Effects of Route Rationalization on Hazardous Materials Transportation Risk

Athaphon Kawprasert and Christopher P. L. Barkan

Hazardous materials traffic originates and terminates at numerous locations throughout the North American railroad network. Rerouting of this traffic, especially toxic inhalation hazard materials, away from populated areas has received considerable attention in recent years as a means of reducing risk. However, rerouting on a route-specific basis is neither simple nor necessarily effective at reducing risk because of physical constraints in the configuration of the rail network and the possible need to increase the miles traveled by hazardous materials so as to avoid populated areas. A more comprehensive approach is rationalization of the transportation route structure for these materials. This does not simply involve trying to reroute traffic between the current set of origins and destinations to avoid population centers en route. Instead, route rationalization encompasses analysis of the entire route structure for a particular material. The objective is to identify opportunities to reduce risk by considering critical factors associated with each possible route, while simultaneously taking into account the production and consumption levels at each location in the network. This paper presents a risk analysis model combined with an optimization technique to formally consider risk reduction by means of rationalization of the hazardous materials transportation rail route structure. The model is flexible and enables optimization of the route structure based on a variety of possible objective functions, including minimization of miles traveled, accident (derailment) probability, likelihood of release, population exposure, and risk.

Railroads have placed a high priority on the safe transportation of hazardous materials for more than a century (*1, 2*). Traditionally, this activity focused on transportation packaging (*3–7*), product hazard identification, placarding, emergency information, and response capability (*8, 9*). Railroads have developed special operating practices intended to reduce the likelihood or severity of accidents involving trains transporting certain hazardous materials (*10*). There has also been research on routing as an option to manage hazardous materials risk (*11–14*). In recent years, the latter has gained increasing popular attention from municipalities eager to reduce the risk to their own constituents and analytical attention among researchers studying route planning for hazardous material transportation (*15, 16*). However, rerouting is neither simple nor necessarily effective at reducing risk because of physical constraints in the configuration of the rail network and the possible need to increase the mileage traveled by hazardous materials so as to avoid populated areas (*13*). Furthermore, the inevitable transferal of risk from one community to another raises significant public policy and political questions.

As a result of security concerns and several fatal railroad hazardous materials accidents, railroads' interest in all possible means of reducing hazardous materials transportation risk has intensified in recent years, especially for toxic inhalation hazard (TIH) materials such as chlorine, ammonia, and approximately two dozen other chemical products classified as TIHs shipped by rail (*4, 9*). This has included increased attention to the traditional means of reducing risk mentioned above, as well as other options not previously given as much consideration. Among the latter category is rationalization of the transportation route structure for TIH materials shipped by rail. This approach differs from the type of routing discussed above because it does not simply involve trying to reroute traffic traveling between the current set of origins and destinations (O-D pairs) to avoid population centers en route. Instead, route rationalization involves a comprehensive analysis of the entire route structure for a particular material and identifying opportunities to reduce the transportation volume or mileage traveled while taking into account the production and consumption levels at each location. This will often involve changing O-D pairs to take advantage of shorter distances between particular production and consumption centers. This paper introduces an optimization model to evaluate the route structure of a particular material to minimize several objective functions, including car miles, probability of derailment, and risk. The problem is similar to a traditional operations research topic known as the transportation problem (*17*) but is modified to account for the different objective functions.

The authors recognize that in practice there may often be constraints on the ability of rail carriers or chemical manufacturers to make the types of changes in distribution patterns considered in this paper. The model and results represent an idealized case that is intended to facilitate consideration of the approach. The objective is not to suggest that such changes are easy or feasible in all cases. Instead, the purpose of this paper is to provide a structure and illustrative example to enhance evaluation of route rationalization as a possible risk management strategy.

The paper has several goals in support of this objective. One goal is to develop and present a basic, formal quantitative structure to enable consideration of route rationalization as an option for managing hazardous materials transport risk. The basic structure provides a framework to which additional constraints and factors can be added if more specificity or realism is desired. It can also help risk managers better understand the types of information needed and the factors to be considered if they wish to evaluate this option. Another goal is to use the model to consider a case study based on rail transport of an actual TIH. In addition to illustrating the model, it provides insight into the potential for risk reduction through use of this approach.

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Finally, preliminary consideration is given to the effect of different risk metrics as objective functions in the optimization process. This is of potential use to both researchers and practitioners because the different metrics may be more or less difficult to develop in different situations. Understanding the relationship of these metrics to one another may yield insight into the likely effect on risk in cases in which complete information is unavailable.

NATURE OF THE PROBLEM

Hazardous materials traffic originates and terminates at many different locations in the North American railroad network. Flows of a particular hazardous material, including TIHs, may involve fewer than a half-dozen origin and destination points, or many hundreds of different points throughout the network. A simple example of a traffic-routing problem is illustrated in Figure 1*a.* Material produced at *X* and *Y* is shipped from *X* to *Y, X* to *Z,* and *Y* to *X.* Route rationalization involves reducing transportation volume by minimizing the car-mileage required to transport the material to the various destination points. This is manifested in two basic ways: either eliminating or reducing flows to locations that also produce and ship material, or by rerouting so that material is shipped to the nearest destination (Figure 1*b*). The computational complexity of the problem is related to the number of O-D pairs, but the basic analytical methodology is the same.

In the simple example illustrated in Figure 1*b,* material produced at *X* is consumed at *X* rather than being shipped to *Y,* and similarly, material produced at *Y* is consumed at *Y.* In addition, material produced at *X* and consumed at *Z* is instead supplied from *Y* because it is closer.

CASE STUDY

To illustrate route rationalization, consider a set of traffic flows based on a particular hazardous material being transported on the North American railroad network. The portion of the network considered comprises six different locations (Figure 2) with the annual carloads and car miles on each link in the network. The route mileage between these locations was determined using rail-routing software. The Princeton Transportation Network Model was used to develop maps of the traffic volume and directional flow, but other suitable railroad network models could also be used for this purpose (*18*). After the route mileage is determined, the car miles are calculated for each O-D flow by multiplying the number of carloads by the mileage.

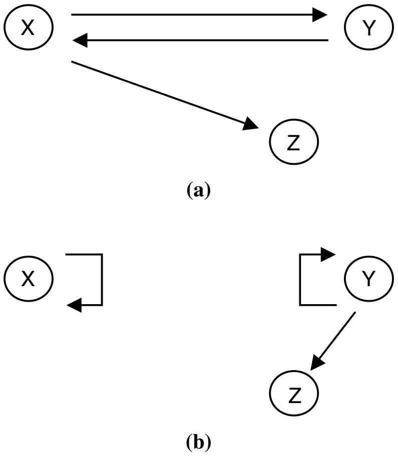


FIGURE 1 Simple transportation network for hazardous material: (*a*) without route rationalization and (*b*) with route rationalization.

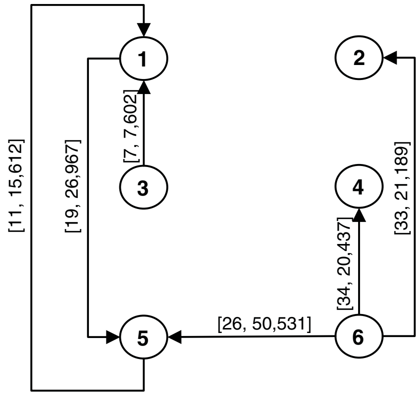


FIGURE 2 Schematic diagram of baseline network flow for case study (carloads, car miles).

To rationalize this traffic flow pattern, the authors first assume that population exposure, derailment probability, and other factors potentially affecting risk are homogenous across the entire route structure. Under these simplifying assumptions, risk will be proportional to the length of the route and the number of cars shipped. In this case, the problem reduces to the basic transportation problem in which the objective function is minimization of car miles. This is synonymous with minimizing risk while holding shipment volume at each origin and destination constant. In reality, of course, these assumptions are too simplistic; there is considerable heterogeneity in various important factors affecting risk along the routes where hazardous materials are shipped, notably accident rates and population exposure. Furthermore, different decisions and policies may require differing consideration of various factors. Accordingly, the model must be capable of accounting for these if it is to provide useful results.

LINEAR PROGRAMMING MODEL FORMULATION

In this section, the authors formulate the linear programming (LP) model to determine the alternative traffic flow considered in the case study. As stated above, the objective function is initially set up to minimize total car miles of hazardous material shipments with the constraint that incoming and outgoing traffic is held constant for each origin and destination. The constraint can be treated as demand and supply requirements at each location and the LP problem for minimizing total car miles is as follows:

$$\text{minimize total car miles} = \sum_{od} m_{od} L_{od} \tag{1}$$

subject to

$$\sum_{o} m_{od} = M_d \qquad \forall d$$

$$\sum_{d} m_{od} = M_o \qquad \forall o$$

and

$$m_{od} \geq 0 \qquad \forall o, \forall d$$

where

m_{od} = shipments (carloads) between origin o and destination d,
L_{od} = mileage from origin o to destination d,
M_d = total shipments (carloads) to destination d, and
M_o = total shipments (carloads) from origin o.

The optimal network flow in which the total car miles are minimized (Figure 3) can be found by solving the LP problem in Equation 1. Using the General Algebraic Modeling System (*19*), the optimal solution yields 96,121 car miles, which is 32.47% less than the original total of 142,339 car miles.

RISK MODEL FORMULATION

The results presented in the previous section show the effect of route rationalization on reducing car miles. However, as discussed previously, this does not guarantee risk reduction because the alternate, shorter routes might have a higher population density or accident rate. Therefore, a more sophisticated risk analysis needs to be conducted to determine other possible alternatives to minimize risk.

This section discusses the formulation of a model for estimation of the risk associated with rail shipments of hazardous materials. The risk analysis is performed using a quantitative risk assessment model to develop numerical estimates of the risk (*20*). Different levels of analysis can be performed depending on the degree of precision required for the problem under consideration. That is, accident rate and population density may be accounted for at the route level or track segment level. The model formulation presented here uses track segment-specific parameters in the risk analysis.

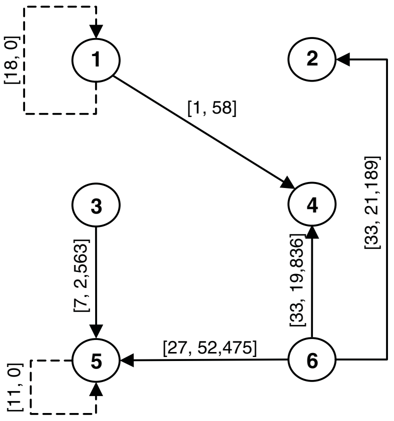


FIGURE 3 Schematic diagram of minimized car miles network flow (carloads, car miles).

It is assumed that the occurrence of a tank car derailment is a random event with a known rate of occurrence that can be modeled using the Poisson distribution. Then, the probability of k cars derailed on a track segment of length L, $P\{N(L) = k\}$, can be expressed as

$$P\{N(L) = k\} = \exp(-ZL)(ZL)^k \big/ k! \tag{2}$$

where

$N(L)$ = number of tank cars derailed on a track segment of length L,
k = 0, 1, 2, . . . , and
Z = tank car derailment rate per unit length of track segment.

Let A be the event that at least one tank car is derailed in an accident and A_i that event occurring on track segment i. The probability that at least one tank car will be derailed in an accident on track segment i, $P(A_i)$, can be expressed as

$$P(A_i) = 1 - P\{N(L_i) = 0\} = 1 - \exp(-Z_i L_i) \approx Z_i L_i$$
$$(\text{since } Z_i L_i \text{ is very small}) \tag{3}$$

where Z_i is the tank car derailment rate for track segment i and L_i is the length of track segment i.

For a route comprising n segments, the probability of derailment, $P(A)$, is expressed by considering a nonhomogeneous Poisson process:

$$P(A) = 1 - \exp\left(-\int_0^L Z dL\right) = 1 - \exp\left(-\sum_{i=1}^{n} Z_i L_i\right) \approx \sum_{i=1}^{n} Z_i L_i \tag{4}$$

Derailment rates, Z_i, can be determined from previous accident statistics for individual track segments or other segments determined to have similar characteristics. Here the FRA track class-specific accident rates developed by Anderson and Barkan (*21*) are used. It is also assumed that the probability of hazardous material tank car derailment in an accident does not depend on the type of material being transported (*22*).

Let R be the event of a hazardous material release from a tank car and R_i that event occurring on track segment i. Then, consider the probability of a hazardous material release on track segment i, $P(R_i)$. Assuming that there will be no release if there is no derailment [i.e., $P(R|A')P(A_i') = 0$], so

$$P(R_i) = P(R|A)P(A_i) \tag{5}$$

where $P(R|A)$ is the conditional probability of a hazardous material release from a tank car given that it is derailed in an accident.

The authors estimate $P(R|A)$ from the probabilities of lading loss developed by Treichel et al. (*23*), which takes into account the design characteristics of the tank car. In this study, the authors assumed that only one type of tank car is used to transport the material. If several types of cars are used but the effect of the different design characteristics is not of interest, then the aggregated conditional probability, $P(R|A)_{\text{agg}}$, can be computed using the weighted mean of the different car types' conditional probabilities:

$$P(R|A)_{\text{agg}} = \sum_t \{w_t P(R|A)_t\} \Big/ \sum_t w_t \tag{6}$$

where w_t is the percentage distribution of tank cars with type *t* design characteristics, and $P(R|A)_t$ is the conditional probability of a hazardous material release from a tank car with type *t* design characteristics given that it is derailed in an accident.

For any particular hazardous material, the level of consequence also depends on the quantity released to the environment, which may vary with the severity of the accident and the atmospheric conditions. To account for different release scenarios, the probability of an event with a specific scenario of release *s* for a track segment *i*, $P(I_{si})$, can be expressed as follows:

$$P(I_{si}) = P(I|R,A)_s P(R|A)_{\text{agg}} P(A_i) \tag{7}$$

where $P(I|R,A)_s$ is the conditional probability that a specific scenario *s* will occur given that there is a hazardous material release from a derailed tank car.

The consequence of the hazardous material release (C) is expressed in terms of the population exposed to possible evacuation from the affected area due to a hazardous materials release. So, the consequence of a specific release scenario *s* for track segment *i*, C_{si}, is written as

$$C_{si} = H_s Y_i \tag{8}$$

where H_s is the affected area where people need to be evacuated or sheltered in place for a specific scenario of release *s*, and Y_i is the average population density in an affected area corresponding to track segment *i*.

The affected area, H_s, was determined in accordance with the U.S. Department of Transportation (DOT) *Emergency Response Guidebook* (ERG) recommended evacuation or shelter-in-place distances (*9*), corresponding to the particular chemical and release scenario. The population density, Y_i, is approximated by considering the weighted average number of people in the U.S. census tracts coincident with the affected area.

The ERG guidelines were developed and are periodically updated by the U.S. DOT. They are determined using a statistical model that incorporates sophisticated emission rate and dispersion models, historical release incident data, meteorological observations in North America, and current toxicological exposure guidelines (*9, 24*). The ERG is widely used by the emergency response community so it should be reasonably correlated with the events likely to occur in an actual hazardous materials spill. Furthermore, the costs in spill accidents are driven to some degree by the extent of the evacuation, so use of the ERG-affected area as a metric for consequences provides some insight regarding relative expense. The ERG guidelines do not reflect injuries or fatalities due to a release. Instead they enable a relative comparison in terms of the number of people who might be affected by a release. The ERG guidelines are generally considered conservative and probably lead to overestimation of the number of people who will actually be affected. This is more likely to affect absolute estimates of risk than the relative estimates that are important in the analyses considered in this paper, so the authors believe it is a satisfactory metric in the context of this study.

The final step is to define the risk metric. In this study, the annual expected number of people who potentially might need to be evacuated or sheltered in place according to the U.S. DOT ERG recommendations as a result of a hazardous material release (or in short, annual risk), *U,* is considered as one possible metric. Another metric for route comparison is the average individual risk, *V,* defined as the total annual risk divided by total population in the exposure area—the area within the radius from track center equal to the U.S. DOT ERG maximum evacuation distance for the worst-case release scenario for a particular hazardous material.

$$U = \sum_{si} P(I_{si})(C_{si}) \tag{9}$$

$$V = \frac{\sum_{si} P(I_{si})(C_{si})}{\sum_{j} (B_j)(E_j)} \tag{10}$$

where B_j is the population density of the census tract *j* coincident with the exposure area, and E_j is the area of census tract *j* coincident with the exposure area.

In addition to the expected risk estimates, the authors developed risk profiles (also known as "F-N curves"). These provide information on the probability distribution of risk outcomes and also enable a better understanding of changes in the probability of incidents of various magnitudes as a result of changes in the factors affecting risk such as population exposure. Risk profiles were developed by listing all pairwise combinations of $P(I_{si})$ and C_{si}, and then sorting by the latter in a descending order and plotting cumulative $P(I_{si})$ against C_{si}.

ESTIMATION OF RISK PARAMETERS

The intermediate location points along the shipment routes were determined by using rail routing software. Then, using geographic information system (GIS) software, the route map layer was created for both the baseline and alternate route patterns using the U.S. DOT national railroad network data (*25*). The route created is divided into segments, indicated by link ID in the network. For the purpose of illustrating the effect of differential accident rates in the model, the authors developed a proxy variable to estimate FRA track class. It was based on the type of traffic control system listed in the U.S. DOT GIS database because this is roughly correlated with allowable train speed and is available in digital database form for the entire U.S. rail network. Train speed reflects FRA track class, which has been shown to be correlated with railroad accident rates (*26*). If data on the actual FRA track classes or other more direct metrics of train accident rate are available for a particular set of routes, these could easily be substituted in the analysis.

Track segment-specific accident rates are determined based on the inferred FRA track classes and corresponding accident rates (*21*). The length of the track segments was determined from the GIS data. It was assumed that all tank cars used were DOT 105J300W pressure cars with a steel jacket, insulation, full-height head shields, and a tank thickness of 0.6875 in. These cars have a conditional probability of release of 0.0691, given that they are derailed in a FRA-reportable mainline accident (*23*).

Four different release scenarios were considered: small and large daytime spills, and small and large nighttime spills. Large spills were defined as those in which more than 5% of the tank car's contents are lost. The proportions of spill sizes from the distribution of quantity of lading loss for pressure cars in mainline accidents are 0.2213 and 0.7787 for small and large spills, respectively (*23*). In this analysis it was assumed that shipments travel in daytime or nighttime with equal likelihood; therefore, the proportions of daytime and nighttime release scenarios are 50% each for day or night, or 0.1106 each for daytime/nighttime small spills and 0.3894 each for daytime/nighttime large spills. In this analysis, the authors did not quantitatively consider the effect of time-of-day-dependent population density, but this can be factored into the model if the particular risk question warrants it and the data are available.

The hazard area of people affected for each release scenario is calculated using the U.S. DOT ERG table of initial isolation and protective action distances (*9*). For the material analyzed, the affected areas for different atmospheric conditions and release sizes are: 0.011 mi^2 for daytime/nighttime small spills, 0.092 mi^2 for daytime large spills, and 0.252 mi^2 for nighttime large spills. Finally, GIS was used to perform an overlay analysis of the affected area and the population density to calculate the consequences of a release along each of the routes analyzed.

ROUTE RATIONALIZATION MODEL

The alternative network flow in which car miles are minimized may or may not have lower risk compared with the baseline traffic flow. In other words, the route that minimizes car miles does not guarantee minimal risk because of the possibility of differential accident rates or population exposure. In this section, risk analysis results are incorporated into the optimization model so minimization of the risk metric is the objective function.

The LP model in Equation 1 has been modified to incorporate the risk parameters described in the previous section. Using Equations 3 through 9, the route rationalization model can be formulated in the LP form as follows:

minimize total annual risk $U =$

$$\sum_{siod} P\left(I \middle| R, A\right)_s P\left(R \middle| A\right)_{\text{agg}} Z_{iod} L_{iod} m_{od} H_s Y_{iod} \qquad (11)$$

subject to

$$\sum_{o} m_{od} = M_d \qquad \forall d$$

$$\sum_{d} m_{od} = M_o \qquad \forall o$$

and

$$m_{od} \geq 0 \qquad \forall o, \forall d$$

where

m_{od} = shipments (carloads) between origin o and destination d,
M_d = total shipments (carloads) to destination d, and
M_o = total shipments (carloads) from origin o.

The objective function of the route rationalization model integrates three major elements in risk analysis: the probability of derailment, the probability of release, and the consequence of release. All parameters in the objective function can be predetermined, except the number of shipments that are to be optimally solved for each O-D pair.

TABLE 1 Comparison of Effect of Different Objective Functions on Different Annual Risk Metrics Considered

Metrics	Baseline Traffic Flow	Objective Function Minimized		
		Car Miles	Release Probability	Annual Risk
Total car miles	142,339	96,121	96,722	96,140
Derailment probability	0.01765	0.01289	0.01280	0.01288
Release probability	0.00122	0.00089	0.00088	0.00089
Annual risk	0.12877	0.10581	0.10814	0.10558
Average individual risk	1.69×10^{-7}	1.38×10^{-7}	1.60×10^{-7}	1.38×10^{-7}

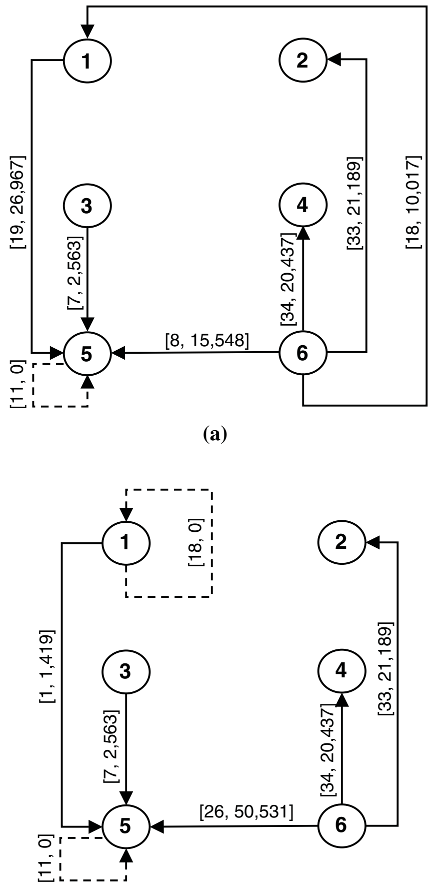
The model can be modified depending on the particular purpose of the analysis. For example, if only release probability is of interest, the last two terms in the expression may be omitted. If risk control is required for any particular O-D pair, the maximum risk level can be specified as a constraint in the model so that the risk for that particular route will not exceed the prescribed level. Furthermore, this approach can be used to determine whether risk reduction options that affect the probability of a derailment (*27, 28*), the probability of release (*2, 7*), or the consequence of release would alter the optimal route structure. Thus, the route rationalization model provides flexibility in the decision criteria that could be used to inform policy and planning questions and objectives.

RESULTS AND DISCUSSION

The route rationalization model in Equation 11 was used to determine the set of optimal traffic flows for the case study, using minimization of three different objective functions: car miles, release probability, and annual risk (Tables 1 and 2). The optimal flows for minimization of release probability and risk are shown in Figures 4*a* and 4*b*, respectively.

TABLE 2 Percentage Change in Various Metrics Relative to the Baseline Case When Different Objective Functions Are Used

Metrics	Baseline Traffic Flow	Objective Function Minimized		
		Car Miles (%)	Release Probability (%)	Annual Risk (%)
Total car miles	142,339	−32.5	−32.0	−32.5
Derailment probability	0.01765	−26.7	−27.3	−26.7
Release probability	0.00122	−27.0	−27.5	−27.1
Annual risk	0.12877	−17.8	−16.3	−17.8
Average individual risk	1.69×10^{-7}	−18.3	−5.3	−18.3



(a)

(b)

FIGURE 4 Schematic diagram of traffic flow when (*a*) release probability is minimized and (*b*) risk is minimized (carloads, car miles).

Minimizing release probability reduced car miles by 32.0% and risk by 16.3%, whereas minimization of risk reduced car miles by 32.5% and risk by 17.8% (Table 2). In this study, the authors assumed a single car design, so the flow with derailment probability minimized is the same as the flow in which release probability is minimized; however, if a mix of cars with different release probabilities was used on different routes, then these would not be equivalent. For the particular hazardous material studied, the traffic flow patterns for the rationalized route structure based on minimization of the three objective functions differ in some of the details. However, the values of the metric associated with each of the optimal flows did not differ by much, except for average individual risk.

In addition to the point estimates of average risk, an understanding of the distribution of risk outcomes is often useful for risk management decisions. This is particularly true regarding routing questions, because routing is one of the few risk reduction strategies with the potential to affect the consequence level of a release, as well as the probability. Use of risk profiles allows comparison of the distribution of risk for the baseline traffic flow compared with the rationalized traffic flows based on the three different objective functions (Figure 5). As was the case with the expected risk estimates, the risk profiles for the different objective functions do not differ much from one another, but all are lower than the baseline case. This difference is true across nearly the entire range of *C*, but the extent of the difference declines as *C* increases (Figure 6). This suggests that rationalizing the route structure for this particular hazardous material has a greater effect on reducing traffic in less populated areas of the route structure relative to the more highly populated portions. At the very highest values of *C*, there is no difference between the baseline and rationalized route structures, indicating that for this hazardous material, exposure to the most densely populated segments is not eliminated by route rationalization. Nevertheless, there is an overall reduction in risk. The authors believe that the degree of difference resulting from the use of various objective functions will depend on the characteristics of the route structure of the material. More study is needed to understand

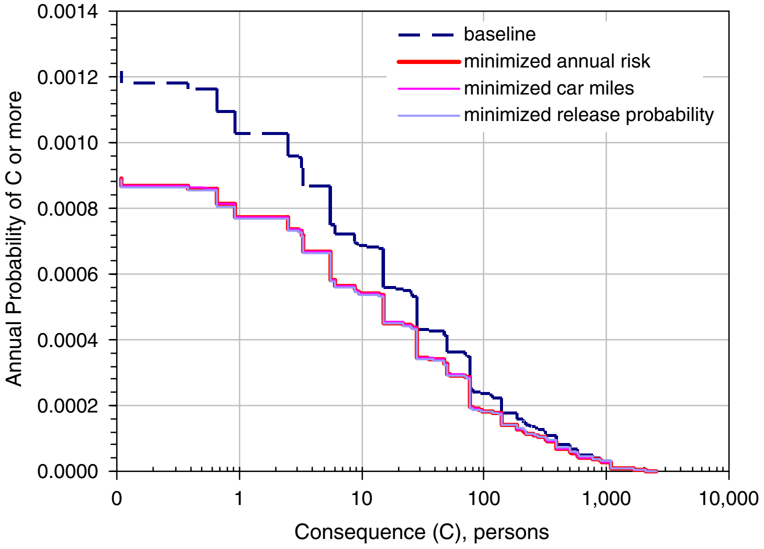


FIGURE 5 Risk profiles for the baseline case compared with rationalized route structures optimized using three different objective functions.

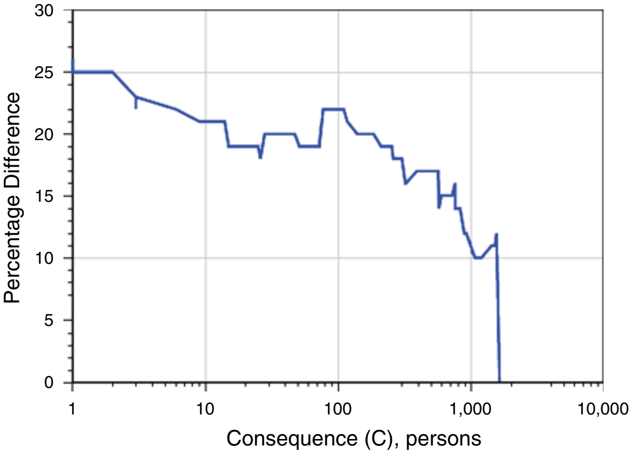


FIGURE 6 Percentage reduction in the probability of *C* or more persons affected in rationalized route structure in which risk is minimized compared with baseline case.

the generality of the results presented here, the degree of variability for different product-specific route structures, and the principal factors involved.

The application of a linear programming model combined with the risk model allows several elements to be integrated and simultaneously considered. In the case study, the average reduction in risk ranged from approximately 16% to 18%, depending on which objective function was being minimized, whereas the mileage reduction was about 32%. It is interesting that the risk reduction was less than the mileage reduction. This is consistent with the result that the rationalized route structure for this particular hazardous material tended to disproportionately reduce exposure to lower population density segments compared with the baseline route structure. This is probably due to the particular nature of the route structure of the material analyzed in the case study. In general, the opportunities for risk reduction will vary depending on the route structure of the particular hazardous material being considered.

CONCLUSION

This paper describes a basic model for evaluation of route rationalization as a means of reducing the risk from rail transport of hazardous materials. The purpose is to introduce and illustrate the concept and to explore the potential benefits that may be possible. A simple case study is considered based on the route structure of a TIH transported in railroad tank cars. The results indicate that for the product evaluated, route rationalization can reduce mileage, accident probability, release probability, population exposure, and risk. In general, the extent of risk reduction possible will depend on the characteristics of the traffic pattern and other constraints of the particular optimization problem. For purposes of illustration and brevity, the authors relaxed some constraints in this study, including neglecting the possibility of schedule conflicts or track unavailability, and did not account for possible temporal variation in production capacity or demand. However, the model was structured so that it can be adapted to incorporate these and other factors, thereby enhancing its general applicability.

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