Integrated Optimization Model to Manage Risk of Transporting Hazardous Materials on Railroad Networks

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Rail transport plays a key role in safely and economically moving hazardous materials from production to consumption points. As a result of heightened safety and security concerns, interest in all possible means of reducing the risk of transporting hazardous materials has intensified in recent years. Various approaches to railroad accident prevention—including infrastructure improvements, packaging enhancements, operational changes, and alteration of the route structure—are available. Operations research techniques have been applied to consider each approach individually, but no technique has integrated the approaches into a single model. This study introduced an integrated mathematical model to formally consider a combination of approaches to reduce risk. The framework enabled simultaneous consideration of route choices, tank car safety designs, and track maintenance to determine an optimal strategy that minimized risk and costs. Model formulation was provided in the form of nonlinear and mixed-integer programming. For illustration, a small-scale, hypothetical network flow of a hazardous material was considered. Numerical results showed that the optimal strategy could substantially reduce risk with a marginal increase in costs. The integrated model provided a framework for choosing the most effective risk-mitigation strategy for a particular rail network given various constraints. It could be applied to multiple types of commodities and adapted to address various questions for local, regional, or systemwide planning and decision making to provide the safest transportation possible given constrained resources. The framework would be particularly beneficial to rail carriers interested in how to best allocate safety and engineering resources to maximize safety.

Reducing railroad hazardous materials transportation risk has long been a priority for industry and government. As a result of security concerns and several fatal accidents this interest has intensified in recent years (*1, 2*). Particular attention has been directed toward over two dozen chemical products classified as toxic inhalation hazard materials, including chlorine and ammonia. Efficient management of the risk posed by these materials requires an understanding of how different approaches may reduce risk and their relative cost-effectiveness both alone and in combination.

There are various approaches to hazardous materials transportation risk reduction. A variety of operations research techniques have been developed and applied to consider each approach individually, including consideration of hazardous materials transportation routing (*3–6*), improving transportation packaging (*7–9*), upgrading track infrastructure (*10*), and managing the operating speed of hazardous materials trains (*11*). Saat and Barkan developed a preliminary comparative analysis of the effect of tank car safety design versus alternative routing (*12*) and infrastructure improvements (*13*). However, the authors are unaware of research that considers and compares more than one approach to risk reduction simultaneously. Such comparison is important to objectively evaluate different approaches, possible interactive effects, and relative cost-effectiveness and to determine optimal strategies.

Each risk reduction strategy has characteristic benefit and cost functions. A release event is typically conditioned on a series of earlier events—a train accident or derailment, hazardous material car involvement, and hazardous material car damage and release. Each event has its own probability distribution, which in turn affects the result of the risk equation. Lowering any of the terms in this equation will reduce risk, but the form and extent of the reduction associated with each term varies. Different risk reduction strategies affect the terms differently. For example, packaging enhancement involving tank car design improvement reduces the conditional probability of release from a tank car involved in an accident but does not reduce accident rates. Conversely, upgrading track infrastructure offers reduction in accident rates but does not affect the conditional probability of release from a tank car involved in an accident provided that operating speed remains the same. However, there are interactive effects among the terms that affect the cost–benefit analysis, which complicates comparison among different risk reduction strategies. The multiplicative form of the risk equation means that the benefit associated with a particular risk reduction strategy is affected by changes to others terms in the equation. Thus improving packaging reduces the benefit derived from improving infrastructure, and vice versa, but the cost associated with each of these strategies is unchanged. Consequently, implementing a risk reduction strategy may reduce the cost-effectiveness of other strategies.

This study presents an integrated risk management framework model to provide a means of choosing the most effective set of risk mitigation strategies for a particular rail network. The model is first formulated using nonlinear programming (NLP) and converted into

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a mixed-integer programming (MIP) problem. For illustration, a small-scale, hypothetical network flow of a hazardous material is considered. The model is used to determine the optimal combination of number of shipments, tank car utilization, and track classes to be maintained on each link that minimizes total cost, given capacity, and demand constraints. The flexibility of the model framework is illustrated by considering different investment scenarios: upgrading track infrastructure, using a more robust tank car, and a combination of both.

ELEMENTS OF RISK ANALYSIS AND OPTIMIZATION FRAMEWORK

Earlier work by Lai et al. identified optimal train routing over a network with capacity constraints and traffic heterogeneity to minimize transportation and track maintenance costs (*6*). Lai et al. also described a model that considers the trade-off between transportation and track maintenance costs and determines the optimal assignment for track class given traffic demand and track maintenance budget (*14*). These models, however, do not incorporate the safety aspect, in particular, the risk involved with transportation of hazardous materials.

In the present study, operations research techniques using network flow mathematical modeling are combined with a quantitative risk analysis model to develop an integrated framework to consider various risk management strategies. The model determines an optimal set of routes, track classes to be maintained, and tank car types that optimize both financial and safety impacts of hazardous materials transportation at the operational level.

Figure 1 depicts the conceptual diagram for the model for the transportation network assignment of hazardous materials. Input parameters include track infrastructure characteristics, tank car safety design features, and product characteristics. Two additional parameters, traffic demand and track capacity, represent the constraints of the optimization problem. The optimization framework is designed to deliver three types of output depending on the objective of interest: hazardous material traffic flows, tank car type, and track classes to be maintained.

This initial stage of model development focuses on the operating cost components related to routes, track classes, and car types. Capital cost components are excluded, but they can easily be added if data are available. The problem is simplified by omitting some risk parameters, including population distribution along rail lines; chemical-specific hazard exposure, which varies with various factors including toxicity (*15, 16*); population densities; and train operating speed, which affects the conditional probability of release (*17–20*). The goal of this paper is to illustrate the fundamental methodology of the integrated model. Additional parameters not considered here will be addressed in future work as the model is further enhanced.

MATHEMATICAL MODEL FORMULATION

Nonlinear Programming Model

The following notation is used in the NLP model:

i and j = indices representing nodes;
N = set of all nodes;
A = set of all existing arcs i, j;
K = set of k, where k corresponds to the kth origin–destination (O-D) pairs of node $(s_1, e_1), (s_2, e_2), \dots, (s_k, e_k)$, in which s_k and e_k denote the origin and destination, respectively, of the kth O-D pair;
Q = set of q, where q represents track class;
$\delta^+(j)$ = station j serving as departure station;
$\delta^-(j)$ = station j serving as arrival station;
A_k = additional number of cars for O-D pair k if the enhanced-safety tank car is selected;
C_{ij} = transportation cost per car mile on arc i, j;
D_k = demand of O-D pair k (in number of cars);
H^q_{ij} = maintenance cost on arc i, j with track class q;

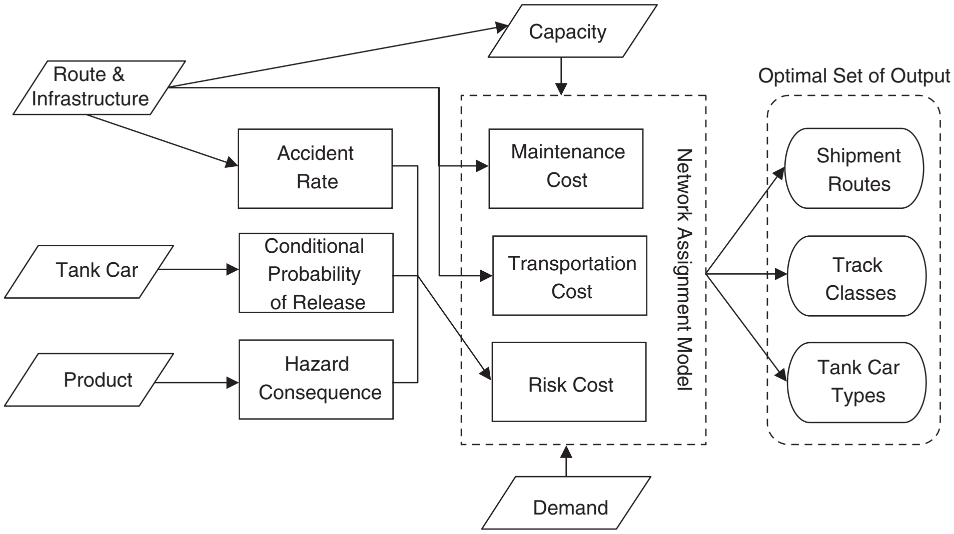

FIGURE 1 Conceptual diagram showing input–output of model for transportation network assignment of hazardous materials.

U_{ij}^{q} = capacity (in number of cars) on arc i, j with track class q;
R_{ij}^{q} = release risk per carload (in monetary value) on arc i, j with track class q; and
W_{ij}^{q} = reduced risk per carload (in monetary value) on arc i, j with track class q if enhanced tank car is selected.

Enhanced-safety tank cars are usually heavier than the baseline tank car, resulting in more cars needed for the same quantity transported. Although a higher track class also requires higher maintenance cost, it offers better safety because it is associated with a lower accident rate (*21*), and it increases the fluidity of the section with higher maximum speed (*22*), resulting in better capacity.

The NLP model has three sets of decision variables. The first variable (x_{ij}^{k}) is a positive integer representing the number of cars running on arc i, j corresponding to O-D pair k. The second variable (y_{ij}^{q}) is a binary variable that determines whether track class q is assigned on arc i, j. The third variable (z_k) is also a binary variable to determine the tank-car enhancement for the kth O-D pair. The network assignment model is expressed in NLP form as follows:

$$\begin{aligned}\min \sum_{(i,j)\in A}\sum_{q\in Q}\sum_{k\in K} H_{ij}^{q} y_{ij}^{q} x_{ij}^{k} + \sum_{(i,j)\in A}\sum_{k\in K} C_{ij} x_{ij}^{k} \\ + \sum_{(i,j)\in A}\sum_{q\in Q}\sum_{k\in K}\left(R_{ij}^{q} - W_{ij}^{q} z_k\right) y_{ij}^{q} x_{ij}^{k}\end{aligned} \tag{1}$$

subject to

$$\sum_{k\in K}\left(x_{ij}^{k} + x_{ji}^{k}\right) \le \sum_{q\in Q} U_{ij}^{q} y_{ij}^{q} \qquad \forall (i, j) \in A, (i < j) \tag{2}$$

$$\sum_{q\in Q} y_{ij}^{q} = 1 \qquad \forall (i, j) \in A, (i < j) \tag{3}$$

$$\sum_{j\in\delta^{-}(j)} x_{ij}^{k} - \sum_{j\in\delta^{+}(j)} x_{ji}^{k} = \begin{cases} D_k + A_k z_k & \text{if } i \in s_k \\ -D_k - A_k z_k & \text{if } i \in e_k \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N, k \in K \tag{4}$$

and

$$\begin{aligned} & x_{ij}^{k} \in \text{positive integer} && \forall (i, j) \in A, k \in K \\ & y_{ij}^{q} \in \{0, 1\} && \forall (i, j) \in A, k \in K \\ & z_k \in \{0, 1\} && \forall k \in K \end{aligned} \tag{5}$$

The objective function in Equation 1 minimizes the sum of total track maintenance cost ($\sum_{(i,j)\in A}\sum_{q\in Q}\sum_{k\in K} H_{ij}^{q} y_{ij}^{q} x_{ij}^{k}$), total transportation cost ($\sum_{(i,j)\in A}\sum_{k\in K} C_{ij} x_{ij}^{k}$), and total risk cost [$\sum_{(i,j)\in A}\sum_{q\in Q}\sum_{k\in K}$ (R_{ij}^{q} – $W_{ij}^{q} z_k$) $y_{ij}^{q} x_{ij}^{k}$]. Equation 2 is the capacity constraint. Equation 3 ensures that only one track class is assigned for each arc i, j. Finally, Equation 4 is the flow conservation constraint. That is, if the enhanced tank car is selected, then additional numbers of tank cars (A_k) will be added. This model determines the optimal assignments of the number of shipments, type of tank cars used, and track classes to be maintained while minimizing the total cost comprising track maintenance cost, transportation cost, and risk cost.

Mixed-Integer Programming Model

To ensure the global optimal solution, the nonlinear model is converted into a linear form by using MIP. The following notation is used in the linear model:

i = index referring to the starting node of an arc;
j = ending node of an arc;
k = kth O-D pairs of node $(s_1, e_1), (s_2, e_2), \ldots, (s_k, e_k)$, in which s_k and e_k denote the origin and destination, respectively, of the kth O-D pair;
q = track class;
t = type of tank car (baseline or enhanced);
T = set of the two car types;
D_{kt} = demand expressed as number of shipments for O-D pair k and type t tank car;
V = set of v, where v is an index representing traffic composition where each v refers to a specific combination of car types [e.g., $v = (N_1, N_2) = (3, 6)$ means there are three baseline tank cars and six enhanced tank cars];
N_t^{v} = number of type t tank cars in traffic composition v;
C_{ij} = transportation cost per carload on arc i, j;
H_{ij}^{vq} = maintenance cost of arc i, j with track class q and traffic composition v;
R_{ij}^{vq} = unit cost of release risk on arc i, j with track class q and traffic composition v; and
U_{ij}^{q} = capacity (in number of cars) on arc i, j with track class q.

This model has three sets of decision variables. The first variable (x_{ij}^{kt}) indicates the number of cars running on arc i, j for O-D pair k and car type t. The second variable (y_{ij}^{vq}) is a binary variable used to determine the traffic composition (v) of arc i, j under particular track class q. The third variable (z_{kt}) is also a binary variable to determine the tank car type t for O-D pair k.

The linear optimization model is formulated as follows:

$$\min \sum_{(i,j)\in A}\sum_{v\in V}\sum_{q\in Q} H_{ij}^{vq} y_{ij}^{vq} + \sum_{(i,j)\in A}\sum_{k\in K}\sum_{t\in T} C_{ij} x_{ij}^{kt} + \sum_{(i,j)\in A}\sum_{v\in V}\sum_{q\in Q} R_{ij}^{vq} y_{ij}^{vq} \tag{6}$$

subject to

$$\sum_{k\in K}\sum_{t\in T}\left(x_{ij}^{kt} + x_{ji}^{kt}\right) \le \sum_{v\in V}\sum_{q\in Q} U_{ij}^{q} y_{ij}^{vq} \qquad \forall (i, j) \in A, (i < j) \tag{7}$$

$$\sum_{v\in V}\sum_{q\in Q} y_{ij}^{vq} = 1 \qquad \forall (i, j) \in A, (i < j) \tag{8}$$

$$\sum_{k\in K}\left(x_{ij}^{kt} + x_{ji}^{kt}\right) \le \sum_{v\in V}\sum_{q\in Q} N_t^{v} y_{ij}^{vq} \qquad \forall (i, j) \in A, (i < j), t \in T \tag{9}$$

$$\sum_{j\in\delta^{-}(j)} x_{ij}^{kt} - \sum_{j\in\delta^{+}(j)} x_{ji}^{kt} = \begin{cases} D_{kt} z_{kt} & \text{if } i \in s_{kt} \\ -D_{kt} z_{kt} & \text{if } i \in e_{kt} \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N, k \in K, t \in T \tag{10}$$

$$\sum_{t\in T} z_{kt} = 1 \qquad \forall k \in K \tag{11}$$

and

$$
\begin{aligned}
&x_{ij}^{kt} \in \text{positive integer} && \forall (i, j) \in A, k \in K, t \in T \\
&y_{ij}^{vq} \in \{0, 1\} && \forall (i, j) \in A, v \in V, q \in Q \qquad (12)\\
&z_{kt} \in \{0, 1\} && \forall k \in K, t \in T
\end{aligned}
$$

The objective function in Equation 6 minimizes the sum of total track maintenance cost ($\sum_{(i,j)\in A}\sum_{v\in V}\sum_{q\in Q} H_{ij}^{vq} y_{ij}^{vq}$), total transportation cost ($\sum_{(i,j)\in A}\sum_{k\in K}\sum_{t\in T} C_{ij} x_{ij}^{kt}$), and total risk cost ($\sum_{(i,j)\in A}\sum_{v\in V}\sum_{q\in Q} R_{ij}^{vq} y_{ij}^{vq}$). Equation 7 is the capacity constraint. Equation 8 ensures that only one traffic composition and track class are selected for arc i, j. Equation 9 is the linking constraint between x_{ij}^{kt} and y_{ij}^{vq} to maintain the consistency of car types assigned. Equation 10 is the flow conservation constraint. Finally, Equation 11 ensures that only one type of tank car is assigned to a particular O-D pair k.

Additional Constraints on Traffic Flow

In some instances, it may be preferable to assign traffic from the same O-D pair to the same route. To implement this routing strategy, a new binary decision variable (w_{ij}^{kt}) and the following two constraints should be added to the original formulation:

$$\sum_{j\in\delta^-(j)} \sum_{t\in T} w_{ij}^{kt} = 1 \qquad \forall i \in N, k \in K \qquad (13)$$

$$x_{ij}^{kt} \le M w_{ij}^{kt} \qquad \forall (i, j) \in A, k \in K, t \in T \qquad (14)$$

The binary variable (w_{ij}^{kt}) equals 1 if arc i, j is selected for O-D pair k and car type t. M is a large number to ensure that x_{ij}^{kt} can have a valid value. Equations 13 and 14 ensure that shipments from the same O-D pair will be combined together on the same route during the traffic assignment.

CASE STUDY

This case study considers a hypothetical transportation network comprising nine nodes, 12 links, and four O-D pairs (Figure 2 and Table 1). The following table shows the input parameters for traffic data:

O-D Pair	*Daily Shipment Volume (gal)*
AI	2,100,000
GC	3,600,000
DI	3,900,000
BI	5,700,000

Two cases (with and without additional traffic flow constraints) are defined and optimized. Route lengths are shown on each link, and FRA track classes are indicated by numbers in italic. Among these nodes, E is considered as a city linked by Class 4 track, C as a medium-sized town linked by Class 3 track with moderate route length, and G as a small village with Class 3 track and longer route length. Track capacity is assumed, and O-D flows are considered of a particular hazardous material using two tank car types (Table 1).

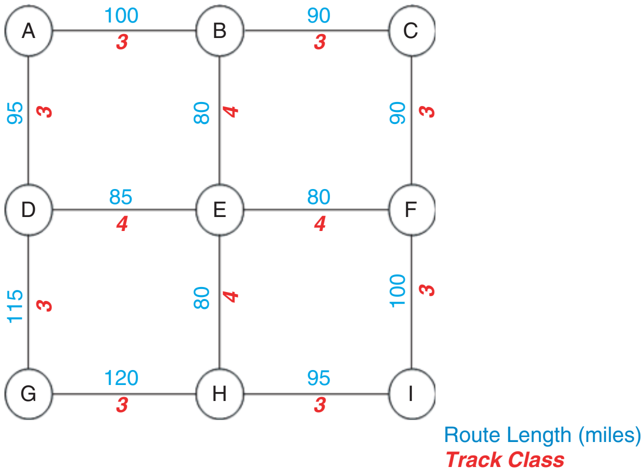

FIGURE 2 Hypothetical network.

For illustration, only one type of product is considered, but the model can be adapted to accommodate multiple commodities.

To estimate risk, the following equation is used:

$$R = P_1 \times P_2 \times M \times L \times C \qquad (15)$$

where

R = risk of hazardous material release (millions of dollars),
P_1 = track class–specific accident rate (cars derailed per car mile),
P_2 = conditional probability of release given that a tank car is derailed in an accident,
M = shipments (carloads),
L = mileage, and
C = average consequence cost per release incident (millions of dollars).

The model uses the derailment rates per car mile developed by Anderson and Barkan (*21*) and the conditional probability of release given that a tank car is derailed in an accident as developed by Treichel et al. (*19*) and shown in the following table:

Tank Car Type	*Capacity (gal)*	*Conditional Probability of Release*
Baseline	30,000	.3527
Enhanced	28,947	.2681

TABLE 1 Input Parameters for Case Study: Track Class Information

Track Class	Accident Rate (cars derailed per car mile)	Track Capacity (cars per day)	Coefficients for Track Maintenance Cost Function (*23*)	
			α	β
3	300×10^{-9}	1,200	651.6	51.5
4	77×10^{-9}	1,700	811.7	57.9
5	42×10^{-9}	2,300	935.9	62.8

The model does not consider the effects of train length and schedule. The results may change with more specific train length, train capacity, and scheduling constraints.

The consequence analysis is simplified by neglecting population distribution along the rail lines, and an average consequence cost of one million dollars per release incident on all track classes is assumed. Unit transportation cost is determined using data from the Association of American Railroads (*24*), resulting in \$0.55 per car mile. For the maintenance cost corresponding to a particular track class, the formulation developed in Lai et al. (*14*) using data from Zarembski et al. (*25*) is adopted. Capital investment cost is excluded in this case study but can be added if data are available. The maintenance cost function is as follows:

$$\mathrm{MC} = \alpha X + \beta \tag{16}$$

where

MC = average maintenance cost (millions of dollars per mile),
X = tonnage (million gross tons), and
α and β = model coefficients.

The railroad network is assumed to use wood ties and has predominantly tangent or moderate curvature track alignment as defined by Zarembski et al. (*25*). The values of α and β are given in Table 1.

To illustrate the potential application of the hazardous materials transportation network assignment model, four scenarios are considered for each case as follows:

- Baseline (neither tank cars nor track infrastructure are upgraded),
- Infrastructure upgrade only,
- Tank car upgrade only, and
- Combined upgrades (both track infrastructure and tank car upgrades are allowed).

Case I. Without Constraint on Traffic Flow

The model is used to determine the flows of hazardous material under each scenario with the objective of minimizing total cost. The model is formulated using the general algebraic modeling system and solved using CPLEX (*26*). In Figures 3 and 4 the first and second numbers in parentheses represent daily shipments (carloads) made

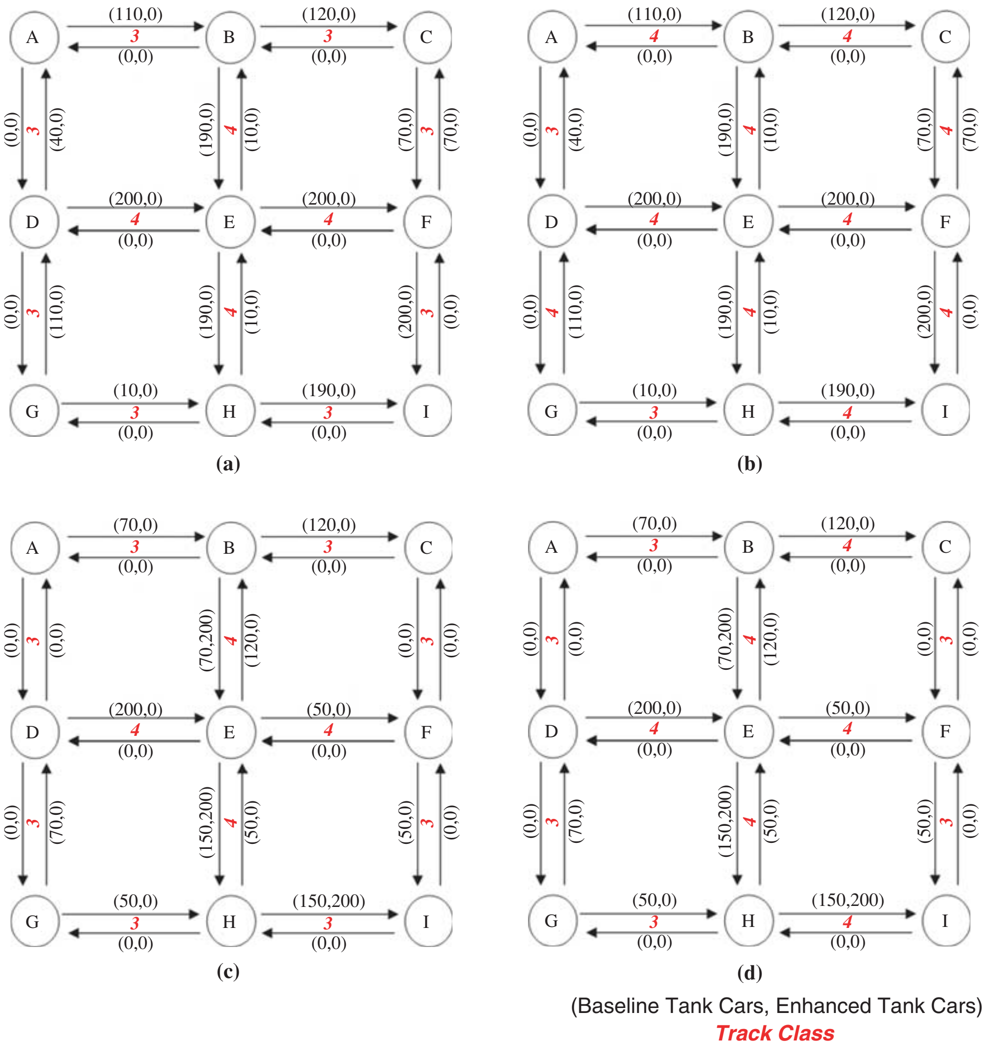

FIGURE 3 Optimal routing and track class assignment in Case I for (*a*) baseline, (*b*) infrastructure upgrade only, (*c*) tank car upgrade only, and (*d*) combined upgrades.

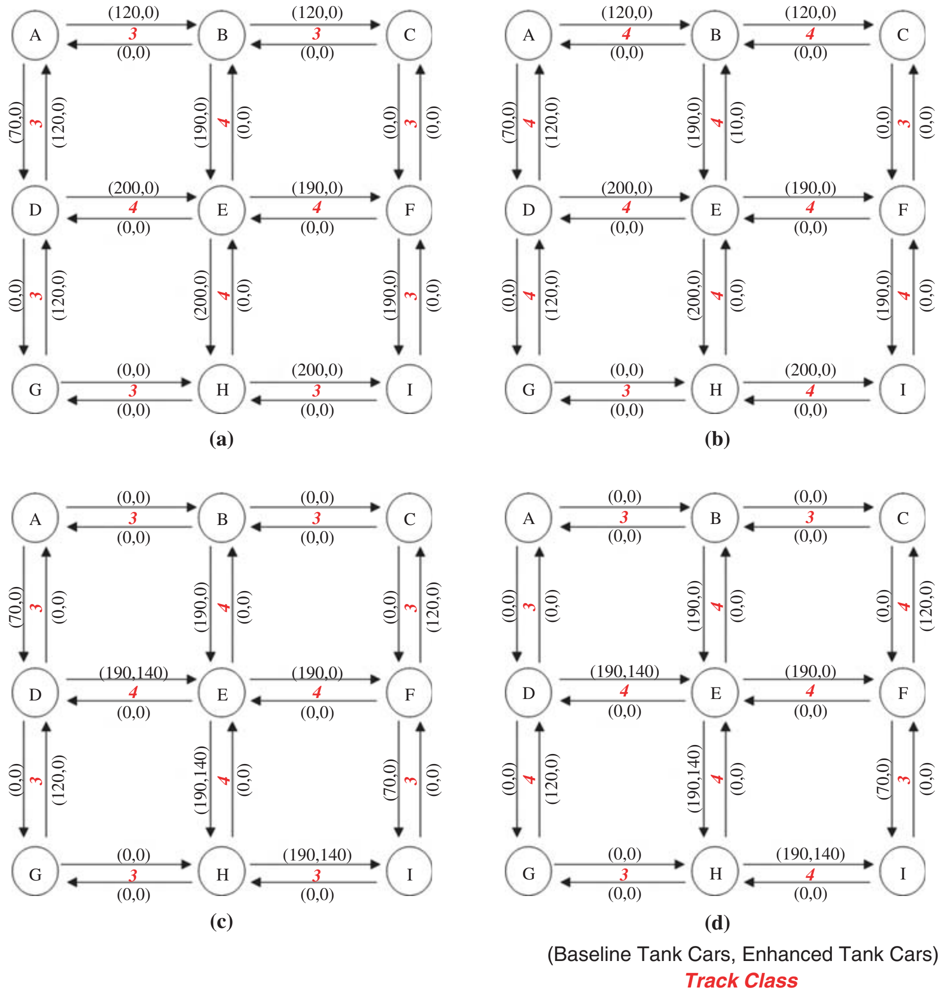

FIGURE 4 Optimal routing and track class assignment in Case II for (*a*) baseline, (*b*) infrastructure upgrade only, (*c*) tank car upgrade only, and (*d*) combined upgrades.

using baseline and enhanced tank cars, respectively. The italicized numbers represent the track class to be maintained.

The solution for the baseline scenario (Figure 3*a*) represents the flows of hazardous material on existing infrastructure using the baseline tank car. In the second scenario, in which only track infrastructure upgrade is allowed (Figure 3*b*), the model suggested upgrading six of eight Class 3 tracks to Class 4, indicating that the maintenance cost will be noticeably higher than the baseline scenario. In the third scenario, in which only tank car upgrade is allowed (Figure 3*c*), traffic flows on some links are eliminated. The fourth scenario represents the case in which both track and rolling stock can be upgraded (Figure 3*d*). The total cost for the latter scenario is expected to be the lowest of the four because of the greater flexibility in choosing upgrade options while reducing risk. Although the enhanced tank car has a lower conditional probability of release, more shipments are needed because of lower capacity compared with the baseline tank car.

Table 2 shows that the total cost of the baseline scenario is the highest and the combined upgrades scenario, the lowest. Upgrading track infrastructure requires a higher cost for track maintenance ($1.98 million or 7.38% greater than baseline), but more than half (59.24%) of the risk can be reduced. Upgrading tank cars offers the smallest reduction in risk, but the reduction in transportation cost is the greatest. A combination of infrastructure and tank car upgrades is the optimal scenario associated with the greatest reduction in total costs. For the problem considered, 44.93% of risk can be reduced with a 2.37% increase in maintenance cost.

Case II. With Constraint on Traffic Flow

In some instances, assigning traffic between the same O-D pair to the same route may be preferable. For this particular case, special routing requirements are implemented for the same problem (Figure 4 and Table 3).

Comparison of the costs among different scenarios shows almost the same trend as the unconstrained traffic flow case (Case I). Most of the costs become slightly higher compared with Case I because of the additional routing constraints. As expected, the traffic, track class assignment, and tank car selection results differ from those in Case I. This illustrates the dynamic nature of the problem and the potential insights that can be gained through application of this integrated optimization framework.

TABLE 2 Comparison of Annual Cost Components Without Constraint on Traffic Flow

	Maintenance		Transportation		Risk		Total	
Scenario	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)
Baseline	26.84	—	31.14	—	4.12	—	62.10	—
Infrastructure upgrade	28.82	(7.38)	31.14	0.00	1.68	59.24	61.64	0.75
Tank car upgrade	26.95	(0.42)	30.98	0.51	3.29	20.22	61.22	1.42
Combined upgrades	27.48	(2.37)	30.98	0.51	2.27	44.93	60.72	2.22

NOTE: — = not applicable.

Case III. Minimizing Risk of Hazardous Material Transportation

The optimization framework described earlier minimizes maintenance cost, transportation cost, and risk cost simultaneously. In this case, risk cost is considered as the only component in the objective function. The optimal results suggest the use of enhanced tank cars and upgrading of all segments with hazardous materials traffic to Class 5 (Table 4). Compared with the full model, which incorporates maintenance cost, transportation cost, and risk cost, the resulting risk cost is much lower, while the total cost is much higher than the previous two cases with consideration of the overall cost (including maintenance cost, transportation cost, and risk cost). If risk cost is excluded, the results will be very similar to those in Cases I and II because risk cost shares only a small portion of the overall cost (Tables 2 and 3).

DISCUSSION OF MODEL RESULTS

Railroad hazardous materials transportation safety depends on the design and condition of the railroad infrastructure and operating practices on the routes they travel (*27*) and the damage resistance of the tank cars transporting them. In addition to routing, improvements to either infrastructure or rolling stock, or both, have some potential to enhance safety, but there are different functional relationships between the cost and safety benefit for each. In different situations, investing in either or both may be the most efficient means of improving safety. This study addresses these elements individually and simultaneously.

The mathematical framework presented in this paper allows better consideration of a combination of different risk reduction strategies that potentially offer the greatest safety benefit at the lowest total cost. Besides incorporating the route-specific consequence elements, the model can be implemented to address a real-world rail network with complete track segment characterization (with variables affecting risk and maintenance cost) and O-D-level traffic information for commodities.

While improving infrastructure is generally more costly than other risk reduction strategies, it also reduces the risk of accidents involving all types of hazardous materials as well as other products traveling over the affected section. However, the benefit is isolated to those locations where the infrastructure was upgraded. In contrast, improving tank car safety design only affects risk for the products being transported, but that benefit is realized everywhere the improved tank cars travel in the network. Meanwhile, routing decisions often involve a complex set of other interacting factors that both increase and reduce safety and risk. Consequently, the net effect will be highly route and commodity specific and will depend on the particular combination of circumstances involved.

The hypothetical case study considered here demonstrates a potential reduction in transportation risk (44% lower than baseline) under combined, optimized strategies of routing, tank car safety design enhancement, and track maintenance with a slight increase in track maintenance cost (2.4% increase from baseline) (Table 4). Both the tank-car-upgrade-only and infrastructure-upgrade-only scenarios improve the performance from the baseline scenario, but integration of both options provides the best solution. Different network conditions or constraints would result in a different optimal result, so an integrated optimization framework such as the one described in this paper is necessary to improve hazardous materials transportation safety in the most efficient manner possible.

The case study presented here is an example of transportation of a single product. It does not consider the effect of train speed on

TABLE 3 Comparison of Annual Cost Components with Constraint on Traffic Flow

	Maintenance		Transportation		Risk		Total	
Scenario	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)
Baseline	26.86	—	31.33	—	4.21	—	62.39	—
Infrastructure upgrade	28.90	(7.61)	31.33	0.00	1.55	63.23	61.77	0.99
Tank car upgrade	26.96	(0.39)	31.01	1.02	3.35	20.35	61.32	1.72
Combined upgrades	28.05	(4.46)	31.01	1.02	1.84	56.36	60.90	2.39

TABLE 4 Comparisons of Annual Cost Components of Minimal Risk Cases Without and With Constraint on Traffic Flow

	Maintenance		Transportation		Risk		Total	
Scenario	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)	Cost ($ million)	Reduction (%)
Without Constraint on Traffic Flow								
Baseline	26.84	—	31.14	—	4.12	—	62.10	—
Infrastructure upgrade	32.22	(20.05)	31.14	0.00	0.84	79.66	64.20	(3.38)
Tank car upgrade	27.18	(1.28)	32.50	(4.38)	3.03	26.48	62.72	(0.99)
Combined upgrades	32.54	(21.23)	32.69	(5.00)	0.70	82.98	65.93	(6.17)
With Constraint on Traffic Flow								
Baseline	26.86	—	31.33	—	4.21	—	62.39	—
Infrastructure upgrade	31.39	(16.89)	31.33	0.00	0.84	79.94	63.56	(1.88)
Tank car upgrade	27.06	(0.78)	31.67	(1.09)	3.06	27.24	61.79	0.96
Combined upgrades	31.75	(18.23)	33.11	(5.70)	0.71	83.12	65.58	(5.11)

conditional probability of release (*17–20*), nor does it take into account population distribution along the route. The model did account for transportation cost and track maintenance and renewal cost. A constant consequence cost and the same unit transportation costs were assumed for all the links in the hypothetical network. The model does not consider the time value of money and assets, such as depreciation and amortization of rolling stock or increases in infrastructure improvement cost caused by the interest rate. If these data are available, more accurate costs that vary with train speed or track class and the change over time could be incorporated. Future research may also consider the differential costs of different tank car types in addition to one-time investment costs in infrastructure and rolling stock. Speed reduction could also be evaluated as a risk management strategy. The model framework developed here can be modified to accommodate all of these additional factors. For example, the conditional probability of release that is dependent on train speed and track segment–specific characteristics and exposure to population could be used in the risk model. Multiple products can be modeled by enlarging the index representing traffic composition (v). Another index representing time can be added to take into account time value of money and assets.

In this study, the optimal combination of different risk reduction strategies was identified on the basis of the assumption of a single decision maker. It was also assumed that the associated costs and benefits are incurred and gained by the same decision maker. In practice, railroad hazardous materials transportation involves a number of different entities including railroads, shippers, consignees, and car owners. Different parties are subject to different liabilities, although railroads generally assume principal liability in accidents unless it can be shown that the accident or release was the fault of one of these other parties. The additional costs for enhanced-safety tank cars are generally incurred by the car owners or shippers (or both), but the benefit of the reduction in risk is generally accrued by the railroad. The optimization model in this paper provides a globally optimal solution if all entities behave in a systematically rational manner with the same risk minimization effectiveness goal. However, with one set of parties paying for the enhancements and another set receiving the benefits, the potential exists for conflicting objectives and constraints. These add to the complexity of optimizing decision making and should be considered when using the model to consider different risk management strategies.

CONCLUSION

An integrated risk management framework with a network assignment model is presented that determines an optimal combination of different strategies to minimize the costs of transportation, track maintenance, and risk in hazardous materials transportation. The model advances understanding of how to most efficiently and effectively manage risk and provides guidance for tactical and strategic operational control, infrastructure and vehicle design, and maintenance for public and private sector policy making.

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