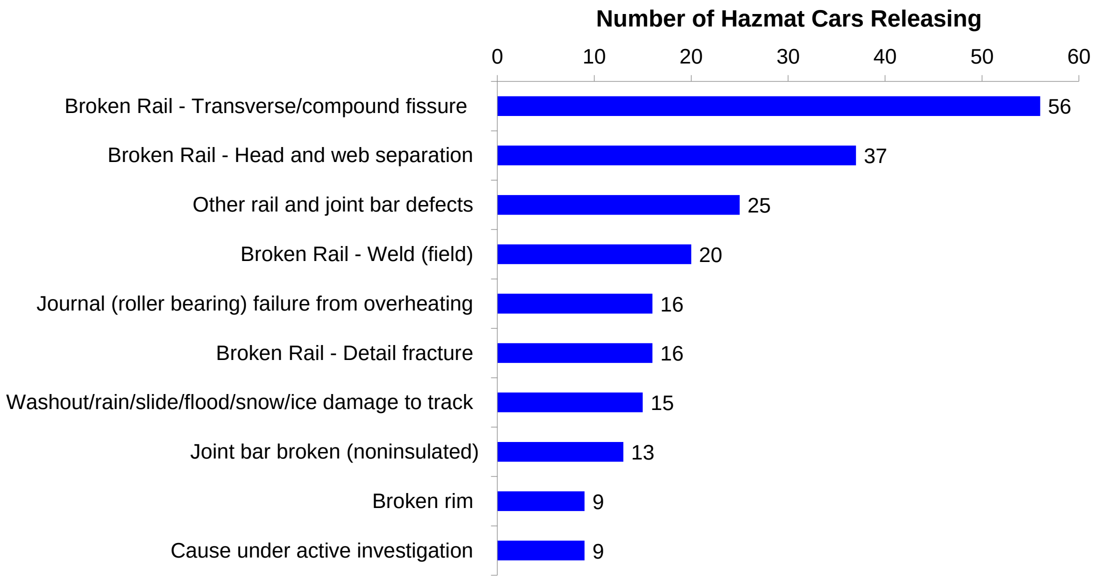


FIGURE 1 Number of hazmat cars releasing in freight-train derailments on U.S. railroads by accident cause from 2002 to 2011.

Broken rails have resulted in several recent derailments involving crude oil and other flammable liquids, such as those in New Brighton, Pennsylvania in 2006; Painesville, Ohio in 2007; Arcadia, Ohio in 2011; Aliceville, Alabama in 2013; and Lynchburg, VA in 2014. Therefore, broken rail prevention has been identified as a promising strategy to mitigate the risk of rail transport of hazardous materials (*6*-*12*).

There are various approaches to preventing broken rails, including rail grinding (*13*), lubrication (*14*), rail replacement (*15*), and non-destructive rail defect inspection (*16*-*18*). This paper focuses on ultrasonic rail defect inspection, a primary non-destructive inspection technology used by railroads in the U.S. since the 1930s. The principal objective of ultrasonic rail defect inspection is to identify rail defects before they grow to critical fracture sizes and potentially cause train derailments and corresponding hazardous materials release incidents.

The frequency of rail defect inspection is a key decision with significant safety and cost implications. Given resource limitations, it is crucial to determine the optimal frequency of rail inspection in order to minimize the risk in a cost-effective manner. To date, we are unaware of any published study directly addressing the optimization of rail defect inspection frequency as a means to manage crude oil by rail risk. In order to minimize both the total route risk and the number of miles inspected, this paper develops a risk-based Pareto optimization model to determine location-specific rail inspection frequency. Using the methodology developed herein, the railroad industry can evaluate broken-rail-caused crude oil transportation risk, identify high risk “hot spots” that may receive more inspections, and better allocate inspection resources accordingly. Although this paper focuses on crude oil transported in unit trains, the methodology can be adapted to other hazardous materials in other types of trains.

This paper is structured as follows. Section 2 reviews relevant literature, identifies knowledge gaps and elaborates on the objectives of this research. Section 3 introduces a new methodology to quantify the relationship between crude oil by rail transportation risk and rail defect inspection frequency. Section 4 addresses the implementation of the methodology and parameter estimation. Section 5 applies the methodology to a numerical case study and draws managerial insights. Section 6 summarizes principal research findings, the limitations of the paper and possible future research directions.

2 LITERATURE REVIEW AND OBJECTIVES OF THE STUDY

2.1 Literature Review

The safety of hazardous materials transportation has long been a focus in the railroad community. A number of previous studies addressed certain aspects of railroad hazardous materials transportation safety and risk. A summary of the prior effort is presented below.

Some studies analyzed how improving tank car safety design could reduce risk (*19*-*23*). They addressed the trade-off between transportation safety and efficiency (in terms of tank car lading capacity) associated with tank car design modification. With respect to operations, Glickman (1983) estimated the effectiveness of routing changes on risk mitigation (*24*). Kawprasert and Barkan (2008) developed an optimization model to identify the optimal network design for railroad hazardous materials transportation (*25*). Kawprasert and Barkan (2010) also investigated the relationship between hazardous materials release risk and train derailment speed, and analyzed the safety benefit of train speed reduction, with and without infrastructure upgrades (*26*). The Center for Chemical Processing Safety (CCPS) provided a guideline for performing effective emergency response practices (*27*). Recognizing that tank car derailment probability varies by its position in a train, Bagheri et al. (2011, 2012, 2014) developed risk models to optimize the placement of hazardous materials tank cars (*28-30*). In the United States, over 70 percent of freight-train derailments on mainlines were caused by infrastructure or equipment failures (*31*). Ouyang et al. (2009) discussed the optimal deployment of wayside detectors to monitor equipment condition, thereby reducing train accident risk (*32*). Schlake et al. (2011) analyzed the effects of wayside detector implementation on railroad safety and efficiency (*33*). Last but not least, infrastructure quality is closely related to train derailment rate (*34, 35*). The Federal Railroad Administration classifies track quality by an index called FRA track class. At higher FRA track classes, higher maximum operating speeds are allowed but correspondingly more stringent track engineering and safety standards apply. Kawprasert and Barkan (*26*) and Liu et al. (*36*) analyzed an upgrade in track class as a means to reduce the risk. A track class upgrade indicates an overall improvement in track safety standards, in commensurate with the increase in the maximum speed. Among all types of infrastructure failures, rail failures are the primary accident causes (*7, 31*). Prior research has focused on the engineering process of rail defect formation. A higher rail defect inspection frequency is associated with a lower rail failure risk (*17, 37*) because more rail defects can be identified before they grow large enough to cause rail failures that may result in train derailments. In practice, limitations on resources and track access time constrain annual inspection frequency. Therefore, an effective rail defect inspection schedule can reduce train derailment occurrence, thereby mitigating hazardous material transportation risk.

2.2 Knowledge Gaps

We are unaware of any published model that explicitly describes how hazardous materials transportation risk is related to rail defect inspection frequency, except for a previous study by (*38*). However, that study does not account for the specific characteristics of possible multiple tank car derailments and releases when crude oil is shipped in unit trains. Additionally, the current practice is to inspect all segments on the same route with equal frequency. As track segments vary by track quality and adjacent population density, they may have different risk levels. If so, there is a need to identify high-risk track segments, and possibly inspect them more frequently to achieve more effective mitigation of the total route risk.

2.3 Research Objectives

This research is developed to attain the following objectives:

1) Develop a new model to quantify crude oil by rail transportation risk by rail inspection frequency
2) Develop a Pareto-optimization model to determine risk-based rail inspection frequencies for different track segments
3) Provide managerial insights regarding effective broken rail prevention for managing the risk of rail transport of crude oil and other hazardous materials

This paper is intended to provide new knowledge, managerial insights and implementation tools to assist the railroad industry in optimizing rail inspection frequencies through risk analysis and optimization models. In the long run, this research can evolve into a larger, integrated risk management framework to reduce hazardous materials transportation risk based on multiple alternative safety improvement strategies, alone or in combination.

3 METHODOLOGY

3.1 Risk Analysis Model

This section introduces a risk analysis methodology to estimate the risk of rail transport of crude oil, as a function of rail inspection frequency. In general, hazardous materials transportation risk can be defined as the multiplication of the likelihood of a release incident and the release consequences (*25, 26, 27, 38, 39, 40*). If the population in the evacuation zone measures the release consequence, the risk is interpreted as the expected number of affected persons. The annual broken-rail-caused crude oil by rail transportation risk is expressed as follows:

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

Where:
R_i = annual broken-rail-caused crude oil transportation risk on the i^{th} track segment
P_i = annual frequency of broken-rail-caused crude oil release incidents on the i^{th} track segment
C_i = consequence of a release (e.g., affected population) on the i^{th} track segment

The probability of a crude oil release incident is a product of the probability of a train accident and the probability that the train accident causes at least one crude oil tank car to release contents. Because a large portion of crude oil traffic is shipped in unit trains with 80 to 120 tank cars all loaded with crude oil, the following risk analysis model is specifically developed for unit-train operation of crude oil. The risk model can be adapted to other types of trains in future research.

$$P_i = P_i(A) \times [1-((1-P_i(R))^{D_i}] \tag{2}$$

Where:
$P_i(A)$ = broken-rail-caused crude oil train accident frequency
$P_i(R)$ = conditional probability of release of a derailed crude oil tank car
D_i = average number of crude oil tank cars derailed per accident

Broken-rail-caused train accident rate can be estimated as a product of broken rail rate and the percentage of broken rails causing accidents (there is presumably no difference in the probability that a broken rail causes a crude oil train accident versus other types of freight trains):

$$P_i(A) = S_i \times L_i \times \theta_i \times V_i \tag{3}$$

Where:
S_i = annual number of broken rails per mile
L_i = segment mileage
θ_i = percentage of broken rails causing train accidents (a previous study by (*13*) found that 0.84% of broken rails resulted in train accidents)
V_i = percentage of the annual number of crude oil trains among all types of trains through a segment

The annual number of broken rails per mile (S_i) by inspection frequency can be estimated using an engineering model originally developed by USDOT Volpe Transportation Systems Center (*16*, *17*). This model represents a comprehensive mechanistic study of rail defect formation and growth. However, this risk analysis framework offers the flexibility for industry practitioners to substitute other valid models regarding broken rail occurrence and inspection frequency in place of Equation (4).

$$S_i = \sum_{j=1}^{K_i} \left\{ M \times \frac{e^{-\left(\frac{N_{i,j-1}}{\beta}\right)^{\alpha}} - e^{-\left(\frac{N_{i,j-1}+X_{i,j}}{\beta}\right)^{\alpha}}}{1+\lambda\left(\frac{T_i}{K_i}-\mu\right)} \times \lambda\left(\frac{T_i}{K_i}-\mu\right) \right\} \tag{4}$$

Where,

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

α = Weibull shape factor, 3.1

β = Weibull scale factor, 2150

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

μ = minimum rail inspection interval, 10 MGT

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

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

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

K_i = annual rail defect inspetion frequency on the ith segment

Equation (4) indicates that annual number of broken rails per mile is a function of inspection frequency. Given all else being equal, the higher the inspection frequency, the lower the broken rail risk. Combining Equations (1) to (4), route-specific broken-rail-caused crude oil transportation risk is expressed as:

$$R_{route} = \sum_{i=1}^{N} \left[\sum_{j=1}^{K_i} \left\{ M_i \times \frac{e^{-\left(\frac{N_{i,j-1}}{\beta}\right)^{\alpha}} - e^{-\left(\frac{N_{i,j-1}+X_{i,j}}{\beta}\right)^{\alpha}}}{1+\lambda\left(\frac{T_i}{K_i}-\mu\right)} \times \lambda\left(\frac{T_i}{K_i}-\mu\right) \right\} L_i \theta_i V_i \left\{1-[1-P_i(R)]^{D_i}\right\} C_i \right] \tag{5}$$

Where, N is the total number of track segments on a route. All other parameters are segment-specific and defined previously. Equation (5) presents an engineering risk analysis model to quantify the risk of rail transport of hazardous materials due to broken rails. The following section will discuss statistical parameter estimators needed for implementing the risk model in the context of crude oil by rail.

3.2 Parameter Estimation

In order to estimate the total route risk, there are a number of parameters that need to be estimated, including the number of cars derailed per broken-rail-caused derailment (D_i), the conditional probability of release of a derailed crude oil tank car ($P_i(R)$), and the consequence of a release incident (C_i). The parameters were developed based on the best data available to the authors. When no information is available, the most relevant information from the literature was used.

1) Number of cars derailed per broken-rail-caused derailment, D_i

After a train derailment occurs, the number of cars derailed is affected by train speed (*34, 35*). As described earlier, maximum speed is associated with FRA track class, with higher FRA track classes corresponding to greater maximum speeds. In general, FRA track class 1 (maximum 10 mph) and track class 2 (maximum 25 mph) represent lower-speed tracks, whereas track class 3 (maximum 40 mph), class 4 (maximum 60 mph) and class 5 (maximum 80 mph, in signaled track territory) represent tracks with higher operating speeds. Because of the speed difference, higher track classes tend to have more cars derailed. Using the FRA Rail Equipment Accident database from 2000 to 2014, we calculated the average number of railcars derailed per freight-train derailment on Class I railroad mainlines. It was found that, on average, a broken-rail-caused freight-train derailment on the track of higher classes (Class 3 to Class 5) caused 16 railcars to derail, whereas the derailment severity was approximately nine railcars derailed on lower track classes 1 and 2.

2) Conditional probability of release of a derailed tank car, $P_i(R)$

The conditional probability of release (CPR) of a derailed tank car reflects its safety performance in accidents (*19-23*). The Association of American Railroads (AAR) and Railway Supply Institute (RSI) have 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. This paper used the latest tank car safety statistics published by the AAR regarding tank cars transporting petroleum crude oil. On May 1, 2015, the USDOT issued a final rule for the new crude oil tank car specification standard, namely the DOT-117 (TC-117 in Canada) tank car (*41*). According to the AAR, the CPR of a derailed DOT-117 tank car is 0.042 (*42*). It means that out of every 100 cars of this type derailed, an average of four tank cars are expected to release contents. Although this is the best information available to the authors, there may be uncertainty regarding tank car release probability under different accident conditions. This paper uses the latest published tank car safety statistics to illustrate the overall methodology. Future research should be directed towards a better understanding of crude oil tank car safety performance under specified accident characteristics.

3) Consequence of a tank car release incident, C

Release consequence can be evaluated 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. Among these consequence measures, population in the affected area (to be protected or evacuated) was often used in previous studies (*25, 26, 43,* *44, 45*). The hazard exposure model provided in the U.S. DOT Emergency Response Guidebook (ERG) includes recommendations for the calculation of affected area (*46*). In this paper, we assume the affected area is a 0.5-mile-radius circle based on the ERG recommendation for a fire caused by flammable hazardous materials releases. 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.

3.3 Pareto-Optimization of Rail Inspection Frequency

Railroads often use a road-rail vehicle that can operate both on railway tracks and conventional roadways to inspect rail defects. This type of inspection method allows for different inspection frequencies on different track segments. By skipping certain lower-risk segments, higher-risk track segments might be inspected more frequently in order to maximize the magnitude of risk reduction. There are two principal factors considered in rail inspection planning, namely the total route risk, and the total miles inspected. Each track segment can be assigned its own inspection frequency (denoted as K_i). The ideal scenario (utopian scenario) is the minimization of total route risk with the fewest miles inspected. Mathematically, this can be formulated as a multi-attribute decision model:

Minimize $R(K_1, K_2, \ldots, K_N)$
Minimize $L(K_1, K_2, \ldots, K_N)$
Decision variables $K_1, K_2, \ldots, K_N$
Where:
R = total hazardous materials transportation risk on a route
L = total miles inspected
K_i = annual inspection frequency on the i^{th} track segment

To illustrate the concept, consider a simple hypothetical example. It is assumed that a route has five track segments, and each segment can be assigned an annual inspection frequency of 2, 3, 4, 5, 6, or 7 inspections per year. In total, there are 6^5 (7,776) possible combinations of rail inspection frequency schedules on this route. For a given number of total miles inspected, some inspection schedules could result in lower risks than others. These “optimal” schedules constitute a so-called Pareto frontier. The Pareto frontier represents the optimal scheduling of rail defect inspection frequency given a total mileage to inspect. The Pareto-solutions can be developed using the following algorithm (R and L represent the total risk and inspected mileages, respectively):

Step 1*: Compute R and L for all possible inspection schedules; set i = 0 (base case); initialize the set of Pareto-optimal solutions, S = {Ø}*
Step 2*: From the i^{th} schedule, find the schedule with the closest L and lower R than the current R(i)*
Step 3*: Insert solution schedule (i+1) that has the minimum R among schedules identified in step 2 to the set of Pareto-optimal solutions*
Step 4*: Repeat steps 2 and 3 until i = total number of schedules minus 1*

In the following section, a numerical example is developed to illustrate the application of the Pareto-optimization model for determining segment-specific annual rail defect inspection frequency.

4 CASE STUDY

This section applies the methodology to a numerical example. For illustration convenience, the analysis focuses on one route. The methodology can be adapted to a rail network in future study.

4.1 Route Information

To preserve security-sensitive information, we used an anonymous, actual hazardous materials rail shipment route in this study, which may not necessarily have crude oil traffic. Our purpose is to illustrate the implementation and implications of the risk and optimization models, without triggering any possible security issues. The route information was analyzed and displayed 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. Using U.S. Census data, the average population density along this route is 349 people per square mile. Table 1 summarizes the route information.

TABLE 1 Route Information

	Value
Total Length (Miles)	2,273
Number of Segments	1,164
Distribution of Track Class (%)	
Class 1	1.1%
Class 2	2.2%
Class 3	14.2%
Class 4	46.1%
Class 5	36.4%
Average Population Density per Square Mile	349

4.2 Baseline Risk

On the case study route, it is assumed that the average rail age (in terms of cumulative tonnage on the rail) is 1,000 million gross tons, annual traffic density is 80 million gross tons and the crude oil is shipped in the new DOT-117 tank car. On average, 25 percent of the trains on this corridor are crude oil unit trains. It is also assumed that all segments on this route are currently inspected three times per year. Based on these assumptions, using Equation (5), the baseline annual risk on this route is 693. This value means that annually 693 people are expected to be affected by a crude oil unit-train release incident caused by broken rails on this corridor.

4.3 Risk Hot Spot Identification

For practical considerations, this paper classifies the segment-specific risk into three categories (low risk, medium risk, high risk) and requires the same inspection frequencies on the segments within the same risk category. Jenks optimization algorithm is used to delineate risk categories. The optimization algorithm minimizes the variance within the same category and maximizes the variance between different categories (*47*). This classification algorithm is widely used and implemented into ESRI's ArcGIS software. Table 2 illustrates the number of segments, mileage and risk within each risk category. Noteworthy is that the 22 track segments with the highest annual risk accounts for only 4% of the route length but 29% 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 2 Segment Risk Classification

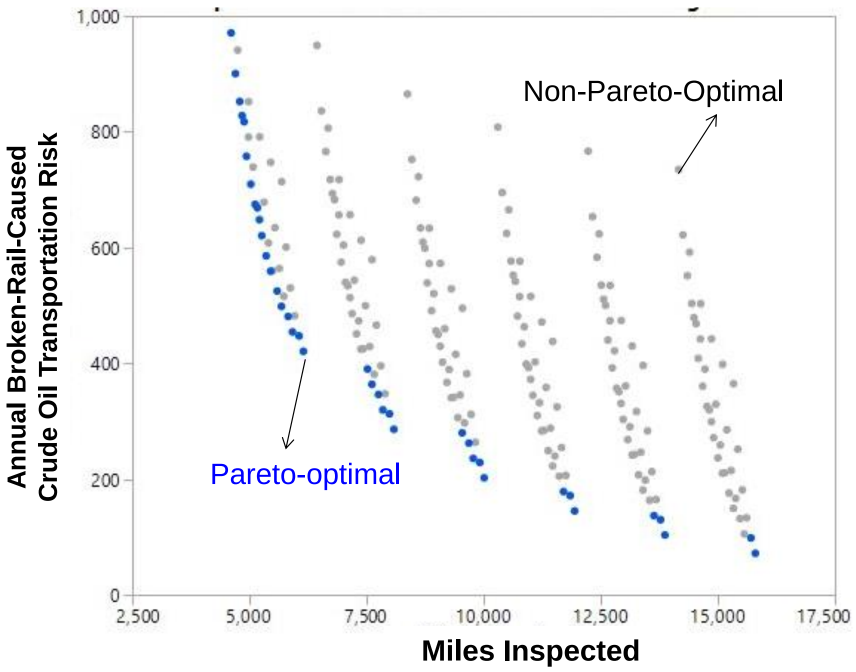
Annual Risk Category on the Segment	Number of Segments	Percentage of Total Mileage	Percentage of Total Risk
Low (0 to 1.63)	1,059	85%	34%
Medium (1.63 to 6.04)	83	10%	37%
High (6.04 to 17.75)	22	4%	29%
Total	1,164	100%*	100%

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

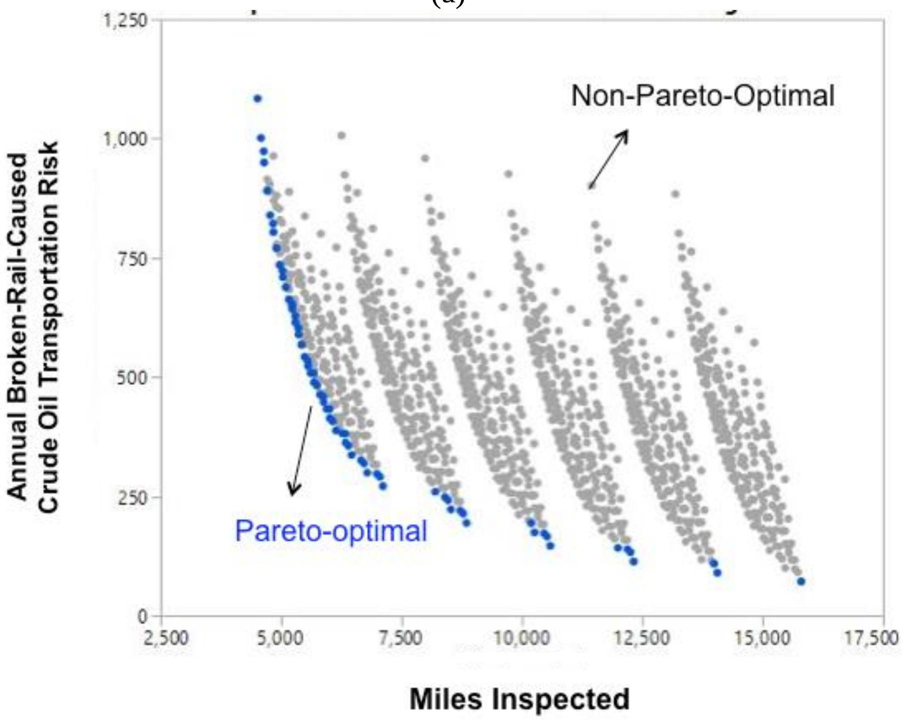
4.4 Pareto-Optimal Rail Defect Inspection Frequency

This paper does not schedule rail testing solely based on broken rail rate. Alternatively, it uses crude oil transportation risk (dependent on broken rail rate, train derailment probability, number of tank cars releasing contents and affected population) as a proxy to optimize rail testing schedules. Also, the optimization model in this paper does not explicitly account for certain regulatory and engineering requirements for scheduling rail testing frequencies. In future research, the methodology can be adapted to account for additional constraints regarding rail testing schedules. 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. Two (2) inspections per year corresponds to an inspection interval around 180 days (365/2). 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 example, consider one schedule where all track segments are inspected five times per year, denoted as (3, 3, 3). 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 (all tracks are inspected five times per year), by using the alternative schedule, the route risk is reduced by 17% while the total inspected mileage is reduced by 13%. This one example indicates that risk-based rail defect inspection optimization may achieve substantial risk reduction in a more cost-effective manner (assuming that inspection cost is related to the amount of track miles inspected)

The estimated broken-rail-caused crude oil unit train transportation risk and total mileage inspected for each possible rail inspection schedule are quantified and plotted. Given the same total miles inspected, some inspection schedules result in lower risk than others. These “optimal” schedules constitute a Pareto frontier (Figure 2a). The Pareto frontier represents the optimal scheduling of rail defect inspection frequency given a total mileage to inspect. Thus, the Pareto frontier demonstrates the “optimal” scheduling given limited inspection resources. Ultimately, a multi-attribute decision model can be developed to determine the inspection frequency based on the decision maker’s preference over the risk and the cost of inspections (inspected mileage as a proxy) and the trade-off between these or other attributes. In Figure 2b, the segment risk is classified into four categories (each with their own inspection frequency) and the corresponding Pareto frontier is identified.



(a)



(b)

FIGURE 2 Pareto-optimization of broken-rail-caused crude oil by rail transportation risk by total miles to inspect (a) segment risk is classified into *three* categories, each category has equal inspection frequency (b) segment risk is classified into *four* categories, each category has equal inspection frequency

5 DISCUSSION

5.1 Contributions to the literature

This research develops a new methodology to evaluate broken-rail-caused crude oil transportation risk by annual rail defect inspection frequency. The analysis shows that effective scheduling of rail defect inspection could reduce broken rail risk, thereby reducing crude oil transportation risk from broken-rail-caused derailments. The model can be adapted to account for segment-specific inspection frequency as discussed above. Also, the model can be further developed to quantify the effectiveness of a number of other broken rail prevention techniques (e.g., improving detection accuracy, adding circuits to non-signaled track territories) for reducing crude oil unit train transportation risk. Ultimately, this could lead to the development of an integrated infrastructure management framework to reduce train accidents, thereby reducing the risk of transporting crude oil or other hazardous materials by rail.

In addition, the methodology developed in this paper integrates accident, traffic, infrastructure and geographic information from various databases to implement a complicated algorithm and yield recommended decision solutions. The approach could potentially be integrated with railroad enterprise infrastructure and maintenance management systems to enable a better-informed decision process to cost-efficiently manage hazardous materials transportation risk.

5.2 Contributions to industry practice

The railroad industry is increasing the use of risk-based approaches to improve track inspection efficiency. One common practice is to inspect all segments on the same route at the same frequency. This research proposes an alternative risk-based approach where certain track segments might be inspected more frequently than the others. This is practically feasible given that many railroads use bi-modal road-rail inspection vehicles for broken rail detection. This type of vehicle can run on roadways and railway tracks. By skipping certain lower-risk segments on some inspection tours, higher-risk track segments might be inspected more frequently to maximize risk reduction. One practical decision would be the risk categorization of different track segments. The risk analysis model and implementation protocol developed in this paper can potentially assist the industry in prioritizing investment to improve rail inspection efficiency and reduce the associated transportation risk.

6 CONCLUSION

This research focuses on assessing the relationship between broken rail risk and crude oil unit train transportation risk. 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 model can be further developed and incorporated into a larger risk management framework for improving rail safety in a cost-efficient manner.

7 FUTURE RESEARCH

This paper focuses on broken-rail-caused crude oil transportation risk. The next step should consider a variety of other factors affecting railroad transportation risk, such as other track failures, rolling stock condition, operating speed, routing, 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, probability of detection, axle load and others (*48, 49*). Furthermore, this paper concentrates on unit-train shipments of crude oil, where all cars in the train contain crude oil. Future research can be directed towards development of more sophisticated risk models for other types of crude oil trains, accounting for the placement of crude oil cars in a train. Future research can also account for possible interdependent tank car releases within the same train accident (*50*). In addition to physical impacts in a derailment, future research should account for tank car releases due to thermal tear. In a crude oil unit 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. Hot fire weakens the tank structure, potentially resulting in a sudden release of large quantities of product (*1*). 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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