Hazardous Materials Transportation with Multiple Objectives: A Case Study in Taiwan

by Ta-Yin Hu and Ya-Han Chang

Hazardous material (hazmat) transportation has been an important issue for handling hazardous materials, such as gases and chemical liquids. In the past, researchers have made great efforts to develop policies and route planning methods for hazmat transportation problems. In 2014, Kaohsiung City in Taiwan suffered a gas pipeline explosion at midnight; 32 people were killed, and hundreds of people were injured. After the incident, policies and routing strategies for hazardous materials (hazmat) transportation in Kaohsiung were initiated to avoid pipeline transportation. Although methodologies for hazmat transportation have been proposed and implemented to minimize potential risks, multiple objectives need to be considered in the process to facilitate hazmat transportation in Taiwan.

In order to consider both government and operators' aspects, a multi-objective formulation for the hazmat problem is proposed and a compromise programming method is applied to solve the problem with two objectives: travel cost and risk. The path risk is defined based on risk assessment indexes, such as road characteristics, population distribution, link length, hazardous material characteristics, and accident rates. An aggregate risk indicator is proposed for roadway segments. The compromise programming approach is developed from the concept of compromise decision and the main idea is to search the compromise solution closest to the ideal solution. The proposed method is applied to Kaohsiung City, Taiwan. The results show that two conflicting objectives keep making trade-offs between each other until they finally reach a compromise solution.

INTRODUCTION

In 2014, Kaohsiung City in Taiwan suffered a gas pipeline explosion at midnight on August 1; 32 people were killed, and hundreds of people were injured. After the incident, policies and routing strategies for hazardous materials transportation were initiated to avoid pipeline transportation. In order to fulfill the needs of chemical production, numerous hazmat cargo tanks are required, but those hazmat cargo tanks on roads pose huge dangers to citizens. Although methodologies for hazmat transportation have been proposed and implemented to minimize potential risks, multiple objectives might still need to be considered in the process to facilitate hazmat transportation in Taiwan.

In order to consider both government and operators' aspects, a multi-objective formulation for the hazmat problem is proposed and a compromise programming method is applied to solve the problem with two objectives: travel cost and risk. Due to the incidents in Kaohsiung, the government wishes to minimize possible risk; in the meantime, operators wish to minimize travel cost. Therefore, two objectives, including travel cost and risk, are selected for illustration purpose in this study.

The path risk is defined based on risk assessment indexes, such as road characteristics, population distribution, link length, hazardous material characteristics, and accident rates. An aggregate risk indicator is proposed for roadway segments. The compromise programming approach is developed from the concept of compromise decision and the main idea is to search the compromise solution closest to the ideal solution. The empirical study based on Kaohsiung City is conducted to illustrate the proposed algorithm.

The rest of this paper is organized as follows. The second section reviews related literature in this research. The third section describes the model formulation and solution algorithm. The fourth section studies the cases in a real-world network, followed by the conclusions and suggestions.

LITERATURE REVIEW

Some relevant literature of hazmat transportation is briefly described, including hazmat transportation, risk models, multi-objective programming models, and the compromise programming approach.

Hazardous Material Transportation

Based on the UN Recommendation on the Transport of Dangerous Goods (UNRTDG) formulated by the United States Department of Transportation (DOT) and the United Nations Economic and Social Council (ECOSOC), the definition of hazardous materials is solids, liquids, or gases that can harm people, other living organisms, property, or the environment. The hazmat can be classified into nine classes, including explosives, gases, flammable liquids, flammable solids, oxidizing substances, organic peroxides, toxic and infectious substances, radioactive material, corrosive substances, and miscellaneous dangerous substances and articles (UNRTDG 2011 p.49-50). The U.S. DOT defined hazardous material as any substance or material that could adversely affect the safety of the public, handlers, or carriers during transportation. The Pipeline and Hazardous Materials Safety Administration (PHMSA) was established to protect people and the environment from the risks of hazardous materials transportation.

List et al. (1991) classified hazmat research into three categories: risk analysis, routing/scheduling and facility location. Risk analysis considers the appropriate ways to assess transport risk, including assessment of incident probabilities and degrees of incidents' consequences. Routing/scheduling problems focus on finding suitable routes under a variety of objectives, such as minimizing cost and risk. Facility location problems consider the locations of facilities and locations that accept hazmat wastes. The problem addressed in this research is mostly related to routing and scheduling problem.

Transportation Risk Assessment

Risk assessment is an important issue of the hazmat transportation problem, and there is plenty of research on risk analysis. Erkut et al. (2007) provides a comprehensive review on risk analysis and pointed out that quantitative risk assessment involves the following key steps: hazard and exposed receptor identification, frequency analysis, consequence modeling, and risk calculation. For more detail, the readers can refer to the comprehensive review. Some related studies are briefly reviewed as follows.

Chang (1990) proposed a set of measurement standards for risk assessment in Taiwan, proposed measures for path risk, and evaluated consequences and routing strategy with sensitivity analysis. Erkut and Verter (1998) provided an overview of risk models for risk assessment of hazardous material transportation, including traditional risk model, population exposure model, incident probability model, and perceived risk model. They also define societal risk as the product of link length, accident rate, conditional release probability, population density, and impact radius.

Chen et al. (2011) applied the concept of risk assessment matrix to determine the risk of hazmat and proposed the feasible options and supporting measures to reduce the risk of hazardous materials transportation. Kang et al. (2014) applied the concept of value-at-risk (VaR) to the assessment of hazardous materials transportation routing strategies to determine routes that minimize the global VaR value in a realistic multi-trip multi-hazmat type framework.

Multi-objective Approach

A multi-objective optimization problem means a problem with more than one objective. While a single-objective problem is looking for an optimal solution, a multi-objective problem is searching for compromise solutions among conflicted objectives. As a result, a variety of multi-objective optimization algorithms are proposed and applied in different fields. In hazmat transportation problems, cost, risk, travel time, and potential exposure are often chosen to be objectives. Objectives and methodologies applied in hazmat transportation problems are reviewed.

Abkowitz et al. (1992) put minimizing incident probability and population rate in the multi-objective schemes. Current and Ratrick (1995) proposed a multi-objective function to minimize total transportation risk, minimize total facility risk, minimize maximum transport exposure, and minimize total operating costs. Erkut and Verter (1998) viewed the risk minimizing problem as a bicriterion optimization problem. They also mentioned that traditional risk is a combination of incident probability and population rate. Finally, they suggested finding the compromise solution for the two criteria and other attributes such as cost and length.

Li and Leung (2011) developed a novel methodology based on the concept of the compromise programming approach for determination of optimal routes for dangerous goods transportation under conflicting objectives. Li et al. (2013) proposed a model based on multi-objective optimization, which takes transportation risk, route, and freight into consideration. Li and Jiang (2013) developed a multi-objective genetic algorithm (MOGA) to determine optimal routes for hazmat transportation under conflicting objectives.

Compromise Programming Approach

The compromise programming approach is developed from the concept of compromise decision (Yu and Leitmann 1973). The main idea of compromise programming is to search the compromise solution closest to the ideal solution. That is, the decision maker will tend to lower the target of each objective when facing numerous conflicting objectives until the solution becomes feasible.

A multi-objective optimization problem is briefly described below. When each objective is minimized independently, the optimal value of each objective can be obtained. The combination of optimal value for each objective is defined as the ideal solution for the problem.

$$\min_{x} Z(x) = [Z_1(x), Z_2(x), \ldots, Z_n(x)]$$

$$\text{s.t } \mathbf{x} \in \textbf{feasible region}$$
$$\text{ideal solution} = (Z_1^*, Z_2^*, \ldots, Z_n^*)$$

The distance between the ideal solution and a compromise solution is defined by the following function.

$$d_p = \left[\sum_{i=1}^{n} \lambda_i^p (x_i - Z_i^*)^p\right]^{1/p}, \quad 1 \le p \le \infty$$

λ_i^p is the weight of objective i, which can be viewed as the preference of the decision maker or the unit adjustment between objectives. Distance parameter p gives a different measure of the distance from the compromise point to the ideal point.

d_1 (p=1) is the city-block distance, which is also known as the Manhattan-block distance. In this situation, all deviations are weighted equally. d_2 (p=2) is the Euclidean distance, which is the linear distance the between compromise point and ideal point. d_∞ (p= ∞) is the one-dimension distance, which is also known as the Chebyshev distance. As p approaches, the problem becomes a min-max problem, which aims to minimize the maximum distance from dimensional aspect.

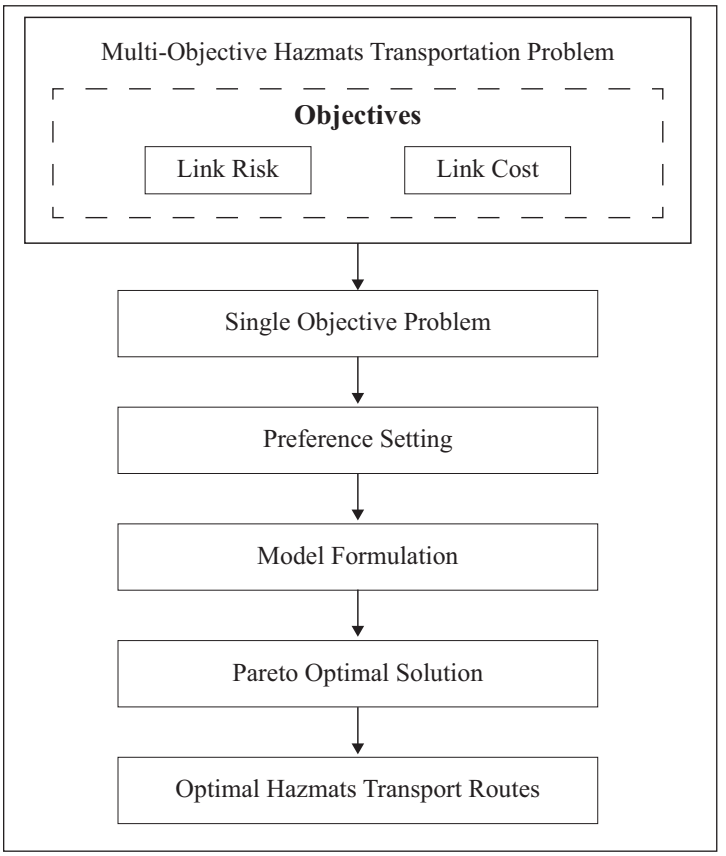
By setting the weights between objectives and fixing the distance parameter p, decision makers can choose the most appropriate solution based on the distance function.

RESEARCH METHODOLOGY

Given a directed network G = (N, A), which includes the set of nodes N and the set of arcs A. Each arc (i,j) is associated with the travel time (C_{ij}) and the transport risk (SR_{ij}). The origin node is s and the destination node is t. A multi-objective compromise programming approach with two conflict objectives, including path cost and risk, is developed. Assumptions of this research include (1) only single hazmat is considered; (2) functional speed for links is assumed to be the speed limit.

The conceptual framework of the hazardous materials transportation problem, as shown in Figure 1, includes five procedures: multiple objectives for hazardous materials transportation, single objective problem for each individual objective, preference setting for each objective, compromise programming model formulation with two objectives, finding the Pareto optimal solution and obtain the optimal transport paths.

Figure 1: Conceptual Framework



Model Formulation

Two objectives considered in this research are path risk and path cost. The notations of the formulation are listed in Table 1. Multi-objective hazardous material transportation routing problem is formulated as follows:

Table 1: Notations of the Formulation

Notation	Definition
Set	
N	The set of nodes.
A	The set of arcs.
P	The set of intermediate nodes.
Variable	
x_{ij}	If the arc (i, j) is selected into the optimal path, x_{ij} is equal to 1. Otherwise, x_{ij} is equal to 0.
SR_{ij}	The total societal risk of the optimal path.
C_{ij}	The total travel cost of the optimal path.
Parameter	
v_{ij}	The functional speed on arc (i, j).
l_{ij}	The length of arc (i, j).
d_{ij}	The population density in the neighborhood of arc (i, j).
r	The impact radius of the hazardous material.
AR_{ij}	The accident rate on arc (i, j).
CR_{ij}	The conditional release probability on arc (i, j).

Objectives:

Path Risk

(1) $\boldsymbol{Min} \sum_{i \in N} \sum_{j \in N} SR_{ij} * x_{ij}$

Path Cost

(2) $\boldsymbol{Min} \sum_{i \in N} \sum_{j \in N} C_{ij} * x_{ij}$

subject to

(3) $\sum_{i \in N} x_{i,j} = 1$ $(i \in origin)$

(4) $\sum_{i \in N} x_{j,i} - \sum_{i \in N} x_{i,j} = 0$ $(\mathbf{i} \in \mathbf{P})$

(5) $\sum_{i \in N} x_{j,i} = 1$ $(i \in destination)$

(6) $SR_{ij} = l_{ij} * AR_{ij} * CR_{ij} * d_{ij} * (\pi) (\mathbf{r})^2 \quad \forall (i,j) \in A$

(7) $C_{ij} = l_{ij} / v_{ij} \quad \forall (i,j) \in A$

(8) $x_{ij} = \mathbf{0}$ ***or*** $\mathbf{1} \quad (i, j \in N)$

Two objectives are described in equations (1) to (2). Objective (1) minimizes the total path risk and objective (2) minimizes the total path cost. Equations (3) to (5) are flow conservation equations. Equation (6) is to calculate the societal risk, which is the product of link length, accident rate,

conditional release probability, population density, and impact radius. Accident and release probability are determined by the road type. The size of impact radius depends on the hazmat under consideration. Equation (7) is to calculate the travel cost, which is estimated as length of arc divided by functional speed. Equation (8) is the 0-1 constraint.

Solution Algorithm

Based on Erkut and Verter (1998), the societal risk is the expected number of people to be impacted in one trip of the hazmat truck on that link. The societal risk of each arc is estimated as follows:

Societal risk = length of link (km) *accident rate on the link (per km) *conditional release probability of the link *population density in the neighborhood of the link (people/km-sq) *(π) (impact radius)^2 (km-sq)

The expected travel time of each arc is estimated as follows:

Travel time = length of link / functional speed,

The goal of the multi-objective hazardous material transportation routing problem is formulated as follows:

(9) $\min_{w} Z(w) = [Z_1(w), Z_2(w)]$

Subject to

(10) $Z_1(w) = \text{Path cost objective} = Min \sum_{i \in N} \sum_{j \in N} C_{ij} * x_{ij}$

(11) $Z_2(w) = \text{Path risk objective} = Min \sum_{i \in N} \sum_{j \in N} SR_{ij} * x_{ij}$

w ∈ feasible region

Ideal solution = (Z_1^*, Z_2^*)

The distance between ideal solution and compromise solution is defined as follows:

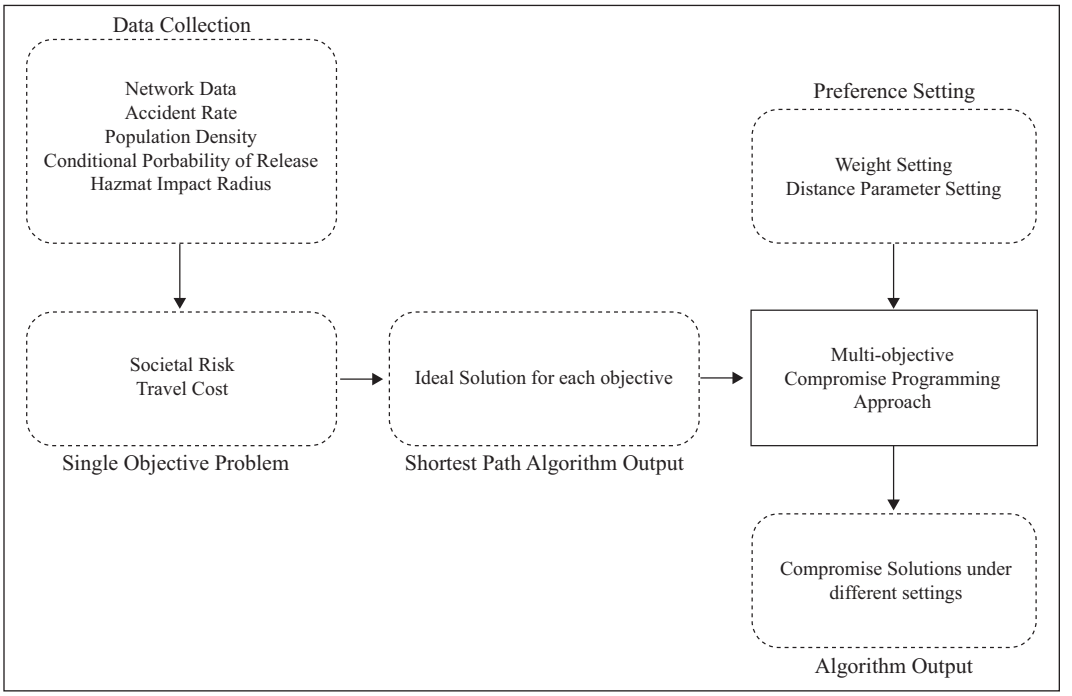
(12) $d_p = \left[\lambda_1^p (w_1 - Z_1^*)^p + \lambda_2^p (w_2 - Z_2^*)^p\right]^{1/p}, 1 \leq p \leq \infty$

By setting the distance parameter p, solutions under different situations are obtained. Distance parameter p represents different measures of the distance from the compromise point to the ideal point. When p = 1, all deviations are weighted equally. When p = 2, the linear distance between compromise point and ideal point is used. As p approaches ∞, the problem aims to minimize the maximum distance from dimensional aspect. By setting the weights between objectives and fixing the distance parameter p, decision makers can choose the most appropriate solution based on the distance function.

ALGORITHM FRAMEWORK

As shown in Figure 2, the algorithm is constructed in three parts: data collection, shortest path algorithm, and compromise programming approach. The data collected in the first part will be the input data for shortest path algorithm, and the output data from shortest path algorithm will be the input data for the compromise programming approach.

Figure 2: The Algorithm Framework

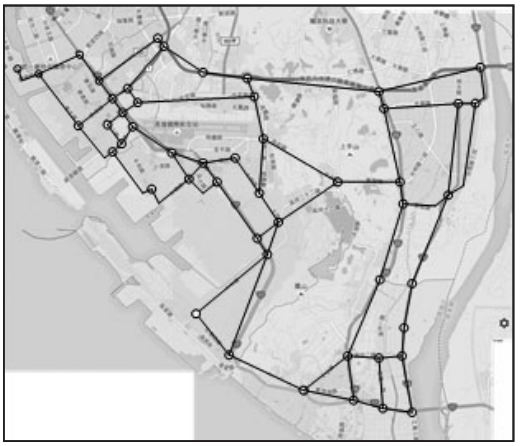


EMPIRICAL ANALYSIS

Basic Data of Experimental Network

The proposed approach is tested in Kaohsiung City shown in Figure 3. The network consists of 50 nodes and 144 links. The links consist of freeways, expressways, and arterial streets with real road characteristics. The origin node is China General Terminal & Distribution Corporation (CGTD) and the destination is Lin Yuan Industrial Zone.

Figure 3: The Network in Empirical Analysis



Accident Rate

Domestic data for hazmat cargo tanks, such as traffic information and accident information, are insufficient. Therefore, the accident information of trucks and freight vehicles are used in the study. The data for Year 2013 are summarized in Table 2, where A1 is defined as the injured persons who died within 24 hours of the accident and A2 is defined as non-fatal traffic accidents.

Table 2: A1+A2 Accident Data in 2013

Road type	A1+A2 accidents	Truck	Freight vehicle	Total
General roads	278,388	18818	3749	22567
Freeways	1233	281	181	462

In order to calculate the total traveled distance of truck and freight vehicles on general roads, we retrieved the domestic cargo transport data from the Directorate General of Highways, MOTC. Total traveled distance of all operating vehicles (Lc) is 4,171,633,457 km, and is used as the total travel distance while calculating accident rate. The average accident rate of trucks and freight vehicles on general roads per car per unit traveled distance is calculated as follows:

(13) $f = \frac{\text{number of } A1 \text{ and } A2 \text{ accidents } (X)}{total\ traveld\ distance}$, accident per km

Year 2013, A1+A2: $f = \frac{(X)}{Lc} = \frac{22567}{4,171,633,457} = 5.41 \times 10^{-6}$ accident/km

Highway data are obtained from different sources, including Taiwan Area National Freeway Bureau and Directorate General of Highways. The average accident rate of trucks and freight vehicles on national freeways per car per unit traveled distance is estimated as:

(14) $= \frac{A1 \text{ and } A2 \text{ accidents of freeways}(Y)}{total\ traveld\ distance}$, accident per km

Year 2013, A1+A2: $f = \frac{(Y)}{Lc} = \frac{462}{5,301,545,312} = 8.71 \times 10^{-8}$ accident/km

Table 3: Accident Rate

	A1+A2 accident (accident/million km)
General Road	
National Freeway	

Population Density

Village is used as the basic unit in estimating population density. Village area and link length are obtained through Google Maps. Based on the statistics data from the Civil Affairs Bureau of Kaohsiung City Government, the population density data of each village can be computed as follows:

Population density on link j = $\frac{\Sigma_i\ village\ population}{\Sigma_i\ village\ area}$ (people per km-sq),

where i represent the villages link j pass through, j represent the links in network

Conditional Release Probability

Conditional release probability is the probability of a hazmat release given an accident involving a hazmat-carrying truck. Since there is no related research and appropriate data of release probabilities in Taiwan, the data of release probability for use in hazmat routing analysis from Harwood et al. (1993) is adopted and presented in Table 4.

Table 4: Release Probability for Use in Hazmat Routing Analysis

Area Type	Roadway type	Probability of release given an accident
Rural	Two-lane	0.086
	Multilane	0.082
	Freeway	0.090
Urban	Two-lane	0.069
	Multilane	0.062
	Freeway	0.062

(Source: Harwood et al., 1993)

Hazmat Impact Radius

In this research, we selected styrene monomer as our hazmat to be transported. The hazard modeling program, ALOHA 5.4.4, is used to estimate hazmat impact radius. ALOHA is a software that allows us to enter details about a real or potential chemical release, which can estimate threat zones associated with different types of hazardous chemical releases. Parameters based on Kaohsiung City are set in ALOHA, and the worst case scenario is simulated. Through the simulation, the fireball diameter is 145 yards, or, 0.13km. Thus, 0.13km is used as impact radius if an accident occurred in Kaohsiung.

Experiment Design

The objective is to obtain an optimal path of hazardous materials transportation under the consideration of trade-off between minimizing travel cost and travel risk. Each scenario includes a different weight λ_i^p and different distance parameter p. Eleven scenarios of different weights and distance parameters are experimented with to observe how the trade-off between conflicting objectives and the setting of distance parameters influences the optimal path decision, as shown in Table 5. Scenarios 1 and 2 are single-objective problems and scenarios 3 to 11 are multi-objective problems. The results of scenarios 1 and 2 are also the ideal solutions for the two objectives.

We standardize the risk and cost of each link for data simplification and unit adjustment, the data standardization method is expressed as: $x_i' = x_i / \bar{x}$.

Table 5: Experiment Scenarios

Scenario	p	λ_c	λ_r	Scenario	p	λ_c	λ_r
1	x	1	0	**7**	2	0.25	0.75
2	x	0	1	**8**	2	0.75	0.25
3	1	0.5	0.5	**9**	∞	0.5	0.5
4	1	0.25	0.75	**10**	∞	0.25	0.75
5	1	0.75	0.25	**11**	∞	0.75	0.25
6	2	0.5	0.5				

The results of Scenarios 1 and 2 are summarized in Table 6. Scenario 1 minimizes the travel cost, and Scenario 2 minimizes the risk. The optimum paths of Scenarios 1 and 2 are illustrated in Figure 4.

Table 6: Results of Scenarios 1 and 2

Scenario	p	λ_c	λ_r	Path (in terms of nodes)	Total cost	Total risk
1	-	1	0	1→2→3→4→8→11→15→20→22 →23→27→30→32→44→46→50	10.165	-
2	-	0	1	1→2→9→8→7→6→16→17→33→35 →38→39→40→42→43→48→47→50		3.832

Figure 4(a): Min Travel Cost

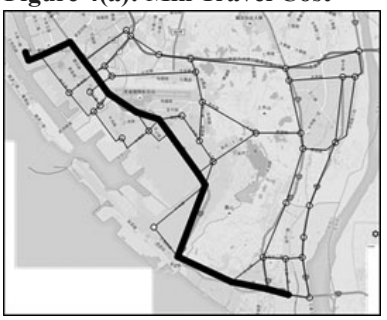
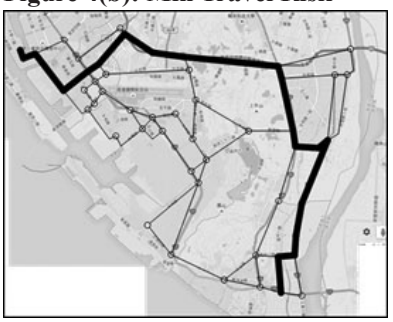


Figure 4(b): Min Travel Risk



The ideal solutions for the two objectives are [*cost**, *risk**] = [10.165,3.832]. For other scenarios, our goal is making the compromise solution as close to the ideal solution as possible. The results are summarized in Table 7, and the optimum paths are illustrated in Figures 5 to 8.

Table 7: Results of Scenarios 3 to 11

Scenario	p	λ_c	λ_r	Path	Distance to Ideal point	Cost	Risk
3	1	0.5	0.5	1→2→9→8→7→6→16→17→33→35 →38→39→40→42→43→48→49→50	1.5995	13.272	3.924
4	1	0.25	0.75	1→2→9→8→7→6→16→17→33→35 →38→39→40→42→43→48→49→50	0.84575	13.272	3.924
5	1	0.75	0.25	1→2→3→4→8→7→6→16→17→33 →35→38→39→41→45→46→50	1.7685	11.255	7.636
6	2	0.5	0.5	1→2→3→4→8→7→6→16→17→33→35 →38→39→40→42→43→48→49→50	1.387429	12.43	5.435
7	2	0.25	0.75	1→2→9→8→7→6→16→17→33→35 →38→39→40→42→43→48→49→50	0.77981	13.272	3.924
8	2	0.75	0.25	1→2→3→4→8→7→6→16→17→33 →35→38→39→41→45→46→50	1.2541	11.255	7.636
9	∞	0.5	0.5	1→2→3→4→8→7→6→16→17→33→35 →38→39→40→42→43→48→49→50	1.1325	12.43	5.435
10	∞	0.25	0.75	1→2→9→8→7→6→16→17→33 →35→38→39→41→45→47→50	0.749	13.161	4.705
11	∞	0.75	0.25	1→2→3→4→8→7→6→16→17→33 →35→38→39→41→45→46→50	0.951	11.255	7.636

Figure 5: Scenarios 3,4,7

Figure 6: Scenarios 5,8,11

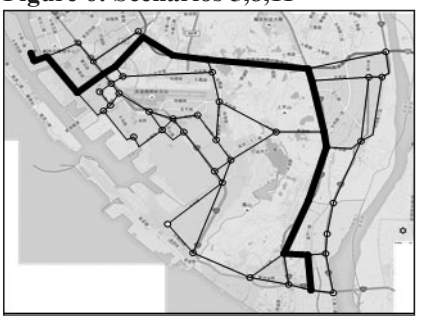


Figure 7: Scenarios 6,9

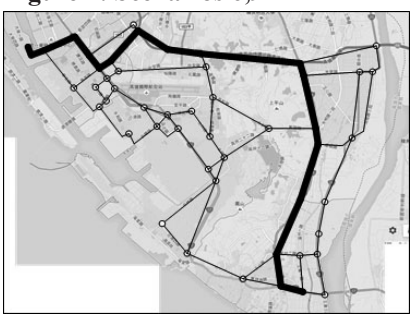
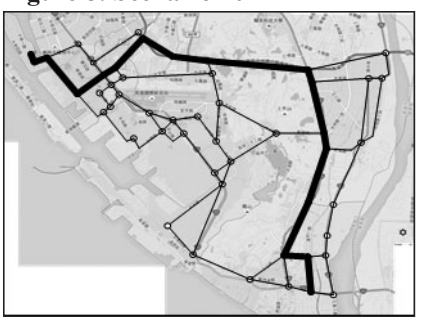


Figure 8: Scenario 10



When considering only the cost minimization, the optimal path includes the usage of the expressway 17th, which has a higher speed limit and shorter travel distance. When considering only the risk minimization, due to the lower accident risk on highways and expressways and also the lower population density, expressway 88th and the Sun Yat-sen Freeway are chosen to be the optimal path in this scenario. When it comes to the multi-objective experiments, we can find that

due to the Sun Yat-sen Freeway and expressway 88th have the highest speed limit and the lowest accident rate in the research network, hence all scenarios choose them as the optimal compromising paths.

When considering the impact of distance parameter settings, the results show that while p is set to be infinite, the distances to the ideal point is smaller than those of p are set to 1 or 2. When the values of p are the same, the distance between compromise solution and ideal point will be the smallest while the weights between cost objective and risk objective is set to be 0.25:0.75, which are scenarios 4, 7, and 10. Under this weight, we can obtain the minimum distance to ideal point while p = 2.

CONCLUSION

The main contribution of this research is to apply the compromise programming algorithm to design an optimal path for hazardous material transportation of Kaohsiung city under the consideration of travel cost and travel risk. The numerical results show that optimal paths under different objectives tend to be different. With the compromising approach, a variety of compromise solutions could be identified based the distance parameter p. The numerical analysis illustrates positive advantages of the compromise programming approach, and other objectives might be able to be considered in the future.

Future research directions include a multi-OD hazmat framework and weight decisions. The former represents a more general framework for the hazmat transport problem in a network, and the latter represents how to choose the distance parameter p. In practice, how to decide appropriate weights for objectives is important, so does the distance parameter p. There are some methods for weighting such as AHP and TOPSIS. How to define the most appropriate method needs to be discussed in the future.

As for the hazmat problem in practice, data are very important to evaluate risk as well as cost. The accuracy and quality of the data could have significant impact on the result. Currently, data for hazmat transportation in Taiwan are insufficient and incomplete. Future research directions include how to establish sufficient databases, how to validate the proposed algorithm, and how to conduct demonstration projects.

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Ta-Yin Hu *received a B.S. in civil engineering, National Chen-Kung University, June 1985; an M.S. in Institute of Traffic and Transportation, National Chao-Tung University, June 1987; and his Ph.D. in civil engineering (transportation engineering), the University of Texas at Austin, in May 1995. He is a professor with the Department of Transportation and Communication Management Science, National Cheng Kung University, Taiwan, R.O.C. He specializes in intelligent transportation systems (ITS), dynamic network analysis, simulation analysis, ITS application in traffic and transportation, transportation planning, and transportation engineering.*

Ya-Han Chang *is a master's student in the Department of Transportation and Communication Management Science, National Cheng Kung University, Taiwan, R.O.C. Current research interests include hazmat transportation and transportation planning.*