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

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The rapid expansion of production of North American petroleum crude oil 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 train accidents caused by broken rails, thereby reducing the hazardous materials transportation risk. This paper describes a new methodology to estimate unit-train crude oil transportation risk by the frequency of location-specific rail defect inspection. The risk model was used to develop a Pareto optimization model that determines the frequency of segment-specific rail defect inspection to reduce the total-route risk in a cost-effective manner. A numerical case study was 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.

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 growth has led to a dramatic increase in the transport of crude oil by rail. In 2005, there were only 6,000 tank carloads of petroleum crude oil shipped in the United States. By 2014, this number had increased to more than 500,000, an 80-fold increase (*1*). Although more than 99.99% of rail carloads of crude oil safely reach their destinations without a release incident (*2*), transport of crude oil by rail still represents a significant safety concern for both the public and private sectors because of the potential impact of a release on human health, property, and the environment. Recently, a spate of accidents involving trains transporting crude oil 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 for reducing the risk of transporting crude oil (and hazardous materials in general) by rail: (*a*) reducing the likelihood of a release incident and (*b*) reducing the consequences of a release (*3, 4*). This study focuses on the former: reducing the likelihood of hazmat release incidents by preventing train accidents.

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

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, Virginia, in 2014. Therefore, preventing the development of broken rails 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 nondestructive rail defect inspection (*16–18*). This paper focuses on ultrasonic rail defect inspection, a primary nondestructive inspection technology that has been used by railroads in the United States 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.

How frequently rail defect inspections should be performed is a key decision with significant safety and cost implications. Given resource limitations, it is crucial to determine the optimal frequency of rail inspection to minimize risk in a cost-effective manner. To date, the authors are unaware of any published study directly addressing the optimization of rail defect inspection frequency as a means to manage the risk of transporting crude oil by rail. Both the total-route risk and the number of miles inspected were minimized in this study by the development of a risk-based Pareto optimization model to determine location-specific rail inspection frequency. Using the methodology developed in this paper, the railroad industry can evaluate the crude oil transportation risk caused by broken rails, identify high-risk "hot spots" that may require additional inspections, and better allocate inspection resources accordingly. Although this paper focused 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: (*a*) a review of relevant literature, identifying knowledge gaps and elaborating on the objectives

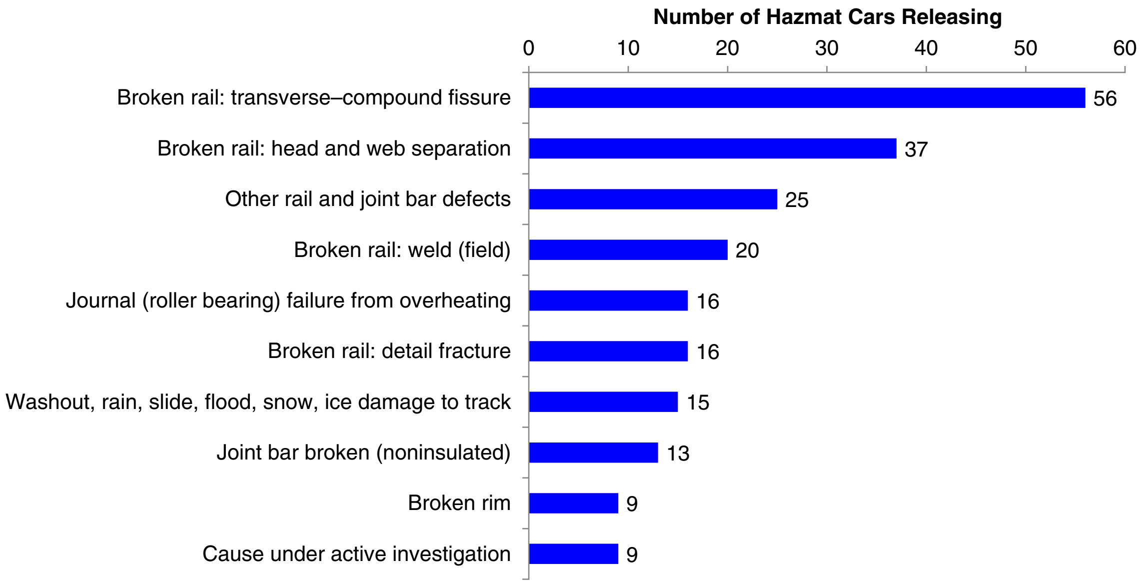


FIGURE 1 Number of hazmat cars releasing in freight train derailments on U.S. railroads in accidents from 2002 to 2011.

of this research; (*b*) an explanation of a new methodology to quantify the relationship between the risk of transporting crude oil by rail and the frequency of rail defect inspection; (*c*) a discussion of the implementation of the methodology and parameter estimation; (*d*) an application of the methodology to a numerical case study, including managerial insights; and (*e*) a summary of the principal research findings and a discussion of the limitations of the paper and possible future research directions.

LITERATURE REVIEW AND OBJECTIVES OF THE STUDY

Literature Review

The safety of hazardous materials transportation has long been a focus in the railroad community. A number of previous studies have addressed safety and risk aspects of hazardous materials transportation by rail: a summary of these efforts is presented below.

Some studies have analyzed how improving tank car safety design could reduce risk (*19–23*). These studies 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 estimated the effectiveness of routing changes on risk mitigation (*24*). Kawprasert and Barkan developed an optimization model to identify the optimal network design for hazardous materials transportation by rail (*25*). They also investigated the relationship between the risk of hazardous materials release and train derailment speed and analyzed the safety benefit of reducing train speeds, with and without infrastructure upgrades (*26*). The Center for Chemical Process Safety has provided guidelines for performing effective emergency response practices (*27*). Recognizing that the probability of tank car derailment varies by the tank car's position in a train, Bagheri et al. developed risk models to optimize the placement of hazardous materials tank cars (*28–30*). In the United States, more than 70% of freight train derailments on mainlines were caused by infrastructure or equipment failures (*31*). Ouyang et al. have discussed the optimal deployment of wayside detectors to monitor equipment condition, thereby reducing the risk of train accidents (*32*). Schlake et al. have analyzed the effects of wayside detector implementation on railroad safety and efficiency (*33*). And finally, infrastructure quality is closely related to the rate of train derailment (*34, 35*). FRA divides track quality into five principal classes commonly used by freight railroads in accordance with FRA track safety standards (*8*). 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. (*8*) analyzed an upgrade in track class as a means to reduce the risk. An upgrade to track class indicates an overall improvement in track safety standards, commensurate with the increase in the maximum speed. Of the types of infrastructure failures, rail failures are the primary cause of accidents (*7, 31*). Prior research has focused on understanding the process of rail defect formation. More frequent rail defect inspection is associated with a lower risk of rail failure (*17, 36*), 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 schedule of rail defect inspection can reduce occurrences of train derailments, thereby mitigating hazardous material transportation risk.

Knowledge Gaps

The authors 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 Liu et al. (*37*). 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 by the density of the adjacent population, 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.

Research Objectives

This research was developed to achieve the following objectives:

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

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 the hazardous materials transportation risk on the basis of multiple alternative safety improvement strategies, alone or in combination.

METHODOLOGY

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 (*25–27, 37–39*). If the population in the evacuation zone is used as a measure of the release consequences, the risk is then interpreted as the expected number of affected people. The annual crude oil transportation risk caused by broken rails is expressed as follows:

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

where

R_i = annual crude oil transportation risk caused by broken rails on the ith track segment,
P_i = annual frequency of incidents of release of crude oil caused by broken rails on the ith track segment, and
C_i = consequence of a release (e.g., affected population) on the ith 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 will cause 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, this risk analysis model was specifically developed for a unit-train operation of crude oil. The risk model can be adapted to other types of trains in future research.

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

where

$P_i(A)$ = frequency of crude oil train accidents caused by broken rails,
$P_i(R)$ = conditional probability of release by a derailed crude oil tank car, and
D_i = average number of crude oil tank cars derailed per accident.

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

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

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 Zarembski and Joseph (*13*) found that 0.84% of broken rails resulted in train accidents], and
V_i = percentage of annual number of crude oil trains among all types of trains traveling through a segment.

The annual number of broken rails per mile (S_i) by inspection frequency can be estimated by using an engineering model originally developed by the U.S. DOT 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 of the occurrence of broken rails and inspection frequency in place of Equation 4.

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

where

M = number of 39-ft rail sections per track-mile (273 in this model);
α = Weibull shape factor (3.1 in this model);
β = Weibull scale factor (2,150 in this model);
λ = slope of the number of rail breaks per detected rail defect versus inspection interval curve (0.014 in this model);
μ = minimum rail inspection interval [10 million gross tons (MGT) in this model];
$N_{i,j-1}$ = 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 (in MGT) between the $(j-1)$th and jth inspection on the ith track segment;
T_i = annual traffic density (in MGT) on the ith segment; and
K_i = annual rail defect inspection frequency on the ith segment.

Equation 4 indicates that the annual number of broken rails per mile is a function of inspection frequency. If all else is equal, the higher the inspection frequency, the lower the risk of broken rails. When Equation 1 and Equation 4 are combined, the route-specific crude oil transportation risk caused by broken rails can be expressed as follows:

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

where N is the number of track segments on a route. All other parameters are segment specific and have been defined previously. Equation 5 presents an engineering risk analysis model to quantify the risk due to broken rails of rail transport of hazardous materials. The following section covers statistical parameter estimators needed for implementing the risk model in the context of transportation of crude oil by rail.

Parameter Estimation

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

Number of Cars Derailed per Derailment Caused by a Broken Rail, D_i

After a train derailment, 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. Data from the FRA Rail Equipment Accident Database from 2000 to 2014 were used to calculate the average number of railcars derailed per freight train derailment on Class I railroad mainlines. It was found that, on average, a freight train derailment caused by a broken rail on track of higher classes (Class 3 to Class 5) caused 16 railcars to derail, whereas approximately nine railcars derailed on track of lower classes, Classes 1 and 2.

Conditional Probability of Release by a Derailed Tank Car, $P_i(R)$

The conditional probability of release of a derailed tank car reflects its safety performance in accidents (*19–23*). The Association of American Railroads and the Railway Supply Institute have maintained an industrywide 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 Association of American Railroads and the Railway Supply Institute periodically publish average tank car release probabilities. The latest tank car safety statistics for tank cars transporting petroleum crude oil, published by the Association of American Railroads, were used in this paper. On May 1, 2015, the U.S. DOT issued a final rule for the new specification standard for crude oil tank cars, namely the DOT-117 (TC-117 in Canada) tank car (*40*). According to the Association of American Railroads, the conditional probability of release of a derailed DOT-117 tank car is .042 (*41*), which means that out of every 100 cars of this type that derails, an average of four tank cars is expected to release contents. Although this was the best information available for this paper, there may be uncertainty regarding the probability of tank car release in different accident conditions. The latest published tank car safety statistics were used in this paper to illustrate the overall methodology. Future research should be directed toward a better understanding of the safety performance of crude oil tank cars under specified accident characteristics.

Consequences of a Tank Car Release Incident, C

Release consequences 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) has often been used in previous studies (*25, 26, 42–44*). The hazard exposure model provided in the U.S. DOT *Emergency Response Guidebook* includes recommendations for the calculation of affected areas (*45*). In this paper, the affected area is assumed to be a circle with a 0.5-mi radius on the basis of the *Emergency Response Guidebook* recommendation for a fire caused by flammable hazardous materials releases. Once the affected area has been 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.

Pareto Optimization of Rail Inspection Frequency

Railroads often use a road–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 segments thus maximizing 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 multiattribute decision model:

$$\begin{array}{ll} \text{minimize} & R(K_1, K_2, \ldots, K_N) \\ \text{minimize} & L(K_1, K_2, \ldots, K_N) \\ \text{decision variables} & K_1, K_2, \ldots, K_N \end{array}$$

where

R = total hazardous materials transportation risk on a route,
L = total miles inspected, and
K_i = annual inspection frequency on the ith track segment.

This concept can be illustrated by 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 by using the following algorithm (R and L represent the total risk and inspected mileages, respectively):

1. Compute R and L for all possible inspection schedules; set $i = 0$ (base case); initialize the set of Pareto optimal solutions, $S = \{\varnothing\}$.
2. From the ith schedule, find the schedule with the closest L and a lower R than the current $R(i)$.
3. Insert the solution schedule $(i + 1)$ that has the minimum R from the schedules identified in Step 2 into the set of Pareto optimal solutions.
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.

CASE STUDY

In this section the methodology is applied to a numerical example. For convenience of illustration, the analysis focused on one route. The methodology can be adapted to a rail network in a future study.

Route Information

Security-sensitive information was preserved in this study by the use of an anonymous, actual hazardous materials rail shipment route, which may not necessarily have crude oil traffic. The purpose was 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 platform. The population density along each track segment was estimated by linking U.S. census data to route data by using geographic information. The geographic information system analysis divided the 2,273-mi route into 1,164 track segments. The majority of the route segments were in signaled territories and maintained to meet FRA Class 4 and Class 5 standards. U.S. census data indicated that the average population density along this route was 349 people per square mile. Table 1 summarizes the route information.

TABLE 1 Route Information

	Value
Total length (mi)	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

Baseline Risk

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

Identification of Risk Hot Spots

For practical considerations, segment-specific risk was classified into three categories (low risk, medium risk, high risk), and inspection frequency requirements were assumed to be the same for segments within the same risk category. The Jenks optimization algorithm was used to delineate risk categories. This optimization algorithm minimizes the variance within the same category and maximizes the variance between different categories (*46*). This classification algorithm is widely used and has been implemented in Esri's ArcGIS software. Table 2 illustrates the number of segments, the mileage, and the risk for each risk category. The 22 track segments with the highest annual risk account 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 a population density of more than 1,000 people per square mile.

Pareto Optimal Rail Defect Inspection Frequency

The model developed in this paper did not schedule rail testing solely on the basis of the broken rail rate. Rather, crude oil transportation risk (dependent on broken rail rate, probability of train derailment, number of tank cars releasing contents, and affected population) was used as a proxy to optimize rail-testing schedules. Additionally, the optimization model in this paper did not explicitly account for certain regulatory and engineering requirements for scheduling rail-testing frequencies. In future research, the methodology can be

TABLE 2 Classification of Annual Risk on Segments on the Case Study Route

Risk Category	Number of Segments	Total Mileage (%)	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

adapted to account for additional constraints related to rail-testing schedules. For illustration, within each risk category specified above, six possible annual inspection frequencies can be considered on those segments, ranging from two to seven inspections per year. Two inspections per year correspond to an inspection interval of approximately 180 days (365/2). If there are three risk categories and each risk category has six possible annual inspection frequencies, there are 6^3 (216) possible combinations of rail inspection schedules. For example, a schedule could call for all track segments to be inspected five times per year; this schedule would be denoted as (5, 5, 5). An alternative inspection schedule could be as follows: the low-risk track segments could be inspected four times per year, medium-risk tracks could receive six inspections per year, and high-risk tracks could be inspected seven times per year; this sample scenario would be denoted as (4, 6, 7). Compared with the first scenario (with an inspection of all tracks five times per year), the alternative schedule would reduce the route risk by 17%, while the total inspected mileage would be reduced by 13%. This example indicates that optimization of risk-based rail defect inspection could achieve substantial risk reduction in a cost-effective manner (assuming that inspection cost is related to the number of track miles inspected).

The estimated crude oil unit-train transportation risk caused by broken rails and total mileage inspected for each possible rail inspection schedule was quantified and plotted. With the same number of miles inspected for each schedule, some inspection schedules resulted in lower risk than others. These "optimal" schedules constitute a Pareto frontier (Figure 2*a*). 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 multiattribute decision model can be developed to determine the inspection frequency on the basis of the decision maker's preferences for the amount of risk versus cost of inspections (inspected mileage as a proxy) and the trade-off between these or other attributes. In Figure 2*b,* the segment risk is classified into four categories (each with its own inspection frequency), and the corresponding Pareto frontier is identified.

DISCUSSION OF RESULTS

Contributions to the Literature

This research developed a new methodology to evaluate crude oil transportation risk caused by broken rails by using the annual rail defect inspection frequency. The analysis shows that effective scheduling of rail defect inspection could reduce the risk of broken rails, thereby reducing crude oil transportation risk from derailments caused by broken rails. The model can be adapted to account for segment-specific inspection frequency as discussed above. Additionally, 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 nonsignaled track territories) for reducing crude oil unit-train transportation risk. Ultimately, this methodology 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 integrated 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 manage hazardous materials transportation risk in a cost-efficient fashion.

Contributions to Industry Practice

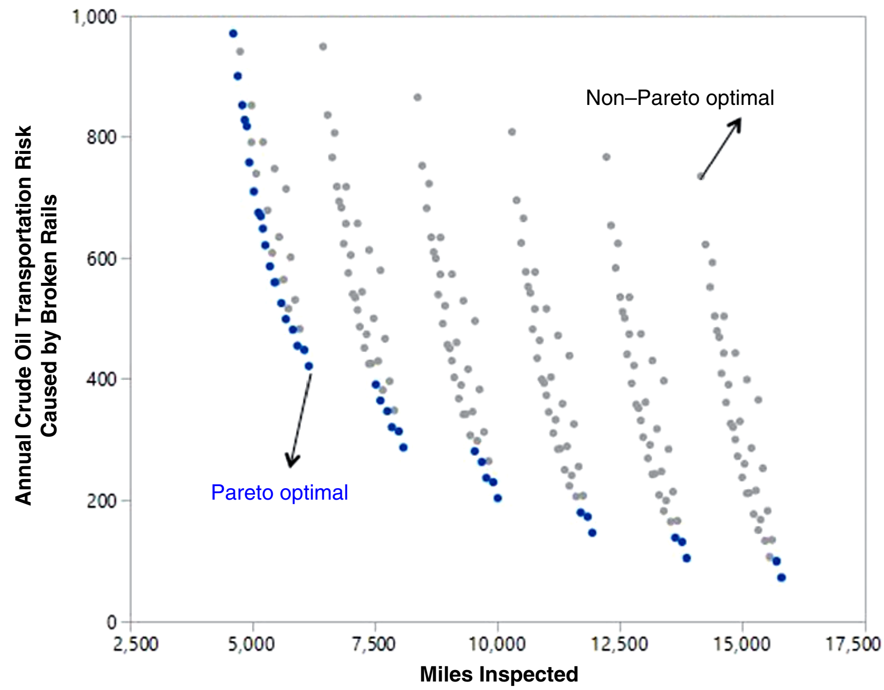
The railroad industry is increasing the use of risk-based approaches to improve track inspection efficiency. One common practice is to inspect all segments on the same route at the same frequency. This research proposed an alternative, risk-based approach in which certain track segments might be inspected more frequently than others. This approach is practically feasible given that many railroads use bimodal road–rail inspection vehicles for the detection of broken rails. This type of vehicle can run on roadways and railway tracks. Skipping inspection of certain lower-risk segments might enable more frequent inspection of higher-risk track segments, thus maximizing the magnitude of 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.

CONCLUSION

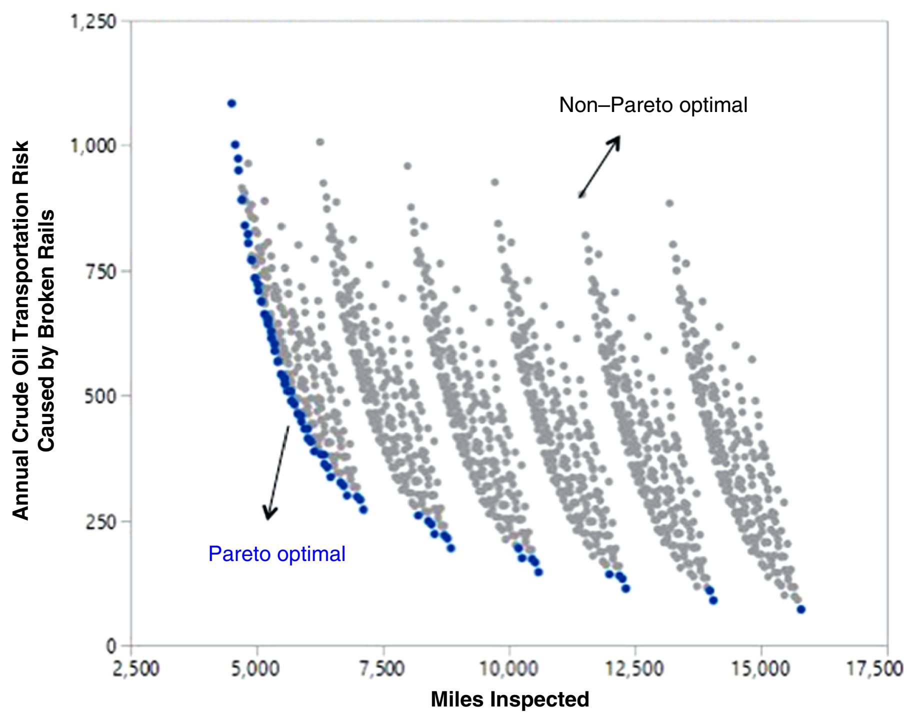
This research focused on assessing the relationship between the risk of broken rails and crude oil unit-train transportation risk. The model was used on an example route to demonstrate the safety effectiveness of optimizing rail inspection frequency for risk reduction. The analysis showed that increased inspection frequency on a small number of high-risk segments might 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.

FUTURE RESEARCH

This paper focused on crude oil transportation risk caused by broken rails. In the next step there should be a consideration of a variety of other factors affecting railroad transportation risk, such as other track failures, rolling stock condition, operating speed, routing, and emergency response. Additionally, future research can account for other 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 (*47, 48*). Furthermore, this paper concentrated on unit-train shipments of crude oil in which all cars in the train contain crude oil. Future research can be directed toward 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 (*49*). In addition to physical impacts in a derailment, future research should account for tank car releases caused by thermal tear. In a crude oil unit-train derailment, a fire frequently ensues because of the flammability of crude oil. These fires can engulf other derailed tank cars that did not fail during the initial derailment. Hot fire weakens the tank structure,



(a)



(b)

FIGURE 2 Pareto optimization of crude oil transportation risk caused by broken rails, by total miles to inspect: (*a*) three categories of segment risk, all with the same inspection frequency, and (*b*) four categories of segment risk, all with the same inspection frequency.

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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