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

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ABSTRACT
Rail transport plays a key role in safely and economically moving hazardous materials from production to consumption points. Due to 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 are available including railroad accident prevention through infrastructure improvements, packaging enhancements, operational changes and alteration of the route structure. Operations research techniques have been applied to consider each approach individually, but none has considered integrating them into one single model. In this study, we introduce an integrated mathematical model to formally consider a combination of different approaches to reduce risk. Our framework enables simultaneous consideration of route choices, tank car safety designs and track maintenance to determine an optimal strategy that minimizes risk and costs. Model formulation is provided in the form of non-linear and mixed-integer programming. For illustration, a small-scale, hypothetical network flow of a hazardous material is considered. Numerical results show that the optimal strategy has the potential to offer substantial reduction in risk with a marginal increase in costs. The integrated model provides a framework to choose the most effective risk mitigation strategy for a particular rail network given various constraints. It can be applied to multiple types of commodities and adapted to address various questions for local, regional or system-wide planning and decision making to provide the safest transportation possible given constrained resources. The framework will be particularly beneficial to rail carriers interested in how to best allocate safety and engineering resources so as to maximize safety.
INTRODUCTION
Reducing railroad hazardous materials transportation risk has long been a priority for industry and government. Due to security concerns and several fatal accidents this interest has intensified in recent years (1, 2). Particular attention has been directed toward Toxic Inhalation Hazard (TIH) materials such as chlorine, ammonia, and approximately two-dozen other chemical products classified as TIHs. 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. Previous work includes consideration of hazardous materials transportation routing (3, 4, 5, 6), improving transportation packaging (7, 8, 9), upgrading track infrastructure (10), and managing operating speed of hazardous materials train (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, we are unaware of previous research that has considered and compared more than one approach to risk reduction simultaneously. Such comparison is important to objectively evaluate different approaches, possible interactive effects, 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 prior events as follows – a train accident or derailment, hazardous material car involvement, and hazardous material car damaged 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.

In this study an integrated risk management framework model is presented to provide a means to choose the most effective set of risk mitigation strategies for a particular rail network. The model is first formulated using non-linear programming and converted into a mixed-integer programming problem. For illustration, we consider a small-scale, hypothetical network flow of a hazardous material. We use the model 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. We also illustrate the flexibility of the model framework 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. (6) identified optimal train routing over a network with capacity constraints and traffic heterogeneity to minimize transportation and track maintenance costs. In another study Lai et al. (14) described a model that considers the tradeoff between transportation and track maintenance costs and determines the optimal assignment for track class given traffic demand and track maintenance budget. These models, however, do not incorporate the safety aspect, in particular, the risk involved with transportation of hazardous materials.

In this 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 hazardous materials transportation network assignment model. Three input parameters are: track infrastructure characteristics, tank car safety design features, and product characteristics. Additionally, two parameters represent the constraints of the optimization problem, i.e. traffic demand and track capacity. 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.

In this initial stage of model development, we focus on the operating cost components related to routes, track classes and car types. We exclude the capital cost components but they can easily be added if data are available. We also simplify the problem by omitting some risk parameters. These include population distribution along rail lines, chemical-specific hazard exposure that varies with various factors including toxicity (15, 16), population densities, and train operating speed that affects the conditional probability of release (17, 18, 19, 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 non-linear programming (NLP) model: $i, j$ are indices representing nodes. $N$ is the set of all nodes and $A$ is the set of all existing arcs $(i, j)$. $k$ corresponds to the $k^{th}$ origin-destination (OD) 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 of the $k^{th}$ OD pair, respectively. $K$ stands for the set of $k$. $q$ represents track class. $Q$ is the set of $q$. $\delta^+(j)$ represents the station $j$ serving as the departure station. And $\delta^-(j)$ represents the station $j$ serving as the arriving station.

$A_k$ is the additional number of cars for OD pair $k$ if the enhanced-safety tank car is selected. These tank cars are usually heavier than the baseline tank car, resulting in more cars needed for the same quantity transported. $C_{ij}$ is the transportation cost per car-mile on arc $(i, j)$. $D_k$ is the demand of OD pair $k$ (in number of cars). $H_{ij}^q$ is the maintenance cost on arc $(i, j)$ with track class $q$. Higher track class also requires higher maintenance cost. $U_{ij}^q$ is the capacity (in number of cars) on arc $(i, j)$ with track class $q$. Higher track class offers better safety because it is associated with lower accident rate (21), and it increases the fluidity of the section with higher maximum speed (22), resulting in better capacity. $R_{ij}^q$ is the release risk per carload (in monetary value) on arc $(i, j)$ with track class $q$. $W_{ij}^q$ is the reduced risk per carload (in monetary value) on arc $(i, j)$ with track class $q$ if enhanced tank car is selected.
There are three sets of decision variables in the NLP model. The first variable is denoted by $x_{ij}^k$, which is a positive integer representing the number of cars running on arc $(i,j)$ corresponding to OD pair $k$. The second variable is a binary variable, denoted by $y_{ij}^q$, which determines whether the track class $q$ is assigned on arc $(i,j)$. The third variable, $z_k$, is also a binary variable to determine the enhancement of tank car for $k^{th}$ OD pair. The network assignment model is formulated in NLP form as follows:

$$
\text{min} \sum_{(i,j)\in A} \sum_{q\in Q} \sum_{k\in K} H_{ij}^q y_{ij}^q x_{ij}^k + \sum_{(i,j)\in A} \sum_{k\in K} C_{ij} x_{ij}^k + \sum_{(i,j)\in A} \sum_{q\in Q} \sum_{k\in K} (R_{ij}^q - W_{ij}^q z_k) y_{ij}^q x_{ij}^k
$$

subject to:

$$
\sum_{k\in K} (x_{ij}^k + x_{ji}^k) \leq \sum_{q\in Q} U_{ij}^q y_{ij}^q \quad \forall (i, j)\in A, (i<j)
$$

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

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

and

$$
x_{ij}^k \in \text{positive integer}, \quad \forall (i, j)\in A, k\in K,
$$

$$
y_{ij}^q \in \{0,1\}, \quad \forall (i, j)\in A, k\in K,
$$

$$
z_k \in \{0,1\}, \quad \forall k\in K
$$

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 non-linear model is converted into a linear form using mixed-integer programming (MIP). The following notation is used in the linear model: $i$ is an index referring to the starting node of an arc, and $j$ is the ending node of an arc; $k$ corresponds to the $k^{th}$ OD 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 of the $k^{th}$ OD pair. $q$ represents track class. $t$ represents the type of tank cars: baseline or enhanced tank car, $T$ is the set of these two car types. $D_{kt}$ is the demand expressed as number of shipments for OD pair $k$ and type $t$ tank car. $v$ 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 that there are three baseline tank cars and six enhanced tank cars. $V$ is the set of $v$. $N^v_t$ indicates the number to type $t$ tank cars in traffic composition $v$. $C_{ij}$ is transportation cost per carload on arc $(i, j)$. $H_{ij}^{vq}$ is the maintenance cost of arc $(i, j)$ with track class $q$ and traffic composition $v$. $R_{ij}^{vq}$ is the unit cost of release risk on arc $(i, j)$ with track class $q$ and traffic composition $v$. $U_{ij}^{vq}$ is the capacity (in number of cars) on arc $(i, j)$ with track class $q$.

There are three sets of decision variables in this model. The first variable is denoted by $x_{ij}^{kt}$, which is the number of cars running on arc $(i, j)$ for the OD pair $k$ and type $t$ car. The second variable is a binary variable used to determine the traffic composition ($v$) of arc $(i, j)$ under particular track class $q$, denoted by $y_{ij}^{vq}$. The third variable is also a binary variable $z_{kt}$ to determine the tank car type $t$ for OD pair $k$.

The linear optimization model is formulated as follows:

$$\begin{align*}
\min & \sum_{(i, j) \in A} \sum_{v \in V} \sum_{q \in Q} H_{ij}^{vq} y_{ij}^{vq} + \sum_{(i, j) \in A} \sum_{k \in K} \sum_{t \in T} C_{ij} x_{ij}^{kt} + \sum_{(i, j) \in A} \sum_{v \in V} \sum_{q \in Q} R_{ij}^{vq} y_{ij}^{vq} \\
\text{subject to:} & \\
& \sum_{v \in V} \sum_{q \in Q} (x_{ij}^{kt} + x_{ji}^{kt}) \leq \sum_{v \in V} \sum_{q \in Q} U_{ij}^{vq} y_{ij}^{vq} \quad \forall \ (i, j) \in A, \ (i < j) \\
& \sum_{v \in V} \sum_{q \in Q} y_{ij}^{vq} = 1 \quad \forall \ (i, j) \in A, \ (i < j) \\
& \sum_{v \in V} \sum_{q \in Q} (x_{ij}^{kt} + x_{ji}^{kt}) \leq \sum_{v \in V} \sum_{q \in Q} N^v_t y_{ij}^{vq} \quad \forall \ (i, j) \in A, \ (i < j), \ t \in T \\
& \sum_{j \in A} x_{ij}^{kt} - \sum_{j \in A} x_{ji}^{kt} = \begin{cases} D_{kt} z_{kt} & \text{if } i \in s_k, \\ -D_{kt} z_{kt} & \text{if } i \in e_k, \\ 0 & \text{otherwise} \end{cases} \quad \forall \ i \in N, \ k \in K, \ t \in T
\end{align*}$$

(6)
\[
\sum_{k} z_{kt} = 1 \quad \forall k \in K \tag{11}
\]

and
\[
x_{ij}^{kt} \in \text{positive integer,} \quad \forall (i, j) \in A, \ k \in K, \ t \in T,
\]
\[
y_{ij}^{vq} \in \{0, 1\}, \quad \forall (i, j) \in A, \ v \in V, \ q \in Q, \tag{12}
\]
\[
z_{kt} \in \{0, 1\}, \quad \forall k \in K, \ t \in T
\]

The objective function in Equation (6) minimizes the sum of: total track maintenance cost \((\sum_{(i,j) \in A} \sum_{q \in Q} H_{ij}^{vq} y_{ij}^{vq})\), total transportation cost \((\sum_{(i,j) \in A, k \in K} \sum_{t \in T} C_{ij} x_{ij}^{kt})\), and total risk cost
\[
(\sum_{(i,j) \in A} \sum_{q \in Q} R_{ij}^{vq} y_{ij}^{vq}).
\]
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 OD pair \(k\).

**Additional Constraints on Traffic Flow**

In some instances, it may be preferable to assign traffic from the same OD pair to the same route. In order 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:
\[
\sum_{j \in S} \sum_{(j) \in A} w_{ij}^{kt} = 1 \quad \forall i \in N, \ k \in K \tag{13}
\]
\[
x_{ij}^{kt} \leq M w_{ij}^{kt} \quad \forall (i, j) \in A, \ k \in K, \ t \in T \tag{14}
\]

The binary variable, \(w_{ij}^{kt}\), equals 1 if arc \((i, j)\) is selected for the OD pair \(k\) and car type \(t\). \(M\) is a large number to ensure that the \(x_{ij}^{kt}\) variable can have a valid value. Equations (13) and (14) ensure that shipments from the same OD pair will be combined together on the same route during the traffic assignment.
CASE STUDY
We consider a case study of a hypothetical transportation network comprising 9 nodes, 12 links, and 4 OD pairs (FIGURE 2 and TABLE 1). We also define and optimize two cases: with and without additional traffic flow constraints. Route lengths are shown on each link and FRA track classes are indicated by numbers in italic. Among these nodes, we consider “E” 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. We assume track capacity and consider OD flows of a particular hazardous material using two different tank car types (TABLE 1). For illustration, only one type of product is considered but our model can be adapted to accommodate multiple commodities.

To estimate risk, we use the following equation:

\[ R = P_1 \times P_2 \times M \times L \times C \]  

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

We use 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) (TABLE 1). We do not consider effects of train length and schedule in our modeling. The results may change with more specific train length, train capacity and scheduling constraints.

We simplify the consequence analysis by neglecting population distribution along the rail lines and assume an average consequence cost of 1 million dollars per release incident on all track classes. We determine unit transportation cost using data from the Association of American Railroads (24) resulting in 0.55 dollars per car-mile.

Regarding the maintenance cost corresponding to particular track class, we adopt the formulation developed in Lai et al. (14) by using data from Zarembski et al. (25). Capital investment cost is excluded in this case study but can be added if data are available. The maintenance cost function is as follows:

\[ MC = \alpha X + \beta \]  

Where \( MC \) is the average maintenance cost in millions of dollars per mile, \( X \) is the tonnage expressed in million gross tons (MGT), \( \alpha \) and \( \beta \) are the 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 \( \alpha \) and \( \beta \) are given in TABLE 1.

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

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

Case I: Without Constraint on Traffic Flow
We use the model to determine the flows of hazardous material under each scenario with the objective of minimizing total cost. The model is formulated using General Algebraic Modeling System (GAMS) and solved using CPLEX (26). The results are depicted in FIGURE 3. The first and second numbers in parentheses represent daily shipments (carloads) made using baseline and enhanced tank cars, respectively. The numbers in italic represent 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 out of eight class-3 track 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 to the baseline tank car.

The result in TABLE 2 shows that the total cost of the baseline scenario is the highest, and the combined upgrades scenario has the lowest total cost. Upgrading track infrastructure requires a higher cost for track maintenance (1.98 million dollars or 7.38\% greater than the
baseline) but more than half of risk can be reduced, a 59.24% reduction. 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 OD pair to the same route may be preferable. For this particular case, special routing requirements are implemented for the same problem (FIGURE 4, TABLE 3).

Comparison of the costs among different scenarios shows almost the same trend compared to the unconstrained traffic flow case (Case I). Almost of the costs become slightly higher compared to Case I due to the additional routing constraints. As expected, the traffic, track-class assignment, and tank car selection results are different 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.

**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, we consider risk cost 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 to the full model in which maintenance cost, transportation cost and risk cost are incorporated, 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 the risk cost is excluded, the results will be very similar to those in the previous case studies because risk cost shares only a small portion of the overall cost (TABLE 2 and TABLE 3).

**DISCUSSION**

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 or both infrastructure and rolling stock have some potential to enhance safety but there are different functional relationships between cost and safety benefit for each. In different situations, investment in one or the other, 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 OD-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 traveling over the affected section, and other products as well. However, the benefit is isolated to those locations where the infrastructure was upgraded. On the other hand, improving tank car safety design only affects risk for the products they transport, but that benefit is realized everywhere they 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, depending on the particular combination of circumstances involved.

The specific hypothetical case study considered here demonstrates a potential reduction in transportation risk (44% lower than the 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 2). As indicated in the case study, 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. Also, 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 material 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 conditional probability of release (17, 18, 19, 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. We do not consider the time value of money and assets, e.g. depreciation and amortization of rolling stock, increase in infrastructure improvement cost due to interest rate. If these data are available, more accurate costs that vary with train speed or track class, and that 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 ($v$). We can also add another index representing “time” to take into account time value of money and assets.

In this study, the optimal combination of different risk reduction strategies was identified based on the assumption of a single decision maker. Additionally, it was 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. Meanwhile, the additional costs for use of enhanced-safety tank cars are generally incurred by the car owners and/or shippers, whereas 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 taken into account when using the model to consider different risk management strategies.
CONCLUSION
We present an integrated risk management framework with a network assignment model that determines an optimal combination of different strategies to minimize costs of hazardous materials transportation comprising: transportation, track maintenance, and risk costs. The model advances understanding of how to most efficiently and effectively manage risk thereby providing guidance for tactical and strategic operational control, infrastructure and vehicle design and maintenance for public and/or private sector policy making.

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<td>AI</td>
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<tr>
<th>Tank Car Information</th>
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<td>Baseline</td>
<td>30,000</td>
<td>0.3527</td>
</tr>
<tr>
<td>Enhanced</td>
<td>28,947</td>
<td>0.2681</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Track Class</th>
<th>Accident Rate (cars derailed per car-mile)</th>
<th>Track Capacity (cars per day)</th>
<th>Track Maintenance Cost Function Coefficients (23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$300 \times 10^{-9}$</td>
<td>1,200</td>
<td>651.6</td>
</tr>
<tr>
<td>4</td>
<td>$77 \times 10^{-9}$</td>
<td>1,700</td>
<td>811.7</td>
</tr>
<tr>
<td>5</td>
<td>$42 \times 10^{-9}$</td>
<td>2,300</td>
<td>935.9</td>
</tr>
</tbody>
</table>

## TABLE 2 Comparison of Cost Components without Constraint on Traffic Flow

<table>
<thead>
<tr>
<th></th>
<th>Maintenance</th>
<th>Transportation</th>
<th>Risk</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td>26.84</td>
<td>-</td>
<td>31.14</td>
<td>-</td>
</tr>
<tr>
<td><strong>Infrastructure Upgrade</strong></td>
<td>28.82</td>
<td>(7.38)</td>
<td>31.14</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Tank Car Upgrade</strong></td>
<td>26.95</td>
<td>(0.42)</td>
<td>30.98</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Combined Upgrades</strong></td>
<td>27.48</td>
<td>(2.37)</td>
<td>30.98</td>
<td>0.51</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th></th>
<th>Million Dollars</th>
<th>Percent Reduction</th>
<th>Million Dollars</th>
<th>Percent Reduction</th>
<th>Million Dollars</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>26.84</td>
<td>-</td>
<td>31.14</td>
<td>-</td>
<td>4.12</td>
<td>-</td>
</tr>
<tr>
<td><strong>Infrastructure Upgrade</strong></td>
<td>28.82</td>
<td>(7.38)</td>
<td>31.14</td>
<td>0.00</td>
<td>1.68</td>
<td>59.24</td>
</tr>
<tr>
<td><strong>Tank Car Upgrade</strong></td>
<td>26.95</td>
<td>(0.42)</td>
<td>30.98</td>
<td>0.51</td>
<td>3.29</td>
<td>20.22</td>
</tr>
<tr>
<td><strong>Combined Upgrades</strong></td>
<td>27.48</td>
<td>(2.37)</td>
<td>30.98</td>
<td>0.51</td>
<td>2.27</td>
<td>44.93</td>
</tr>
</tbody>
</table>
TABLE 3 Comparison of Cost Components with Constraint on Traffic Flow

<table>
<thead>
<tr>
<th></th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td>Million Dollars</td>
</tr>
<tr>
<td>Baseline</td>
<td>26.86</td>
</tr>
<tr>
<td>Infrastructure Upgrade</td>
<td>28.90</td>
</tr>
<tr>
<td>Tank Car Upgrade</td>
<td>26.96</td>
</tr>
<tr>
<td>Combined Upgrades</td>
<td>28.05</td>
</tr>
</tbody>
</table>
### TABLE 4 Comparison of Cost Components of Minimal Risk Cases

(a) Without Constraint on Traffic Flow and (b) With Constraint on Traffic Flow

(a)

<table>
<thead>
<tr>
<th></th>
<th>Annual Cost</th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maintenance</td>
<td>Transportation</td>
<td>Risk</td>
<td>Total</td>
<td>Maintenance</td>
<td>Transportation</td>
<td>Risk</td>
</tr>
<tr>
<td></td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
</tr>
<tr>
<td>Baseline</td>
<td>26.84</td>
<td>-</td>
<td>31.14</td>
<td>-</td>
<td>4.12</td>
<td>-</td>
<td>62.10</td>
</tr>
<tr>
<td>Infrastructure Upgrade</td>
<td>32.22</td>
<td>(20.05)</td>
<td>31.14</td>
<td>0.00</td>
<td>0.84</td>
<td>79.66</td>
<td>64.20</td>
</tr>
<tr>
<td>Tank Car Upgrade</td>
<td>27.18</td>
<td>(1.28)</td>
<td>32.50</td>
<td>(4.38)</td>
<td>3.03</td>
<td>26.48</td>
<td>62.72</td>
</tr>
<tr>
<td>Combined Upgrades</td>
<td>32.54</td>
<td>(21.23)</td>
<td>32.69</td>
<td>(5.00)</td>
<td>0.70</td>
<td>82.98</td>
<td>65.93</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th></th>
<th>Annual Cost</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maintenance</td>
<td>Transportation</td>
<td>Risk</td>
<td>Total</td>
<td>Maintenance</td>
<td>Transportation</td>
<td>Risk</td>
</tr>
<tr>
<td></td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
<td>Percent Reduction</td>
<td>Million Dollars</td>
</tr>
<tr>
<td>Baseline</td>
<td>26.86</td>
<td>-</td>
<td>31.33</td>
<td>-</td>
<td>4.21</td>
<td>-</td>
<td>62.39</td>
</tr>
<tr>
<td>Infrastructure Upgrade</td>
<td>31.39</td>
<td>(16.89)</td>
<td>31.33</td>
<td>0.00</td>
<td>0.84</td>
<td>79.94</td>
<td>63.56</td>
</tr>
<tr>
<td>Tank Car Upgrade</td>
<td>27.06</td>
<td>(0.78)</td>
<td>31.67</td>
<td>(1.09)</td>
<td>3.06</td>
<td>27.24</td>
<td>61.79</td>
</tr>
<tr>
<td>Combined Upgrades</td>
<td>31.75</td>
<td>(18.23)</td>
<td>33.11</td>
<td>(5.70)</td>
<td>0.71</td>
<td>83.12</td>
<td>65.58</td>
</tr>
</tbody>
</table>
FIGURE 1 Conceptual diagram showing input-output of hazardous materials transportation network assignment model.
FIGURE 2 Hypothetical network considered.
FIGURE 3 Optimal routing and track class assignment in Case I for scenarios: (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 scenarios: (a) baseline, (b) infrastructure upgrade only, (c) tank car upgrade only, and (d) combined upgrades.