



A multimodal location and routing model for hazardous materials transportation

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HIGHLIGHTS

- ▶ An innovative multimodal HAZMAT location and routing model is proposed.
- ▶ The nonlinear model initially developed is converted into a mixed integer linear form.
- ▶ The new model can simultaneously optimize transfer yard locations and routing plans.
- ▶ Two case studies are conducted and demonstrate the applicability of the new model.

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ABSTRACT

The recent US Commodity Flow Survey data suggest that transporting hazardous materials (HAZMAT) often involves multiple modes, especially for long-distance transportation. However, not much research has been conducted on HAZMAT location and routing on a multimodal transportation network. Most existing HAZMAT location and routing studies focus exclusively on single mode (either highways or railways). Motivated by the lack of research on multimodal HAZMAT location and routing and the fact that there is an increasing demand for it, this research proposes a multimodal HAZMAT model that simultaneously optimizes the locations of transfer yards and transportation routes. The developed model is applied to two case studies of different network sizes to demonstrate its applicability. The results are analyzed and suggestions for future research are provided.

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1. Introduction

HAZMAT transportation has received considerable attention in the past couple of decades. Most existing location and routing studies focused on modeling HAZMAT transportation exclusively via highways. Only a few of them considered other modes such as railways [1]. According to the 2007 United States Commodity Flow Survey [2], 18.7 million tons of HAZMAT were transported by multiple modes in 2002. While in 2007, this number jumped to 111.0 million tons. Also, for HAZMAT transported by a single mode, the average transport distance per shipment was 65 miles (105 km) in 2007. The corresponding distance for multiple modes was 849 miles (1366 km), suggesting that multimodal transportation plays an increasingly important role in transporting HAZMAT, especially for long-distance shipments.

The increasing multimodal HAZMAT transportation demand and the scarcity of literature on multimodal HAZMAT location and routing necessitate additional research. Modeling multimodal

HAZMAT location and routing is significantly different from its single-mode counterpart. It requires the transfer of HAZMAT containers or tanks between different modes, which typically needs special equipment and trained operators with particular expertise. Due to budget and cost considerations, it would be unwise for the carriers/shippers to invest in all candidate intermodal facilities (transfer yards) and to make them available for HAZMAT transfer. In addition, the locations of these transfer yards can have a significant impact on the optimal routing decisions and consequently on the total transportation risk and cost. It is important to consider the locations of HAZMAT transfer facilities and the routing plans simultaneously.

Some researchers also pointed out the importance of multimodal HAZMAT location and routing. In a recent study conducted by Chang et al. [3], the authors developed an algorithm that can efficiently find the minimum cost intermodal paths given time-dependent travel costs and delays for both links and transfer nodes. In our research, the multimodal HAZMAT location and routing problem is addressed from a different perspective and a joint facility location and routing model is proposed, which is the first attempt to simultaneously optimize the multimodal transfer yard locations and transportation routes based on an extensive

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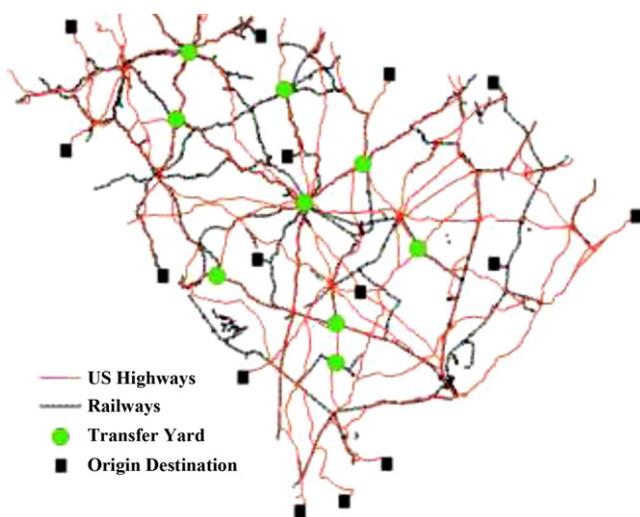


Fig. 1. Example of a network for multimodal HAZMAT transportation.

literature review. Using railways and highways as an example, a sample multimodal HAZMAT transportation network in Fig. 1 is utilized to illustrate the proposed idea. For this multimodal network, highways and railways are connected only at transfer yards, where HAZMAT can be transferred from trucks to railcars and vice versa. The rectangles in Fig. 1 denote origins or destinations of HAZMAT. The circles represent candidate locations for transfer yards, which are usually determined by HAZMAT carriers/shippers based on safety, security, availability, cost, and accessibility concerns. The problem to be addressed in this research is to identify an optimal subset of locations from all candidate transfer yards and also to find the best transportation plans/routes based on the selected transfer yards. The number of transfer yards can be either pre-specified or optimized based on cost, as the HAZMAT carriers/shippers usually have a limited budget for transfer equipment and trained workers. This problem is first formulated as an integer nonlinear program. It is further converted into an integer linear program so that it can be solved more efficiently. This linear program model is applied to a small-size network using CPLEX [4] to illustrate how it works. It is then applied to a large-size network to demonstrate its applicability to solve realistic multimodal HAZMAT location and routing problems.

2. Overview of previous work

Existing HAZMAT transportation studies can generally be categorized into the following groups: vehicle routing and scheduling [5–10], network design [11], risk modeling [12–15], facility location [16], integrated location and routing [17], and development of decision support systems [18]. Several milestone reviews [19–20] have been conducted to summarize the HAZMAT transportation research published prior to the 1990s. Although there is a need to update the surveys by including significant recent studies, it is out of the scope of this research given the many papers published in the past two decades. In this review, we choose to only focus on relevant HAZMAT transportation research, including vehicle routing, facility location, and integrated location and routing studies.

A number of studies have addressed the HAZMAT vehicle routing problems. Sherali et al. [5] proposed a routing model to minimize the risk of low probability-high consequence accidents, in which both the expected risk of accidents and the conditional expectation given that an accident has happened are considered. Nozick et al. [6] proposed an integrated routing and scheduling model based on time-varying routing parameters. Along the same

line, several other researchers [7–9] also investigated HAZMAT routing problems with time-varying link attributes (e.g., travel time). In a recent study by Kazantzi et al. [10], the authors utilized the Monte Carlo simulation for risk assessment to account for the uncertainties in model inputs. They also proposed a framework that can handle routing decisions over multiple decision periods. Other than highways, Iakovou et al. [21] developed a multi-commodity and multiple OD model for maritime HAZMAT routing. Recently, Verma [1] proposed a bi-objective model to minimize the risk of transporting HAZMAT via railway network. A similar study was conducted by Verma et al. [22] and the authors developed a genetic algorithm to solve it.

In addition to vehicle routing, many studies have also been conducted on facility location and integrated facility location and routing for HAZMAT transportation. Current and Ratick [16] conducted one of the pioneering studies to jointly model facility location and HAZMAT routing. The authors formulated the problem as a multi-objective mixed integer program and solved it by an off-the-shelf optimization tool. A similar model was developed by Cappanera et al. [17] for the location and routing of obnoxious activities. The authors solved the model by Lagrangian relaxation and a Branch and Bound algorithm. Helander and Melachrinoudis [23] developed a facility location and routing model to site a single facility. A path reliability measure was introduced to find the best facility location. A number of other studies also investigated the optimal locations and routing of hazardous materials [24–28]. However, all these studies considered a single-mode (either railway or highway) network and the goal is to optimally site disposal/treatment facilities, which is different from the multimodal location and routing model to be developed in this research.

The HAZMAT location and routing problems reviewed are often formulated as multi-objective optimizations. Several different objectives have been proposed, including transportation and facility risks [16,21,22,24–29], transportation and facility costs [16–17,21–22,24,26–28], travel time [25,29], expected number of accidents [23], individual disutility [24], equity [27], and property damages [29]. In order to incorporate multiple objectives in the optimization process, a commonly used strategy is to assign weights to the selected objectives and combine them into one [1,21–22,26–27]. This method gives the decision maker a lot of flexibility to choose the weights, which reflect the relative importance of various objectives in the decision maker's opinion. Another possibility is to provide the dollar values of each objective, although this is not an easy task. Zografos and Davis [29] introduced a goal programming method. This method can avoid assigning weights directly to various objectives. However, it still needs to assign weights to the deviational variables associated with different objectives in the objective function. In this research, we choose to use the weight method, since it is very flexible and has been adopted in many previous studies [1,21,22,26–27].

Another important aspect closely related to the HAZMAT facility location and routing is risk modeling. List et al. [19] conducted a comprehensive survey of risk studies for HAZMAT transportation prior to the 1990s. The risk analyses in these studies are mostly based on methods developed by the nuclear power industry, including the fault tree method and a three-stage framework [19]. Among them, the three-stage framework divides the HAZMAT risk analysis into three stages: (1) HAZMAT accident probability estimation, (2) level of exposure analysis, and (3) magnitude of the consequence analysis. The accident rates are route specific and can be easily estimated given reliable historical HAZMAT accident data. A number of other risk analysis models [30–33] have also been proposed since then, and some require very detailed input data such as wind direction [32–33]. With the assistance of modern computers, these complicated risk models can be readily implemented. In addition, there exist many other risk modeling methods in

HAZMAT transportation publications [12–15]. Since our focus is not risk modeling, a detailed review of these methods is beyond the scope of this research. In this study, a simple while commonly used risk model is adopted and is detailed in Section 4.2.

The problem under investigation in this study is fundamentally different from all previous research. First, we choose to optimize the HAZMAT location and routing plans that involve multiple modes. As discussed in the introduction section, this is becoming increasingly important for HAZMAT transportation. However, this particular area has not been adequately studied yet and most previous studies on HAZMAT location and routing dealt with single mode. Second, all existing integrated location and routing HAZMAT models are designed specifically for siting either disposal or treatment facilities, while this research aims at optimally siting transfer yards. In the next section, the problem under investigation and its formulations are presented in detail.

3. Mathematical formulation

A multimodal network consisting of railways and highways is considered in this research. This network is described by a directed graph $G=(N,E)$, where $N=\{N_H, N_R, N_{HR}\}$ is the node set and $E=\{E_H, E_R\}$ is the edge set. The node set consists of three subsets: N_H, N_R, N_{HR} . N_H represents nodes where highways connect or end; N_R represents nodes where railways connect or end; and N_{HR} is for nodes where railways connect to highways and HAZMAT shipments can be transferred between the two modes. There are no transfer activities at highway (N_H) or railway (N_R) nodes. Since HAZMAT transfer yards require special equipment and trained operators, only selected nodes in N_{HR} will be made available for HAZMAT transfer. At the planning stage, all nodes in N_{HR} can be considered as the candidate locations for HAZMAT transfer yards. Each candidate transfer yard $i \in N_{HR}$ has a per-shipment risk (r_i) associated with it due to the potential HAZMAT spills caused by the transfer operations. Each candidate transfer yard also has a total cost (f_i) consisting of an annualized capital cost and an operating cost. These risk and cost factors will affect whether a candidate site should be selected or not. Each edge, $(i,j) \in E$, has a per-shipment risk (r_{ij}) and per-shipment cost (l_{ij}) associated with it. A per-shipment cost (l_{ij}) is considered for edges because it is directly related to the number of HAZMAT shipments. For transfer yards, their total costs (f_i) in many cases are affected not only by the number of HAZMAT shipments, but also by other important factors such as the size/capacity of the yards. For instance, the HAZMAT demand of a particular yard may change over time, the yard owner however still needs to pay approximately the same rent, utility, salaries, etc. each year. These costs in general are independent of the demand (number of shipments per year). In addition, the total cost (f_i) in this study also includes the annualized capital cost, which is independent of the number of HAZMAT shipments as well. Last but not least, the developed model is for planning purpose. For future studies focusing on operations, it would be more interesting and relevant to consider detailed data such as the average transfer cost for a single shipment. Since the proposed model is for planning purpose, deterministic and time-independent link travel risk and cost are considered. In addition, we consider multiple Original-Destination (OD) pairs and a single type of HAZMAT.

3.1. Nonlinear model

The aforementioned problem is initially formulated as a multi-objective integer program in Eqs. (1)–(8). There are four major components in the objective function (Eq. (1)), which

account for the total link risk, total link cost, transfer yard capital and operating costs, and total risk during the transfer process.

$$\text{Min} \sum_{c \in C} \sum_{(i,j) \in E} n^c (\alpha r_{ij} + \beta l_{ij}) X_{ij}^c + \sum_{i \in N_{HR}} \left[\beta f_i Y_i + \alpha \left(\sum_{c \in C} R_i^c n^c \right) r_i \right] \quad (1)$$

s.t.

$$\sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c = \begin{cases} +1 & i = \text{orig}(c) \\ -1 & i = \text{dest}(c) \forall i \in N_H, c \in C \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

$$\sum_{(i,m) \in E_R} X_{im}^c - \sum_{(m,i) \in E_R} X_{mi}^c = \begin{cases} +1 & i = \text{orig}(c) \\ -1 & i = \text{dest}(c) \forall i \in N_R, c \in C \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

$$\sum_{(i,k) \in E_H} X_{ik}^c + Y_i \sum_{(i,m) \in E_R} X_{im}^c - \sum_{(k,i) \in E_H} X_{ki}^c - Y_i \sum_{(m,i) \in E_R} X_{mi}^c = 0 \quad \forall i \in N_{HR}, c \in C \quad (4)$$

$$1 - Y_i \left(\sum_{(i,m) \in E_R} X_{im}^c - \sum_{(m,i) \in E_R} X_{mi}^c \right) = 0 \quad \forall i \in N_{HR}, c \in C \quad (5)$$

$$T_i^c = \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \quad \forall i \in N_{HR}, c \in C \quad (6)$$

$$\gamma_{ij} \sum_{c \in C} X_{ij}^c n^c \leq \text{Max}_L \text{Risk} \quad \forall (i,j) \in E \quad (7)$$

$$\gamma_i \sum_{c \in C} T_i^c n^c \leq \text{Max}_N \text{Risk} * Y_i \quad \forall i \in N_{HR} \quad (8)$$

$$\sum_{c \in C} T_i^c n^c \leq \text{CAP}_i * Y_i \quad \forall i \in N_{HR} \quad (9)$$

$$0 \leq X_{ij}^c \leq 1 \quad \forall (i,j) \in E, c \in C \quad (10)$$

$$Y_i = \{0, 1\} \quad \forall i \in N_{HR} \quad (11)$$

$$0 \leq T_i^c \leq 1 \quad \forall i \in N_{HR}, c \in C \quad (12)$$

where, n^c – number of shipments for the c th OD pair; γ_{ij} – risk per shipment on edge $(i,j) \in E$; l_{ij} – cost per shipment on edge $(i,j) \in E$; X_{ij}^c – fraction of shipment for OD pair c served by edge (i,j) (decision variable); f_i – capital and operating costs for candidate transfer yard i ; Y_i – 1 if candidate transfer yard i is selected, 0 otherwise (decision variable); r_i – risk per shipment at candidate transfer yard i ; T_i^c – fraction of the shipment for the c th OD pair transferred at yard i (decision variable); N_H – set of highway nodes; N_R – set of railway nodes; N_{HR} – set of candidate transfer yards; E_H – set of highway network edges; E_R – set of railway network edges; E – set of all network edges, $E = E_H \cup E_R$; C – set of OD pairs; $\text{Max}_L \text{Risk}$ – maximum link risk; $\text{Max}_N \text{Risk}$ – maximum transfer yard risk; CAP_i – capacity of candidate transfer yard i ; $\text{orig}(c)$ – origin node of the c th OD pair; $\text{dest}(c)$ – destination node of the c th OD pair; α – weight for risks; and β – weight for costs.

The first set of constraints (Eq. (2)) is to ensure flow conservation for highway nodes (N_H); similarly, the second set of constraints (Eq. (3)) is for flow conservation of railway nodes (N_R); Eqs. (4) and (5) are the flow conservation constraints for candidate transfer yards; Eq. (6) defines a new variable T_i^c representing the percentage of shipments for the c th OD pair that are transferred at the i th candidate yard. This variable is included in the objective function to calculate the total transfer risk. Eq. (7) is to ensure that the total risk on each link is less than a specified value; similarly, Eq. (8) is to make

sure that each selected transfer yard will not cause the surrounding area to be exposed to HAZMAT risk higher than a threshold value; each candidate transfer yard can only handle a limited number of HAZMAT shipments and this capacity is reflected in Eq. (9). Since this is a multi-objective optimization problem, two weights are included to denote the relative importance of transportation cost and risk.

3.2. An improved linear formulation

The model formulation introduced in the previous section is easy to understand. However, it is nonlinear and also contains an absolute term, which makes it very difficult to solve. In this section, this model is reformulated. Several new constraints are introduced to replace the nonlinear and the absolute terms. Although the new formulation is less straightforward, it is in a mixed integer linear form and is relatively easy to solve. Specifically, we reformulate the nonlinear constraints (Eqs. (4)–(6)) in the previous model and convert them into the following linear forms, where M denotes a very large value. All other symbols used in Eqs. (13)–(16) have been introduced previously and will not be duplicated here.

$$-M \cdot Y_i \leq \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \leq M \cdot Y_i \quad \forall i \in N_{HR}, c \in C \quad (13)$$

$$\sum_{(m,i) \in E_R} X_{mi}^c - \sum_{(i,m) \in E_R} X_{im}^c - M \cdot (1 - Y_i) \leq \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \quad (14)$$

$$\sum_{(m,i) \in E_R} X_{mi}^c - \sum_{(i,m) \in E_R} X_{im}^c + M \cdot (1 - Y_i) \quad \forall i \in N_{HR}, c \in C$$

$$-M \cdot Y_i \leq \sum_{(i,m) \in E_R} X_{im}^c - \sum_{(m,i) \in E_R} X_{mi}^c \leq M \cdot Y_i \quad \forall i \in N_{HR}, c \in C \quad (15)$$

$$-T_i^c \leq \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \leq T_i^c \quad \forall i \in N_{HR}, c \in C \quad (16)$$

Eqs. (13) and (14) are equivalent to Eq. (4). They are to ensure that if candidate yard i is not selected ($Y_i=0$), the in- and out-highway HAZMAT flows at node i must be equal. Also, if candidate yard i is selected, the in- and out-HAZMAT flows of all modes at node i are equal. Eq. (15) is equivalent to Eq. (5). This constraint is to make sure that the in- and out-railway flows at node i are balanced if candidate yard i is not selected. Eq. (16) corresponds to Eq. (6). As shown above, the new constraints (Eqs. (13)–(16)) are essentially equivalent to the nonlinear and discontinuous constraints in Eqs. (4)–(6). By getting rid of the nonlinear and discontinuous terms, the original model formulation becomes a mixed integer linear program, which can be solved directly by some off-the-shelf optimization tools such as CPLEX.

4. Computational results

Two case studies are conducted to demonstrate how the proposed model can be used for multimodal HAZMAT location and routing modeling. The first case study considers a small-size network with only nine nodes and two OD pairs. For this simple network, we are able to provide detailed model outputs to better illustrate how the developed model works. Case study II is based on a realistic-size network consisting of major railways and interstate highways in twenty southern states (e.g., California, Arizona, Texas, Georgia, South Carolina, Florida, etc.) in the United States. The main purpose of case study II is to evaluate the applicability of the developed model for realistic-size problems and its computational efficiency.

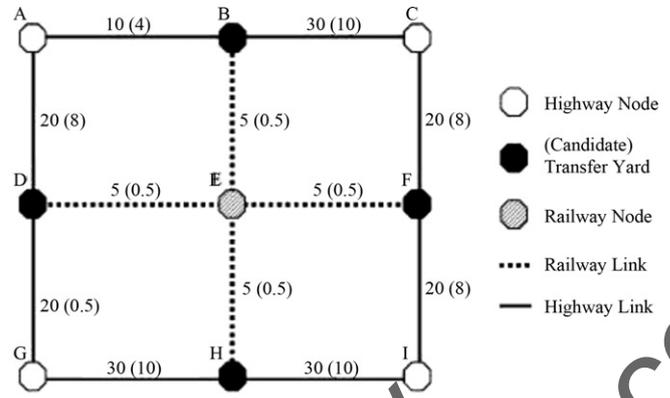


Fig. 2. Network for case study I.

Table 1 Case-study I: candidate transfer yard information.

| Yard ID | f_i , construction and operating cost (\$/year) | CAP, yard capacity (shipments/year) | γ_i , risk per shipment (number of people/shipment) |
|---------|---|-------------------------------------|--|
| B | 6000 | 500 | 3 |
| D | 9000 | 1000 | 3 |
| F | 4000 | 400 | 3 |
| H | 9000 | 1000 | 3 |

4.1. Case study I

Fig. 2 shows the network for case study I. Numbers next to each link and not in parentheses describe the cost per shipment (\$/shipment), and those numbers in parentheses next to each link represent the risk per shipment (number of people/shipment). Nodes B, D, E, and H are candidate transfer yards. Their annualized construction and operating costs, capacities, and per-shipment risks are listed in Table 1. The link and yard per-shipment risk values can be calculated using the same method to be introduced in Section 4.2 (Eqs. (17)–(19)). However, to keep this first example as straightforward as possible, detailed discussions on their calculation method are deferred to Section 4.2. The maximum risk a link can receive is limited to be 5000 people per year, and the maximum risk a transfer yard can take is limited to be 2000 people per year. In addition, it is assumed that every year there are 200 shipments of HAZMAT from A to I and 300 shipments from G to C.

Four scenarios with different weights (α and β) are considered as shown in Table 2, where “# of Constr.” reports the total number of constraints and “# of Var.” represents the total number of variables for case study I network. The proposed model is coded in CPLEX studio using OPL and solved to optimality for all scenarios. For scenarios 1, each OD pair has only one optimal route. For other scenarios, an OD pair may have two optimal routes and HAZMAT shipments for that OD pair are split between the two routes. Note that if a candidate yard is on an optimal route, this does not necessarily mean this candidate yard is selected unless there are transfer activities at this yard. As the result in Table 2 suggests, more candidate yards are selected when larger risk weights (α) are considered. Such a result is reasonable for this particular example, since all the HAZMAT either originate or end at a highway node and the railways are much safer and less costly than the highways. This trend however may not hold true for other problem settings, as the number of candidate transfer yards selected depends on several factors, including the costs of candidate yards, the number of HAZMAT origins and destinations connected to highways or railways, and obviously the distances of candidate yards to various origins and destinations. As expected, the computation time for this small-size network is not an issue. In fact, for all the scenarios tested, it

Table 2
Case-study I: scenarios produced by different weights.

| Scenario | α (risk weight) | β (cost weight) | Selected yards | Optimal routes | # of Constr. | # of Var. |
|----------|------------------------|-----------------------|----------------|---|--------------|-----------|
| 1 | 0.0 | 1.0 | None | 1: A-B-C-F-I (100%) 2: G-D-A-B-C (100%) | 106 | 61 |
| 2 | 0.4 | 0.6 | D, F | 1: A-B-C-F-I (50%) 1: A-D-E-F-I (50%) 2: G-D-E-F-C (100%) | | |
| 3 | 0.6 | 0.4 | D, F | 1: A-D-E-F-I (100%) 2: G-D-A-B-C (33%) 2: G-D-E-F-C (67%) | | |
| 4 | 1.0 | 0.0 | B, D, F | 1: A-B-E-F-I (100%) 2: G-D-E-B-C (33%) 2: G-D-E-F-C (67%) | | |

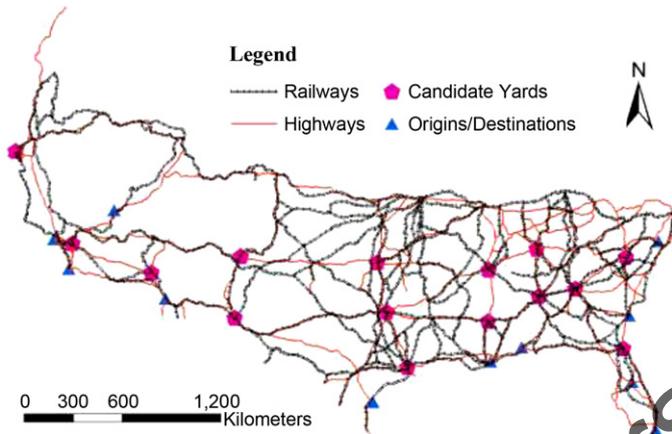


Fig. 3. Network for case study II.

takes less than one second to solve the formulated problem using a laptop with an i7 2.30 GHz CPU and 8 GB RAM.

4.2. Case study II

Case study II considers a medium-size network consisting of 630 railway links and 568 interstate highway links shown in Fig. 3. The highway and railway networks are obtained from the US Census Bureau's TIGER [34] GIS database and are stored in the ArcGIS [35] shape file format. To facilitate this research, we developed several Visual Basic for Applications (VBA) [36] programs to convert the ArcGIS network data into the format required by the CPLEX studio. In this case study, 15 candidate yards and 25 origins/destinations are considered. Finally, 600 OD pairs with randomly generated HAZMAT demands are used as the model input. These random integer numbers are uniformly distributed between 300 and 1000 shipments per year. For the input of case study II, only the distances between nodes are based on the real world data. All other link and transfer yard attributes (e.g., risks, costs, capacities, and maximum acceptable risk values), number of candidate yards, number of OD pairs, etc. are based on hypothetical values.

The transportation costs for railways [37] and highways [38] are set to be \$0.24 and \$1.07 per kilometer per shipment, respectively. The unitary accident frequency for railways and highways are assumed to be 0.19×10^{-6} [39] and 0.62×10^{-6} [40] per kilometer per shipment, respectively. Similar to some previous studies [41–42], the risk for each homogeneous road segment is measured as the multiplication of the accident rate and the number of people affected by a potential HAZMAT accident as shown in Eq. (17). The total risk for a road link consisting of several homogeneous segments is calculated using Eq. (18). Similarly, the risks for transfer yards are calculated by Eq. (19). p_{ijk} , POP_{ijk} , and Len_{ijk} represent the

Table 3
Case-study II: candidate transfer yard information.

| Yard ID | f_i , annual cost (in \$1000/year) | CAP, yard capacity (shipments/year) | γ_i , risk per shipment (number of people/shipment) |
|---------|--------------------------------------|-------------------------------------|--|
| 1 | 645 | 67,241 | 0.59 |
| 2 | 853 | 31,863 | 0.02 |
| 3 | 722 | 31,497 | 0.52 |
| 4 | 998 | 53,780 | 0.36 |
| 5 | 657 | 39,308 | 0.56 |
| 6 | 846 | 37,437 | 0.85 |
| 7 | 754 | 45,556 | 0.88 |
| 8 | 592 | 43,328 | 0.70 |
| 9 | 914 | 45,783 | 0.74 |
| 10 | 510 | 49,998 | 0.95 |
| 11 | 999 | 62,452 | 0.17 |
| 12 | 714 | 33,595 | 0.01 |
| 13 | 774 | 49,576 | 0.86 |
| 14 | 561 | 67,833 | 0.70 |
| 15 | 569 | 33,316 | 0.17 |

accident probability per shipment, population density, and length for the k th segment of road link (i, j) , respectively. p_i is the accident probability per shipment for transfer yard i and POP_i is the number of people that may be at risk. The units for both γ_{ij} and γ_i are number of people per shipment.

$$\gamma_{ijk} = p_{ijk}POP_{ijk}Len_{ijk}, \quad (i, j) \in A \tag{17}$$

$$\gamma_{ij} = \sum_k \gamma_{ijk} = p_{ijk}POP_{ijk}Len_{ijk}, \quad (i, j) \in A \tag{18}$$

$$\gamma_i = p_iPOP_i, \quad i \in N_{HR} \tag{19}$$

There are various ways of modeling link risk [12–15] and the method adopted here may not be the best one. However, since the focus of this research is to develop and evaluate a new location and routing model formulation, the adopted method should be sufficient for the purpose of this research. The costs, risks and capacities for the candidate transfer yards are listed in Table 3. Due to the lack of real-world data, the numbers in Table 3 and the population data used are all hypothetical values. For real-world HAZMAT transportation applications, the above assumed numbers should either be properly adjusted or replaced by observed values based on the type of HAZMAT being modeled. In addition, the cost and risk values per kilometer per shipment should also be carefully calibrated based on each link's characteristics in the real world.

As mentioned earlier, there are a total of 600 OD pairs that can be included in the modeling process. Including more OD pairs may substantially increase the computation time for finding the optimal solutions. To quantify such impact, tests with different numbers of OD pairs are conducted and the results are presented in Table 4. For all the tests, both α and β are set to be 0.5 to ensure consistency in comparison. The same laptop used for case study I is utilized

Table 4
Case-study II: computational details.

| Test scenario | # of OD pairs | Total computation time (seconds) | # of iterations | # of Var. | # of Constr. | Gap (%) |
|---------------|---------------|----------------------------------|-----------------|-----------|--------------|---------|
| 1 | 5 | 2 | 6162 | 6081 | 3778 | 24.44 |
| 2 | 10 | 2 | 14,952 | 12,146 | 6328 | 22.30 |
| 3 | 20 | 3 | 18,878 | 24,276 | 11,428 | 9.92 |
| 4 | 30 | 15 | 162,508 | 36,406 | 16,528 | 0.00 |
| 5 | 40 | 17 | 170,333 | 48,536 | 21,628 | 0.00 |
| 6 | 50 | 24 | 240,718 | 60,666 | 26,728 | 0.00 |
| 7 | 60 | 32 | 281,702 | 72,796 | 31,828 | 0.00 |
| 8 | 80 | 64 | 405,424 | 97,056 | 42,028 | 0.17 |
| 9 | 100 | 92 | 923,692 | 121,316 | 52,228 | 1.50 |
| 10 | 135 | 133 | 839,436 | 163,771 | 70,078 | 2.61 |
| 11 | 165 | 216 | 1,001,528 | 200,161 | 85,378 | 3.09 |
| 12 | 200 | 258 | 1,581,379 | 242,616 | 103,228 | 4.01 |
| 13 | 250 | 443 | 2,553,498 | 303,266 | 128,728 | 2.17 |
| 14 | 300 | 666 | 2,479,936 | 363,916 | 154,228 | 1.57 |
| 15 | 450 | 1065 | 1,398,430 | 545,866 | 230,728 | 4.11 |
| 16 | 600 | 2332 | 1,058,748 | 727,816 | 307,228 | 2.98 |

Table 5
Case-study II: scenarios produced by different weights.

| Scenario | α (risk weight) | β (cost weight) | Total risk (number of people/year) | Total cost (in \$1000/year) |
|----------|------------------------|-----------------------|------------------------------------|-----------------------------|
| 1 | 0.00 | 1.00 | 167,790 | 61,654 |
| 2 | 0.03 | 0.97 | 87,620 | 61,695 |
| 3 | 0.06 | 0.94 | 87,071 | 61,725 |
| 4 | 0.10 | 0.90 | 82,571 | 62,160 |
| 5 | 0.20 | 0.80 | 79,171 | 62,787 |
| 6 | 0.30 | 0.70 | 76,105 | 63,920 |
| 7 | 0.35 | 0.65 | 67,843 | 67,557 |
| 8 | 0.40 | 0.60 | 62,586 | 70,791 |
| 9 | 0.50 | 0.50 | 62,543 | 70,832 |
| 10 | 0.60 | 0.40 | 60,926 | 72,811 |
| 11 | 0.70 | 0.30 | 58,645 | 76,711 |
| 12 | 0.80 | 0.20 | 57,051 | 81,001 |
| 13 | 0.90 | 0.10 | 56,696 | 82,861 |
| 14 | 1.00 | 0.00 | 56,634 | 88,999 |

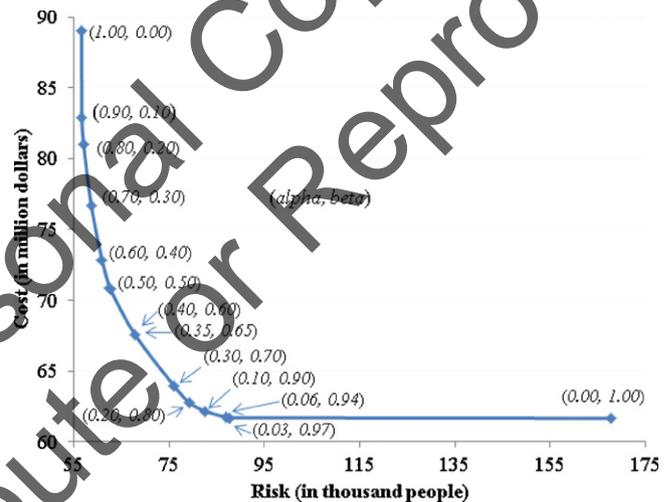


Fig. 4. Case study II: total cost as a function of total risk.

for solving the case study II network problem and the results are shown in Table 4. “# of Constr.” is the total number of constraints, “# of Var.” is the total number of variables, and “Gap (%)” is the percentage difference between the final optimal solution and the best bound found. As can be seen, the computation time increases drastically as the number of OD pairs increases. This phenomenon is typical for location and routing models of large sizes. To address this issue, researchers often resort to heuristic or approximate algorithms. Developing these heuristics or approximate algorithms requires considerable time and efforts. Due to limited time, this research is only focused on developing and evaluating the multimodal HAZMAT model.

In addition to computation time, different scenarios are investigated to find out how the objective function value changes as a result of varying the risk and cost weights. For all the scenarios, the case study II network with 100 OD pairs is considered. The values of the risk and cost components in the objective function for different scenarios are presented in both Table 5 and Fig. 4. The results suggest that, for this particular example, choosing an $\alpha \geq 0.70$ can result in a substantially larger cost component value. Similarly, choosing a $\beta \geq 0.8$ will lead to a much larger value for the risk component. Table 5 and Fig. 4 can be helpful for finding the best weights. For instance, if one is not quite sure or does not have a strong opinion about the relative importance of risk and cost, the weight combinations for scenarios 5–10 probably are better options for this example. Outside this range, an insignificant decrease in risk will result in a substantial increase in cost and vice versa.

5. Conclusion remarks

In this paper, we propose a multi-objective and multimodal model that can simultaneously optimize transfer yard locations and HAZMAT transportation routes subject to risk and cost constraints. The proposed model is formulated as a mixed integer linear program and coded in CPLEX studio using OPL. It is also extensively tested on two sample multimodal networks consisting of highways and railways.

From the results based on the first sample network (case study I), it is found that the risk and cost weights in the objective function can have a significant impact on the number of candidate transfer yards to be selected. Since railways typically have much lower accident rates than highways (as shown in Section 4.2) and many HAZMAT transportation demand nodes are connected to the highway network directly, in general for long-distance shipments the larger the risk weight is, the more candidate transfer yards will be selected to take advantage of the low-risk feature of railways. This hypothesis has been supported by the case study I results. The developed model is further tested on a medium-size network with approximately 1200 links, 15 candidate yards, and 600 OD pairs. It is solved to optimality in about 40 min. Considering the fact that a regular laptop computer is used, the computational performance of the developed model is quite encouraging. In case study II, a sensitivity study is also conducted to quantify the impact of the risk

and cost weights and to demonstrate the importance of choosing proper values for them.

According to the 2007 United States Commodity Flow Survey [2], multimodal transportation is playing an increasingly important role in HAZMAT transportation practices, which requires more research on multimodal HAZMAT location and routing modeling. Despite the growing needs, little attention has been paid to this relatively new area. This research is among the few studies focusing on the location and routing modeling of multimodal HAZMAT transportation. It also is the first attempt to address the optimization of transfer yard locations and routing plans simultaneously. It is our hope that this study could inspire additional in-depth research and discussions on this topic as discussed in Section 6.

6. Future research

The main objective of this research is to develop a multimodal location and routing model for HAZMAT transportation and hopefully open up a new research area (i.e., multimodal HAZMAT location and routing modeling). Thus, this paper focuses on the location model development instead of other issues such as link and yard risk models, delay at yards, uncertainties in model inputs, equity issues, and the consideration of real-world data, even though these topics are also very important. Future research can incorporate these additional factors into the proposed model to further enhance its applicability and capability. Additionally, only one commodity type is considered in this research, future studies can build upon the proposed model and take more commodity types into account. Finally, it would be interesting to research on heuristic or more efficient exact algorithms for the proposed model.

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