A GIS BASED ANALYSIS FOR TRANSPORTATION OF HAZARDOUS MATERIALS FROM DIFFERENT PERSPECTIVES

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by
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September 2002

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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Transportation of hazardous materials (hazmats) has been calling attention of regulators, hazmat carriers, environmentalist groups and academia for many years. In the hazmat literature, there exists two different hazmat transportation problems for two important decision maker groups. The problem of the first group, namely the regulators, is to minimize the 'risk' that is generated by the hazmat carriers. The problem of the second group, namely the hazmat carriers, is to select the routes that minimize their transportation costs. However, there exists another group of Decision Maker that needs to satisfy both of the objectives (transportation 'risk' and costs), which in most cases conflict mutually.

In this study, we propose solutions to the hazmat transportation problem from both government's and a hazmat producer and supplier firm's point of view. We also introduce a new decision-maker type that has been neglected in the hazmat literature.

Keywords: Transportation of Hazardous Materials, Geographical Information Systems (GIS)

ÖZET

FARKLI BAKIS AÇILARINDAN TEHLIKELI MADDE TASIMACILIGI IÇIN COGRAFI BILGI SISTEMLERI TABANLI BIR ANALIZ

Hakan Ümit
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Tehlikeli madde tasimaciligi yillardir resmi otorite, tehlikeli madde tasiyici firmalar, çevreci gruplar ve bilim çevrelerinin dikkatini önemli ölçüde çeken bir konu olmustur. Tehlikeli madde tasimaciligi literatüründe iki önemli karar verici grubun iki ayri problemi yer almaktadir. Birinci grup yani resmi otoritelerin problemi tehlikeli madde tasiyanlarin çevreye karsi yarattigi 'risk'i enazlamaktir. Ýkinci grup yani, tasiyici firmalarin problemi ise kendi tasima maliyetlerini enazlayan güzergahlari seçmektir. Ancak literatürde yer almayan ve çogunlukla birbiriyle çelisen bu iki amaca (tasima 'risk' ve maliyetleri) sahip olan baska bir karar verici grup da bulunmaktadir.

Bu çalismada hükümet ve tehlikeli madde üretici bir firmanin tehlikeli madde tasimaciligi problemine çözümler önerilmektedir. Ayrica çalismada, literatürde simdiye kadar ihmal edilmis yeni bir karar verici grup tanitilmaktadir.

Anahtar Kelimeler: Tehlikeli Madde Tasimaciligi, Cografi Bilgi Sistemleri

To my parents and my sister…

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

In today's world, one of the most fundamental needs to provide the quality of our lives is hazardous materials. Hazmats, or dangerous goods, include explosives, gases, flammable liquids and solids, oxidizing substances, poisonous and infectious substances, radioactive materials, corrosive substances and hazardous wastes. Hazardous materials are processed in petroleum refineries, chemical processing plants and nuclear power plants. Furthermore, the transportation of hazmats from industrial facilities to the consumers or other facilities has been very common. Dangerous goods can be extremely harmful to the environment and to the human health, since exposure to their toxic chemical ingredients may lead to injury or death of plants, animals and humans.

It is estimated that over 40 million tons of hazardous materials are consumed and circulated annually in Turkey. This poses a great risk over the society and the environment as we infer from previous hazmat transportation accidents that have occurred in Turkey as well as in many other countries in the world. Therefore, hazmat transportation problem has become a very delicate issue, by the strict influences and requirements of the regulators (governments), environmentalists, public and the media. Moreover, we see that the problem has been a matter of responsibility for many hazmat producers, suppliers and carriers in the recent years.

Chapter 1. INTRODUCTION

Hazmat logistics has been a very active area of research: *Transportation Science* devoted an issue to hazmat logistics in 1991 and *Transportation Research Record* published two special issues in 1988 and 1989. The major concerns in hazmat logistics are the risks associated with them, the spatial distribution of risks, and the costs incurred during the management process.

In this study, we bring solutions to hazmat transportation problem, both from a government's and a hazmat supplier's point of view, specific to Turkey. We focus on petroleum products, as they constitute a major position of the hazmat transportation in Turkey.

In the next chapter, we give the status of hazmat transportation in Turkey. Hazmat transport regulations, the magnitude of the petroleum products and previous hazmat accidents in Turkey are the main topics of this chapter. In Chapter 3, we present the state-of-the-art literature in hazmat transportation. We give a brief summary of the previous studies in four sections for convenience including the explanation of the risk definitions that were used in the previous models. Chapter 4 consists of the definition of the problem in this study. We present the structure of the problem with all parameters, and state the problem in detail within Chapter 4. In Chapter 5, we present the solution methodology that we employ to solve the problem. Then we discuss our computational results in the remainder of this chapter. In Chapter 6 we approach the hazmat transportation problem from a completely different point of view. We propose solutions to "Hazardous Network Design Problem" by making use of three heuristics we developed. Finally, we discuss the results of all heuristics at the end of Chapter 6. To give a brief summary of our study, we present our conclusions, contributions and future research directions in Chapter 7.

Chapter 2

HAZARDOUS MATERIALS TRANSPORTATION IN TURKEY

Turkey, as a developing country, is on her way to become an industrialized country for many years. As a natural result, the use of hazardous materials has been a priority not only because of the requirements of industrialization but also because of the lifestyle we pursue in our daily life.

Among hundreds of hazmat types, over 28 million tons of petroleum products, which can be considered as hazardous materials, are consumed and circulated in the country every year. Expert ideas from State Statistics Institute certify that hazardous petroleum products such as; Refinery fuel gas, LPG, naphtha, gasoline, jet fuel, solvent, diesel oil, asphalt and fuel oil constitute the majority (above %80) of total hazardous materials in Turkey. As the magnitude of petroleum products in Turkey is significant enough to incorporate in a study, we focus on petroleum products, which can be considered as hazardous materials.

The principal way of shipping hazardous materials is highway transportation in Turkey. There are government institutions which deal with the Regulation of Transportation of Hazardous Materials in Turkey. In 1976, General Directorate of Highways has published the Regulation of Transportation of Hazardous Materials on Highways. The regulation consists of the following:

General definition of carrying hazardous materials and transportation types

Transportation vehicles and their special containers & tanks

Classification of Hazardous Materials

General Transportation conditions (loading limits of the vehicles, vehicle specifications and attributes, usage of special signs to distinguish vehicles etc.)

This regulation is still valid but said to be obsolete by both the government and the industry.

There is also an international agreement, published by United Nations Economic Commission for Europe, called ADR-European Agreement, concerning the International Carriage of Dangerous Goods by Road. This regulation may be regarded as a more extended & updated version of Turkish Hazmat Transportation Regulation. In 1994, Turkish Ministry of Transportation has appealed ADR to the Parliament in order to become party of this agreement however, the corresponding commission of the Parliament is still working on the proposal.

In addition to the hazmat transport regulations, there is a general traffic regulation in Turkey. Even though it is for general transportation, it does include hazmat transportation. There is a special topic for commercial drivers:

Commercial drivers can not drive more than 9 hours in total and non-stop 5 hours in a 24 hours period,

In case of a non-stop five-hour drive, the driver must take at least one break of 30 minutes,

Hazmat trucks can not exceed the speed limits of 30 km/hr in urban areas, 50 km/hr in rural areas, and 60 km/hr on the motorways.

Turkish Ministry of Energy and Natural Resources determines policies concerning energy and natural resources. Turkish petroleum industry activities in terms of exploring, refining and pricing of the petroleum products, issuing import and export permits and all other legal, economical and engineering issues have to be approved by this office.

There are three major oil producer & suppliers operating in Turkey; two of them owned by foreign investors and the other is a formerly state owned company. On the other hand there are five petroleum refineries currently supplying these petroleum companies. The refineries will be covered in the next section more extensively.

2.1 Petroleum Refineries in Turkey

There are five petroleum refineries in Turkey, which produce & supply petroleum products to the fuel companies and hundreds of gas stations in the country. In Turkey, 27 million tons of crude oil is refined annually, where 23.8 million tons of this crude oil is imported from several countries such as Saudi Arabia, Iran, Iraq, Libya and Egypt.

	Crude Oil Refined Annually (Million-Tons)
TÜPRAS – Izmit (Derince) Refinery	8.5
TÜPRAS – Izmir (Aliaga) Refinery	11
TÜPRAS – Kirikkale Refinery	3.2
TÜPRAS – Batman Refinery	0.86
ATAS – Mersin Refinery	3.5

Table 2-1: Annual Amount of Refined Crude Oil in Turkish Refineries

Table 2-1 indicates the petroleum refineries, currently producing & supplying petroleum products in Turkey. Refineries in Izmir and Izmit, which belong to TÜPRAS, and ATAS – Mersin Refinery, which is owned by foreign companies (BP, Shell, and Conoco), are located on the coasts. Kirikkale Refinery, one of the refineries, which is located on land, is fed with crude oil flowing through the pipeline that originates from the southern part of the country. Batman Refinery has its own oil wells.

The location of the refinery plants, the strategic position of industrialized zones and the population density difference of west and east parts of Turkey indicate that the majority of petroleum products is consumed in the west and mid parts of the country. Hence we may expect the hazmat traffic density in the west and mid part of Turkey to be more than the eastern part. The hazmat traffic density however constitutes a disadvantageous situation, as we infer from accident statistics and hazmat accident news in the national newspapers.

2.2 Hazmat Accidents in Turkey

In Turkey, most of the petroleum products are transported on the highways, which brings out a potential risk over the society and the environment. According to State Statistics Institute data (1999), in Turkey there are 52 fatalities and 1244 injuries per 100,000 vehicles. Again per 100,000 vehicles there are 15 fatalities and 1030 injuries in Germany and 13 fatalities and 1348 injuries in Japan.

Statistical data also indicates that there is a decrease in the number of fatalities in traffic accidents in recent years in Turkey. Although the number of fatalities has decreased by 1600 people between 1990 and 1999, the number of accidents has increased from 115,295 to 438,338.

Table 2-2a indicates a more detailed Accident and Road Traffic data for various countries:

	A	B	C	D	E	F	G	H
JAPAN	850,363	10,372	77,810,000	126,686,000	13	1348	8	828
GERMANY	395,689	7,772	50,609,000	82,037,000	15	1030	9	635
HUNGARY	18,923	1,306	2,706,000	10,092,000	48	912	13	244
KOREA	275,938	10,756	13,083,000	46,430,000	82	3080	23	868
SWEDEN	15,834	580	4,607,000	8,854,000	13	477	7	248
TURKEY	63,515	4,596	8,837,403	64,385,000	52	1244	7	171

Table 2-2a: Road Traffic and Accident Data Comparisons for Various Countries (1999)

A: # of Accidents		E: # of Fatalities Per 100,000 Vehicle
B: # of Fatalities		F: # of Injuries Per 100,000 Vehicle
C: # of Vehicles		G: # of Fatalities Per 100,000 People
D: Population		H: # of Injuries Per 100,000 People

Table 2-2b: Key to Table 2-2a

There has been 2623 hazmat accidents, which involve only tankers in 1999. According to the consequence of the accidents, there is a total fatality of 146 people where 62 of them were drivers, 68 of them were passengers and 16 of them were third party.

There are many examples of hazmat accidents that took place in Turkey in the past decade. All of them were carried to headlines in the national newspapers, in many of them 10-50 people were killed per accident. Some important hazmat accidents, which may be classified as “serious incidents” are the following:

1. Bus crashed petroleum tanker in Samsun in 1998; resulted with 20 fatalities; fuel leakage out of the tanker caused explosion.

2. LPG loaded vehicle crashed a bus in Eskisehir in 1998; resulted with 10 fatalities and 20 injuries.
3. Diesel loaded tanker crashed a minibus on Sanliurfa-Birecik road in 1998; resulted with 20 fatalities.

Accidents involving hazmat vehicles pose great risk for the society and the environment however, very few hazmat accidents cause a catastrophic event. If a hazmat vehicle involves an accident that leads to a catastrophe, this accident is called an “incident”. According to this definition, in case of a hazmat transport, an undesirable event is an accident that results in the release of a hazardous substance, which is usually a big spill or a blow-up (Erkut and Verter 1998). Undesirable event mentioned here is usually expressed as the number of fatalities that are involved with the accident. However there are also other ways of expressing an undesirable consequence such as economic losses, environmental damage etc.

Although there have been a significant number of hazmat accidents in Turkey, there were few accidents, which fortunately did not lead to an incident. For instance, in 1997 a hazmat truck caught fire on the highway in southern part of Turkey, while it was on the road, without any external effect. The accident zone was closed to traffic for many hours and only after many hours, firemen could manage to extinguish the fire. In another case, a truck crashed into a building in a residential zone in Istanbul at midnight, which could have been a disaster in the metropolis.

In the last ten years, Turkish Government brought many precautions into force to prevent road accidents. These regulations include more effective punishments and extra control points on highways. In effect, there is a decrease in the number of fatalities in year 1999, however the accident frequency data still indicates that our annual accident frequency remains high above the average, among many countries in the world.

Chapter 3

STATE-OF-THE-ART IN HAZMAT TRANSPORTATION

The problem of transportation of hazardous materials has been analyzed since the beginning of 1980s (List et al. 1991). Researchers developed models to define risk and bring solutions to hazmat transportation problems. We categorize the hazmat literature into four groups for convenience:

1. Risk definitions that were used in the hazmat literature
2. Routing models that were determined for hazmat transportation problems
3. Different approaches that were brought to the hazmat literature in recent years
4. Decision-Maker structures in the hazmat literature

Before we go through the next sections, we define some preliminary basics, which will be used in the remainder of this study.

We represent the existing highway system by a network $G=(N, A)$, where N denotes the set of nodes and A denotes the set of highway links that connect the nodes. A shipment of hazmat type m is transported across G from its origins ($o \in N$) to its destinations ($d \in N$).

3.1 Definitions of Risk in the Hazmat Literature

Modeling hazmat transportation problem aims to mitigate the risk that is exposed to the public and environment, however employing a reasonable and justifiable risk definition is another matter of consideration. Hence, there are different definitions of risk in the hazmat literature.

Earlier studies, which began with risk assessment of transporting hazardous materials, mostly dealt with determining a definition for "risk". Erkut and Verter (1995) reviewed hazardous materials logistics extensively and provided a detailed review of risk models that were used in previous studies. They examine the idea behind the risk definitions that were used until 1995.

Saccomanno and Chan (1985) define risk as the **likelihood of an accident** and measure it by incorporating the relative frequency of truck accidents and employing two types of random environmental influences (stochastic and deterministic) which are expressed in probabilistic terms. Stochastic influences arise as pavement surface condition (wet, dry etc.) and visibility while deterministic influences are road design characteristics (speed limits of different types of roads), which are expected to affect general accident rates.

To give a formal definition of this risk model, let P denote a path between an origin-destination (*o*-*d*) pair and p_s denote the probability of having an incident on a unit road segment on link s. The following is a basic assumption in the hazmat literature:

<u>*Assumption 1*</u>*:* p_s is constant on link s.

It is possible to divide a link that violates this assumption into sub-links, each with constant incident probability. Thus the probability of having an incident on unit segment k of link s is $(1-p_s)^{k-1}p_s$. Let $p_s^{'}$ denote the probability of having an incident on link *s* and l_s denote the length of link *s*. Observe that,

$$p_s^{'} = p_s + (1-p_s)p_s + (1-p_s)^2 p_s + \ldots + (1-p_s)^{l_s-1} p_s$$

$$= \sum_{i=0}^{l_s-1} (1-p_s)^i p_s$$

Given that the incident probabilities are in the order of 10^{-8} (for North America), the following assumption is quite common in the hazmat literature (Verter and Kara 2002):

<u>Assumption 2</u>: $p_s^i \cong 0$ for $i > 1$.

Observe that, now $p_s^{'} = l_s p_s$. Without loss of generality, let $P = \{1,2,\ldots,r\}$. The **Incident Probability** of a single shipment on path P is:

$$p_1^{'} + \sum_{s=2}^{r} \prod_{k=1}^{s-1} (1-p_k^{'}) p_s^{'}$$

Based on assumptions 1 and 2, the incident probability of path *P* simplifies to:

$$\sum_{s=1}^{r} p_s^{'} = \sum_{s=1}^{r} l_s p_s$$

Pijawka et al. (1985) also used hazmat accident probability to define risk in the same manner. For each route, they calculated the number of accidents by a hazmat carrier expected per year by multiplying the accident rate by the number of total miles of exposure in the hazmat transport.

On the other hand, Abkowitz et al. (1992) employed the same risk definition with the name of *Release-causing Accident Likelihood*. They derived the accident rates based on truck accident rates involving hazmat movements that appear in the U.S. highway network. Release probabilities are based on various container configurations and highway locations.

Population exposure is another definition of risk in the hazmat literature. According to this risk definition, the area within l-neighborhood of a point c on link (i,j) is under potential risk (Batta and Chiu 1988), where l varies for different hazmat types.

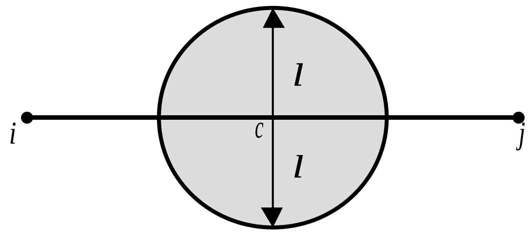


Figure 3-1: Population Exposure of a Single Truck at Point c on Link (i,j)

The idea behind population exposure is assuming that the probability of death for an individual within l-neighborhood of a point c on link (i,j) due to the incident is one (Erkut and Verter 1995).

A *danger zone* of a single hazmat incident is defined with a circle of l radius, which is centred at the position where the accident takes place. l, is the impact radius of the hazmat that is being carried, which may change according to the hazmat type. The *exposure zone* of a link is the union of the danger zones along that link. Finally, the number of people within an exposure zone is the *population exposure* of the corresponding link. This may also be regarded as a truck drawing a “risk corridor” on both sides of a link as it moves along that link.

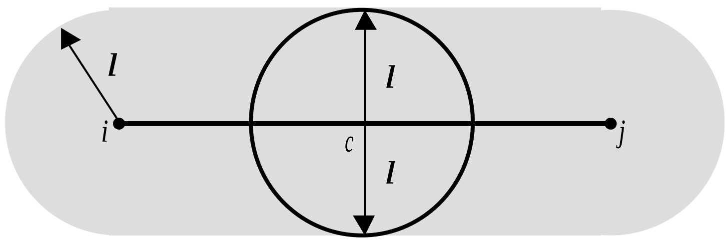


Figure 3-2: Population Exposure of a Single Truck on Link (*i,j*)

Representation of the spatial distribution of population, within the geographical region of concern, is another critical issue in hazmat transport risk assessment. Recently Erkut and Verter (1995) proposed a model, in which population centres are represented as polygons rather than points. Let d_s denote the population density around a unit road segment on link s. The following is a common assumption in the hazmat literature:

<u>*Assumption 3*</u>*:* d_s is constant on link *s*.

Let $C_{s,m}$ denote the number of people living within danger zone around link *s*, and λ_m denote the impact radius of hazmat type *m*.

$$C_{s,m} = \pi \lambda_m^2 d_s$$

Denote the exposure zone of hazmat type *m* around link *s* as $EZ_{s,m}$. Let

$\overline{C}_{s,m}$ represent the number of people living in $EZ_{s,m}$ (Observe that, when link s is a straight line $\overline{C}_{s,m} = d_s(2l_s\lambda_m + \pi\lambda_m^2)$).

The population exposure on path P is:

$$\sum_{s=1}^{r} \overline{C}_{s,m}$$

When the links are not straight line, then we need to calculate the area within the exposure zone by integration, which may be time-consuming. There is however an easier way of calculating population exposure when Geographical Information Systems (GIS) tools are utilized.

Classic or traditional definition of risk arises as Societal Risk (accident probability multiplied by the number of people in the danger zone) in the hazmat literature. Several authors preferred to use this risk definition as it combines both incident probability and number of people exposed, which in most cases become more effective and justifiable.

Based on the assumptions mentioned above, the societal risk of path P is:

$$\sum_{s=1}^{r} p_s^{'} C_{s,m} = (\sum_{s=1}^{r} l_s p_s d_s)\pi\lambda_m^2$$

Pijawka et al. (1985) named Societal Risk as *Population-at-Risk Factor* and multiplied hazmat accident probability by Population at Risk/Mile.

Abkowitz et al. (1992) also applied the traditional risk definition in their study as it is consistent with the definition of risk used in federal routing criteria guidelines by U.S. Department of Transportation. What distinguishes their application is that they used Geographical Information system (GIS) in calculation of population exposed, in their study.

Alp (1995) modeled the hazmat transportation problem with the traditional definition of risk, however he made use of fault tree and event tree analysis to determine hazmat accident probabilities. A fault tree shows how a system can fail whereas an event tree is used to identify and quantify possible outcomes of an event.

There are two other risk definitions that were used in the hazmat literature: Perceived Risk (Abkowitz et al. 1992) and Conditional Risk (Glickman 1991). However, Erkut and Verter (1998) argued against using the conditional risk and perceived risk models since they violate three axioms that need to be satisfied by a risk model for hazmat transport. These axioms are: monotonicity axiom for path evaluation models, optimality principle for path selection models and monotonicity axiom for risk models.

3.2 Routing Models in the Hazmat Literature

In the hazmat literature, we observe that prevailing studies modeled the routing problem with a single objective which in most cases appear to be the minimization of the total risk exposed to the public.

List et al. (1991a) surveyed an extensive research on hazardous materials transportation considering Risk Analysis, Routing/Scheduling and Facility Location. In their study, it has been stated that the earliest studies dealing with multiple objectives belong to Shobrys (1981) and Robbins (1981).

Saccomanno and Chan (1985) also dealt with multiple objectives to solve the hazmat transportation problem. The authors discussed three distinctive routing strategies for the road transportation of hazardous materials which are; minimize total risk (three types of damage which are represented as dollars, number of fatality & injuries and zone impact), minimize the accident likelihood (relative frequency of accidents on selected road links) and minimize operating truck costs. Each routing strategy was applied to the Toronto road network, and recommended safe routes were analyzed for cost-effectiveness for a wide range of environmental conditions. Two important aspects emerge from the cost-effectiveness analysis: (a) minimum risk routing strategy produces net economic gains in the form of enhanced safety, and (b) significant trade-offs are of fundamental concern to the implementation of this type of safety enhancement strategy for the transportation of hazardous materials.

Abkowitz at al. (1992) considered five objectives and determined two extreme route results, i.e. determination of minimum cost and minimum risk routes. Furthermore, the authors examined the routes that could provide intermediate solutions by assigning weights (between 0-1) to the objectives of risk and cost. However, very few combinations were presented in the study.

Alidi (1996) modeled the problem of petrochemical waste management with eight objectives. The solution methodology is goal programming where goal priorities were determined via Analytical Hierarchy Process (AHP) to be applied by the decision-maker. The author provided a hypothetical example in the study.

Iakovou et al. (1999) and Iakovou (2001) present the development of a strategic multiobjective network flow model, allowing for risk analysis and routing with multiple commodities, modalities (vessels) and origin-destination pairs. Two objectives are involved in the problem; minimization of the total cost and total risk. Risk was defined as the spatial empirical probability distribution of past spills along with the total dollar cost estimate of damage inflicted by each specific historical spill. Risk calculation was supported by a geographical information system (GIS). The required data contains the location of spill, the amount of the spill, the type of the substance spilled, the date and time of the release, wind time series, and the extent of the cleanup of the spill. The solution process was initialized by two solutions obtained from two problems namely, minimization of cost and minimization of risk. Once the non-dominated basic solutions are determined, the decision-maker is asked to identify a linear combination of the two objectives. The development of an interactive solution methodology is also presented with its implementation via a World Wide Web-based software package. An illustrative application for the Gulf of Mexico is also provided.

There are also some studies in the hazmat literature that consider hazmat transportation problem together with a location aspect.

Revelle et al. (1991) considered the hazardous waste management problem by incorporating routing and siting components with two objectives: the minimization of total transportation burden and the minimization of total perceived risk. Transportation burden was accounted in ton-miles and perceived risk as tons-past-people or people-tons.

List et al. (1991b) presented a combined routing/siting model for making routing decisions and siting decisions for waste treatment facilities. Risk, cost and risk equity is considered jointly in a multi-objective framework, seeking pareto optimal solutions that combine them. A simplified form of the model was applied to the Capital District of the State of New York. The case study considers a single type of hazardous waste.

Current et al. (1995) proposed a multiobjective mixed-integer model to minimize risk, equity and cost of locating facilities and transportation throughout a given network. Five objectives are involved in the study including minimization of; a) the total transportation risk, b) risk generated from locating a facility at a particular node, c) maximum transportation exposure faced by any individual, d) minimization of the maximum facility risk faced by any individual and e) minimization of the total transportation, facility and operating costs of the system. In the study, 12 non-inferior solutions were generated using the weighting method.

Most recently, Giannikos (1998) addressed hazardous materials transportation and location problem with a multiobjective model. Objectives employed in this study are the same with the objectives that are used in the hazmat literature. The author use goal programming to model the problem, where a target is specified for each goal so as to find a solution that comes as close as possible to these targets. To mitigate the unsatisfactory results of the weighted goal programming model, the author changed the assumption of "any marginal deviation is of equal importance no matter how distant it is from a target" to "any deviational variable with respect to its target value is penalized according to a constant marginal penalty".

In almost all studies in the hazmat literature there have been single/multi objective models to be solved individually or simultaneously. We observe that there is an unavoidable multiple objective case to be considered in many hazmat transportation problems. Regardless of the decision maker type, which will be covered more extensively in section 3.4, there is a multiobjective situation in many hazmat problems.

3.3 Different Recent Approaches in the Hazmat Literature

Since the hazmat transportation models, risk definitions and solution methodology could not respond the requirements of real life problems, approaches that are more accurate and useful modifications were brought into the hazmat literature in recent years.

An early distinguished study by Erkut (1995) discusses about a previous model which finds hazardous materials routes proposed by Sivakumar et al. (1993). Erkut stated that the model violates a monotonicity axiom for path evaluation and selection models. Small numerical examples were given in order to demonstrate the violation results in the selection of solutions that may be undesirable in the hazardous materials routing.

Erkut and Verter (1998) question two traditional assumptions in the hazmat literature. One basic assumption is that, residents living inside a circle at an incident site, with a given impact radius, will experience the same undesirable consequence, and residents living outside the circle will experience no undesirable consequence. According to the authors, this assumption is inevitable since the data necessary for an accurate assessment of risks to humans do not exist for many hazmats. As long as one is interested in the relative risks of different paths, the danger zone approximation will provide valid comparisons.

The second basic assumption is that the products of incident probabilities equal to zero, which is Assumption 2 mentioned in Section 3.1. It was shown that this approximation does not result in significant inaccuracies in the estimation of incident probabilities.

In many multiobjective hazmat transportation problems, it is necessary to provide a set of alternative paths. This is due to the case of a possible infeasibility of the “best” route(s) (road construction or certain roads closed to hazmat traffic temporarily) that is selected by the carrier.

Akgün et al. (2000) considered the problem of finding a number of spatially dissimilar paths between an origin and destination. They state that a number of dissimilar paths can be useful in solving capacitated flow problems or in selecting routes for hazardous materials. A critical discussion of three existing methods; Iterative Penalty Method (IPM), Gateway Shortest Paths (GSPs) and Minimax Method is offered for the generation of spatially dissimilar paths. Computational experience using these methods and the advantages and disadvantages of each method are also reported. They concluded that each of three existing methods has a number of drawbacks. An alternative solution technique is proposed as a p-dispersion problem. If a large number of suitable candidate paths can be generated, then the application of the p-dispersion model is said to be an effective way to solve the problem.

A more recent study that were brought into the hazmat literature by Kara and Verter (2000) is distinguished from the rest of the hazmat literature. The study approaches to the hazmat transportation problem from a regulator’s point of view, which makes use of closing certain links of the road network to hazmat transportation in order to mitigate the transport risk. Kara and Verter (2000) demonstrated each Decision-Maker's (DM) dependent situation in a unique way in their study.

According to this approach, the regulator identifies the allowable links in the network for hazmat transportation to mitigate the risk associated with the hazmat transportation. The carriers try to maximize their utility, namely minimize their transportation costs by selecting the shortest routes in the remaining network. Governments do not have the authority of determining the routes for the carriers, but they can as well close certain links in order to indirectly influence the carriers to "safer" routes. Kara and Verter proposed a bilevel model, which has two different objectives from Government and Carrier's point of view respectively.

3.4 Decision Maker Structures in the Hazmat Literature

We observe that there are two main Decision-Makers (DM) that were used in the hazmat literature: the regulators (the government) and the hazmat carriers.

As the hazmat transportation problem emerged from mitigating societal and environmental risk, the problem was modeled from a regulator's point of view in most of the studies. The main attribute of this DM is that a regulator has the only objective of minimizing risk and does not hold the authority of dictating certain routes to hazmat carriers. Studies until Kara and Verter's (2000) new approach tried to solve the hazmat transportation problem from regulator's viewpoint, however the justification of the previous models were questionable.

One important remark in the hazmat maritime transportation is that a maritime regulator (coastal guard) holds the jurisdiction of dictating certain routes to the hazmat carriers (Iakovou et al. 1999).

The second DM type represents the hazmat carriers. The basic assumption with this DM is that a hazmat carrier will base its routing policy on selecting the paths which minimize the total transportation cost. Therefore, the objective of this DM happens to be minimizing transportation costs.

To sum up, we can conclude that most of the studies in the hazmat literature approach the problem from the regulator's point of view in the sense that the methodologies developed aimed at minimizing the risk (or some combinations). However, the actual shipments are done by carriers for whom minimizing the risk exposed to the people and the environment is not an issue unless they are forced to do so. There are however, some studies that suggested multiobjective models for the use of hazmat carriers, which were mentioned in section 3.2. With these two Decision-Makers, multicriteria approaches seem to be irrelevant since the DMs of the multiobjective model are two different DMs. To the best of our knowledge, none of the studies in the hazmat literature have identified or clarified this property.

During our analysis of hazmat transportation problem we observe that there is another type of DM in the hazmat transportation area, which has been neglected in the literature so far. In the next chapter, we will present the new DM together with its problem specifications.

C h a p t e r   4

PROBLEM DEFINITION

In the previous chapter, we have discussed the DM types that took place in the hazmat literature. In this chapter, we will introduce a new DM type, which we argue that it has been omitted in the hazmat literature. We conducted a joint research with one of the biggest petroleum companies in the country, Shell Turkey. Our new DM happens to be the “missing” DM in the hazmat literature who will use all these multicriteria type of approaches.

Before we go through our case study, we examine the structure of the company, as well as its jurisdictions and requirements.

4.1 Company Structure

Shell is the second largest petroleum products producer & supplier in the world with over $70 billion total fixed assets and the third largest oil company in Turkey. Shell has two main customer groups in Turkey:

1. Commercial customers, who purchase Shell products in bulks for their own business such as companies in agricultural, construction and transportation (aviation and maritime) industries.
2. Retailers, who constitute the largest portion of total Shell customers (%75). There are currently 575 retailers, namely gas stations throughout Turkey.

Shell Turkey supplies 2,000,000 tons of petroleum products annually where 1,500,000 tons are supplied to 575 gas stations. There is a variety of products which consists of:

1. Unleaded Gasoline-Extra
2. Diesel-Extra
3. Diesel
4. Gasoline
5. Gasoline-Extra
6. Unleaded Gasoline
7. LPG

There are eleven supply points currently serving Shell where, three of them are refineries and eight of them are terminal points which are usually located on the coasts. Figure 4-1 indicates the location of the eleven supply points.

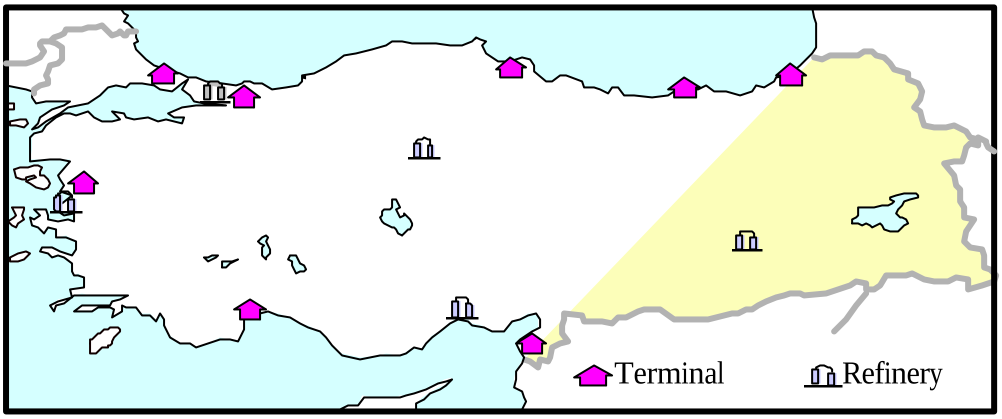


Figure 4-1: Supply Points of Shell in Turkey

Shell customers have two delivery options for the products they purchase.

They can either pick up their purchase by using their own trucks and drivers or send an order to Shell to do the delivery for them. The details about these transport modes are as follows:

1. **Customer own pick-up:** Most of Shell customers (%70) have their own tanker-trucks. These trucks must suffice the requirements of Turkish Hazardous Materials Transport Regulation and must have a safe pass sticker, after being approved by Shell. Gas station owners, who prefer to use their own trucks for product shipments, transport them at their own risk. Shell is not responsible for any risk in this transportation mode.
2. **Shell Fleet:** Shell provides shipping service to its customers since 1998, with three subcontractor transport companies. The structure of the business is as follows:

Investments such as trucks, hiring drivers etc. belong to the subcontractor transport companies, namely the hauliers. The fleet consists of 43 trucks of various sizes, which have been assigned to nine supply points by Shell to serve between various *o-d* pairs. Although there are eleven supply points, Shell assigned its fleet to nine of these supply points. Table 4-1 indicates the supply points and the number of trucks that are assigned to these supply points by Shell.

A typical delivery process is as follows: Hauliers,

take the orders and the routes to follow

are told about the specific road links to avoid & to follow in special occasions[1] and;

are given the delivery time[2] (interval) & place by Shell.

Supply Point	Type	# of Trucks Assigned
1. Ýstanbul-Ambarli	Terminal	5
2. Ýzmit-Derince	Terminal	13
3. Ýzmir-Aliaga	Terminal	8
4. Antalya	Terminal	3
5. Samsun	Terminal	1
6. Trabzon	Terminal	3
7. Hopa	Terminal	1
8. Mersin	Refinery	4
9. Kirikkale	Refinery	5
10. Ýskenderun	Terminal	-
11. Batman	Refinery	-

Shell Fleet (points 1–9); Customer Own Pick-up (points 1–11)

Table 4-1: Supply Points of Shell

Shell pays the hauliers on the basis of per kilometers travelled and fixed costs, which may be regarded as depreciation costs. The fare of per kilometers traveled varies for each haulier, since three of the hauliers are independent companies.

To evaluate the performance of the hauliers and the drivers, Shell created two evaluation systems called Drivers' League (DL) and Hauliers' League (HL).

In HL, performance of each haulier is determined among particular weighted

[1] In case of an exogenous change (an accident or a closed road) within a specified route, the drivers are advised not to choose a tunnel as an alternative, but to follow a safer link such as a highway.

[2] Every gas station has a different receiving time interval of the purchased goods.

criteria such as the number of traffic accidents/month, average speed of a shipment, customer evaluations and haulier's monthly accident reporting performance. Evaluation in DL is in the same fashion, however there are other criteria such as; maintenance of the vehicles, fuel consumption and potential accident reports and "near misses" (a near miss is an accident that a driver is just about to involve).

There are some constraints for this transportation mode:

1. Shipments must be made within 24 hours
2. The tanks fixed on the trucks are physically divided into compartments of various capacities. No half-filled compartments are allowed due to security and economic reasons.
3. Multiple destinations for a shipment is not desired due to set-up costs such as paperwork, connecting the hoses to the trucks etc.

4.2 The Problem

Each haulier undertakes the consequences (all costs of a damage; economic loss of goods that are being transported and third party damages) of a hazmat transport incident. This situation calls for the following question as Shell is not responsible for economic losses in the hazmat transportation: Do we still have a hazmat transportation problem?

Yes. Although the cost of an incidence is taken care of by the hauliers, Shell does not totally ignore the risk exposed to public and the environment. There are some reasons:

1. Shell's way of doing energy business is in a responsible manner

2. The international structure of the company necessitates requirements such as HSE-Health Security and Environment policies
3. The fleet consists of Shell branded trucks, which means that Shell will be accused by public and media in case of an incident.

In addition to the transportation risk, Shell requires the transportation costs to be economically feasible as well since profitability is another important objective of the company. Thus, Shell wants to reduce the impact of a possible incident (minimize the risk exposed to public and environment), however keeping the transportation costs economically feasible is at least of equal importance.

Shell is the leader of the game and holds the jurisdiction. Hauliers' role here is like an "employee" of Shell because they do not hold the authority of making the routing decisions. When it comes to the costs associated with an incident, hauliers do care about it, because in case of an accident, they will have to cover all the loss instead of Shell.

This situation allows us to introduce a **New Decision-Maker**, which considers both objectives ("risk" and cost) that are not in mutual competition. The reason that we need to introduce a new DM is that, Shell's case does not fit in the DM structures that currently exist in the hazmat literature.

When we consider the traditional DM type that represents the hazmat carriers, we realize that Shell's situation does not correspond to this DM type. Because Shell is not the actual hazmat carrier in our problem. Considering the government as an alternative DM to suit Shell's case we again understand that Shell and its hauliers do not reflect the situation in that model. Regarding Shell and its hauliers' dependent relations to suit Kara and Verter's (2000) model, we observe that there is a basic property with the regulators that, a regulator can not dictate the carriers the paths to be followed. However, we already mentioned that Shell could actually dictate its sub contractor companies which routes to be taken.

The new decision-maker represents the companies producing and supplying hazardous materials but not doing the actual transportation business with the company facilities. The attributes of this new decision maker is the following:

1. The hazmat supplier company is not involved in the transportation business, but has them done by sub contractor firms.

2. Sub contractor firms determine the fares according to per kilometers traveled.

3. The hazmat producer company holds the jurisdiction over the sub contractor firms, such as being able to dictate the routes to be followed

4. The damage costs of hazmat transportation belong to the hauliers.

In summary, the hazmat transportation problem for Shell is, to minimize the total "risk" of the hazmat transportation in consideration with keeping the hauling costs economically feasible.

Chapter 5

SOLUTION METHODOLOGY

In Chapter 4, we argued that Shell's situation would not fit in the traditional DM type, which represents hazmat carriers. Moreover, we introduced a new decision maker type who does not actually do the hazmat transportation but hires sub contractor firms to do the transportation and undertake the cost of damage involved in the transportation business.

There are two objectives in the problem, which are to minimize total transportation risk and minimize total transportation cost. As these two objectives are to be considered simultaneously for Shell, we need to develop a model that contains both of the objectives.

Let us start from the simplest transportation problem where we have only one objective function without any constraints other than the flow balance. For a single *o-d* pair, it is obvious that the problem is a *shortest path problem,* which may have one or more optimal solution(s).

When we have the transportation problem with *n* distinct *o-d* pairs, we need to consider every single problem concurrently to get an optimal solution. This means that we have *n* independent shortest path problems to be solved simultaneously. The problems are independent since the only constraint set is the flow balance, so there are no coupling constraints. Hence, we can solve the transportation problem that consists of *n* different *o-d* pairs, by solving each problem as a single *o-d* shortest path problem separately or sequentially.

The problem we have in this study necessitates multicriteria consideration. Therefore, we need to incorporate multiple objectives into our problem, since single objective shortest path problem would not suit our DM's purposes.

The studies dealing with multiple objectives in the hazmat literature mainly focused on two methodologies in solving their problems: Weighting Method and Goal Programming.

List et al. (1991), Revelle et al. (1991), Abkowitz et al. (1992), Current et al. (1995) and Iakovou et al. (1999) calculated weighted combination of the objectives and solved the problem with the new weighted objective function. Alidi (1996) and Giannikos (1998) employed goal programming to tackle the multiobjective situation in hazmat transportation problem.

Goal programming necessitates expert user (DM) interaction such as, setting target values and ranking the targets in order of relative importance etc. Our discussions with company representatives regarding Shell's interaction to the problem led us to employ weighted combination of the objectives and present the corresponding results. Therefore, we use weighting method to solve the hazmat transportation problem in our study.

Let us consider single/multiple *o-d* pair(s) with multiple objectives in a transportation problem. These objectives are expressed in different units, e.g. total risk (number of people living around a link within a specified distance l) of the paths and total cost (length of a link) of the paths, both to be minimized. These two units of measure can be considered as individual arc impedances when a single objective shortest path problem is of concern. Aggregating these two arc impedances (after being normalized) will yield a new value f, which can be considered as a new arc impedance. Based on minimizing total "cost" of paths, *f*, we again have a single objective shortest path problem. For a particular aggregation of two arc impedances, we have:

$$f_{ij} = w_1 l_{ij} + w_2 r_{ij}$$

where, w_i is a weight, $w_i = [0,1]$ and $\sum_i w_i = 1$, to represent the importance of arc cost values l_{ij}, length of link (*i*,*j*) and r_{ij}, risk value of link (*i*,*j*). f_{ij} becomes the new arc impedance in our problem.

As both of the cost functions are expressed in different units of measure, we normalize the cost attributes of each link before the calculation of each weighted combination. To express both arc impedances in a common unit, we divided each value of an arc by the sum of the corresponding cost value. Namely,

$$f_{ij}^* = w_1 l_{ij}^* + w_2 r_{ij}^*, \text{ where}$$

$$l_{ij}^* = \frac{l_{ij}}{\sum_{(i,j)\in A} l_{ij}} \text{ and } r_{ij}^* = \frac{r_{ij}}{\sum_{(i,j)\in A} r_{ij}}, \ \forall \ (i,j).$$

A shortest path problem minimizing $\sum_{(i,j)\in A} f_{ij}^* X_{ij}$, where X_{ij} is 1 when link (*i*,*j*) is used in a path *P* and 0 otherwise, will find an efficient point on the trade-off curve.

The problem is however to find the "best" combination of l_{ij}^* and r_{ij}^* that meets the DM’s requirements and goals. Therefore, we present several weighted combination results to the DM to decide which combination best suits their purposes. Previous methodology of solving *n* independent shortest path problems is still valid for every weighted combination.

5.2 Implementation

We have a series of shortest path problems with multiple objectives for various *o-d* pairs. The best way to solve the problem is to use Geographical Information System (GIS). GIS enables us to represent the *o-d* pairs on their accurate locations and calculate the arc impedances easily.

We used ESRI’s ArcView GIS 3.1 software package to calculate arc impedances. Population centers are represented using polygons, which illustrate real life situations better than in point representation of the population centers (Erkut and Verter 1995). We use a digitized population center census division map of Turkey (67 cities), which is available on ESRI’s web based library. We also obtained a digitized highway map of Turkey from ISYAM. For each link, we calculated the length in kilometers and the risk (population exposure) values using GIS tools.

We have a 670-arc and 499-node network, which is the highway network of Turkey. The (*o-d*) shipments are between origins *o* = {Aliaga (Ýzmir), Ambarli (Ýstanbul), Derince (Ýzmit), Kirikkale, Trabzon, Samsun, Hopa (Artvin), Atas (Mersin), Antalya} and 562 destinations, which are located on their exact geographical positions.

We focus only the shipments made by Shell fleet in 2001, as Shell is not responsible for the customer own pick up transportation mode. There is a total of 1582 shipments made by Shell Fleet, which equals to 586,000 tons of petroleum products/year. However, we focused only the shipments that are more than a truck in a year. Therefore, we have 562 shipments of various sizes. This equals to 502,988 tons of petroleum products over a year.

The number of shipments from nine supply points is as follows:

ORIGIN	# of Shipments	Demand (tons)	Truck Equivalent (Truck Cap: 35 Tons)
ALÝAGA (ÝZMÝR)	108	114,897	3334
AMBARLI (ÝSTANBUL)	50	115,795	3331
DERÝNCE (ÝZMÝT)	144	151,975	4409
KIRIKKALE	85	24,592	741
TRABZON	23	9,015	267
SAMSUN	34	13,907	413
HOPA (ARTVÝN)	23	16,786	488
ATAS (MERSÝN)	52	27,952	823
ANTALYA	43	28,067	820
TOTAL	**562**	**502,988**	**14,626**

Table 5-1: Demand Distributed to Different Supply Points (2001)

We use **Population Exposure** as our risk measure. We determined ***l*** to be 800 meters, as Transport Canada requires evacuation of people residing within 800 meters of an incident site when petroleum products are involved (Verter and Kara 2002). The impact radius is the same for all hazmats we studied. The types of hazmats we have in our study are Diesel-Extra, Diesel, Gasoline,

Gasoline-Extra, Unleaded Gasoline, and Unleaded Gasoline-Extra.

Our computations are based on solving several groups of shortest path problems for two different arc impedances and their combinations. A *Minimum Length Path* (MinLength) is the path that is determined based on selecting a shortest path in terms of the kilometers traveled. A *Minimum Risk Path* (MinRisk) is the path, which is determined based on selecting a path that poses the least risk to the public and the environment.

We determined Minimum Risk and Minimum Length paths for each shipment sequentially. When routing is based on selecting shortest paths, total path length results of *Minimum Length Path* solutions constitute a lower bound for the total path length of all shipments. On the other hand total path risk results of *Minimum Risk Path* solutions constitute a lower bound for the total path risk of the shipments when routing strategy is based on minimizing path risk. Besides these two extreme case results, we also determined intermediate results, which come from the weighted combination of the risk and cost functions.

We used Dijkstra Algorithm implementation provided in the Network Analyst 1.b extension of ArcView GIS 3.1 in our shortest path calculations.

5.3 Computational Results

For a particular routing criterion, we have two results to be compared by the DM in order to make a decision. The first one is the total risk of a path and the second is the total length of a path. For a particular shipment, a Minimum Length and a Minimum Risk Path are depicted in Figure 5-1.

In Figure 5-1, observe that the Minimum Length path is 356 km. and exposes risk to 49,290 people. Same shipment but with different routing criterion, Minimum Risk path has a length of 379 km. and population exposure of 47,273 people.

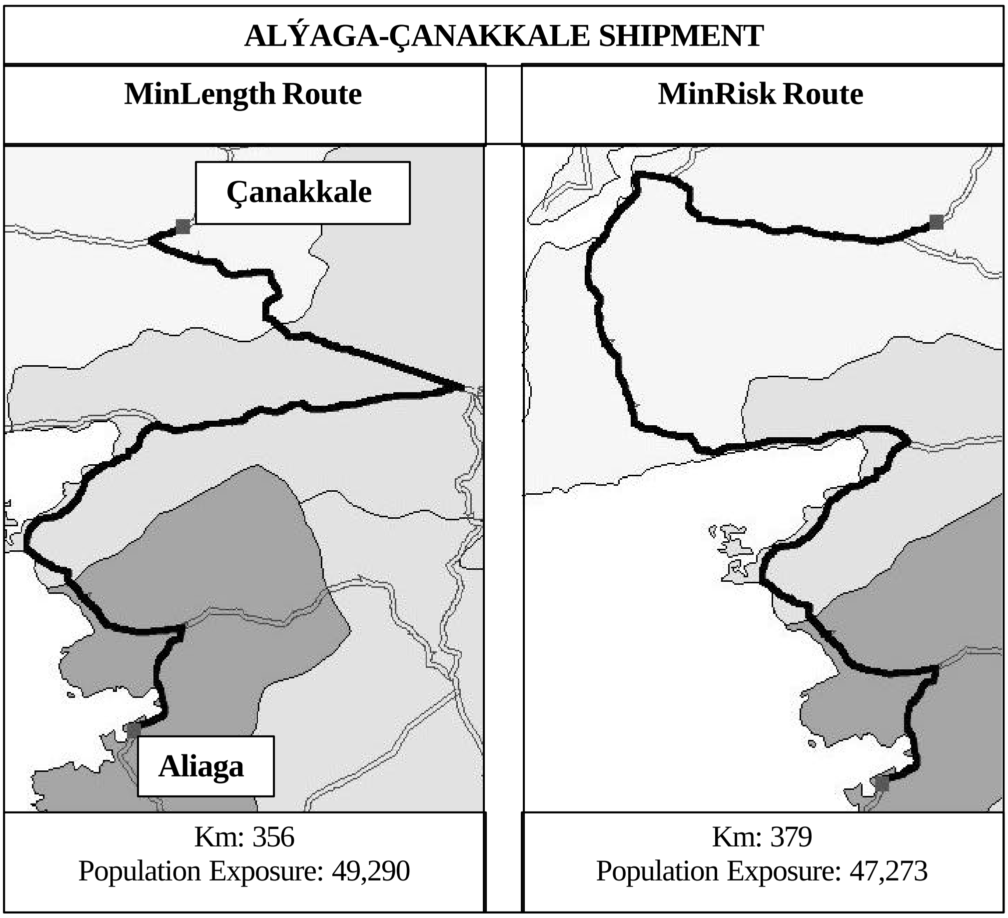


Figure 5-1: Aliaga-Çanakkale Shipment

These results illustrate the cost and the exposure of a single-truck. However, the amount of this particular shipment is 56 trucks/year, so we incorporate the cost and the exposure of every truck to get a meaningful result. For each supply point, the corresponding number of trucks of each shipment is multiplied by every shortest path result. Hence, we have two measuring units, which are *Truck-People* for the total population exposure and *Truck-Km* for the total cost of the paths.

Finally, two extreme case results (Minimum Risk and Minimum Length Paths) and an equally weighted combination result for all 562 shipments originating from nine supply points are as follows:

Supply	**Minimum Risk**		**Minimum Length**		**%50 Risk-%50 Length**	
	Truck People	**Truck Km**	**Truck People**	**Truck Km**	**Truck People**	**Truck Km**
ALÝAGA	193,160,611	646,001	195,718,341	626,294	193,716,312	629,703
AMBARLI	402,953,384	184,834	403,451,512	182,881	402,954,936	184,446
DERINCE	338,377,090	665,397	341,032,680	628,517	339,726,605	633,395
KIRIKKALE	32,728,918	218,624	35,521,938	200,260	33,459,920	204,407
TRABZON	6,996,427	48,249	7,317,735	38,102	7,087,512	38,983
SAMSUN	18,612,010	191,962	20,662,113	138,744	20,554,890	139,227
HOPA	4,043,449	72,832	6,778,629	55,907	4,045,563	67,277
ATAS	39,382,299	233,509	40,245,728	228,687	39,687,660	229,331
ANTALYA	8,878,217	88,956	8,942,109	88,208	8,942,109	88,208
TOTAL	**1,045,132,405**	**2,350,364**	**1,059,670,785**	**2,187,600**	**1,050,175,507**	**2,214,977**

Table 5-2: Minimum Risk, Minimum Length and %50Risk-%50Length Results

There is a significant decrease in the total transportation risk, which is equal to 14.5 million truck-people, when Minimum Risk is the routing criterion instead of Minimum Length. There is a trade-off, which requires total transportation cost to be increased by 162,764 truck-kms, which is total extra kms to be made by Shell fleet in a year.

Among 562 shipments, 379 shipments have similar paths, namely 379 shipments have the same path results for either minimum risk or minimum length routing consideration. To give a ratio, only %33 percent of the shipments have dissimilar path results. This also corresponds to 1531 trucks among 14,626 total trucks.

The shipments, originating from different supply points, differ in terms of their total path risk and total path cost results. For instance, the difference of total path risk of MinLength and MinRisk results from supply point AMBARLI is 498,128 truck-people and the corresponding trade-off is 1953 truck-kms. However, the achievement and the trade-off for the shipments from HOPA are 2,735,180 truck-people and 16,925 truck-kms. Despite the fact that the annual demand from supply point HOPA is only %14 of the annual demand from supply point AMBARLI, there is a significant difference between the achievement and the trade-off values of these two supply point originating shipments. This is due to the following reasons:

When we compare the extreme case results for each supply point, we see that geographical position of the supply point as well as its demand points can be effective to change total risk and total cost results. Even though some supply points, such as AMBARLI and ALÝAGA are located on the most densely populated cities (Ýstanbul and Ýzmir respectively) and they provide service to %25 of Shell Turkey's market, the achievement (in terms of number of people that can be saved from potential risk when routing strategy is based on MinRisk instead of MinLength) is quite low comparing to the supply points which serve a relatively small market, such as HOPA. This is due to the allocation of demand points to the supply points and the geographical position of the *o-d* pairs. When the distribution of demand points of each supply point is observed on the map thoroughly, it can be seen that most of the supply points serve some cluster of the market. For instance, AMBARLI serves only the European part of Turkey, which results in mostly similar paths for both

Minimum Length and Minimum Risk routing considerations. On the other hand, KIRIKKALE which can also be named as the "default" supply point of Turkey, serves almost all over the country, which results in completely dissimilar paths for almost every KIRIKKALE based shipment. Thus, we can conclude that, the allocation of *o-d* pairs as well as the geographical position of the allocated supply and demand points affects the results of our analysis. It is clear from the above results that the *o-d* assignments of Shell Turkey are quite effective.

There is another result presented in Table 5-2, which combines risk and cost functions evenly. %50 Risk-%50 Length saves 9.5 million truck-people with a quite low trade-off, 27,377 truck-kms, in comparison to the trade-off value of Minimum Risk Path result.

Altering the weights of the objective functions with new values will result in new alternatives for the decision-maker. When we assign a %25 of importance to risk and %75 to cost, we have a 5.1 million truck-people saved with 5,790 truck-kms of trade-off, in comparison to Minimum Length.

Supply	%25Risk -%75Length		%75Risk-%25Length	
	Truck People	Truck Km	Truck People	Truck Km
ALÝAGA	194,332,540	626,986	193,377,479	635,141
AMBARLI	403,346,347	182,966	402,954,934	184,446
DERINCE	340,679,227	629,059	338,626,382	646,552
KIRIKKALE	33,741,943	202,712	32,811,366	212,210
TRABZON	7,317,735	38,102	7,078,508	39,075
SAMSUN	20,647,245	138,767	18,996,600	161,710
HOPA	5,833,629	57,405	4,045,563	67,277
ATAS	39,706,756	229,185	39,392,461	232,762
ANTALYA	8,942,109	88,208	8,883,061	88,705
TOTAL	**1,054,547,531**	**2,193,390**	**1,046,166,354**	**2,267,878**

Table 5-3: Weighted Combination Results

The opposite weighted combination result, which is %75 risk-prone, results with 13.5 million truck-people to be saved for 80,278 truck-kms to trade.

To provide more alternative solutions, we solved our problem for 13 different combinations, which range from %10 to %90 Risk and %10 to %90 cost. These 13 results, the trade-off curve of these results and illustrated examples are presented in Appendix-A, B and C respectively.

From the total transportation risk and total transportation cost results, we observe that %50Risk-%50Length routing strategy is far better than Minimum Risk criterion, which was also commented so by our Decision Maker.

Further analysis regarding the achievement and the trade-off for a single truck, results in more interesting values which is presented in Table 5-4. Considering Minimum Risk versus Minimum Length results, we already know the total number of people we can save from potential risk and the total kms we need to trade to take advantage of this achievement, which are 14.5 million truck-people and 162,764 truck-km respectively. When we take the average of these values by dividing total number of truck equivalents, which is 14626, we see that there is a clear difference between two routing considerations.

We save 649 people from potential risk by only making extra 1.8 kilometres per truck on the average in %50Risk-%50Length versus MinLength. On the other hand, MinRisk versus MinLength criterion saves 994 people for every 11 kilometres per truck on the average. Although the average of achievement and trade-off values per truck are as stated above, the average achievement and trade-off values differ for the shipments originating from different supply points.

Supply	**50R/50L vs. Min Length**		**Min Risk vs. Min Length**	
	People	**Extra Km**	**People**	**Extra Km**
ALÝAGA	600 (*max:10298*)	1.022 (*max:10*)	767 (*max:10298*)	5.9 (*max:125*)
AMBARLI	149 (*max:4499*)	0.470 (*max:17*)	150 (*max:4499*)	0.6 (*max:17*)
DERÝNCE	296 (*max:10794*)	1.106 (*max:76*)	602 (*max:6594*)	8.4 (*max:200*)
KIRIKKALE	2783 (*max:65012*)	5.596 (*max:135*)	3769 (*max:20870*)	24.8 (*max:114*)
TRABZON	862 (*max:10963*)	3.300 (*max:42*)	1203 (*max:10963*)	38.0 (*max:258*)
SAMSUN	260 (*max:30835*)	1.169 (*max:152*)	4964 (*max:23958*)	128.9 (*max:337*)
HOPA	5601 (*max:29264*)	23.299 (*max:146*)	5605 (*max:29264*)	34.7 (*max:146*)
ATAS	678 (*max:15399*)	0.783 (*max:14*)	1049 (*max:15399*)	5.9 (*max:350*)
ANTALYA	0	0.000	78 (*max:2684*)	0.9 (*max:22*)

Table 5-4: Achievement and Trade-off Results per Truck

As presented in Table 5-4 above, there is an interesting result for the shipments originating from two distinct supply points AMBARLI and HOPA. Although the number of people that could be saved from potential risk is nearly the same for %50Risk - %50Length and Minimum Risk results, the extra kms that must be traded is lower in %50Risk - %50Length criterion.

5.4 Use of Black Spots

In this section, we investigate the "accidental risk" of the Shell-shipments based on a particular routing strategy, in order to analyze the transportation risk from a different point of view. We analyze whether Shell trucks pass along the "dangerous roads", namely *Black Spots* that are identified by the Turkish Government.

Black Spots are certain segments of the highway network in Turkey, on which the traffic accident occurrence frequency is defined to be "high" by the General Directorate of Highways (GDH). Some of the black spots are as follows:

1. Road segment connecting Istanbul Bosphorus Bridge to Ýzmit
2. Road segment crossing Bolu Mountain
3. Road segment between Ürgüp and Kayseri-West
4. Çesme-Ýzmir road

According to the *Black Spots Map* of Turkey, which is provided on the GDH internet web site, we associated 71 links as "dangerous roads" on our road network.

Given the results of Minimum Length, Minimum Risk and %50Risk - %50Length paths, we analyze the usage of the *black spots* like the following:

Out of 71 dangerous links, shipments based on Minimum Risk routing criterion uses 63 links with a total of 23,721 trucks traversed (Mean:334; Max:3024) along the links. We observe that, all 63 of the links are inevitably used in MinRisk criterion since these links are also used in the Minimum Length routing criterion, which means that the links correspond to similar paths resulted in both MinLength and MinRisk strategies for particular shipments.

In Minimum Length criterion, we have 69 links used out of 71 dangerous links, with a total of 24,347 trucks traversed (Mean:343; Max:3030). We observe that 6 links that were not used in the MinRisk paths, were used in the MinLength paths.

According to %50Risk - %50Length combination-based shipment results, we have 68 links used in 71 dangerous links, where 3 of these links do not correspond to links that possess similar shipments. The total number of trucks that used these links are 23,940, where Mean:337 and Max: 3030.

Observe that, the usage of Black Spots results in the same fashion with our Minimum Length, Minimum Risk and %50Risk-%50Length results, i.e. we have the maximum usage of Black Spots in MinLength, the least usage in MinRisk and nearly an average usage in %50Risk-%50Length results, by chance.

Chapter 6

HAZARDOUS NETWORK DESIGN PROBLEM

In the previous chapters, we approached the hazmat transportation problem from a new DM's point of view, where the DM's objectives are to minimize both risk and cost of the hazmat transportation. In this chapter we will consider a completely different scenario and propose three heuristics to solve that hazmat transportation problem.

We approach the problem from the government's point of view and adopt the hazmat transportation model proposed by Kara and Verter (2000).

As explained in Chapter 3, Kara and Verter's model incorporates the behaviors of both the regulator and hazmat carrier companies. According to the model, a regulator identifies the allowable links of the highway network for hazmat transportation, where the hazmat carrier companies select the shortest routes within the given network.

Once the hazmat carriers select a particular routing strategy, the government evaluates total risk of the shipments and identifies the links to be closed to hazmat traffic so as to force the hazmat carriers to select "safer" routes. This model can be regarded as an iterative game, in which the action of each player affects the behavior of the next player. Figure 6-1 depicts the dependent situation of the government and the hazmat carrier companies in the hazardous network design problem.

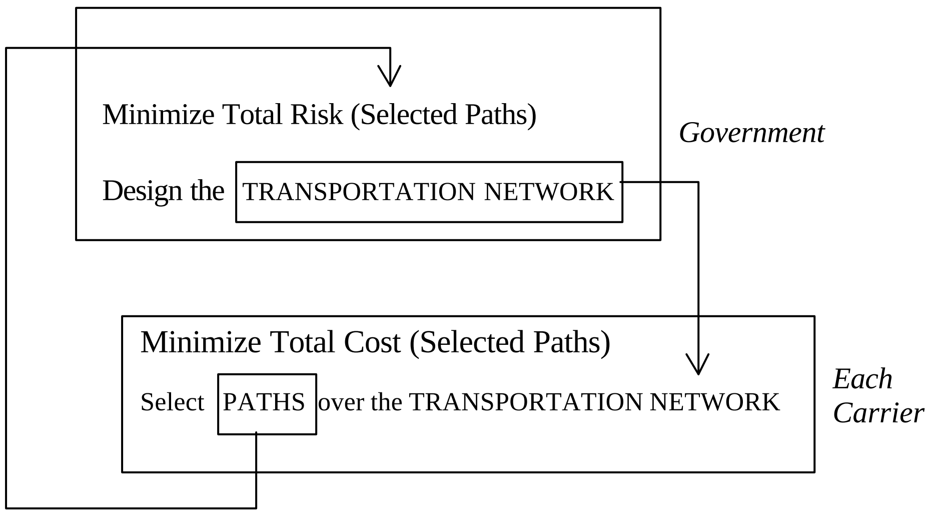


Figure 6-1: Hazardous Network Design Problem

Kara and Verter propose a bilevel model to solve the problem, where the outer problem belongs to the government and the inner problem belongs to the hazmat carrier companies.

6.1 The Original Mathematical Model (Kara & Verter, 2000)

Before we go through our proposed methodology to solve the hazardous network design problem, we examine the structure of the original mathematical model developed by Kara and Verter.

Recall that, $G = (N, A)$ is the existing network, where N denotes the set of nodes and A denotes the set of road links (indexed by (i,j): $i,j \in N$) that connect the nodes. Let C (indexed by c) denote the set of all shipments across G. Each shipment is characterized by its origin $o(c)$: $(o \in N)$ and destination $d(c)$: $(d \in N)$ and the type of hazmat carried $m(c)$. Let Z denote the set of population centers (indexed by *z*) affected by the hazmat transportation activity.

The parameters of the problem are:

$\boldsymbol{r}_{ij}^{z,m}$ the number of people in population center *z* exposed to a truck carrying hazmat type *m* through link (*i*,*j*)

l_{ij} length of link (*i*,*j*)

n^c number of trucks used for shipment *c*

The decision variables are:

Y_{ij}^{m} 1 if link (*i*,*j*) is available for hazmat transportation of hazmat type *m*, 0 otherwise

X_{ij}^{c} 1 if link (*i*,*j*) is used for shipment *c*, 0 otherwise.

The original hazardous network design problem is as follows:

$$\text{(HND)} \min_{Y_{ij}^{m} \in \{0,1\}} \sum_{z \in Z} \sum_{(i,j) \in A} \sum_{c \in C} n^c \boldsymbol{r}_{ij}^{z,m(c)} X_{ij}^{c}$$

Where X_{ij}^{c} solves:

$$\min \sum_{c \in C} \sum_{(i,j) \in A} n^c l_{ij} X_{ij}^{c} \tag{1}$$

s.t.

$$\sum_{(i,k) \in A} X_{ik}^{c} - \sum_{(k,i) \in A} X_{ki}^{c} = \begin{cases} +1 & i = o(c) \\ -1 & i = d(c) \\ 0 & o.w. \end{cases} \quad \forall\, i \in N,\ c \in C \tag{2}$$

$$X_{ij}^{c} \le Y_{ij}^{m(c)} \qquad \forall\, (i,j) \in A,\ c \in C \tag{3}$$

$$X_{ij}^{c} \in \{0,1\} \qquad\qquad \forall\,(i,j) \in A,\ c \in C \qquad\qquad (4)$$

The inner problem is represented by (1)-(4). The binary decision variables of the outer problem, Y_{ij}^{m}, constitute parameters for the inner problem. Given the values of Y_{ij}^{m}, the inner problem boils down to a *Minimum Cost Network Flow Model*. Constraints (2) are the flow balance constraints, whereas (3) ensures that only the links made available by the government can be used by the carriers.

The solution strategy to solve HND is via the representation of the inner problem by the use of Karush-Kuhn-Tucker (KKT) conditions. Once the Y_{ij}^{m} values are given, the inner problem is unimodular. Hence, the integrity requirements (4) in the inner problem can be replaced by $X_{ij}^{c} \geq 0$ without loss of optimality. This enables us to represent the inner problem via KKT conditions of its LP relaxation. The optimum solution to inner problem can be obtained by solving the feasibility problem defined by (2), (3) and the following set of constraints:

$$X_{ij}^{c} \geq 0 \quad \forall\,(i,j) \in A,\ c \in C \qquad (4')$$

$$n^{c} l_{ij} - w_{i}^{c} + w_{j}^{c} - v_{ij}^{c} + \boldsymbol{l}_{ij}^{c} = 0 \quad \forall\,(i,j) \in A,\ c \in C \qquad (5)$$

$$v_{ij}^{c} X_{ij}^{c} = 0 \quad \forall\,(i,j) \in A,\ c \in C \qquad (6)$$

$$\boldsymbol{l}_{ij}^{c}\left(X_{ij}^{c} - Y_{ij}^{m(c)}\right) = 0 \quad \forall\,(i,j) \in A,\ c \in C \qquad (7)$$

$$v_{ij}^{c} \geq 0,\ \ \boldsymbol{l}_{ij}^{c} \geq 0,\ w_{i}^{c}\ \text{free} \quad \forall\,(i,j) \in A,\ c \in C \qquad (8)$$

The nonlinear constraints (6) and (7) can be linearized by taking advantage of the binary nature of X_{ij}^{c} and Y_{ij}^{m}. When R is a large number, the following constitutes the linearization:

$$v_{ij}^{c} \leq R\left(1 - X_{ij}^{c}\right) \quad \forall\ (i,j) \in A,\ c \in C \tag{6′}$$

$$\boldsymbol{l}_{ij}^{c} \leq R\left[1 - \left(Y_{ij}^{m(c)} - X_{ij}^{c}\right)\right] \quad \forall\ (i,j) \in A,\ c \in C \tag{7′}$$

Thus, the following model is equivalent to (HND):

$$\text{(HND′)} \quad \min_{Y_{ij}^{m} \in \{0,1\}} \sum_{z \in Z} \sum_{(i,j) \in A} \sum_{c \in C} n^{c}\, \boldsymbol{r}_{ij}^{z,m(c)} X_{ij}^{c}$$

s.t. (2), (3), (4), (5), (6′), (7′), (8)

$$Y_{ij}^{m(c)} \in \{0,1\} \qquad \forall\ (i,j) \in A,\ m \in M$$

The solution of the model prescribes the road network that should be available to hazmat carriers as well as the carriers' route choices on the network. The corresponding objective function determines the minimum population exposure attainable by banning certain road segments to hazmat vehicles.

Kara and Verter use HND′ to design the hazardous network for South-Western-Ontario. In our study we intend to determine the hazardous network of petroleum products for Turkey by using HND′. Hence we use the annual shipment data of Shell to design our hazardous network.

In our earlier analysis we applied the original model HND′ on our network, 670-arc and 499-node, via CPLEX 7.0 running on a 12*400 MHz computer with 3GB of memory. However, we couldn't be able to find any feasible solution even after 300 hours. Therefore, we propose two "one-shot" and an iterative heuristic solution methodology.

6.2 Our Approach

The size of the network in our problem constitutes a disadvantageous situation while attempting to solve the problem optimally. Therefore, we seek sub-optimal solutions in which computational time is at acceptable values.

To solve the hazmat transportation problem from a regulator's point of view, we propose two new approaches that are not iterative in nature but determines quick solutions. Additionally, we present a greedy algorithm that seeks solutions to design a hazardous network.

6.2.1 First Approach: *The Union of MinRisk Paths*

We begin our analysis by first investigating whether the union of the Minimum Risk Paths constitutes the allowable network for hazmat transportation. The idea behind this consideration is: when all the links that are other than the ones included in Minimum Risk Paths, are closed; will the remaining network force the shipments select minimum risk paths?

We identified the union of Minimum Risk Paths for all 562 shipments using GIS tools. The new network consists of 502 links, i.e. 168 links are closed to hazmat traffic (We define the closed link set as K, $K=(N,A)$). According to this approach ($|K| = 168$), total path risk and total path length results are presented in Table 6-1a and 6-1b respectively.

Note that we present the solutions of Minimum Length results of the new network (502-arc) in Table 6-1 since all the shipments will be based on selecting MinLength paths according to the bilevel model. We also present the Minimum Length and Minimum Risk results of the original network (670-arc) for reference.

TOTAL PATH RISK (Truck-People)			
Supply	$\bigcup$ **(MinRisk Paths)**	**Original Network**	
	Min Length	**Min Length**	**Min Risk**
ALÝAGA	195,738,963	195,718,341	193,160,611
AMBARLI	402,961,163	403,451,512	402,953,384
DERÝNCE	342,942,875	341,032,680	338,377,090
KIRIKKALE	35,823,205	35,521,938	32,728,918
TRABZON	7,317,735	7,317,735	6,996,427
SAMSUN	20,662,113	20,662,113	18,612,010
HOPA	6,779,627	6,778,629	4,043,449
ATAS	39,548,680	40,245,728	39,382,299
ANTALYA	8,948,001	8,942,109	8,878,217
TOTAL	**1,060,722,362**	**1,059,670,785**	**1,045,132,405**

Table 6-1a: Comparison of Total Path Risk Results for the First Approach

TOTAL PATH LENGTH (Truck-Km)			
Supply	$\bigcup$ **(MinRisk Paths)**	**Original Network**	
	Min Length	**Min Length**	**Min Risk**
ALÝAGA	626,856	626,294	646,001
AMBARLI	184,562	182,881	184,834
DERÝNCE	647,631	628,517	665,397
KIRIKKALE	204,665	200,260	218,624
TRABZON	38,102	38,102	48,249
SAMSUN	138,774	138,744	191,962
HOPA	56,030	55,907	72,832
ATAS	230,656	228,687	233,509
ANTALYA	88,368	88,208	88,956
TOTAL	**2,215,644**	**2,187,600**	**2,350,364**

Table 6-1b: Comparison of Total Path Length Results for the First Approach

As seen in Table 6-1a, the new network does not force the shipments to follow Minimum Risk Paths. Moreover, most of the shipments originating from different supply points followed the paths that pose more risk than Minimum Length Paths do in the original network.

Tables 6-1a and 6-1b identify an important result: Imposing a network which contains only these arcs for MinRisk routes (with a hope that the paths selected by the carriers will again be a MinRisk path) provides even more risk than the original network.

When we observe supply point-based shipments, all the shipments except the ones originating from AMBARLI and ATAS, have a greater risk value than the original Minimum Length total-risk results. Although there may be "good" solutions for the shipments originating from the supply points other than AMBARLI and ATAS, we focus on these two supply points.

In order to improve the solution, we identify the links that were closed by the effect of the shipments originating from AMBARLI and ATAS. Hence, we only have 11 arcs to be closed to hazmat traffic by the effect of the shipments belonging AMBARLI and ATAS, which also allows other supply point-based shipments follow MinLength routes. Note that the identified 11 links do not intersect with the MinLength routes of the other 7 supply point based shipments.

We now investigate whether we would get a better solution when we redefine our closed link set with these 11 new arcs. Our new results are the following for the new closed link set *K*, where $|K| = 11$ are presented in Table 6-2.

The corrected network of union of MinRisk paths has a better result than the previous network, with a 1,303,369 truck-people of achievement and 6031 truck-kms of trade-off. However, the results indicate that closing supply point-based links do not yield the results we expected.

Observe that AMBARLI and ATAS had better results in the previous network although we closed the same links associated with these supply points in the corrected network. Moreover the other supply points were projected to select Minimum Length paths but quite interestingly ALÝAGA, DERÝNCE and KIRIKKALE based shipments have better results now.

Supply	Corrected Network (11-arc closed)	
	Total Risk	**Total Length**
ALÝAGA	195,636,140	626,781
AMBARLI	402,968,854	184,447
DERÝNCE	340,794,330	631,432
KIRIKKALE	35,487,586	200,334
TRABZON	7,317,735	38,102
SAMSUN	20,662,113	138,774
HOPA	6,778,629	55,907
ATAS	39,774,028	229,486
ANTALYA	8,948,001	88,368
TOTAL	**1,058,367,416**	**2,193,631**

Table 6-2: Total Path Length and Risk Results for the 11-arc Closed Network

When we observe particular shipment results for two new network designs, we see that there are distinct shipments, originating from different supply points, whose mutually competitive paths have common links. These links may or may not be regarded in the closed link set due to their relative achievement and trade-off values. To illustrate this situation with specific examples we determine the following:

<u>Case 1</u>: **Links** 357 and 358 lie on **Minimum Risk paths** of four shipments (*Antalya-Burdur*, *Antalya-Denizli*, *Antalya-Milas* and *Antalya-Bodrum*) which originate from ANTALYA and **Minimum Length paths** of shipments (*Kirikkale-Marmaris* and *Kirikkale-Bodrum*) originating from KIRIKKALE.

According to our first consideration, which is designing a network that consists of union of MinRisk paths, we should close these two links. This means that shipments originating from ANTALYA will select MinLength paths and the shipments originating form KIRIKKALE will select some k^{th} shortest paths. This will bring out an exposure value of 765,265 truck-people in total.

Allowing these two links remain open yields a different result. This time, when both links are open, shipments originating from both of the supply points will select MinLength paths. This will result in 756,583 truck-people, which is lower than the previous result. Therefore, the reliability of the network that consists of the union of minimum risk paths is questionable.

Let us now consider another example, which describes the complexity of the situation from a different angle.

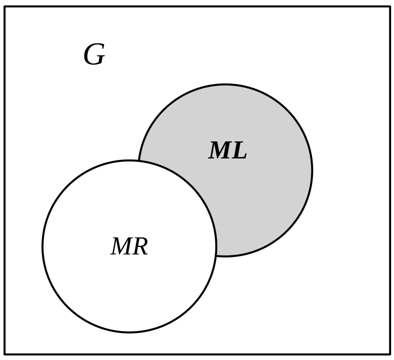
<u>Case 2</u>: Links 379 and 389 lie on Minimum Length paths of shipments (*Antalya-Denizli*, *Antalya-Milas* and *Antalya-Bodrum*) originating from ANTALYA and Minimum Risk path of shipment (*Kirikkale-Marmaris*) originating from KIRIKKALE.

When both links are closed to hazmat traffic, there will be a total exposure value of 314,523 truck-people, whereas the risk value will be 319,158 truck-people in the opposite situation.

In both cases, we have different links but the same shipments. In Case 1, we observed how these shipments may produce confusing results. Nevertheless, in Case-2 we see that the same shipments bring out completely reasonable values when the network of the union of MinRisk paths is of concern. This implies the complexity of the problem clearly.

6.2.2 Second Approach

Our second approach to this problem evolves from our observations in the first trial. This time we take both the Minimum Risk and Minimum Length paths into consideration. We examine whether closing links that are within the union of the MinLength paths that do not intersect with the union of the MinRisk paths, will result in better solutions. The shaded area in Figure 6-2 indicates the links to be closed to hazmat traffic within this approach. The difference of this approach from the first one is remaining the links open, which do not intersect with both MinLength or MinRisk paths in the hazardous network.



$G = (N,A)$

$MR = \bigcup$ (MinRisk Paths)

$ML = \bigcup$ (MinLength Paths)

Figure 6-2: MinRisk and MinLength Paths over the Network *G*

According to this consideration, we have 40 links to be closed to hazmat traffic. While $|K|$=40, Minimum Risk and Minimum Length path results are in Table 6-3a and 6-3b respectively.

In Table 6-3a, observe that we again have a better result in the original Minimum Length path results than in our new hazardous network with

$|K|$=40. It can be seen that shipments originating from supply points ALÝAGA, AMBARLI and ATAS have better results, while the rest of the shipments have results which are the same with the original Minimum Length results or greater than that.

TOTAL PATH RISK (Truck-People)			
Supply	**40-arc closed Network**	**Original Network**	
	Min Length	**Min Length**	**Min Risk**
ALÝAGA	195,636,140	195,718,341	193,160,611
AMBARLI	402,968,854	403,451,512	402,953,384
DERÝNCE	342,388,055	341,032,680	338,377,090
KIRIKKALE	35,801,146	35,521,938	32,728,918
TRABZON	7,317,735	7,317,735	6,996,427
SAMSUN	20,662,113	20,662,113	18,612,010
HOPA	6,779,627	6,778,629	4,043,449
ATAS	39,824,925	40,245,728	39,382,299
ANTALYA	8,948,001	8,942,109	8,878,217
TOTAL	**1,060,326,596**	**1,059,670,785**	**1,045,132,405**

Table 6-3a: Comparison of Total Path Risk Results for the Second Approach

TOTAL PATH LENGTH (Truck-Km)			
Supply	**40-arc closed Network**	**Original Network**	
	Min Length	**Min Length**	**Min Risk**
ALÝAGA	626,781	626,294	646,001
AMBARLI	184,447	182,881	184,834
DERÝNCE	645,194	628,517	665,397
KIRIKKALE	204,613	200,260	218,624
TRABZON	38,102	38,102	48,249
SAMSUN	138,774	138,744	191,962
HOPA	56,030	55,907	72,832
ATAS	230,067	228,687	233,509
ANTALYA	88,368	88,208	88,956
TOTAL	**2,212,346**	**2,187,600**	**2,350,364**

Table 6-3b: Comparison of Total Path Length Results for the Second Approach

In Table 6-3b, we have the total path length results, which indicate that most of the shipments selected some k^{th} shortest paths in the existing network.

We follow the same procedure as we did in our first approach, we select the shipments that originate from different supply points, which have better results than Minimum Length path results. The corresponding supply points are, ALÝAGA, AMBARLI and ATAS.The shipments that originate from these supply points contributed the risk reduction process with 9 links. Therefore we change the closed link set to $|K|$ = 9. After closing these links, we have a better result, however we again have the same problem, namely mutually competitive paths dilemma, which we confronted in our first approach.

The results of the corrected network are as follows:

Supply	Corrected Network-2 (9-arc closed)	
	Total Risk	**Total Length**
ALÝAGA	195,636,140	626,781
AMBARLI	402,968,854	184,447
DERÝNCE	340,794,330	631,432
KIRIKKALE	35,521,938	200,260
TRABZON	7,317,735	38,102
SAMSUN	20,662,113	138,774
HOPA	6,778,629	55,907
ATAS	40,245,728	228,687
ANTALYA	8,948,001	88,368
TOTAL	**1,058,873,468**	**2,192,758**

Table 6-4: Total Path Length and Risk Results for the Corrected Network of the Second Approach

We have an achievement of 797,317 truck-people and a trade-off value of 5,158 truck-km in this approach. The achievement of the first approach is better than the second one.

6.2.3 A Greedy Approach

In this section, we present an iterative approach to design a hazardous network. Although we have a 670-arc 499-node network, which requires 2^{670} number of iterations to find an optimal solution; we take iterations for a number of network designs so as to find the hazardous network that results in the least total path risk value.

We begin our analysis by closing a link set including 10 links, which we select among all 670 arcs in the original network. Once we get a result from this network design, we update the closed link set with additional 10 links and do the iteration for the new network.

Before we proceed our iteration results, we go through how we determine the priority of the links to be added in the closed link set. We define the priority of a link to be closed by a ratio, as follows:

$$\boldsymbol{a}_{ij} = \frac{l_{ij}}{\boldsymbol{r}_{ij}} \ , \ \forall\, (i,j)$$

where l_{ij} is the length and $\boldsymbol{r}_{ij}$ is the population exposure value of link (i,j).

The reason we define such a ratio is to give the priority to the links that possess the most number of people per km.

Our iterations are initialized by closing the first 10 links that suffice Min{ $\boldsymbol{a}_{ij}$ } requirement and we continue iterating by updating the closed link set by adding the next 10 Min{ $\boldsymbol{a}_{ij}$ }s until we determine the maximum number of links we are allowed to close simultaneously.

It takes 3 minutes for a single run, i.e. calculating shortest paths for 562 shipments, using ArcView GIS 3.1, running on a Pentium-III PC at 700 Mhz with 128 MB of memory.

We have 67 iterations, which resulted surprisingly, i.e. all the set of closed links except two, caused a disconnection in the network. The first three set of links disconnect the network when each of them are considered separately. The 4th set of links give a positive result, however the next 30 set of links disconnect the network, when one of them is considered with set-4 simultaneously. The only set combination, which is #4 and #35 combined, give a positive result in our all 67 iterations. The results of these iterations are worse than our first two approach, which are also presented in Table 6-5 below:

	Iteration-1 (10-arc closed)		**Iteration-2 (20-arc closed)**	
Supply	**Total Risk**	**Total Length**	**Total Risk**	**Total Length**
ALÝAGA	196,423,270	654,742	196,464,296	654,744
AMBARLI	404,658,067	183,004	404,658,067	183,004
DERINCE	388,640,103	846,417	388,640,103	846,417
KIRIKKALE	36,210,612	202,337	34,930,037	205,416
TRABZON	7,317,735	38,102	7,381,207	39,143
SAMSUN	20,662,113	138,744	19,186,508	191,405
HOPA	6,778,629	55,907	6,780,196	56,320
ATAS	40,246,932	228,706	40,246,932	228,706
ANTALYA	8,963,009	88,532	8,963,009	88,532
	1,109,900,470	**2,436,491**	**1,107,250,355**	**2,493,687**

Table 6-5: Iteration Results for the Greedy Approach

When we analyze the usage of links in the original network, we see that %72 of all 670 links are used in the Minimum Risk paths and %78 of the links are used in the Minimum Length paths.

For the sake of reducing the complexity of the problem, we narrow our search space by eliminating some of the links from candidacy, despite the fact that the objective function may increase. We seek possible extensions of our second heuristic, namely use of 40-arc closed network. The common property of these 40 links is; they are used in some MinLength paths, which do not intersect with MinRisk paths.

We do the iterations in the same fashion, except that this time we close the links one by one; i.e. initialize by closing the link that suffices Min$\{\boldsymbol{a}_{ij}\}$ requirement and continue iterating by updating the closed link set with the next Min$\{\boldsymbol{a}_{ij}\}$ until all 40 links are closed. The results of 40 iterations are presented in Table 6-6 and the results of total population exposure for each run is plotted in a graph in Figure 6-3.

From the Table 6-6, we observe that there is a 569,149 truck-people of difference between the first and the last iteration. The best result is achieved at the 37th iteration with a minor difference (19,753 truck-people) from the total risk result of the MinLength paths of the original network (670-arc). It is trivial to infer that the results of the first two heuristics in sections 1 and 2 are better than the results of this approach.

Itera-tion	# of links closed	Total Risk (Truck-People)	Total Length (Truck-Km)	Itera-tion	# of links closed	Total Risk (Truck-People)	Total Length (Truck-Km)
1	1	1,060,895,745	2,187,696	21	21	1,060,241,547	2,199,667
2	2	1,060,877,340	2,187,723	22	22	1,060,241,547	2,199,667
3	3	1,060,790,580	2,186,781	23	23	1,060,241,547	2,199,667
4	4	1,060,761,978	2,187,086	24	24	1,060,241,547	2,199,667
5	5	1,060,054,568	2,188,113	25	25	1,060,312,104	2,199,927
6	6	1,061,130,591	2,193,097	26	26	1,060,173,800	2,200,473
7	7	1,060,892,241	2,196,012	27	27	1,060,173,800	2,200,473
8	8	1,060,823,453	2,196,893	28	28	1,060,173,800	2,200,473
9	9	1,060,880,233	2,197,689	29	29	1,060,348,184	2,200,630
10	10	1,060,880,233	2,197,689	30	30	1,060,271,875	2,201,277
11	11	1,060,832,878	2,197,729	31	31	1,061,034,017	2,207,777
12	12	1,060,832,878	2,197,729	32	32	1,061,034,017	2,207,777
13	13	1,060,832,878	2,197,729	33	33	1,061,027,765	2,208,025
14	14	1,060,832,878	2,197,729	34	34	1,061,027,765	2,208,025
15	15	1,060,832,878	2,198,729	35	35	1,061,253,485	2,210,889
16	16	1,060,832,878	2,198,729	36	36	1,061,253,485	2,210,889
17	17	1,060,265,834	2,199,299	37	37	1,059,651,032	2,212,274
18	18	1,060,272,084	2,199,343	38	38	1,060,326,596	2,212,346
19	19	1,060,272,084	2,199,343	39	39	1,060,326,596	2,212,346
20	20	1,060,262,949	2,199,393	40	40	1,060,326,596	2,212,346

Table 6-6: Total Risk and Total Km Results for 40 Iterations

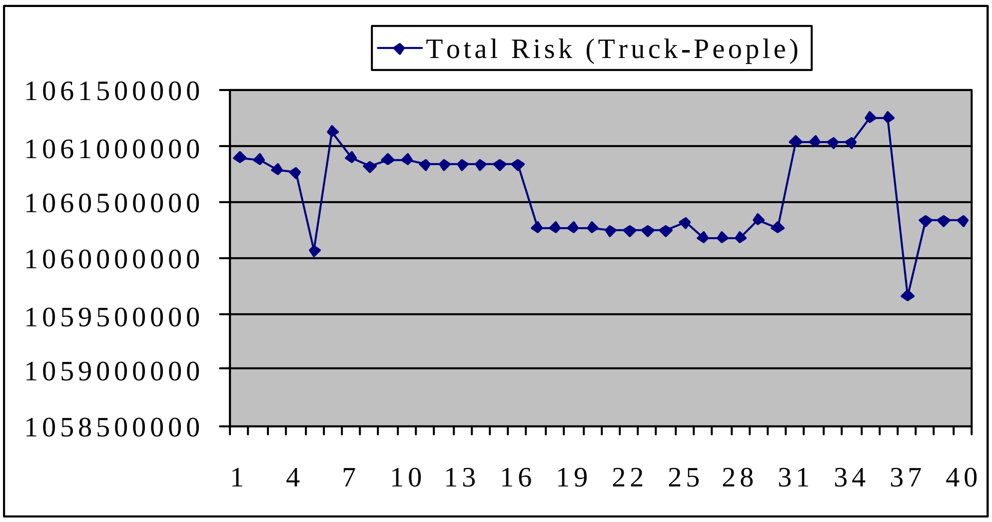


Figure 6-3: Total Risk Results for 40 Iterations

One possible correction strategy for this approach can be done by eliminating the links that caused an increase of the total risk value comparing to that of the previous iteration, although we know that all the iterations yield unique results given a closed link set. Because, a link that causes an increase in a total risk value may or may not give better results when we exclude that link from the closed link set.

The link set that cause a decrease in the total risk values of particular iterations consists of 14 links. When we close only these links we have the following results:

	14-arc closed network	
Supply	**Total Risk**	**Total Length**
ALÝAGA	195,636,140	626,781
AMBARLI	403,346,347	182,966
DERINCE	340,493,110	632,913
KIRIKKALE	34,934,214	201,603
TRABZON	7,317,735	38,102
SAMSUN	20,662,113	138,744
HOPA	6,779,627	56,030
ATAS	39,678,684	229,257
ANTALYA	8,948,001	88,368
	1,057,795,971	**2,194,764**

Table 6-7: Results of the 14-arc Closed Network

As seen in Table 6-7, we have better results now. Moreover, these results are better than our first two approach.

We do further analysis to improve the above results. We again focus on specific supply point-based shipments, specially AMBARLI and HOPA. We question whether we already closed the links that cause a decrease in the total risk results of the shipments, which originate from AMBARLI and HOPA.

After investigating the network thoroughly, we see that there may be a possible reduction in the total risk when we close some additional links which are mostly associated with the two origins. We determine 7 more links that can be closed to hazmat traffic in addition to 14 links.

These results are presented in the following table:

	21-arc closed network	
Supply	**Total Risk**	**Total Length**
ALÝAGA	195,636,140	626,781
AMBARLI	402,968,854	184,447
DERINCE	340,493,110	632,913
KIRIKKALE	34,934,214	201,603
TRABZON	7,087,512	38,983
SAMSUN	20,662,113	138,744
HOPA	5,834,627	57,528
ATAS	39,678,684	229,257
ANTALYA	8,948,001	88,368
	1,056,243,255	**2,198,624**

Table 6-8: Results of the 21-arc Closed Network

Seven more links affected our results in a better way; we have better results for the shipments originating from AMBARLI and HOPA, and even we have a better result now for TRABZON-based shipments.

Our final results indicate that we have an achievement of 3,427,530 truck-people in comparison to the Minimum Risk results of the original network. We know that there is a total achievement of 14,538,380 truck-people in the original network, which is the difference of the total risk results of MinLength and MinRisk paths. ♦

To summarize this chapter we have the following remarks: The hazmat transportation problem that requires closing certain links of the network to hazmat traffic is quite complex in nature and highly depends on the spatial distribution of the *o-d* pairs, the magnitude of the shipments in terms of trucks as well as the geographical positions of the *o-d* pairs and the demographic situations of their corresponding divisions.

Chapter 7

CONCLUSION

In this chapter, we will provide a brief summary of the contributions of this thesis and address some possible extensions of this study for future research. In our study, we focus on hazmat transportation problem from two Decision Maker's point of view.

The first problem belongs to a petroleum products producer and supplier company (Shell), which does not involve in the hazmat transportation physically, but hires sub-contractor firms to do the transportation for Shell. In the second problem, which is the *hazardous network design problem*, our approach is however, from a regulator's point of view unlike our first consideration, using the annual shipment data of Shell. In this problem, we propose alternative solution methodology to bring sub-optimal solutions to Kara and Verter's (2000) bilevel model.

In the first hazmat transportation problem, we bring solutions to suit Shell's needs and requirements by using real data. During our study, we have discovered a new Decision-Maker type that has been neglected in the hazmat literature. This new DM type enabled us to solve the hazmat transportation problem of a hazmat producer & supplier company in a justifiable manner.

With this large-scale implementation, we derived various alternative routing strategies to be selected by the company representatives. During our recent discussions with Shell, it has been stated that %50Risk-%50Length routing strategy best suits their purposes and some of their current routes already match with the results from %50Risk-%50Length routing consideration. Their feedback regarding the improvement of this study led us to address some future research directions as follows:

We have used the population exposure, as a risk definition. However, there may also be another approach by making use of a risk model that includes accident probabilities to determine hazardous routes. Solving this hazmat transportation problem with various risk definitions, would bring interesting results and allow possible comparisons while making routing decisions. One possible extension for the GIS applications would be using a more sensitive population data, which includes the districts within cities. This may bring more accurate solutions while attempting to calculate population exposure values as arc impedances.

Our second approach to the hazmat transportation problem is the hazardous network design. The original model to solve hazardous network design problem belongs to Kara and Verter (2000), where the authors provide an optimal solution for South-Western Ontario. We adopted their model, however, we propose three alternative heuristics to bring solutions to this problem.

We derived our best results from a corrected extension of the *iterative approach*, where we close 21 arcs to hazmat traffic in the transportation network. We discuss the complexity of the problem extensively and infer that the complexity of the problem depends on the spatial distribution of the origin-destination pairs, the magnitude of the shipments and the size of the transportation network.

To address some possible future research directions to solve this very new model, we think that determining new heuristics or attaining powerful linearizations for the original mathematical model to derive optimal solutions in a reasonable CPU time, would bring better results.

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APPENDIX

C h a p t e r   A

COMPUTATIONAL RESULTS FOR VARIOUS WEIGHTED COMBINATIONS

Supply	Minimum Risk		Minimum Length	
	Truck-People	**Truck-Km**	**Truck-People**	**Truck-Km**
ALÝAGA	193,160,611	646,001	195,718,341	626,294
AMBARLI	402,953,384	184,834	403,451,512	182,881
DERINCE	338,377,090	665,397	341,032,680	628,517
KIRIKKALE	32,728,918	218,624	35,521,938	200,260
TRABZON	6,996,427	48,249	7,317,735	38,102
SAMSUN	18,612,010	191,962	20,662,113	138,744
HOPA	4,043,449	72,832	6,778,629	55,907
ATAS	39,382,299	233,509	40,245,728	228,687
ANTALYA	8,878,217	88,956	8,942,109	88,208
	1,045,132,405	**2,350,364**	**1,059,670,785**	**2,187,600**

Table A-1: Minimum Risk and Minimum Length Results

Supply	%75Risk-%25Length		%25Risk-%75Length	
	Truck-People	**Truck-Km**	**Truck-People**	**Truck-Km**
ALÝAGA	193,377,479	635,141	194,332,540	626,986
AMBARLI	402,954,934	184,446	403,346,347	182,966
DERINCE	338,626,382	646,552	340,679,227	629,059
KIRIKKALE	32,811,366	212,210	33,741,943	202,712
TRABZON	7,078,508	39,075	7,317,735	38,102
SAMSUN	18,996,600	161,710	20,647,245	138,767
HOPA	4,045,563	67,277	5,833,629	57,405
ATAS	39,392,461	232,762	39,706,756	229,185
ANTALYA	8,883,061	88,705	8,942,109	88,208
	1,046,166,354	**2,267,878**	**1,054,547,531**	**2,193,390**

Table A-2: %75Risk-%25Length and %25Risk-%75Length Results

Supply	%90Risk-%10Length		%10Risk-%90Length	
	Truck-People	**Truck-Km**	**Truck-People**	**Truck-Km**
ALÝAGA	193,220,988	638,904	194,336,728	626,971
AMBARLI	402,953,552	184,512	403,364,754	182,939
DERINCE	338,616,534	646,859	340,967,920	628,559
KIRIKKALE	32,765,712	213,163	35,474,583	200,300
TRABZON	7,078,508	39,075	7,317,735	38,102
SAMSUN	18,882,520	166,431	20,662,113	138,744
HOPA	4,045,563	67,277	6,778,629	55,907
ATAS	39,387,447	232,959	40,245,728	228,687
ANTALYA	8,878,217	88,956	8,942,109	88,208
	1,045,829,041	**2,278,136**	**1,058,090,299**	**2,188,417**

Table A-3: %90Risk-%10Length and %10Risk-%90Length Results

Supply	%80Risk-%20Length		%20Risk-%80Length	
	Truck-People	**Truck-Km**	**Truck-People**	**Truck-Km**
ALÝAGA	193,377,479	635,141	194,332,540	626,986
AMBARLI	402,954,936	184,446	403,346,347	182,966
DERINCE	338,626,382	646,552	340,788,070	628,820
KIRIKKALE	32,811,366	212,210	34,216,989	201,775
TRABZON	7,078,508	39,075	7,317,735	38,102
SAMSUN	18,923,521	163,760	20,647,245	138,767
HOPA	4,045,563	67,277	5,833,629	57,405
ATAS	39,389,582	232,839	40,245,728	228,687
ANTALYA	8,883,061	88,705	8,942,109	88,208
	1,046,090,398	**2,270,005**	**1,055,670,392**	**2,191,716**

Table A-4: %80Risk-%20Length and %20Risk-%80Length Results

Supply	%70Risk-%30Length		%30Risk-%70Length	
	Truck-People	**Truck-Km**	**Truck-People**	**Truck-Km**
ALÝAGA	193,377,479	635,141	194,175,862	627,408
AMBARLI	402,954,936	184,446	403,346,349	182,966
DERINCE	338,626,382	646,552	340,403,710	629,783
KIRIKKALE	32,811,366	212,210	33,741,943	202,712
TRABZON	7,078,508	39,075	7,317,735	38,102
SAMSUN	18,923,521	163,760	20,647,245	138,767
HOPA	4,045,563	67,277	5,833,629	57,405
ATAS	39,389,582	232,839	39,706,756	229,185
ANTALYA	8,883,061	88,705	8,942,109	88,208
	1,046,090,398	**2,270,005**	**1,054,115,338**	**2,194,536**

Table A-5: %70Risk-%30Length and %30Risk-%70Length Results

Supply	%60Risk-%40Length		%40Risk-%60Length	
	Truck-People	**Truck-Km**	**Truck-People**	**Truck-Km**
ALÝAGA	193,716,312	629,703	194,175,862	627,408
AMBARLI	402,954,936	184,446	403,346,349	182,966
DERINCE	339,676,336	633,880	340,403,710	629,783
KIRIKKALE	32,962,125	209,647	33,741,943	202,712
TRABZON	7,080,604	39,038	7,317,735	38,102
SAMSUN	19,856,934	145,512	20,647,245	138,767
HOPA	4,045,563	67,277	5,833,629	57,405
ATAS	39,456,616	231,426	39,706,756	229,185
ANTALYA	8,883,061	88,705	8,942,109	88,208
	1,048,632,487	**2,229,634**	**1,054,115,338**	**2,194,536**

Table A-6: %60Risk-%40Length and %40Risk-%60Length Results

C h a p t e r B

TRADE-OFF CURVE

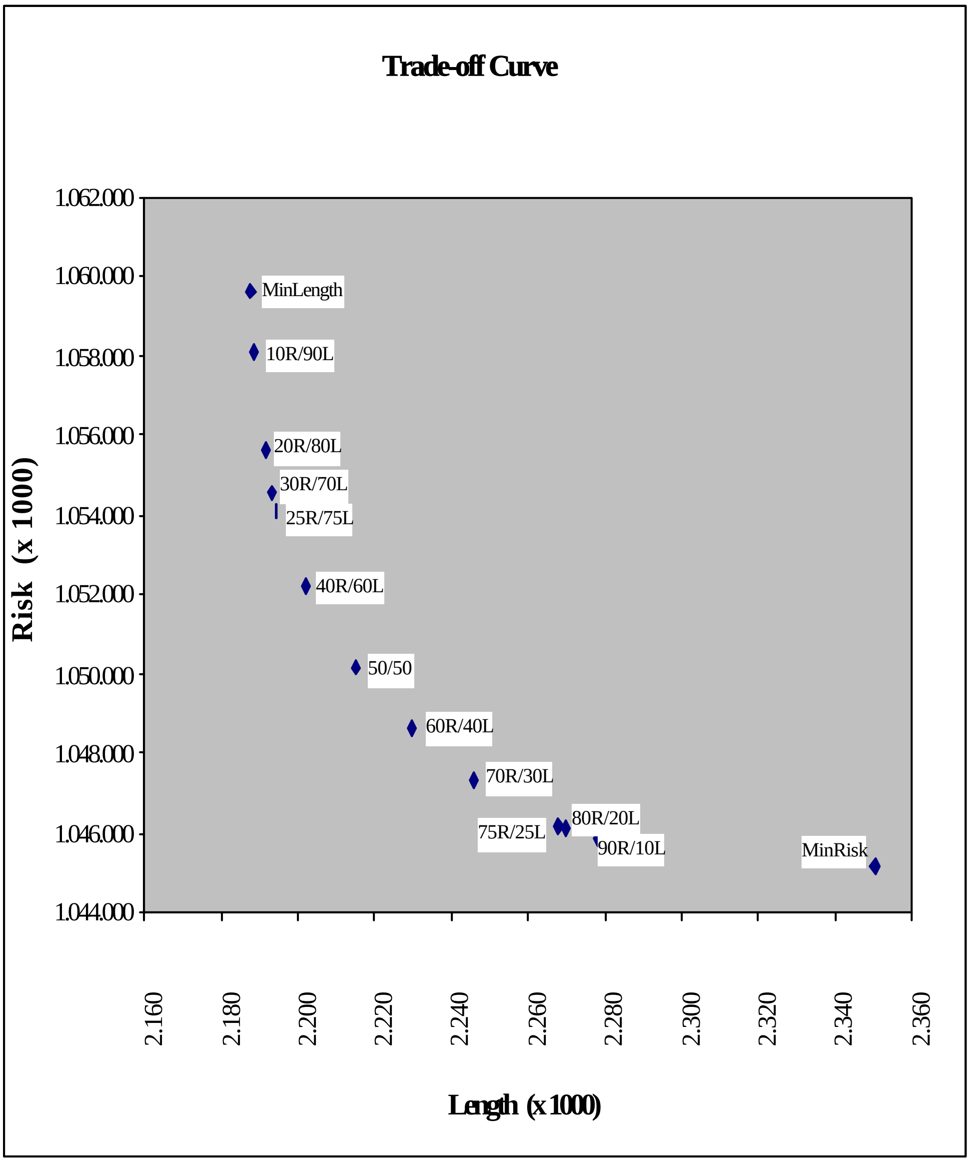
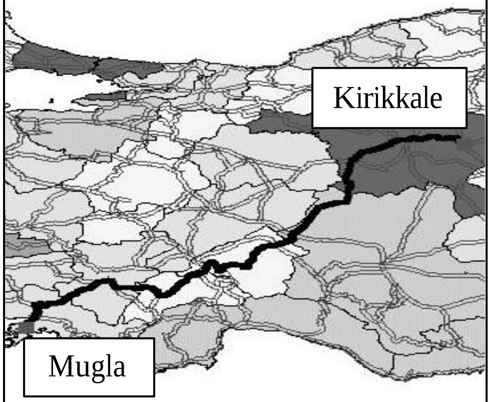
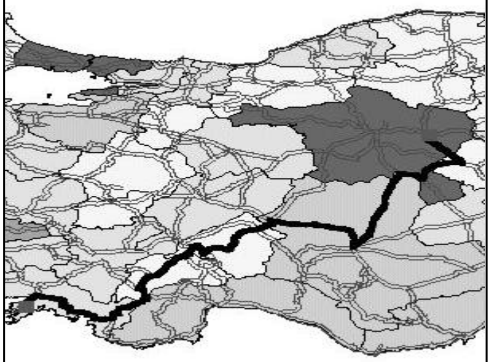


Figure B-1: Trade-off Curve

Chapter C

ILLUSTRATED EXAMPLES

KIRIKKALE-MUGLA SHIPMENT

Minimum Length		**Minimum Risk**
		
919 Km, 104717 People		1127 Km, 97255 People

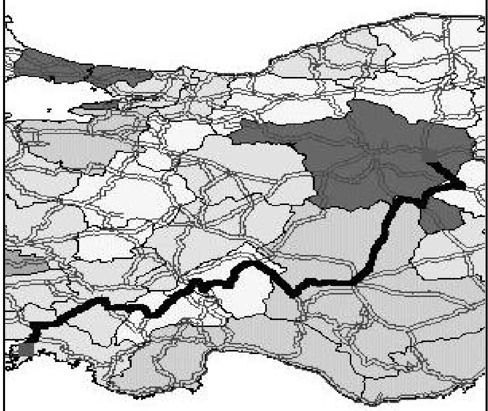
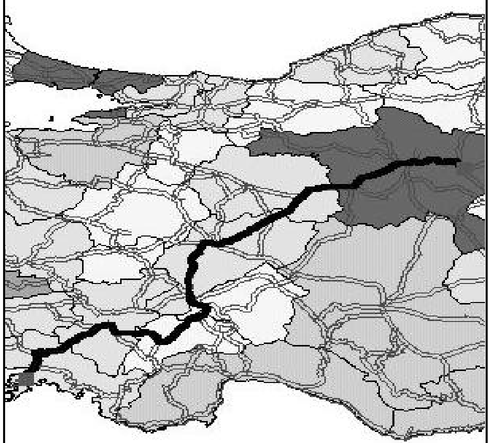
%90Risk-%10Length		**%50Risk-%50Length**
		
1075 Km, 97331 People		925 Km, 100045 People

Figure C-1: Kirikkale-Mugla Shipment

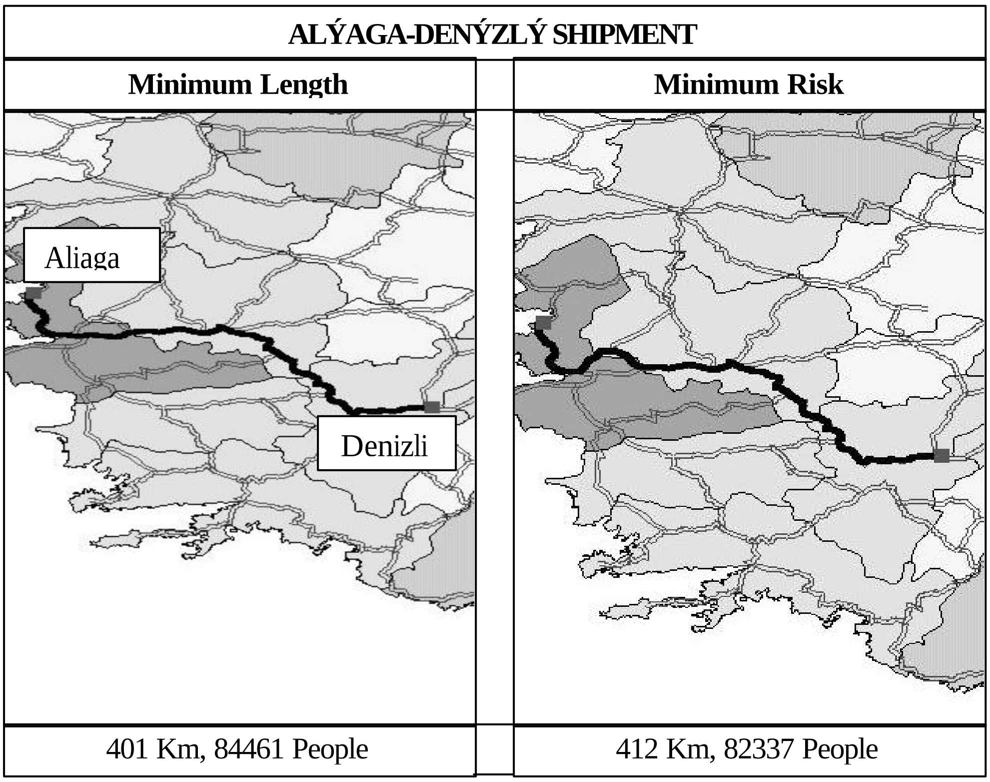


Figure C-2: Aliaga-Denizli Shipment

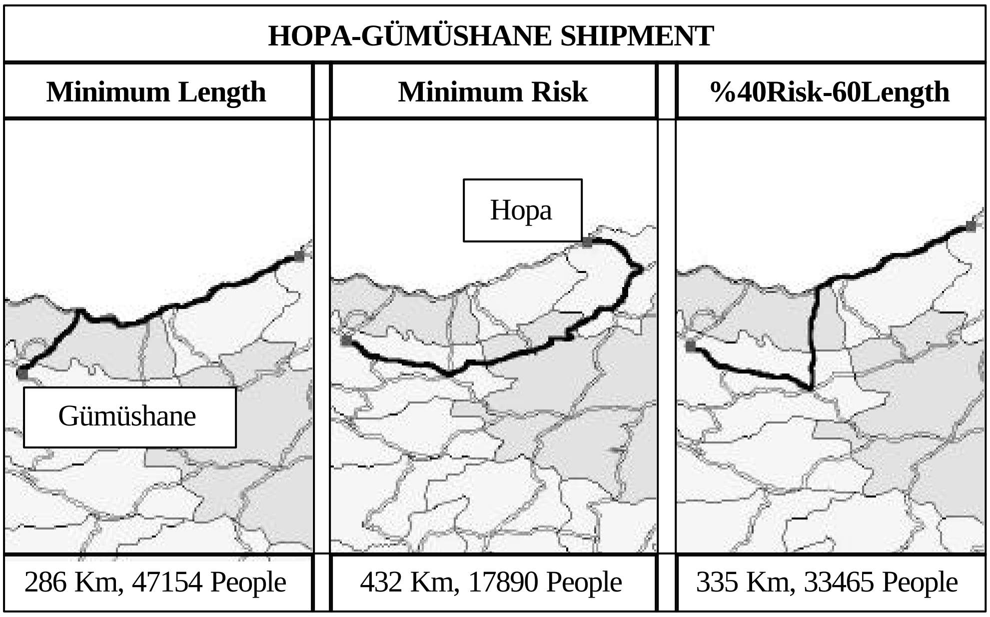


Figure C-3: Hopa-Gümüshane Shipment