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SAFETY EFFECTIVENESS OF INTEGRATED ACCIDENT PREVENTION STRATEGIES

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ABSTRACT

There are potential interactions among approaches to reduce or prevent certain accident causes. Given the overlapped safety benefits of various measures for accident prevention, it is necessary to identify their interactions and quantify the safety effectiveness of combined accident prevention strategies. This study focuses on strategies to prevent broken rails and broken wheels, respectively. Improved wheel condition reduces the impact load on the rail, thereby may reduce broken-rail-caused derailments. In this paper, we propose a quantitative framework to assess the safety effectiveness of combined accident prevention strategies under various operational conditions. In the larger context of railroad hazardous materials risk management, integrated accident prevention can be compared to other means of risk reduction measures, such as tank car safety design enhancement or operational changes.

INTRODUCTION

Train accidents cause damage to infrastructure and rolling stock, disrupt service, and may cause casualties and harm the environment. Therefore, accident prevention is of great importance for the rail industry and government. An accurate assessment of the cost-effectiveness of accident prevention measures, individually or in combination, enables optimal allocation of resources for safety improvement. When multiple accident prevention strategies are applied, their safety benefits may overlap. For example, reducing wheel defects may not only prevent broken-wheel-caused derailments, but also reduce the likelihood of broken rails due to reduced impact load at the wheel-rail interface. A more detailed illustration of the interaction between track-related and rolling stock-related defects is presented in Fig.1.

The interaction between accident causes makes it more complex to estimate the safety effectiveness of combined accident prevention strategies. The focus of this paper is to evaluate the safety benefits of a combination of broken rail prevention and broken wheel prevention.

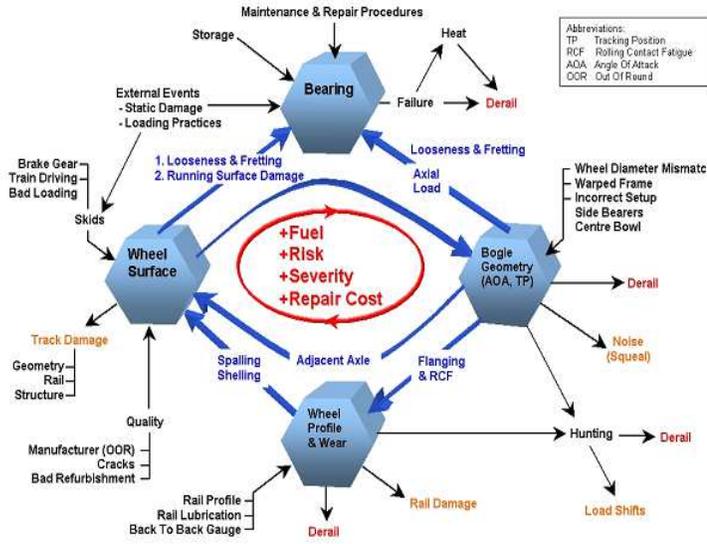


Fig.1. Illustrative interaction between accident causes [1]

Methodology

Let $F(E_i)$ represent number of train derailments preventable by the i^{th} accident prevention measure. $F(E_{\text{inte}})$ represents the total number of train derailments preventable by combined accident prevention strategies. The following equation presents the relationship between the integrated accident prevention strategies, the individual accident prevention strategy and their interactions.

$$F(E_{\text{inte}}) = F(E_1 \cup E_2 \dots \cup E_n) = \sum_i F(E_i) - \sum_{i < j} F(E_i, E_j) + \dots + (-1)^{n+1} F(E_{1,2,\dots,n}) \quad (1)$$

Where:

$F(E_i)$ = train derailment frequency preventable by i^{th} accident prevention strategy

$F(E_{ij})$ = train derailment frequency preventable by both i^{th} and j^{th} accident prevention

The mathematical details of Equation 1 can be found in [2]. When there are two accident prevention strategies, namely broken rail prevention and broken wheel prevention, respectively. Equation 2 is developed to assess their combined safety effectiveness.

$$F(E_r \cup E_w) = F(E_r) + F(E_w) - F(E_{rw}) \quad (2)$$

Where:

$F(E_r \cup E_w)$ = total number of train derailments preventable by the combination of broken rail and broken wheel prevention

$F(E_r)$ = number of derailments preventable by broken rail prevention

$F(E_w)$ = number of derailments preventable by broken wheel prevention

$F(E_{rw})$ = number of derailments preventable by both accident prevention strategies

First, we explain why some derailments can be reduced by both broken rail and broken wheel prevention strategies. The engineering explanation is derived from the wheel-rail damage model presented by Resor and Zarembski (2004) [3].

$$D = \left[\frac{P}{P_0} \right]^{n-1} \quad (3)$$

Where:

D = relative damage (for the base load, $D=1$)

P = new impact load

P_0 = base impact load

n = exponential component ($n=2.3$ for track; $n=1.64$ for wheel)

This model is used to approximately estimate the change of relative damage to rail or wheel, in response to the change of impact load. The exponential component, n , is estimated based on field test results by the Transportation Technology Center Inc. (TTCI) of the Association of American Railroads (AAR). To illustrate, consider that the impact load on the wheel-rail interface decreases by θ ($0 < \theta < 1$) from the base load P_0 . The new impact load is $P_0(1-\theta)$. Using Equation 3, the new relative damage to the track and wheel are:

$$D_{\text{track}} = \left[\frac{P_0(1-\theta)}{P_0} \right]^{2.3-1} = (1-\theta)^{1.3} \quad (4)$$

$$D_{\text{wheel}} = \left[\frac{P_0(1-\theta)}{P_0} \right]^{1.64-1} = (1-\theta)^{0.64} \quad (5)$$

Let ΔD_{track} , ΔD_{wheel} represent the percent reduction of damage to track and wheel, respectively.

$$\Delta D_{\text{track}} = 1 - (1-\theta)^{1.3} \quad (6)$$

$$\Delta D_{\text{wheel}} = 1 - (1-\theta)^{0.64} \quad (7)$$

The mathematical relationship between the change of damage to track and wheel and the change of impact load is shown in Fig. 2. It shows that track damage is more sensitive to impact load compared to wheel damage. For example, if the impact load reduces by 40%, the damage to track decreases by 49%, by contrast with 28% reduction of wheel damage. In order to examine the relative difference between the track and wheel in response to the change of impact load, we define the following ratio:

$$\theta_w = \frac{1 - (1 - \theta)^{1.3}}{1 - (1 - \theta)^{0.64}} \quad (8)$$

The mean of θ_w is 1.62. It means that, on average, track damage is 62% more sensitive to impact load than the wheel damage. Therefore, in this paper, we focus on the effect of broken wheel prevention on reducing the likelihood of broken rails.

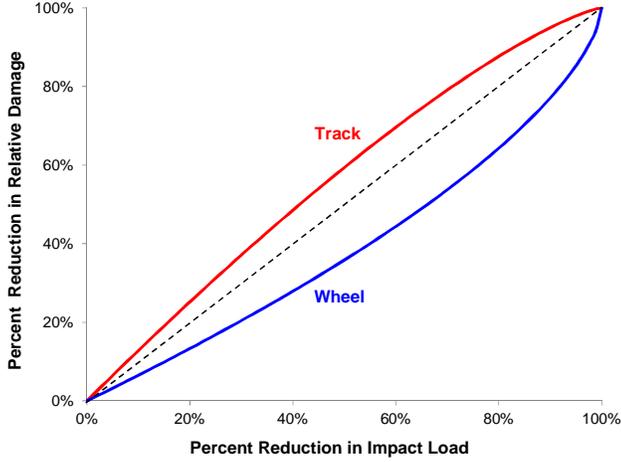


Fig.2. Damage to rail and wheel by impact load

Given traffic exposure, consider that there are N_1 broken-rail-caused train derailments, and N_2 broken-wheel-caused derailments. It is assumed that a broken rail prevention strategy reduces the number of broken-rail-caused derailments by αN_r ($0 < \alpha < 1$). A broken wheel prevention strategy reduces the number of broken-rail-caused derailments by βN_r , and reduces the number of broken-wheel-caused derailments by λN_w ($0 < \beta < 1$; $0 < \lambda < 1$). The relationship between β and λ is estimated as below.

It is assumed that a non-broken wheel has 65 kips load on the rail (the threshold for maintenance/repair attention), while a broken wheel has 140 kips load on the rail (the threshold for required maintenance/repair), based on AAR's Field Manual [4]. If λ ($0 < \lambda < 1$) broken-wheel-caused train derailments are prevented, it is assumed that the average impact load reduces to $140(1 - \lambda) + 65\lambda = 140 - 75\lambda$. Correspondingly, the percent reduction in the impact load is $\theta = 75\lambda/140 = 0.54\lambda$. Using Equation 6,

$$\Delta D_{\text{track}} = 1 - (1 - \theta)^{1.3} = 1 - (1 - 0.54\lambda)^{1.3} \approx 0.6537\lambda \quad (0 < \lambda < 1)$$

($R^2 = 0.998$; $P < 0.01$)

This reduction of rail damage is attributable to broken wheel prevention. It is assumed that there is a linear relationship between rail damage and number of broken-rail-caused derailment, given all else being equal (Equation 9):

$$N_{\text{rail}} = a \times D + b \quad (9)$$

Where:

N_{rail} = number of train derailments due to broken rails

a, b = parameter coefficients

D = rail damage

Based on the linearity assumption, $\Delta N_{\text{rail}} = \Delta D_{\text{rail}} = 0.6537\lambda$ (Δ represents percent change). By definition, $\Delta N_{\text{rail}} = \beta$ (β represents the percentage reduction of broken-rail-caused derailments by preventing broken wheels). Therefore, $\beta = 0.6537\lambda$. Let ϕN_1 represent the number of train derailments preventable by both broken rail prevention and broken wheel prevention. Accounting for this interaction, the effectiveness of integrated accident prevention is measured by the percentage reduction in the train derailment rate:

$$E_{\text{inte}} = \frac{(\alpha N_r + 0.6537\lambda N_r + \lambda N_w - \phi N_r)/N_{\text{total}}}{(\alpha + 0.6537\lambda - \phi)N_r/N_{\text{total}} + \lambda N_w/N_{\text{total}}} \quad (10)$$

where:

N_r = number of train derailments due to broken rails

N_w = number of train derailments due to broken wheels

N_{total} = total number of train derailments due to all accident causes

α = percent reduction of broken-rail-caused derailments by broken rail prevention

λ = percent reduction of broken-wheel-caused derailments by broken wheel prevention

ϕ = interaction parameter

When $\phi = 0$, there is no overlapped safety benefit between broken rail prevention and broken wheel prevention. When $\phi = 0.6537\lambda$, all the reduction of broken-rail-caused derailments attributable to improved wheel condition are also preventable by broken rail prevention. It is assumed that ϕ follows a uniform distribution between $[0, 0.6537\lambda]$. The Federal Railroad Administration (FRA) of U.S. Department of Transportation (U.S. DOT) specifies 389 accident cause codes to represent a variety of conditions leading to a train accident. These cause codes are hierarchically organized and categorized into major cause groups - track, equipment, human factors, signal and miscellaneous. Within each of these major cause groups, FRA organizes individual cause codes into subgroups of related causes such as roadbed, track geometry [5]. From Equation (10), the safety effectiveness of combined accident prevention is affected by the marginal safety effectiveness of each individual accident prevention strategy, their interaction and the probability that a derailment is due to a specific accident cause. N_r/N and N_w/N represent the probability that a derailment is due to broken rails and broken wheels, respectively. Table 1 presents the distribution of freight-train derailment by accident cause on Class I mainlines from 2001 to 2010. Class I freight railroads (operating revenue exceeding \$378.8 million in 2009) accounted for approximately 68% of U.S. railroad route miles, 97% of total ton-miles transported and 94% of the total rail freight revenue [6].

Table 1

Broken-rail-caused and broken-wheel-caused freight-train derailments by FRA Track Class, Method of Operation and Annual Traffic Density, Class I mainlines, 2001 to 2010

Track Class	Annual Traffic Density	Method of Operation	Number of Train Derailments			Percentage of All Causes	
			Broken Rails	Wheel Defects	Total	Broken Rails	Wheel Defects
Class 1 to 3	<20MGT	Non-Signaled	167	16	626	26.7%	2.6%
Class 1 to 3	<20MGT	Signaled	42	36	416	10.1%	8.7%
Class 1 to 3	≥20MGT	Non-Signaled	35	15	153	22.9%	9.8%
Class 1 to 3	≥20MGT	Signaled	61	49	576	10.6%	8.5%
Class 4 to 5	<20MGT	Non-Signaled	35	12	178	19.7%	6.7%
Class 4 to 5	<20MGT	Signaled	31	34	289	10.7%	11.8%
Class 4 to 5	≥20MGT	Non-Signaled	34	15	159	21.4%	9.4%
Class 4 to 5	≥20MGT	Signaled	110	130	1064	10.3%	12.2%

Note: maximum freight-train speed by FRA track class

Class 1 = 10 mph

Class 2 = 25 mph

Class 3 = 40 mph

Class 4 = 60 mph

Class 5 = 80 (mph)

A non-signaled track has speed limit 49 mph

Table 1 indicates that the proportion of train derailments due to an accident cause may be dependent on operational conditions. The probability that a derailment is caused by an accident cause can be estimated using a logistic regression model:

$$P_{c|a} = \frac{\exp(\beta_0 + \beta_1 x_1 + \dots + \beta_n x_n)}{1 + \exp(\beta_0 + \beta_1 x_1 + \dots + \beta_n x_n)} \quad (11)$$

Where:

$P_{c|a}$ = probability that a train derailment is due to an accident cause

x_i = explanatory variables

β_i = parameter coefficients

The likelihood ratio (LR) test [7] is used to examine the statistical significance of each explanatory variable on the probability that a derailment is due to broken rails or broken wheels, respectively (Table 2). The method of operation (non-signaled versus signaled) has a significant effect on broken-rail-caused train derailment probability, whereas the method of operation and FRA track class are significant on broken-wheel-caused train derailment rate, at 95% confidence level.

Table 2

Likelihood ratio (LR) test of explanatory variables

(a) Broken rail

Variable	Chi-Square	P-value
Method of Operation	80.02	<0.0001
Track Class	1.32	0.2501
Annual Traffic Density	0.14	0.7055

(b) Broken wheel

Variable	Chi-Square	P-value
Method of Operation	2.02	0.0003
Track Class	36.49	0.0013
Annual Traffic Density	1.81	0.0954

Table 3 presents the predicted probability that a derailment is due to broken rails or broken wheels under various operational conditions. The probability that a derailment is caused by broken rails is twice higher in a non-signaled track, than in a signaled track. A higher FRA track class has a greater likelihood of broken-wheel-caused derailments.

Table 3

Predicted probability that a derailment is due to an accident cause

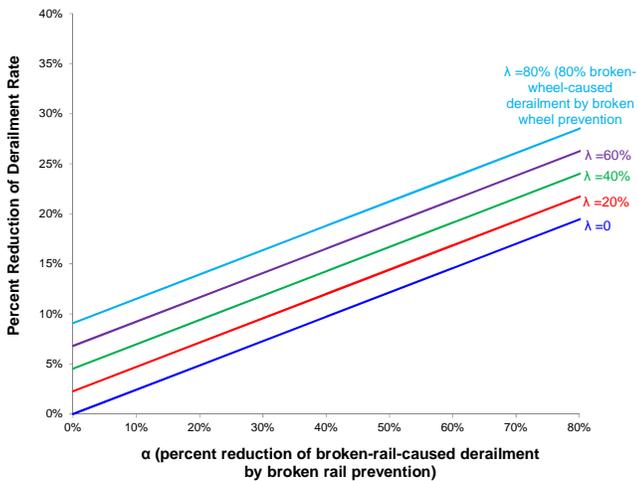
Track Class	Annual Traffic Density	Method of Operation	Predicted Percentage of All Causes	
			Broken Rails	Wheel Defects
Class 1 to 3	<20MGT	Non-Signaled	24.3%	3.4%
Class 1 to 3	<20MGT	Signaled	10.4%	6.7%
Class 1 to 3	≥20MGT	Non-Signaled	24.3%	3.4%
Class 1 to 3	≥20MGT	Signaled	10.4%	6.7%
Class 4 to 5	<20MGT	Non-Signaled	24.3%	5.2%
Class 4 to 5	<20MGT	Signaled	10.4%	10.8%
Class 4 to 5	≥20MGT	Non-Signaled	24.3%	5.2%
Class 4 to 5	≥20MGT	Signaled	10.4%	10.8%

In a non-signaled, lower class track with lower annual traffic density (<20MGT), the predicted proportion of freight-train derailments due to broken rails and broken wheels are 24.3% and 3.4%, respectively. In this track territory, the probability that a derailment is caused by broken rails is 7 times greater than broken wheels. Therefore, the combined safety benefits may be dominated by broken rail prevention. Because we assumed that the interaction between two accident prevention strategies is a random variable, the safety effectiveness of the integrated accident prevention strategies is a random variable. The mean of the effectiveness can be estimated as:

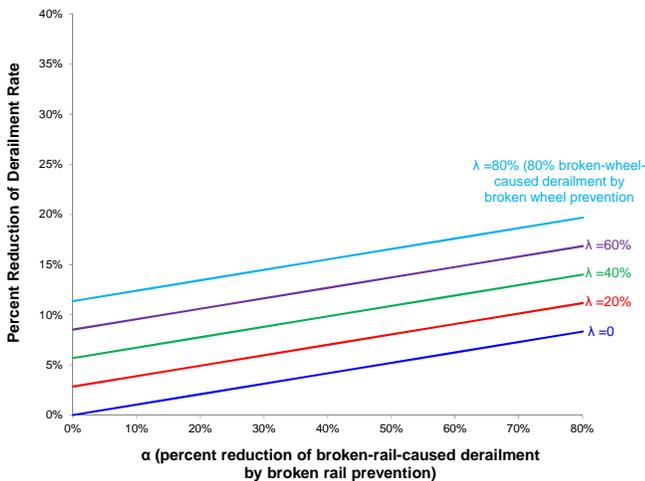
$$E[e_{integrated}] = \int_{\phi=0}^{0.6537\lambda} [(\alpha + 0.6537\lambda - \phi)N_r/N + \lambda N_w/N]d\phi$$

$$= (\alpha + 0.6537\lambda / 2)N_r/N + \lambda N_w/N \quad (12)$$

Fig. 3 shows the average safety effectiveness of a combination of broken rail prevention and broken wheel prevention under different track conditions, by different marginal effectiveness of broken rail prevention (α) and broken wheel prevention (λ).



(a) FRA track class 1 to 3, non-signalized, lower traffic density (<20MGT)



(b) FRA track class 4 to 5, signalized, higher traffic density (≥ 20 MGT)

Fig.3. Safety effectiveness of integrated accident prevention

CONCLUSION

The reduction of broken rails due to broken wheel prevention results in the interactive effects between broken rail prevention and broken wheel prevention. A quantitative model is developed to estimate the safety effectiveness of combined accident prevention strategies accounting for their interactions under various operational conditions. The model provides a better understanding of effective prevention of major accident causes. Ultimately, the model will be incorporated into a larger framework of integrated railroad safety management.

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