A Proposed Risk Model and a GIS Framework for Hazardous Materials Transportation[1]

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***Abstract*—This paper presents a Geographical Information System (GIS) based risk assessment model for road transportation of hazardous materials (hazmat). Existing and proposed risk models are applied to truck shipments of hazmat through the road network of Istanbul. Our empirical analysis on the Istanbul road network points out that different risk models usually select different routes between a given origin-destination pair. In this study, we propose a new risk assessment model named as "time-based risk model" for hazmat transportation. We speculate that the proposed model is the most suitable one for the city of Istanbul and alike.**

***Index Terms*—Hazardous materials, Geographical Information System (GIS), Risk Assessment.**

I. INTRODUCTION

US Department of Transportation (US DOT) defines a hazardous material as "any substance or material capable of causing harm to people, property, and the environment" [1]. Many thousands of hazmat types are used daily under the main categories of explosives and pyrotechnics, compressed gasses; flammable liquids, flammable solids, oxidizers, poisons; radioactive materials, corrosive liquids, and others [1].

Hazmat transportation and its potential consequences raise public interest typically when there is a release due to an accident. Because hazmat accidents are generally being regarded as low probability – high consequence events, accidents do attract public attention when the death toll or economic losses are high. For example, as recent as in 2004, about 300 fatalities and some 450 injuries were reported due to a train derailment near the Iranian town of Neyshabour. For this reason, understanding the potential risk and threats associated with hazmat transportation is crucial for maintaining safety of the public in general and for managing the shipment operations.

As detailed in the Hazardous Materials Shipments report, hazardous materials traffic levels in the U.S. now exceed 800,000 shipments per day and result in the transport of more than 3.1 billion tons of hazardous materials annually [2]. According to Turkish Statistical Institute's transportation statistics, there are about 725,785 trucks officially registered in Turkey as of November 2007, some of which are involved in hazmat transportation activity.

Istanbul is one of the most crowded cities in the world with an official Census 2007 population of more than twelve and a half million people. Due to its location, the city is regarded by many a bridge that connects Asia and Europe. It is the leading manufacturing and trade center in Turkey with the highest production volume, number of officially registered vehicles and traffic density recorded. Also, a number of small, medium, and large size factories that use chemical materials for production are located in Istanbul. Therefore, it is very common to see trucks carrying hazmat to and from these facilities on the city's major highways as well as downtown boulevards and connecting roads. Consequently, the amount of hazmat traffic on these roads creates a major risk exposure on resident population and commercial districts of the city.

In this paper, we study hazmat risk assessment within an urban setting and propose an improved risk assessment model for densely populated cities such as Istanbul. We integrate this risk assessment model with a GIS-based framework for quantifying as well as visualizing hazmat transportation risk. We illustrate routes calculated according to routing criteria that are based on various risk assessment models, including the one we propose. Our study not only proposes an improved way of measuring risk in a populated city, but also provides a GIS decision support framework for helping authorities to determine the most suitable routing alternatives for hazmat transportation.

We have organized this paper as follows: In Section II, we review existing risk models from the literature and then we present our proposed risk assessment measure for hazmat route selection. In Section III, we present the GIS framework we have developed along with computational findings and route comparisons. This is followed by some concluding remarks in Section IV.

II. A RISK ASSESSMENT FRAMEWORK FOR HAZMAT TRANSPORTATION

A. *Modeling of Risk*

There are various methods for quantifying risk. Most commonly, risk is defined as the product of the probability of an undesirable event and the consequence of that event [3]. In the context of hazmat transportation, an undesirable event is an accident followed by the release of a hazardous substance.

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This is usually referred to as an "incident" [3]. The consequences of a hazmat release can include economic or environmental losses as well as damage to human population in the form of injuries and fatalities. In this study, we confine our discussion to risks imposed on human populations [4].

A "traditional risk model" where risk is evaluated along a path traversed by a hazmat truck is given by this formula:

$$TR(r) = \sum_{l=1}^{n} p_l c_l \tag{1}$$

This equation can be interpreted as the expected value of the consequence of a hazmat truck traveling along path r [5], given the probability p_l of an accident on segment l of path r expressed as the following function of accident rates on l:

$$P(A_l) = TAR_l \times L_l \tag{2}$$

where TAR_l is the truck accident rate (accidents per vehicle-km) along the route segment l; and L_l is the length of the route segment l [6]. Tuck accident rates for each highway class are typically computed as

$$TAR_i = \sum_{l} \frac{A_{li}}{VKT_{li}} \tag{3}$$

where TAR_i is average truck accident rate for highway class i; A_{li} is the number of accidents in one year on route segment l in highway class i; and VKT_{li} is the annual vehicle-kilometers of travel on route segment l in highway class i [6].

Hazmat trucks are generally referred to as moving "danger circles". The circular area around the truck is where the population is exposed to risk. The equation below calculates c_{lm}, the number of people in a danger circle moving along a unit road segment l, and exposed to risk due to hazmat type m:

$$c_{lm} = \pi r_m^2 d_l \tag{4}$$

where r_m is the impact radius of the danger circle along the road segment l according to hazmat type m; and d_l is the population density around the road segment l [7]. According to Emergency Response Guidebook (2004), the radius of a danger circle r_m can vary between 30 m and 11 km depending on the type of the dangerous good.

In addition to the "traditional risk model" described above, other popular models for choosing a hazmat truck shipment route take into account shortest travel distance (or time), minimum societal risk, minimum population exposure, minimum DoT (U.S. Department of Transportation) risk, minimum accident probability and minimum incident probability (the probability of a hazmat release).

Under the *Shortest Path (Time)* model, it is assumed that hazmat carriers choose to use the shortest (or fastest) path between an origin and a destination. *Societal Risk* on a road segment can be estimated as follows [3]:

Societal risk = length of the link ×
accident rate on the link (per vehicle-km) ×
conditional release probability given an accident ×
population density around the edge (persons per sq-km) ×
impact radius r (5)

Minimum Population Exposure is the number of people within the danger circle and calculated cumulatively along a path. *Minimum DoT Risk* model is similar to the societal risk definition, but there are two differences between them: the exposure zone in the DoT case is a rectangle instead of a circle, and the conditional release probabilities are not used [3]. However, in our empirical case study, we have opted for a danger circle to calculate the number of impacted people and accident probabilities when computing the minimum DoT risk.

In case of *Minimum Incident Probability* model, incident probability is calculated according to the formula

$$P(R)_l = TAR_l \times P(R|A)_l \times L_l \tag{6}$$

where $P(R)_l$ = probability of an accident involving a hazmat release on route segment l; and $P(R|A)_l$ is the probability of a hazmat release given an accident [6]. Incident probability can depend on the road types, weather conditions, traffic density and accident type, as described in [6]-[9].

Although traditional risk models are the most common evaluators of risk, use of these expressions may be incompatible with reality. That is, these models make the tacit assumption that the truck will travel along every link on the path, regardless of what happened on earlier links [5]. Reference [5] presents a more complicated path evaluation function which can replace the probability p_l of an accident on link l with the expression $(1 - p_1)(1 - p_2)\ldots(1 - p_{l-1})\, p_l$, which includes the probability that the truck travels along links 1 through $l - 1$ without accident. Hence, the relevant model formula is:

$$TR'(r) = \sum_{l=1}^{n} \prod_{j=1}^{l-1} (1 - p_j) p_l c_l \tag{7}$$

B. Proposed Risk Model

When a truck transporting hazmat is traveling on a road segment, population within the danger circle along this link is exposed to risk. We contend that the amount of exposed risk should also be a function of the total *time* it takes to traverse the link. Hence, our proposed model suggests that the risk is positively correlated with two factors: the size of population exposed to risk and the duration of the exposure. In urban settings where traffic congestions are extremely common and trucks spend more time in traffic than many traditional models assume, we think this model provides a more accurate representation of risk.

In our model, duration of risk exposure is calculated by dividing the length of the road segment traversed by the average or anticipated speed on that segment. During this duration, all population within the danger circle is exposed to risk due to hazmat type *m*. The “time-based” total risk (*TBR*) along the road segment *l* can then be formulated as:

$$TBR_{lm} = (L_l \div V_l) * c_{lm} \qquad (8)$$

Where V_l is the truck speed (e.g. km/hr) on link *l* and c_{lm} is the total population within a danger circle. In our empirical calculations, however, we take a reverse approach and calculate this risk from the viewpoint of population centers represented by point locations in a geographical region. In this case, population center data we use have such level of detail that each point location represents an individual building, and the population in that building can either be estimated or be drawn from detailed census records. In order to maintain some level of anonymity, we have chosen to use the first approach, where we allocate the total population of a district to individual buildings within the district, using another piece of data on number of households in a building. We then perform GIS operations to find out which road segments expose risk on a single building, and repeat this query for all buildings to calculate total time-based-risk exposed by all road segments.

C. Framework for Empirical Analysis and Case Study

Risk assessment of hazmat transportation by trucks is data-intensive and its analysis requires several data sources such as population density, value of property and environment that could be impacted by a hazmat truck release, length of road segments, impact radius by hazmat type, number and amount of hazmat shipments, vehicle-miles or vehicle-kilometers driven and origin-destination locations, if available, for specific routes [8]. In our study, we apply the following models on the data we have collected for the city of Istanbul, and report selected results:

- Shortest travel distance,
- Shortest travel time
- Minimum population exposure
- Minimum societal risk
- Minimum DoT risk
- Minimum incident probability
- Minimum time-based risk

In our calculations, we use the default release probabilities that are reported in [6]. These values are reproduced in Table I. Since we are dealing with this problem in an urban setting, we use urban highway values for quantifying risk.

For accident probabilities, we have elected to use the rates by different road types published for California state highways in [6], but adjusting them with a factor of 1.26. This factor is calculated as the ratio of accidents with truck involvement to the annual truck-kilometers driven, on Istanbul highways. The latter data were available from statistics published by the General Directorate of Security in Istanbul.

TABLE I

DEFAULT RELEASE PROBABILITY FOR USE IN HAZMAT ROUTING ANALYSES

Area type (1)	Roadway type (2)	Probability of release given an accident (3)
Rural	Two-lane	0.086
Rural	Multilane undivided	0.081
Rural	Multilane divided	0.082
Rural	Freeway	0.090
Urban	Two-lane	0.069
Urban	Multilane undivided	0.055
Urban	Multilane divided	0.062
Urban	One-way street	0.056
Urban	Freeway	0.062

To perform all the calculations and analysis we report in this paper, we have used a widely available GIS software package named ArcInfo 9.2. This software, along with other applications included in the product suite, allows us to create, visualize, analyze and in general manage all geographic data. ArcMap, which is the main application of ArcInfo 9.2 provides mapping as well as location-based querying and analysis functions. ArcMap presents geographic information as a collection of layers and other elements in a map view.

The required data needed for hazmat risk calculations are stored in the attribute table of each geographic layer. These attribute tables consist of columns and rows of textual or numeric information, much like Microsoft Excel worksheets.

In our empirical analysis, we have used Istanbul highway network and building XY coordinate data obtained from Istanbul Metropolitan Municipality. These data are incorporated into ArcInfo as two geographical layers and then visualized as a map using the mapping application ArcMap. An overall view of the Istanbul, with the street network and the highway network, can be seen in Figure 1.

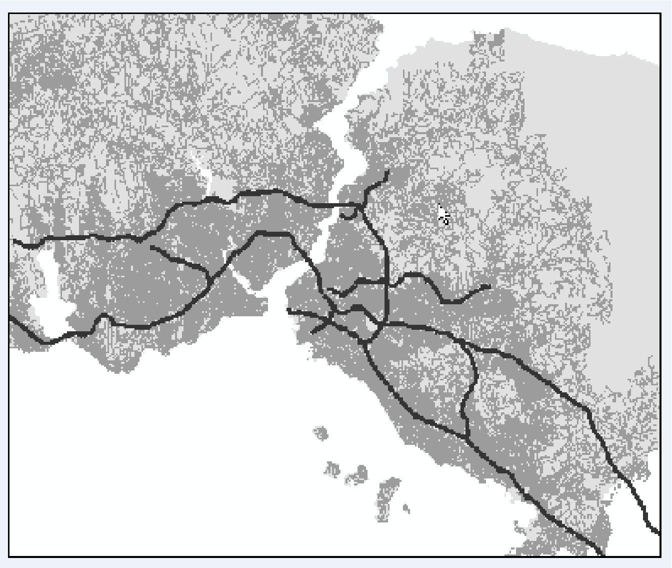
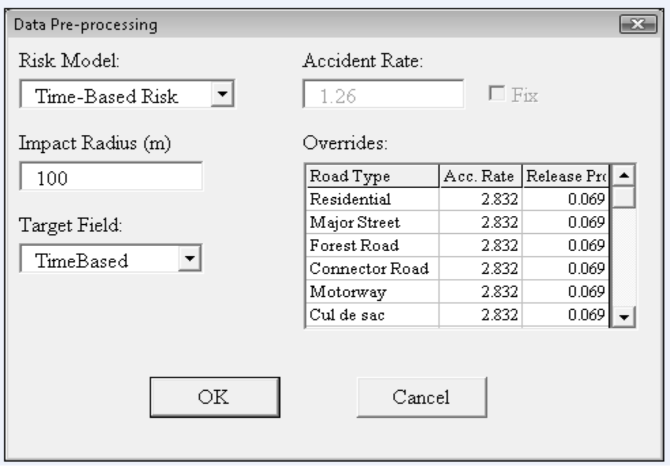


Fig. 1. Overview of Istanbul with its road network

To calculate hazmat transportation risk, first we have completed a data preparation step, where we calculated, through the use of VBA (Visual Basic for Applications) macros in ArcMap environment, impedance values for road segments. A screenshot of the graphical interface we have created to automate this process is provided in Figure 2.



Data Pre-processing

Risk Model: Time-Based Risk

Accident Rate: 1.26

☐ Fix

Impact Radius (m) 100

Target Field: TimeBased

Overrides:

Road Type	Acc. Rate	Release Pr
Residential	2.832	0.069
Major Street	2.832	0.069
Forest Road	2.832	0.069
Connector Road	2.832	0.069
Motorway	2.832	0.069
Cul de sac	2.832	0.069

Fig. 2. Data Preparation Screenshot

The impedance values we have calculated at this step basically correspond to the seven risk measures listed previously. These models take input parameters such as impact radius and accident rates wherever applicable.

To calculate the risk impedance values based on the time-based risk model proposed in this paper, we have taken a more detailed approach using some of the tools available in the GIS framework. For each building point location, we have created a circular zone (or “buffer”) around the location. Then we have performed a “clip” operation to extract the road segments that fall within the zone. Each road segment found this way is such a road that when a truck travels on it, the building location is exposed to time-based risk. We cumulatively calculate total risk (sum of all {time × population} terms) associated with all these road segments, applying this method to each building location. The speed values (by road type) we have used in this process are listed in Table II.

TABLE II
TRUCK SPEED VALUES FOR USE IN HAZMAT ROUTING ANALYSES BY ROAD TYPE

Area type (1)	Roadway type (2)	Speed values (km/hr) (3)
Urban	Two-lane major street	50
Urban	Two-lane-residential	30
Urban	Multilane divided	70
Urban	Connector road	50
Urban	Freeway/Motorway	80

For some of the remaining models (minimum population exposure, minimum societal risk and minimum DoT risk), we used buffering tools available in GIS to create buffered zones around road segments. Using these buffered zones, we have estimated the total population around the road segment by means of certain spatial query functions of the GIS software.

In the end, our data preparation step has concluded with impedance values calculated and stored for each road segment under each of the seven risk criteria. These impedance values are used in path generation in the second phase of the computational analysis, which is detailed in the next section.

III. COMPUTATIONAL RESULTS

In our computational study, we have first attempted to create a visual appreciation of the “risk map” of Istanbul and understand the “distribution” of risk. In many places throughout the city, industrial zones are mixed up with residential areas, and hazmat shipment to/from facilities in these areas (e.g. gas stations, factories) is very much likely. For this reason, we have elected to study a specific part of Istanbul that has a dense residential population mixed up with occasional industrial zones or facilities.

For the study area that we picked, we have created the risk exposure map as shown in Figure 3, using our proposed time-based risk model. The road segments or areas that are shown in darker colors in Figure 3 indicate areas where risk exposure on the population is higher, and therefore such roads should be avoided by hazmat trucks. Because our risk measure combines duration of travel along a road segment with the population around it, roads with lighter color either have high travel speeds (as in motorways) or little population within their impact radius. To generate this risk map, we have calculated buffers with impact radius of 100 meters, for approximately 100,000 building locations.

Fig. 3. Risk Exposure Map of an Istanbul district with time-based risk model.

The next step we have taken in our computational study was to investigate the impact of these several risk models on actual routes to be used by trucks. Figure 4 shows routes generated using four of these models (shortest travel time, minimum societal risk, minimum time-based risk, and minimum population exposure). The origin location selected in this case is a facility located in the industrial part of the region we are studying, and the destination is a gas station to which gasoline and LPG must be delivered.

From Figure 4, it is clear that different routes are likely to be generated for hazmat delivery based on different criteria. Because the road segment impedances are different under each risk model, the resulting "shortest" paths between the origin and destination are different. This may seem as a disadvantage for the city planners or the decision-making authority, which might be looking for *the* route that minimizes risk. However, in our opinion, this is advantageous in that it provides the decision-maker many alternatives to choose from. Instead of allowing trucking companies to pick their delivery routes (which are typically chosen as the shortest or fastest routes), city planners can offer one of these alternatives as long as they are consistent with one another in terms of measuring the risk exposure. While trucking companies are likely to object to any route offered by the city planners other than the time- or distance-minimizing one, availability of a set of routes with measurable amounts of risk will nevertheless help city planners develop policies, ordinances, etc.

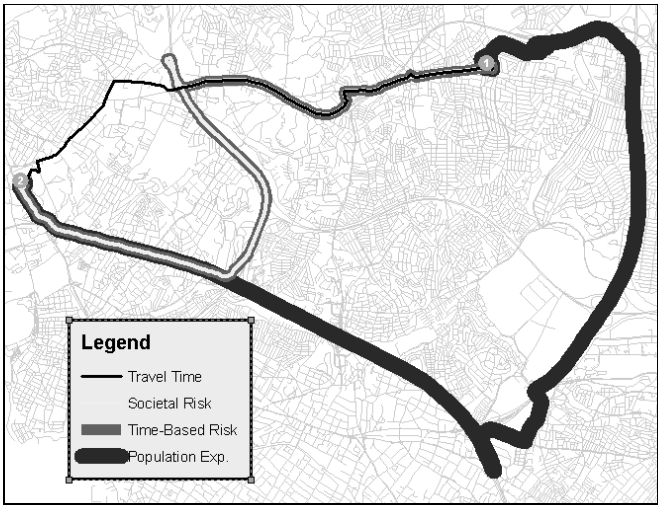


Fig. 4. Comparison of paths generate with multiple risk models

To compare routes generated using various models, one can optimize the route under one risk model, while collecting the statistics under the remaining models. We have generated this information in Table III for the four routes that are shown in Figure 4. This information allows the decision maker to see how a route optimized by one criterion is performing against the other criteria. In our case, for instance, the route that has minimum population exposure (50035 people) has a time-based risk measure of 4542.5 people-minutes, and this value is the largest value among all four routes. This is an interesting result, considering the fact that this route (indicated by thick black line) follows major highways. Although population exposed along the route is at minimum and the travel speeds along the path are relatively high, the route is long enough that it does not perform well according to the time-based risk model.

TABLE III
HAZMAT ROUTE COMPARISON
BY RISK MODEL

Optimized by	Travel Time	Societal Risk	Time Based	Population Exposure
Travel Time	8.5	1000.5	3839.6	81272
Societal Risk	11.5	806.1	2921.5	65828
Time-Based	11.5	806.2	2912.3	66100
Population	16.9	1207.4	4542.5	50035

IV. CONCLUSION

In this paper, we have studied risk assessment models for hazardous materials transportation and proposed a new model that we think is more suitable in an urban setting. Because our model is based on the amount of time (or duration) the population is exposed to risk, it is more realistic in cases where traffic congestions and reduced travel speeds are common. The GIS framework we have used has allowed us to process the data at a greater level of detail and also to perform routing analysis to generate and compare alternative routes. The framework is also an interactive environment where the analyst can change road network settings (such as travel speeds, open/close roads, add routing restrictions such as barriers) and assess the impact on risk exposed. For instance, by introducing congestion in an area during the rush-hour, an analyst can evaluate the amount of increased risk, and using this information, the decision maker can dictate routes. Further interaction might be possible by allowing the analyst to designate parts of the city (e.g. by drawing polygons) as inaccessible to truck traffic at different times of the day. The information collected in this environment in this manner can even be used for decisions such as locating emergency response teams at the most critical locations.

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