Effect of Train Speed on Risk Analysis of Transporting Hazardous Materials by Rail

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This paper considers the effect of train speed on railroad hazardous materials transportation risk. A statistical method was developed to estimate the speed-dependent conditional probability of release (CPR) of hazardous material from tank cars involved in accidents. The objective was to assess how accounting for speed affects the results of risk analysis. A case study of a representative hazardous materials route was conducted. In that case study, risk estimates were developed by using conventional, average-speed CPR, and the estimates were compared with those obtained by analyzing the same route using speed-dependent CPR. The differences in calculated risk indicate that the use of the speed-dependent CPR may be an important refinement for the accurate calculation of the risk of a route. The effects of track-class upgrades on risk were also considered. Track with higher Federal Railroad Administration classes has lower accident rates, but the higher permissible speeds increase the CPR if a tank car is derailed in an accident. Consequently, evaluation of the effect of track upgrades must account for both factors to understand the net impact on risk. Two scenarios were considered in the track-class upgrade analysis: upgrades without an increase in speed and upgrades with an increase in speed. The increased tank car hazardous material release rate at the higher speeds permissible on higher track classes was more than offset by the reduction in the accident rate for all the track-class upgrade scenarios considered. For the particular route analyzed in the case study, use of the speed-dependent CPR resulted in a slight increase in the overall risk estimate, and upgrading of Class 3 track provided the greatest reduction in risk. Such results will be route specific; however, the use of a speed-dependent CPR enables the more accurate analysis of local risk and provides a better evaluation of risk reduction options that involve changes in operating and track characteristics.

Train operating speed is one of the factors affecting the likelihood of a release in railroad accidents involving tank cars transporting hazardous materials. With a higher speed of derailment, more cars are likely to derail, and for those derailed cars there is a higher probability that one or more will suffer a release (*1*). Nevertheless, previous studies have generally simplified this aspect of railroad hazardous materials transportation risk analysis by using a single value for the conditional probability of release (CPR) that does not account for variations in train speeds (*2–5*). Use of a single value of CPR, independent of the train speed, simplifies the risk analysis but also implies an average speed of derailment (*6*). Because this average-speed CPR may be higher than the actual operating speed in some situations and lower in others, use of the average-speed CPR will have the effect of overestimating the probability of release on lower-speed sections and underestimating the probability of release on higher-speed sections of the route.

The relationship between speed and CPR has been considered previously (*7–9*). The most recent study (*7*) provides estimates for both the average-speed CPRs and the speed-dependent CPRs of tank cars, but only the average-speed CPR accounts for specific safety design features. Earlier work was not specific to tank cars (*8*) or did not enable the application of speed-dependent effects to specific tank car designs (*9*). In the study described here, the authors explicitly considered the effects of train speed on hazardous materials transportation risk analysis and developed a technique that enables estimation of the speed-dependent CPR for specific tank car designs using published data on the safety performance of tank cars in accidents (*7*) that permits the application of adjustment factors derived from a group of car types to a specific car type.

The use of tank car design enhancements as options to reduce risk has become more prevalent over the past decade, and the model introduced here provides flexibility that enables the effects of these enhancements to be considered by using the most up-to-date published data available. Furthermore, the effect of tank car safety design can be integrated with other options.

In this paper, the authors specifically consider the interaction of infrastructure quality, train speed, and tank car performance to understand the effect on risk estimates using the speed-dependent CPR. A case study that uses a representative hazardous material transportation route is presented. The results of a risk analysis that uses the average-speed CPR are compared with those of a risk analysis that uses the speed-dependent CPR.

The second part of the paper highlights the importance of using CPR adjusted for speed by further considering its utility as part of an assessment of the effect of an upgrade in the track class on risk. Upgrading the track class has been shown to be correlated with the reduction of certain types of accidents and, consequently, risk (*8*). However, if the upgrade is also intended to allow increased operating speeds, it may increase the probability of release if an accident does occur (*1, 7*). The CPR and the accident rate are the two principal elements in hazardous materials transportation risk analysis. The consideration of each one as a function of speed enables the more accurate estimation of route-specific risk. This also facilitates proper consideration of the benefit of infrastructure improvement. Two scenarios were analyzed: a track upgrade without a speed increase and a track upgrade with a speed increase. The degree of risk reduction varies with these options, and consideration is given to which option offers the greatest safety benefit for the problem analyzed.

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REVIEW OF RISK ANALYSIS METHODS

Hazardous materials transportation risk can be quantitatively expressed as the frequency of a release incident multiplied by the consequence of that release. In this study, frequency is the product of the annual rate of tank car involvement in an FRA–reportable derailment on main-line track, the number of shipments, the total mileage from the origin to the destination, and the CPR given that a tank car derails. The consequence of a release incident is the impact of the released material and is affected by the characteristics of the released product, its quantity, and the rate of spillage; atmospheric conditions; and the population density along the route analyzed.

The consequence can be expressed by using several metrics. In the present study, the authors used the number of people who might be affected because of the release of a hazardous material from a tank car, in accordance with the product-specific recommendations presented in the U.S. Department of Transportation (USDOT) *Emergency Response Guidebook* (ERG) (*10*) and elsewhere (*11*). The consequence can be estimated by multiplying the area affected by using the evacuation distances recommended in ERG by the population density within the affected area.

The risk metric calculated by using the method described above is the annual expected number of people who might be evacuated or sheltered in place because of the release of hazardous materials. Specifically, risk is calculated from the product of the accident rate, the traffic volume (measured in car miles), the tank car CPR, the probability distribution of release sizes, the affected area corresponding to the release size, and the population density in the affected area summed over all segments on the route.

The risk model in Equation 1 incorporates these segment-specific parameters and gives the estimate of risk associated with shipments of hazardous materials on the route.

$$S = \sum_{j=1}^{\Pi} \sum_{j=1}^{k} Z_i V_i L_i R_i P_j A_j D_i \qquad (1)$$

where

- S = annual risk (number of people affected per year);
- Z = rate of tank car involvement in an FRA-reportable derailment (number of cars derailed per car mile);
- V_i = annual shipments (number of carloads per year);
- L_i = length of track segment (miles);
- R_i = CPR given that a tank car derails;
- P_j = CPR of specific scenario j given that there is a hazardous material release from a derailed tank car;
- A_j = affected area corresponding to a specific release scenario, according to the USDOT ERG recommendation (square miles);
- D_i = average population density along track segment (number of people per square mile);
- i = track-specific segment;
- n = total number of segments along the route considered;
- j = specific release scenario (e.g., spill size, fire involvement, and time of day); and
- k = total number of scenarios considered.

CASE STUDY

A typical, representative route that is part of the distribution network of a particular hazardous material on the North American rail network was considered. The distance from the origin to the destination of the route is 1,400 mi, the route comprises 598 segments, and the average segment length is 2.34 mi. These track segments correspond to links in the FRA rail transportation network obtained from the Bureau of Transportation Statistics (*12*). The authors assumed 100 annual carloads over the entire route using a noninsulated, USDOT-111A100W1 tank car with $\frac{7}{16}$-in. tank thickness and no special safety design features beyond the USDOT minimum requirements.

For some materials, consideration of multiple release scenarios may be appropriate. However, on the basis of expert opinion of the manufacturer of the product and the objectives of the present study, use of a single release scenario was satisfactory. Thus, the major factors affecting risk in this analysis were the product characteristics, the track-class-specific accident rate, the shipment volume, the safety design of the tank car, the operating speed, and the population exposure along the route.

The case study is used to analyze the effects of train speed on the risk estimate for the route and the contributions of various other factors to the risk, including population density and FRA track class. In addition, the case study is used to illustrate the merit of using the speed-dependent CPR in an assessment of the effect of a track infrastructure upgrade on risk reduction. These will be discussed in more detail in the subsequent sections.

ESTIMATION OF PARAMETERS AFFECTING RISK

FRA track-class-specific accident rates were used in this study (*13*). The track speed reflects the FRA track class, which has been shown to be correlated with railroad accident rates (*8*). The authors used railroad timetable speeds to infer the FRA track class and other local operating restrictions for all segments along the route. The next step was to estimate the CPR given that a tank car is derailed in an accident. The relationships developed by Treichel et al. were used to determine the CPR of the particular design of tank car considered in this study (*7*). Because CPR is also affected by train accident speed (*1, 7–9*), the authors adjusted it according to the timetable speed for each track segment. The authors calculated the speed-dependent CPR using the procedure described in the following section.

To estimate the consequences of a release, the authors used geographic information system software, ArcGIS Desktop, Version 9.2, to create the shipment route using the USDOT national rail network (*12*). An overlay analysis of the population distribution along the rail network was conducted by using census tract data from the Environmental Systems Research Institute, Inc., (ESRI) Data and Maps electronic database (*14*), and a buffer representing the exposure area was created. This was the area within the radius from the track center equal to the USDOT ERG maximum evacuation distance for the material considered. The average population density of the affected area corresponding to each track segment was then determined.

The procedure used to estimate and measure risk is similar to that described in previous studies (*2, 6*), except that this study focuses on refining the method to understand the effect of the speed-dependent CPR.

SPEED-DEPENDENT CONDITIONAL PROBABILITY OF RELEASE

Treichel and colleagues described the lading loss probability on the basis of the four major cause-specific loss events as (*7*)

$$P = P\left(E_h \cup E_s \cup E_t \cup E_b\right) \qquad (2)$$

where

P = probability that a tank car released its contents given that it derailed in an accident,
E_h = event in which the contents were lost because of head damage,
E_s = event in which the contents were lost because of shell damage,
E_t = event in which the contents were lost because of top fitting damage, and
E_b = event in which the contents were lost because of bottom fitting damage.

The cause-specific loss events have low correlations (*7*), so the authors assumed that E_h, E_s, E_t, and E_b are independent. Therefore,

$$\begin{aligned} P &= 1 - P^c \\ &= 1 - P\left(E_h^c \cap E_s^c \cap E_t^c \cap E_b^c\right) \\ &= 1 - P\left(E_h^c\right)P\left(E_s^c\right)P\left(E_t^c\right)P\left(E_b^c\right) \\ &= 1 - \left[1 - P\left(E_h\right)\right]\left[1 - P\left(E_s\right)\right]\left[1 - P\left(E_t\right)\right]\left[1 - P\left(E_b\right)\right] \end{aligned} \tag{3}$$

where c is the complement of an event.

Let R equal the CPR given that a tank car derails in an accident, unadjusted for speed, and that R_h, R_s, R_t, and R_b are the CPRs, unadjusted, attributed to head, shell, top fitting, and bottom fitting, respectively, so that

$$R = 1 - \left(1 - R_h\right)\left(1 - R_s\right)\left(1 - R_t\right)\left(1 - R_b\right) \tag{4}$$

where

R = tank car CPR, unadjusted;
R_h = CPR from head, unadjusted;
R_s = CPR from shell, unadjusted;
R_t = CPR from top fittings, unadjusted; and
R_b = CPR from bottom fittings, unadjusted.

The speed-dependent CPR was calculated by multiplying the unadjusted CPR by the speed adjustment factors. This adjustment to the CPR associated with each specific source of release can be made by use of Equation 5:

$$R' = 1 - \left(1 - R_h J_h\right)\left(1 - R_s J_s\right)\left(1 - R_t J_t\right)\left(1 - R_b J_b\right) \tag{5}$$

where

R' = tank car CPR, adjusted for speed,
J_h = speed adjustment factor for CPR from head,
J_s = speed adjustment factor for CPR from shell,
J_t = speed adjustment factor for CPR from top fittings, and
J_b = speed adjustment factor for CPR from bottom fittings.

To determine the speed adjustment factors in Equation 5, the authors first developed the relationships between train speed and CPR for each release source by using the proportion of tank cars losing lading from each source. The authors used statistical software (SAS, Version 9.1) to fit a simple linear regression equation with zero intercept to the published data on tank car safety performance (*7*) (Figure 1). A simple linear regression was used without weighting by the number of observations at each speed, consistent with a similar analysis by Treichel et al. (*7*). The fitted functions are shown below, and the corresponding test statistics are summarized in Table 1.

$$Y_h = 0.00786X \tag{6}$$

$$Y_s = 0.00674X \tag{7}$$

$$Y_t = 0.00460X \tag{8}$$

$$Y_b = 0.00150X \tag{9}$$

where

Y_h = proportion of nonpressure cars releasing from heads, corresponding to train speed X;
Y_s = proportion of nonpressure cars releasing from shells, corresponding to train speed X;
Y_t = proportion of nonpressure cars releasing from top fittings, corresponding to train speed X;
Y_b = proportion of nonpressure cars releasing from bottom fittings, corresponding to train speed X; and
X = train speed (mph).

In the next step, the authors used the data from Treichel et al. (*7*) to calculate the weighted average train speeds for releases from the tank head, shell, top fittings, and bottom fittings, which were 38.5, 41.2, 28.7, and 35.5 mph, respectively. These average speeds were then substituted into Equations 6 through 9 to determine the proportion of cars releasing from each source at the average speed (denoted by the subscript *a*), yielding the following values for the noninsulated USDOT-111A100W1 tank car considered here: $Y_{ha} = 0.30260$, $Y_{sa} = 0.27753$, $Y_{ta} = 0.13178$, and $Y_{ba} = 0.05330$, respectively.

The speed adjustment factors were then determined by dividing the proportion of nonpressure cars releasing at a particular speed by the proportion of cars releasing corresponding to weighted average speed, for example, $J_h = Y_h/Y_{ha}$. The speed adjustment factors applicable to nonpressure cars were

$$J_h = 0.02597X \tag{10}$$

$$J_s = 0.02429X \tag{11}$$

$$J_t = 0.03491X \tag{12}$$

$$J_b = 0.02814X \tag{13}$$

The cause-specific CPRs for the particular tank car considered were estimated by using the data from Treichel et al. (*7*) as $R_h = 0.0799$, $R_s = 0.1092$, $R_t = 0.1577$, and $R_b = 0.0625$. By using Equation 4, the average-speed (unadjusted) CPR for this tank car is 0.3527. Substituting the values of cause-specific CPRs into Equation 5, the speed-dependent CPR was estimated as follows:

$$R' = 1 - \left[\left(1 - 0.0799J_h\right)\left(1 - 0.1092J_s\right)\left(1 - 0.1577J_t\right)\left(1 - 0.0625J_b\right)\right] \tag{14}$$

Figure 2 shows the speed-dependent CPRs compared with the average-speed CPR of the noninsulated USDOT-111A100W1 tank car considered. This method can be adapted for any other type of tank car for which suitable data are available (*7*).

EFFECTS OF TRAIN SPEED ON RISK

The authors evaluated the effects of train speed by comparing the risk estimates calculated by using the speed-dependent CPR with those from the baseline case calculated by using the average-speed CPR. Use of the speed-dependent CPR yielded an annual risk of 1.428 people affected per year, whereas the annual risk is 1.291 people affected per year if the average-speed CPR is used, an 11% difference. Further detail regarding the effect of speed-dependent CPR

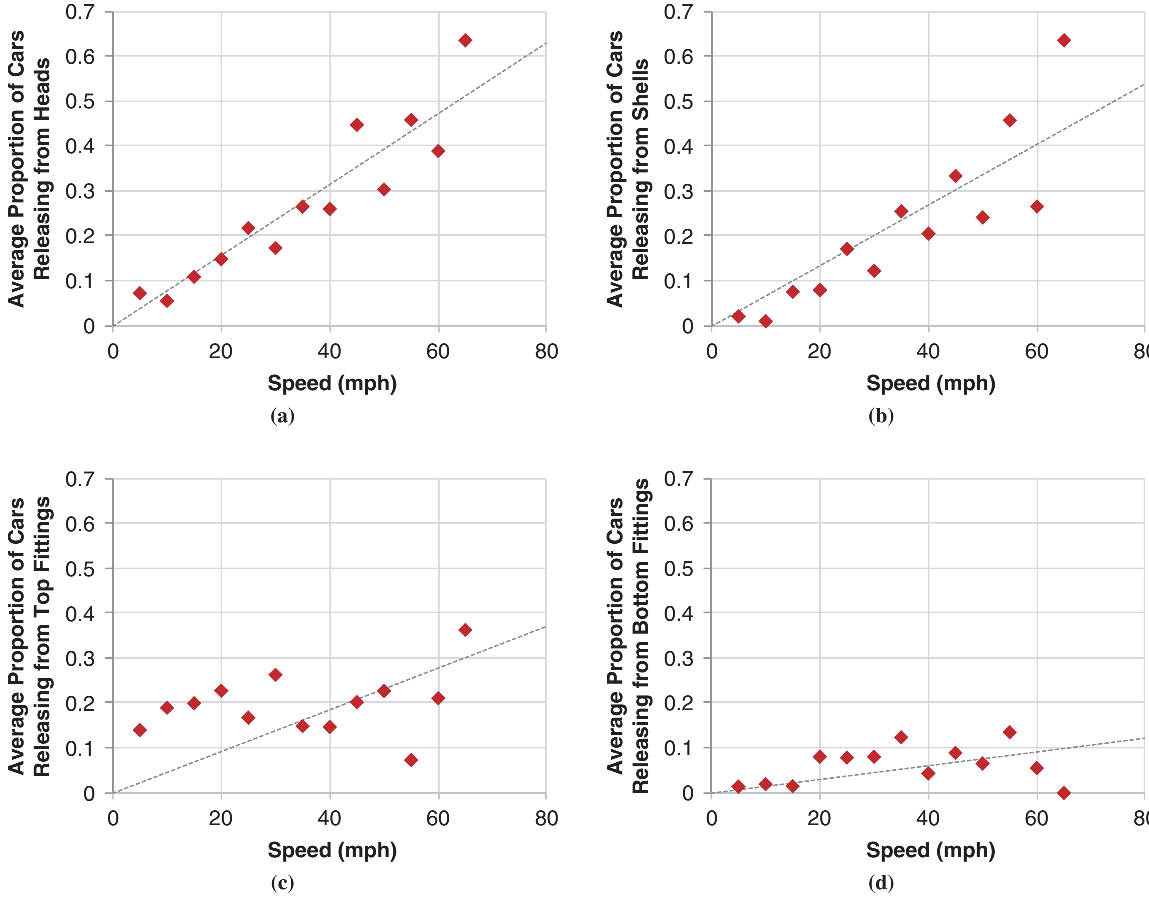

FIGURE 1 Proportion of nonpressure tank cars releasing versus speed for releases from (*a*) heads, (*b*) shells, (*c*) top fittings, and (*d*) bottom fittings.

can be seen by comparing the risk profiles calculated by using the speed-dependent and the average-speed CPRs (Figure 3*a*).

These differences in estimated risk obtained when speed-dependent CPR is used are specific to the characteristics of the particular route analyzed in this case study. In general, the effect on risk estimates will depend on the distribution of speeds along a route. Specifically, routes with a larger percentage of higher-than-average-speed trackage will tend to have increased risk estimates when the speed-dependent CPR is used, and those with a lower percentage will tend to have reduced risk estimates.

In previous work, it was found that a large percentage of the risk along a route was attributable to a small percentage of its length (*6*). In the case study described here, the 100 segments with the highest

TABLE 1 Parameter Estimates of Linear-Speed CPR Models

Model	Estimate of Regression Coefficient, β	Standard Error	*t*-Value	Pr > |*t*|	R^2
$Y_h = \beta_h X$	0.00786	0.00044925	17.49	<.0001	.9622
$Y_s = \beta_s X$	0.00674	0.00061609	10.94	<.0001	.9089
$Y_t = \beta_t X$	0.00460	0.00072981	6.30	<.0001	.7677
$Y_b = \beta_b X$	0.00150	0.00031975	4.69	.0005	.6468

risk per mile (Figure 3*b*) accounted for 18% of the route length but 92% of the risk. Of these segments, all but 22 had higher estimated risks when the speed-dependent CPR was used than when the average-speed CPR was used. Interestingly, these 22 segments were among the segments with the very highest risk in the entire analysis, accounting for 2% of the route length but 23% of the total risk. In contrast to the overall risk analysis results for the route, use of the speed-dependent CPR for these segments resulted in risk estimates lower than those when average-speed CPR was used.

It is not surprising that use of the speed-dependent CPR resulted in higher overall risk estimates in the case study considered because the segments with higher-than-average speeds comprised a majority of the overall route length, that is, 1% for speeds of 11 to 25 mph (Track Class 2), 16% for speeds of 26 to 40 mph (Track Class 3), 39% for speeds of 41 to 60 mph (Track Class 4), and 44% for speeds 61 to 70 mph (Track Class 5). FRA regulations permit the operation of freight trains up to 80 mph on Class 5 track (*15*); however, 70 mph is a more typical maximum speed and was the case for the route studied. The maximum speed for Key trains, which are subject to a special set of operating practices defined by the Association of American Railroads (*16*), is 50 mph, but the particular hazardous material considered in this study does not affect Key train status. For the purposes of this study, the maximum permissible speeds from railroad timetables were used to infer the FRA track class and were assumed to represent the operating speeds on each track segment.

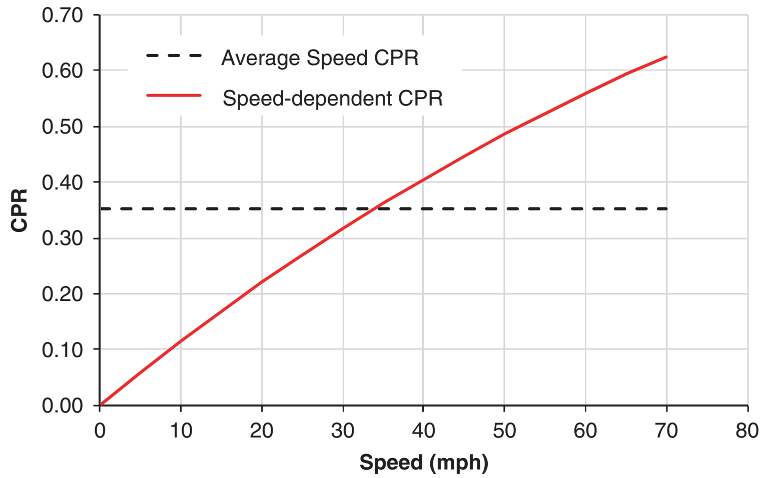

FIGURE 2 Estimated CPR on basis of speed for tank car considered (USDOT-111A100W1).

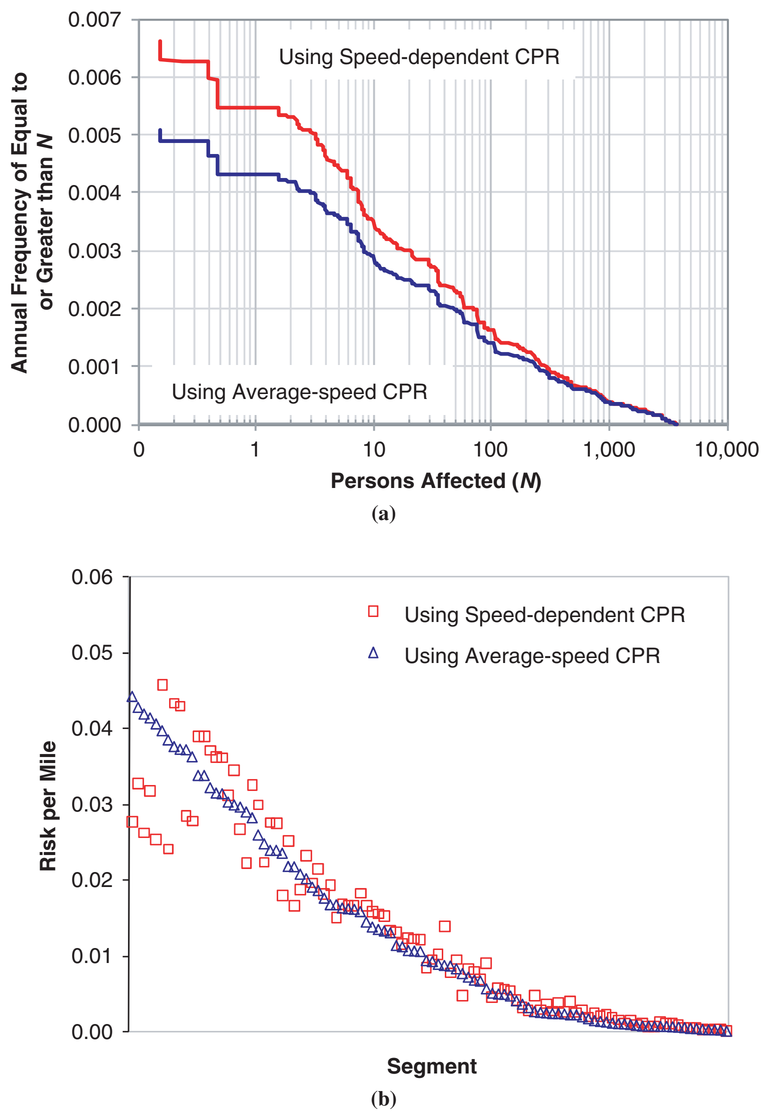

FIGURE 3 Comparison of route-specific results when speed-dependent CPR is used: (*a*) risk profiles (*F-N* curves) and (*b*) top 100 segments with the highest risk per mile.

A potential drawback of using timetable speeds to infer track class is that some segments may actually have higher-quality track and correspondingly lower accident rates than would be assumed on the basis of inferences made from the timetable speeds. In some circumstances, railroads may be maintaining trackage to a higher standard than that required by the track safety regulations for the particular speed shown in the timetable. If information on actual maintenance standards and operating speed is available, the information can be formally incorporated into the risk model, allowing more accurate estimates of accident rates for these segments.

Even in the absence of such information, the use of the speed-dependent CPR instead of the average-speed CPR provides more accurate risk estimates because it better reflects the particular operating characteristics of a route and their effects on risk. Such refinement is particularly important for comparison of the risk associated with different route alternatives, for example, a shorter route passing through urban areas with lower train speeds versus a longer route that goes through less populated areas where trains may operate at higher speeds. Such considerations are germane to railroads and the USDOT, when the results of route risk assessments, as required under HM-232E (*17*), are considered.

RISK CONTRIBUTION BY POPULATION DENSITY AND TRACK CLASSES

The authors analyzed the contributions to risk of different population density groups, using both average-speed and speed-dependent CPRs, to understand their effects on risk estimates with respect to the different population densities for the representative route. Track segments that are located in highly populated areas contribute a large proportion of the route risk. For example, those segments located in areas where the population density exceeds 6,500 people per square mile represent the smallest proportion of the total route length but account for the largest percentage of the risk when the speed-dependent CPR is used (Figures 4*a* and 4*b*).

For the route considered, the use of the speed-dependent CPR yields higher risk estimates (Figure 4*a*, solid line) than the use of the average-speed CPR (Figure 4*a*, dashed line) for all population density groups. The difference between risk estimates for the two CPRs is the largest for the highest-density group and the smallest for the lowest density group. However, when the contribution is expressed as a percentage of the total route risk instead of an absolute estimate; use of the speed-dependent CPR results in a lower contribution for

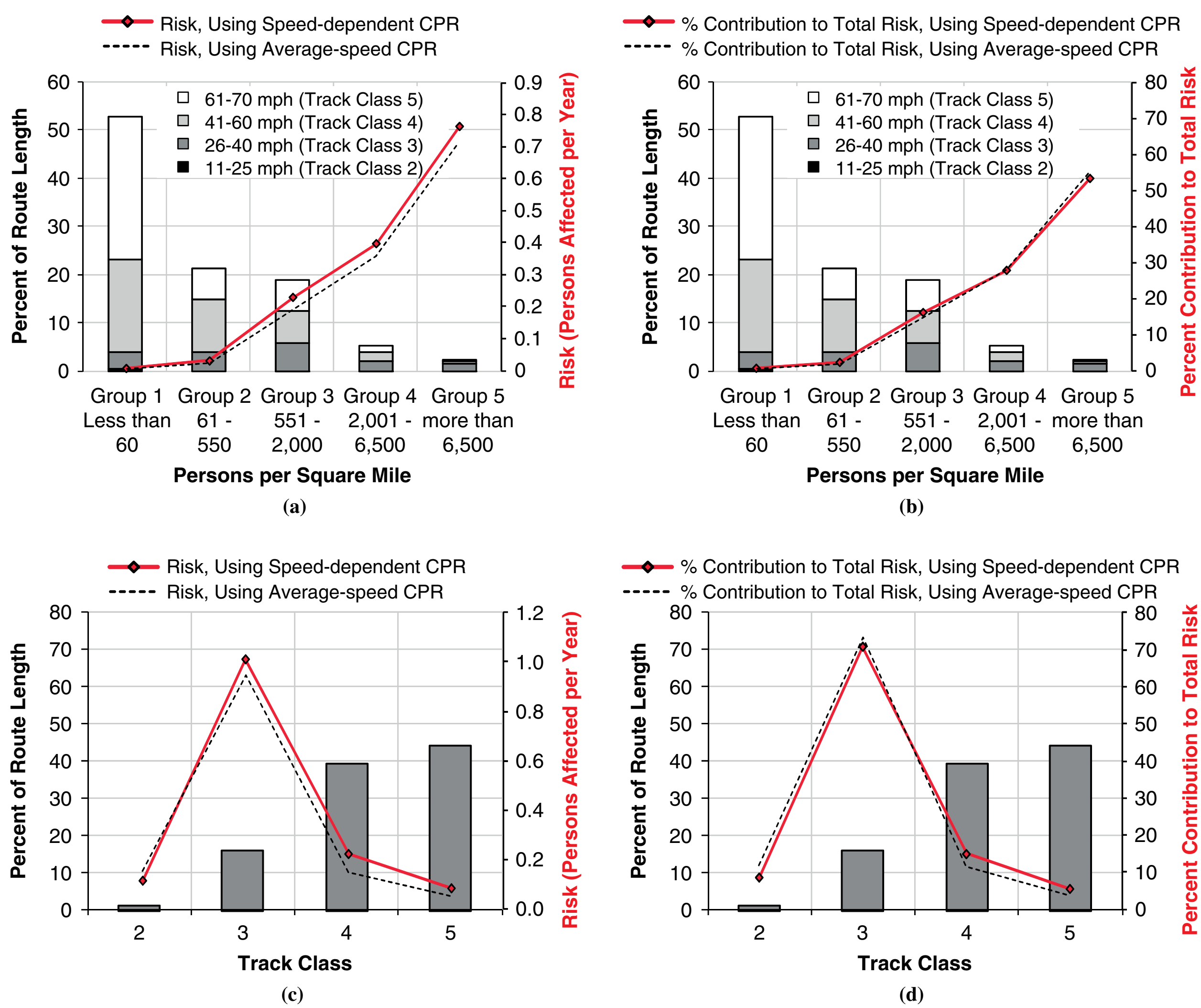

FIGURE 4 Percentage of route length and contribution to risk on route studied: (*a*) population density versus risk, (*b*) population density versus percentage of total risk, (*c*) track class versus risk, and (*d*) track class versus percentage of total risk.

the highest population density group relative to that obtained by use of the average-speed CPR (Figure 4*b*).

Some urban area segments do not experience the reduction in estimated risk when the speed-dependent CPR is used because in the case study these segments had speeds higher than average. On the other hand, some segments in nonurban areas had lower risk when the speed-dependent CPR was used because of speed restrictions on these segments. Figures 4*a* and 4*b* also show that the majority of the representative route is Class 4 and Class 5 track. Most of these segments are located in areas with moderate to low population densities. Class 3 segments, however, are more evenly distributed over different population classes, from the lowest to the highest density.

The segments with higher track classes do not contribute much risk, despite their greater percentage of route length. By contrast, the segments with lower track classes contribute a larger percentage of the total route risk because of a combination of the accident rate and the population densities associated with them, despite the lower CPRs.

Use of the speed-dependent CPR yields a lower estimate of risk on Class 2 track but higher estimates for Track Classes 3, 4, and 5 (Figure 4*c*). When the percent contribution to total risk is considered (Figure 4*d*), use of the speed-dependent CPR results in a lower percentage of risk on Track Classes 2 and 3 and larger percentages on Track Classes 4 and 5 compared with the values obtained when the average-speed CPR is used. This analysis, based on the representative route, illustrates that use of the speed-dependent CPR takes into account the effect of differential operating speeds on risk for each categorical variable considered: population density, and track class.

In the context of this discussion, it is useful to consider the ratio of the percentage of total risk to the percentage of route length. For the route analyzed, the risk/route length ratios, based on the speed-dependent CPR, were 8.6, 4.4, 0.4, and 0.1 for Track Classes 2, 3, 4, and 5, respectively. Although Class 2 track has the highest risk contribution per track mile, the overall contribution from Class 2 track is not as high as that from Class 3 track because of the small percentage of Class 2 track on the route. Because Class 3 track contributes the largest percentage of risk on this route, measures to reduce this are likely to have the greatest overall effect. In the next section, the authors consider the effects of infrastructure upgrades on risk and illustrate how the use of speed-dependent CPRs enables the better assessment of the safety benefits of track infrastructure upgrades.

EFFECTS OF INFRASTRUCTURE UPGRADES

In the case study, the authors considered the effect of upgrading all Class 2, Class 3, and Class 4 segments to the next higher class, that is, to Classes 3, 4, and 5, respectively, as three distinct upgrade options. The authors first considered the effect of track-class upgrade strictly as a means of reducing the accident rate and, consequently, the risk and therefore assumed that the operating speeds were held constant after the track upgrades. Upgrading Class 2, 3, and 4 tracks to the next higher class yielded reductions in risk of 5%, 53%, and 7%, respectively. Upgrading Class 3 segments offered the greatest reduction in risk, primarily because of the relatively large reduction in the accident rate combined with the fact that Class 3 tracks make up a fairly large percentage of the route analyzed.

Track upgrade principally affects track-caused accidents; however, not all track-related accidents are affected in the same way by track-class upgrades. Furthermore, there are a wide variety of potential causes of accidents (*18*). Non-track-related causes may have no relationship or only an indirect one to track class. Some causes of accidents, notably, certain ones attributable to equipment failure, such as broken wheels or axles, may actually increase with track-class upgrades if the operating speed also increases. Hence, increasing the track class affects the likelihood of only some types of accidents, and the functional relationship between each of these accident causes and the track class varies. When one also considers that different accident causes have different relationships to the likelihood that a derailed car carrying hazardous materials would suffer a release (*1*), it further complicates calculation of the effect of track-class upgrades on risk reduction. Further research on both the statistical and the causal relationships between the track class and accident frequency and severity is needed to improve quantitative assessments of the effects of changes in infrastructure quality on safety and risk. Until such research is completed and comprehensive data on critical infrastructure parameters are generally available, track class remains the best proxy statistic for estimating track quality, the derailment rate, and ultimately, the risk.

COMBINED EFFECTS OF INFRASTRUCTURE AND TRAIN SPEED

This section examines the relationships between track class, accident rate, and speed-dependent CPRs. It was assumed that train speeds increase in accordance with track-class upgrades. That is, trains are assumed to operate at the maximum normal operating speed corresponding to the upgraded track classes. Therefore, for each segment, the accident rate will be reduced because of the track-class upgrade, but the tank car CPR will increase because of the higher speed (Figure 5). The overall release rate, which is the product of the accident rate and CPR (in this example, for a noninsulated USDOT-111A100W1 tank car), is dominated by the accident rate and thus also declines. The difference in the magnitude of the release rate between consecutive track classes is the smallest for Track Classes 4 and 5.

The authors examined each individual segment to understand the change in risk as a result of track infrastructure upgrade and an increase in speed. Figure 6 shows the distribution of the segment-specific risk per mile for three cases for each track class: (*a*) the baseline case (no upgrade), (*b*) upgrade to a higher class without an increase in speed, and (*c*) upgrade to a higher class with an increase in speed. Speed-dependent CPRs were used in all scenarios. For clarity, only the top 10 segments with the highest risk per mile, ordered by the baseline risk, are shown. These charts indicate that upgrading Class 3 segments to Class 4 yields the largest reduction in risk, whereas upgrading Class 4 track to Class 5 offers little reduction in risk for the representative route. Furthermore, the difference between the risk per mile for a segment when speed is held constant compared with the risk when the speed is increased is the highest for the case in which Class 2 segments are upgraded to Class 3. The magnitude of the difference varies because of the different initial operating speeds on each segment (Figure 6*a*). Overall, use of the speed-dependent CPR enables individual consideration of both of the factors affecting risk, in this case, the reduction in the accident rate due to the upgraded track class, and the increase in CPR due to the higher operating speed.

DISCUSSION OF RESULTS

When risk estimates for each of the scenarios analyzed in the case study are summarized, several results can be discerned (Table 2).

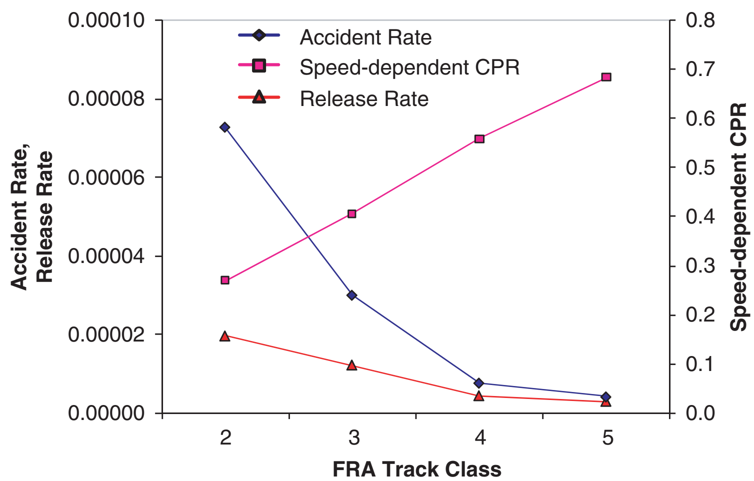

FIGURE 5 Relationship between track classes, accident rates, speed-dependent CPRs, and release rates for tank car considered (USDOT-111A100W1).

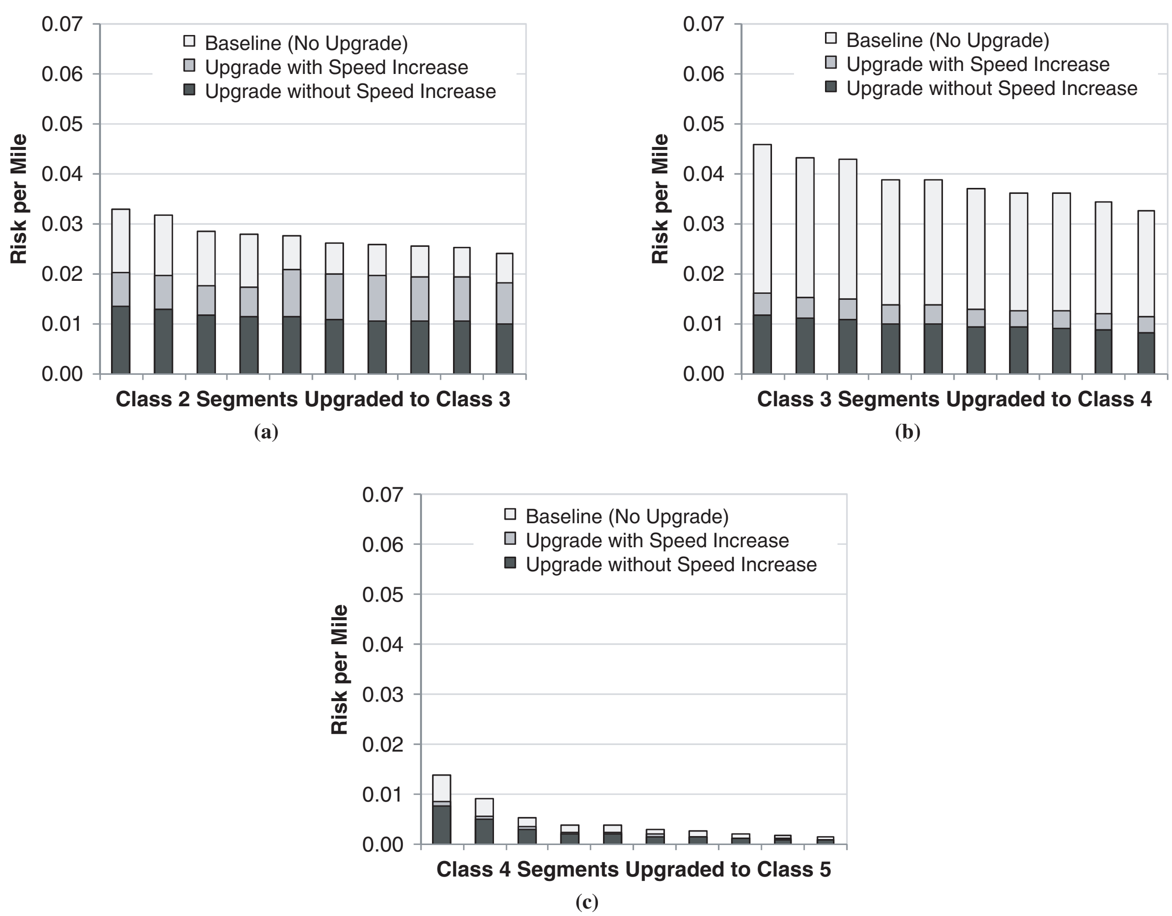

FIGURE 6 Effects of infrastructure upgrade and speed on risk reduction for top 10 segments with highest risk per mile: (*a*) Class 2 upgraded to Class 3, (*b*) Class 3 upgraded to Class 4, and (*c*) Class 4 upgraded to Class 5.

TABLE 2 Summary of Estimates

Track Class Considered for Upgrade to One Higher Class	Total Distance Upgraded (m)	Accident Rate (cars derailed per year)	Release Rate (releases per year): Using Average-Speed CPR	Release Rate: Using Speed-Dependent CPR, Without Speed Increase	Release Rate: Using Speed-Dependent CPR, With Speed Increase	Annual Risk (persons affected per year): Using Average-Speed CPR	Annual Risk: Using Speed-Dependent CPR, Without Speed Increase	Annual Risk: Using Speed-Dependent CPR, With Speed Increase
Before Track Upgrade (baseline)		0.0144	0.0051	0.0066		1.2913	1.4281	
After Track Upgrade								
Class 2	11	0.0140	0.0049	0.0065	0.0066	1.2018	1.3621	1.3881
Class 3	230	0.0093	0.0033	0.0046	0.0050	0.5879	0.6753	0.8003
Class 4	545	0.0125	0.0044	0.0056	0.0059	1.2248	1.3276	1.3484
Percent Reduction from Baseline								
Class 2	11	3.1	3.9	1.5	0.7	6.9	4.6	2.8
Class 3	230	35.5	35.3	30.3	24.2	54.5	52.7	44.0
Class 4	545	13.2	13.7	15.2	10.6	5.1	7.0	5.6
Percent Reduction per Mile Upgraded								
Class 2	11	0.28	0.36	0.13	0.06	0.63	0.42	0.25
Class 3	230	0.15	0.15	0.13	0.11	0.24	0.23	0.19
Class 4	545	0.02	0.03	0.03	0.02	0.01	0.01	0.01

First, in the consideration of track infrastructure upgrades, there are different opportunities for risk reduction based on the distribution of track classes on the route and the differential effects on risk reduction with respect to each track class. Upgrading the lowest track class provides the highest risk reduction per track mile; however, it represents the smallest proportion of the route, so that it does not offer much opportunity to reduce risk. On the other hand, upgrading Class 3 track segments to Class 4 provides the highest risk reduction overall, even though these segments do not represent the largest percentage of the route compared with the percentages for the other track classes.

Second, use of the speed-dependent CPR allows the effects of speed on different routes to be properly accounted for, whereas use of the average-speed CPR does not. Furthermore, the speed-dependent CPR is necessary for proper evaluation of the effect of track-class upgrades on risk with or without a speed increase.

Third, for the representative route, use of the speed-dependent CPR yields annual risk estimates slightly higher than use of the average-speed CPR. This is because the majority of the route has higher-than-average track speeds. This result will vary depending on route-specific characteristics.

Fourth, upgrading the track class with the commensurate speed increase actually reduces the risk relative to that for the baseline case. This is because the incremental effect of the lower accident rate due to the higher track class more than offsets the slight increase in the CPR due to the higher speed.

Completing the analyses used to illustrate the effect of speed-dependent CPR on risk estimates required several assumptions. As mentioned, for track-class upgrades with an increase in speed, it was assumed that trains would operate at the maximum allowable speed corresponding to the upgraded track class. This will result in estimates of speed higher than those that would actually be used on some segments, thus overestimating the risk for those segments. Inferring track class on the basis of the timetable speed may not always represent actual maintenance conditions for some track segments, also resulting in the overestimation of risk. For both of these circumstances, if data for actual operating speed are available, they can be incorporated into the model and use of the speed-dependent CPR will make such adjustments more accurate. Additionally, the relationships developed to estimate the speed-dependent CPR in this study do not account for other possible speed-dependent effects, such as the number of cars derailed or the spill size distribution, but these factors can also be incorporated into the model, if suitable data are available.

The intent of this research was to develop a general method to calculate the speed-dependent CPR by using published data for railroad tank cars. The authors then used a case study to compare several different scenarios that affect or that are affected by speed to gain insight into the effect of using the speed-dependent CPR on estimates of safety and risk. Analysis of these scenarios is not meant to suggest that these are necessarily the most cost-effective approaches to risk reduction. Instead, the methodology presented here is intended to describe and illustrate the utility of speed-dependent CPR and how it may be incorporated into safety and risk analysis calculations. The scenarios considered here include upgrading the track class both with and without speed increases. Either scenario would entail considerable additional capital and maintenance expense (*19*). Rational consideration of these options would require data on their incremental cost and, ideally, information on the cost-effectiveness of other options that might also affect risk. This would enable informed decisions about when and where risk reduction options should be implemented and which ones are the most cost-effective to be made.

CONCLUSIONS

In this paper, the authors present a technique that incorporates the effects of different train speeds on accident rate and CPR and incorporate both of these into a hazardous materials transportation risk analysis model. The relationship was developed to estimate the speed-dependent CPR, thereby allowing more accurate estimates of route risk. Although previous work has addressed various aspects of this question (*1, 7–9*), the method used to calculate the speed-dependent CPR described here can be used to develop estimates for specific tank car designs, which was not previously possible. Additionally, the statistics and methodology presented here are based on the most up-to-date, published data on tank car performance in accidents. The utility of the speed-dependent CPR is illustrated by using a case study of track infrastructure upgrades in which the authors analyzed the effects of train speed and track improvement independently and together to assess their effects on route risk. Different options in a track infrastructure upgrade problem were considered to determine the option that may provide the greatest reduction in risk for the particular route studied.

Previous work has not explicitly considered the nature or the extent of the effect of using the average-speed CPR versus the speed-dependent CPR on risk estimates. Although use of the average-speed CPR may often be appropriate for national or systemwide estimates of risk, it does not satisfactorily account for differences in operating characteristics when routes are compared. Different routes will almost certainly have different speed distributions and population exposures. Use of the average-speed CPR can lead to both under- and overestimates of the overall risk along the route and at specific locations along the route. Both of these may affect risk management decisions; therefore, the ability to calculate them more accurately is important. In addition, use of the speed-dependent CPR affects the ability to assess the effects of certain types of track infrastructure upgrades quantitatively, as illustrated in the case study. The speed-dependent CPR calculation methodology and its application to risk analysis models should enable more accurate risk calculations not only for comparisons of the risks on different routes but also for assessment and evaluation of the benefits of infrastructure improvements that affect operating speeds.

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