Development of a GIS-Based Hazardous Materials Transportation Management System

A Demonstration Project

Samina T. Panwhar and Robert Pitt
Department of Civil and Environmental Engineering
University of Alabama at Birmingham
Birmingham, Alabama 35294

Michael D. Anderson
Department of Civil Engineering
University of Alabama in Huntsville
Huntsville, Alabama 35899

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16. Abstract

There has been a significant growth in the amount of hazardous materials transported within the US during the past few decades. More than 90 percent of these shipments are transported by trucks on the nation's highways. During recent years, there has also been a significant increase in the number of accidents involving hazardous materials transportation. This has compelled planners and engineers to address many issues related to the transportation of these materials, including optimizing routes to decrease the risk associated with any accidents. This report presents the development and a simple demonstration of a geographic information system (GIS) based hazardous waste transport system that is intended to reduce the impact of potential incidents regarding hazardous waste shipments through an urban area.

The methodology demonstrated in this report uses a probabilistic risk assessment framework, which takes into account the probability of accidents for each road segment and the consequences of an accident, as route selection parameters. The facilities most vulnerable to the impact of accidents, such as schools, hospitals, and day care centers, are considered and should be avoided to the extent practical in the routing of hazardous materials. Vulnerability of the facilities is calculated as a function of the distance of the facilities from the transportation routes and the population of the vulnerable facility.

The system uses ArcView 3.2 GIS to perform spatial analyses to assist the optimization procedure. Network Analyst 1.0b, an extension of ArcView GIS, is used as a 'best routing' engine to calculate the safest route for the transportation of hazardous materials. The system is written in Avenue scripting language, which is the built-in object-oriented language for ArcView. The model calculates the risk for each segment, using a simple set of site conditions based on the risk analysis model, and then selects the optimized route for transportation of hazardous materials.

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Executive Summary

During the past few decades there has been a significant growth in the amount of hazardous materials transported within the US. More than 90 percent of these shipments are transported by trucks on the nation's highways. During recent years, there has been a significant increase in the number of accidents involving hazardous materials transportation. In addition, there had been an increase in public awareness for the potential risks associated with the transportation of hazardous materials. All of this has compelled planners and engineers to address many issues related to the transportation of these materials. Optimizing routes for transportation is one way to decrease the risk. This report presents the development and a simple demonstration of a geographic information system (GIS) based hazardous waste transport system that is intended to reduce the impact of potential incidents regarding hazardous waste shipments through an urban area.

This methodology uses a probabilistic risk assessment framework, which takes into account the probability of accidents for each road segment and the consequences of an accident as route selection parameters. The facilities most vulnerable to the impact of accidents, such as schools, hospitals, and day care centers, are considered and should be avoided in the routing of hazardous materials. The demonstrated model considers the accident rates for each road segment and the locations of these vulnerable facilities. Vulnerability of the facilities is calculated as a function of the distance of the facilities from the transportation routes and the population of the vulnerable facility.

The system uses ArcView 3.2 GIS to perform spatial analyses to assist the optimization procedure. Network analyst 1.0b, an extension of the ArcView GIS, is used as a 'best routing' engine to calculate the safest route for the transportation of hazardous materials. The system is written in Avenue scripting language, which is the built-in object-oriented language for ArcView. The model calculates the risk for each segment, using a simple set of site conditions, based on the risk analysis model and then using Network Analyst. The model then selects the optimized route for transportation of hazardous materials.

This model demonstrates how different parameters can be easily modified to reflect specific attributes of each risk element, such as by modifying the weighting and importance of the different elements and by applying more complex relationships between distance and risk.

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Section 1
Literature Review, Introduction and Background

During the past few decades there has been a large growth in the type and the amount of hazardous materials transported within the United States. The reason is quite apparent as hazardous chemicals are widely used in industry, agriculture, medicine, research, and even in consumer goods. These materials come in the form of explosives, flammable and combustible substances, poisons, and radioactive materials. Because of the amount and complexity of these materials and the drastic incidents that have occurred in the past, citizens, industry, and governmental agencies have become increasingly concerned about the risks associated with transporting these materials.

Hazardous Materials

Hazardous wastes and hazardous substances are groups of materials identified by the U.S. Environmental Protection Agency (EPA). Hazardous wastes are designated by EPA under the Resource Conservation and Recovery Act (RCRA), 42 U.S. Code 6901. Hazardous substances are designated under the Clean Water Act, 33 U.S. Code 1251, and the Comprehensive Environmental Restoration, Compensation and Liability Act (CERCLA, or Superfund), 42 U.S. Code 9601. Hazardous material is defined as any material that could present a danger during shipment by ground, air, sea or any other mode of transportation such as pipe line. An example would be the transporting of explosives from one place to another. Hazardous waste, on the other hand, is defined by the Resource Conservation and Recovery Act (RCRA) legislation (1976) as:

> "A solid waste, or combination of solid waste, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may (a) cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or (b) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed".

All of these statutes apply to all facilities that handle such materials, including fixed facilities, rolling stock, vessels, vehicles, and other transportation facilities.

Laws Governing Shipments of Hazardous Materials

The Hazardous Materials Transportation Act of 1975 (HMTA) as amended, is the major transportation-related statute regulating the transportation of hazardous materials. The objective of the HMTA, according to the policy stated by Congress, is "to improve the regulatory and enforcement authority of the Secretary of Transportation to protect the Nation adequately against

risks to life and property, which are inherent in the transportation of hazardous materials in commerce."

In 1990, Congress enacted the Hazardous Materials Transportation Uniform Safety Act (HMTUSA) to clarify the maze of conflicting state, local, and federal regulations. Like the HMTA, the HMTUSA requires the Secretary of Transportation to promulgate regulations for the safe transport of hazardous material in intrastate, interstate, and foreign commerce. The Secretary also retains authority to designate materials as hazardous when they pose unreasonable risks to health, safety, or property. In October 1994, the Federal Highway Administration (FHWA) issued a rule, which established standards for the designation of such routes.

Significance of Road Transportation
In the U.S., there are over 500,000 shipments of hazardous materials made every day [1]. More than 90 percent of these shipments are transported by truck on the nation's highways. At any given time, 5 to 15 percent of the trucks on the road are carrying hazardous materials regulated under the Hazardous Materials Transportation Act of 1975 (HMTA). Almost 50 percent of these materials are gasoline and other corrosive or flammable petroleum products, and 13 percent are chemicals. The remaining shipments represent any of the 2,700 chemicals considered hazardous when transported in interstate commerce. Table 1 and Figure 1 shows the US hazardous waste incidence statistics by mode from 1992 to 1999 [2]. By far, the highest number of incidents occurred on highways, with railway accidents a distance second. The number of deaths, injuries and monetary damages were also the highest for highway transportation of hazardous materials. However, the monetary damage amounts are much closer for rail and highway accidents than when the incident numbers alone are compared due to the much larger individual accidents that occur with railway accidents.

Table 1. Hazardous Waste Incident Statistics by Mode and Reporting Year [2]

Mode	1992	1993	1994	1995	1996	1997	1998	1999	Total
Incidents by Mode									
Air	1	1	1	0	0	2	3	2	10
Highway	377	549	519	652	424	379	378	402	3,680
Railway	33	23	27	24	34	38	40	32	251
Water	0	1	0	0	0	0	0	0	1
Other	0	0	0	0	0	0	0	0	0
TOTALS	411	574	547	676	458	419	421	436	3,942
Deaths by Mode									
Air	0	0	0	0	0	0	0	0	0
Highway	0	0	0	0	1	0	0	0	1
Railway	0	0	0	0	0	0	0	0	0
Water	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0	0
TOTALS	0	0	0	0	1	0	0	0	1
Injuries by Mode									
Air	0	0	0	0	0	0	2	0	2
Highway	50	5	4	23	10	9	4	21	126
Railway	1	0	1	1	3	1	1	6	14
Water	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0	0
TOTALS	51	5	5	24	13	10	7	27	142
Damages by Mode (in Dollars)									
Air	0	1	0	0	0	75	5,175	2,000	7,251
Highway	1,132,085	832,944	1,153,436	1,612,542	1,861,803	3,376,202	872,908	1,270,616	12,112,536
Railway	67,487	63,789	1,296,204	466,580	43,960	35,520	29,645	1,071,257	3,074,442
Water	0	17,630	0	0	0	0	0	0	17,630
Other	0	0	0	0	0	0	0	0	0
TOTALS	1,199,572	914,364	2,449,640	2,079,122	1,905,763	3,411,797	907,728	2,343,873	15,211,859

Figure 1. Hazardous materials incidents, 1985-1999 [2].
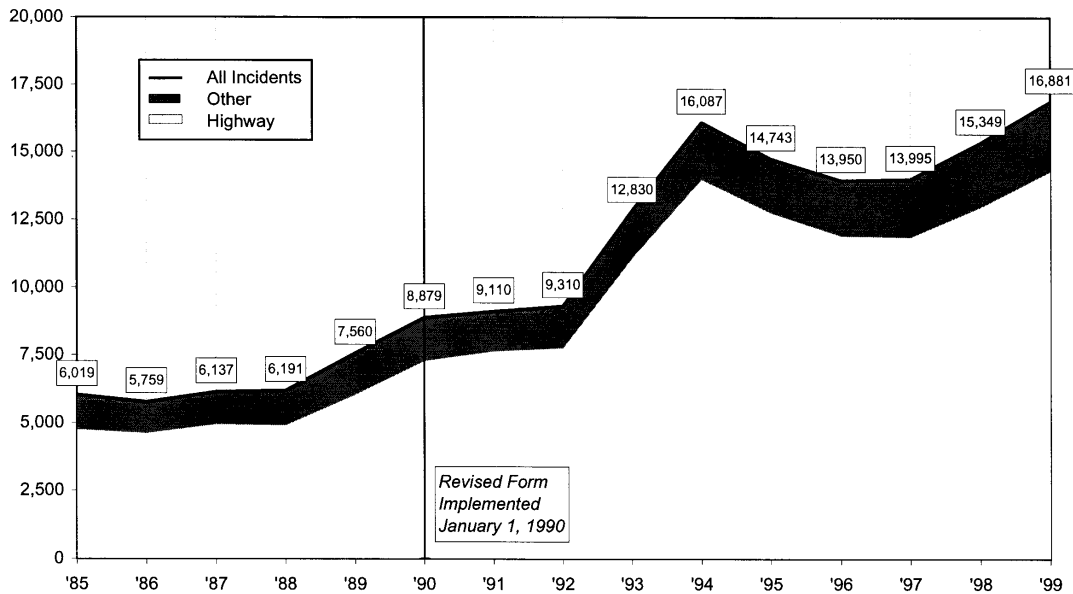
While there is little data available for the State of Alabama, it is estimated that over 20,000 shipments carrying hazardous materials are made every day. As Alabama industries continue to grow and as more hazardous materials are transported into the State (Alabama is currently a "net importer" of hazardous materials), increased amounts of hazardous materials will be transported on Alabama roads and highways.

Alabama's status as a net importer of hazardous waste and the enormous adverse impacts on the environment and human health associated with incidents involving the release of hazardous materials combine for a potentially dangerous situation. In an attempt to increase public safety during hazardous waste shipments, this research develops and demonstrates a low-cost, portable, easy-to-use, hazardous waste transport system to identify routes which minimizes potential impacts of incidents resulting in possible spills of hazardous materials from the point source origin to destination (landfills, waste-to-energy, recycling plants or reprocessing plants). While many of the characteristics used in the example problems are hypothetical, they do illustrate how the system can be easily modified to reflect accurate site-specific information.

Accidents/Incidents and their Impacts
Transportation incidents can occur during the loading, unloading, transportation or temporary storage of hazardous materials. Incidents are spills or releases of hazardous materials from transport containers. Accidents can be defined as vehicle collisions with another vehicle or object, vehicle turnovers, or vehicles unintentionally leaving the highway [3].

It is important to understand that various groups bear differing risks associated with the movement of hazardous materials [4]. The following are some examples of actual accidents from National Transportation Safety Board records, which may help to identify these groups:

- An accident at East St. Louis, Illinois, in 1973 resulted in injuries to 247 persons in an explosion of the contents from a single tank car. Over 230 of the injured were <u>residents</u> of the community in which the incident occurred.

- Six <u>crewmen</u> died when spilled gasoline vapors on a barge ignited during the transfer of the cargo to a shore side facility.

- Thirteen <u>passengers</u> were fatally injured at a grade crossing when a railroad passenger car struck a fuel truck at a grade crossing, and fire engulfed the car.

- Four <u>occupants</u> of an automobile died after prolonged exposure to an escaping toxic mixture following a car truck collision on a quiet rural road in Florida.

- Over 60 <u>firemen</u> were injured when a fire and explosion erupted at Crescent City, Illinois, following a railroad derailment.

These incidents illustrate that bystanders, operating crews, passenger joint occupant, and emergency response groups are at risk during transportation of hazardous materials.

Routing Design

Historical evidence has shown that the risks arising from the transportation of hazardous materials are often of the same magnitude of those at fixed installation sources. Thus, it is extremely important to pay the same attention and make appropriate routing decisions. The National Governor's Association (NGA) produced a report in 1989 [5] that focused on coordinated federal and state regulatory enforcement systems regarding hazardous materials transportation by all modes. The report surveyed agencies in all 50 states and found that of those responding only 14 had designated highway routes. Virtually all states surveyed by NGA reported that funding for hazardous materials transportation programs and personnel is an overriding need. Another paper, presented by Novak [6], discussed the views of local governments regarding hazardous materials transportation legislation. The author stated that most mid-size to smaller cities and rural areas are slow in responding to statutory provisions and need the most training and equipment.

Geographic information systems (GIS) are widely used in risk analysis in the transportation of hazardous materials. GIS models help in quantifying the risk and provide better accuracy in analyzing the risk considering various parameters. The Oak Ridge National Laboratory is supporting the Department of Energy (DOE) in development of the Transportation Routing Analysis Geographic Information System (TRAGIS), a user- friendly GIS-based transportation and analysis model. Primary reasons for development of TRAGIS are to improve the ease of

selecting locations for routing, graphically displaying the route calculated, and to provide for additional geographic analysis of the route.

Geographic Information

Geographic information (GI) is "information which can be related to a location (defined in terms of a point, area or volume) on the Earth, particularly information on natural phenomena, cultural and human resources."[7] The positional data can be a specific set of spatial coordinates, or can cover less precise locations or areas, such as addresses, postal codes or administrative boundaries, regions or even whole countries. Most GI also includes a time dimension, since the world is not a static place.

GI can be divided into two major classes: *base data* (sometimes called *core data* or *framework data)*, which are necessary for most applications, and application-specific data, sometimes referred to simply as *thematic data.*

Base data may include:

• the basic geodetic frameworks for determining geographic location,

• elevation data,

• thematic data on the location of natural objects, such as rivers, coasts and lakes, and anthropogenic features such as roads, railways, towns and cities, and

• administrative boundaries at national, regional and local levels (e.g. NUTS boundaries and post-code districts), and

• linkage data, permitting non-spatial data to be more easily analyzed spatially (e.g. relating addresses to coordinate systems).

Application specific data covers all other kinds of GI that may be used in one application but not in all applications. Examples include socio-economic data from planning studies and censuses and natural resource data such as soil information or groundwater quality, or special purpose versions of the base data (e.g. the use of road center lines for auto navigation). Application specific data are largely thematic and may range from measures of reflected radiation captured by remote sensing sensors to data on utility networks to information about land ownership, land use and natural resources, or demography and health.

Base data have long been collected and distributed in analogue form by national organizations. Today, these data are widely available at the national level in digital form. By means of computerized *Geographical Information Systems (GIS)* they can be exchanged, used, modified and combined with other spatial and non-spatial data in an unlimited number of ways. However, such exchange, conversion and integration are not always a straightforward activity. Identifying ways and means to better re-use existing GI data is also important and will lead to increased market size by permitting new information products and services to be created at lower cost.

Why GI is Important

The ability to relate information on activities and resources to a spatial location and to monitor or predict changes over time is fundamental to modern society. In this respect, the importance of socio-economic data, such as that produced by national censuses, cannot be overstressed. International, national, regional and local governments use GI for a host of applications from defense and policing activities through regional planning, strategic studies for renewable energy resources, environmental management and risk avoidance through urban and rural policy decisions to day-to-day operational activities such as land registration, property taxation or routing of traffic. Industry and commerce use GI in many ways. Utility companies (power, gas, water, and telephone) are major investors in digital GI technology for managing and monitoring their supply networks, often on an international basis. Businesses use GI together with other economic information to determine optimal delivery routes, the location of potential markets or the site of outlets or factories. Constructors of major infrastructure (roads, railways, and bridges) use GI to estimate the amounts and costs of material needed. In sectors such as agriculture, forestry, water resources or mining, GI is used to assess yields and management strategies. In service industries, GI is used by consultants to advise on how to improve business efficiency, or to provide services for tourism and transport. In social investigations, GI is used to help analyze spatially varying attributes of the population such as income, crime, health or the quality of housing. GI is used in a wide range of practical environmental issues from global warming and sea level rise to erosion, flooding and soil, air and water pollution.

Geographic Information System, GIS

A GIS is a computer-based tool for mapping and analyzing things that exist and events that happen on earth. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps (Figure 2). These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies.
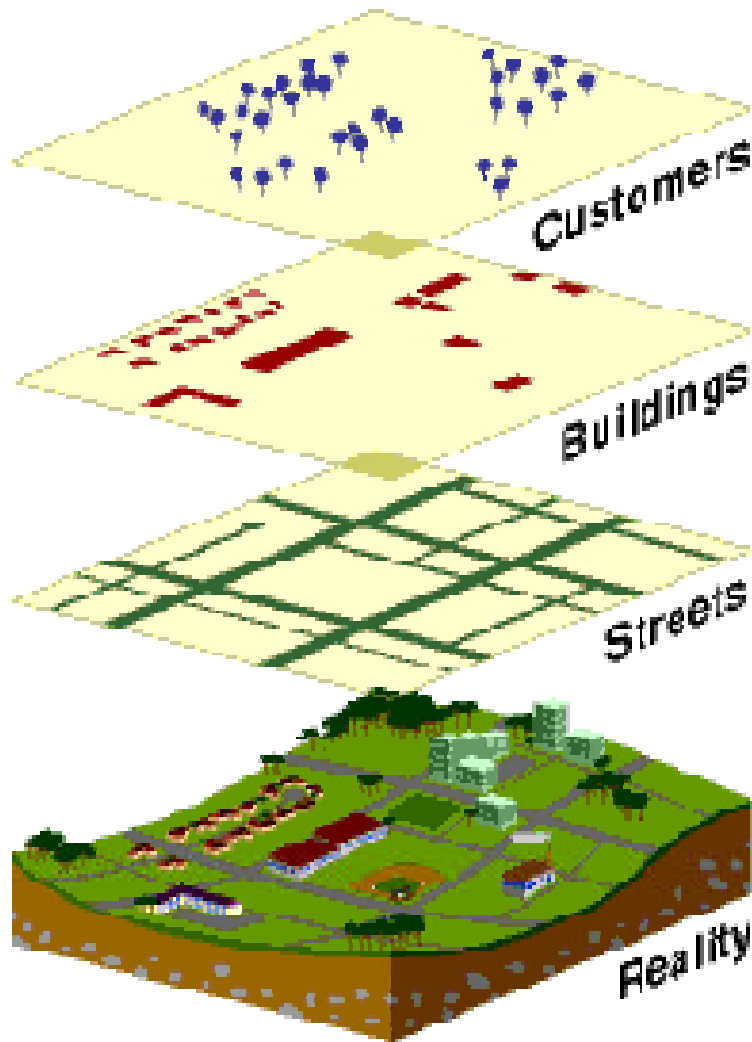
Figure 2. Common data base information compared to reality [Graphic provided courtesy of ESRI and is used herein with permission. Copyright ESRI. All rights reserved.].

GIS provides a useful set of tools for planning, decision-making, operations management and inventory. GIS is now being employed in a wide range of applications including urban and regional planning, environmental risk analysis, forest management, hazard analysis, emergency response, marketing, transportation planning, wildlife management, agriculture, and health care management. A working GIS integrates five key components: hardware, software, data, people, and methods.

Data types used in GIS
Two types of data structures, vector and raster, are commonly used to store and represent geographic information (Figure 3) [17].

Figure 3. Raster and vector representations of real world data [17].

Vector data represents geographic entities by means of an x-y coordinate system. Raster data uses a matrix of cells, which form a grid. Each method has certain advantages depending on the type of information being stored, and on the intended application.

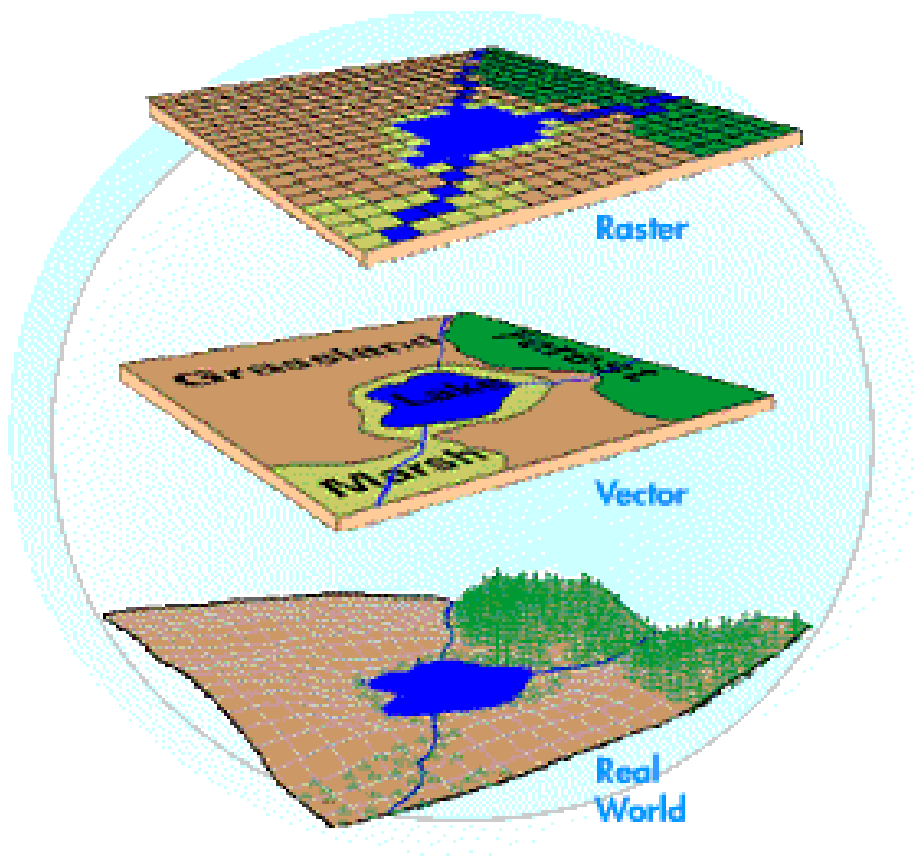In a vector structure, geographic entities are represented as points, lines, and areas mapped onto a flat, 2-dimensional surface. An object's location on the surface is referenced to an x-axis and a y-axis radiating from a common origin. Each point is identified by a single x-y location; lines are identified by a sequence of x-y coordinates; areas are identified by a series of x-y coordinates defining line segments that close to form a polygon, or multi-sided area. Using this method, any spatial entity can be represented as a list of x-y coordinates.

In a raster representation, a matrix or rectangular array of cells is used to represent geographic information. Where image data are stored in a raster representation, cells are termed picture elements, or pixels. Where other spatial data are stored as a raster representation, the cells are termed grid cells. In either case, the grid is organized into rows and columns that are referenced to a common origin. Each pixel is assigned a value representing a geographic phenomenon such as elevation, land use, or population density. The raster structure is also used in image data such

as scanned maps and aerial photographs, or satellite imagery. In the case of image data, cell values typically represent reflectance or brightness as opposed to geographic entities.

This research project is also a PC-based application program utilizing a GIS to identify travel routes for the transport of hazardous materials. ArcView GIS, a GIS software, is used to store roadway data and other socio-economic data for Jefferson county, Alabama, identifying sensitive locations as well as to integrate them and develop the safest route. The routing analysis uses a combination of roadway length, length of time in transit, population exposure and proximity to sensitive area within the state such as schools, day care centers, retirement homes, and hospitals. It also considers the timing of the day for the specific facilities as the exposure greatly varies with different timings of the day. For example, most of the schools will be at highest risk during 7:00 am to 3:00 pm, whereas at off-peak hours and holidays, the risk associated with these facilities will be minimal. This system is designed to select the safest route for transporting hazardous materials with different impact characteristics and it compares that route with the shortest route.

An Overview of ArcView GIS
ArcView GIS is the software for desktop GIS and mapping. ArcView has the capability to explore, query, and analyze the data geographically. ArcView comes with ready-to-use data, which can be used to create various maps and to solve problems by uncovering and analyzing trends and patterns. Additional data that can be used with ArcView is available from many organizations working on the development of GIS databases. It has many extensions that allow it to be geared towards individual needs. These extensions are add-on programs that provide specialized GIS functionality. ArcView comes with its own integrated object-oriented programming language and development environment called Avenue. By programming in Avenue it is possible to automate individual tasks, customize ArcView's user interface, or create complete ArcView applications.

Section 2
Literature Review on Risk Analysis

Criteria for Risk Analysis

Aspects of the risk in transportation of hazardous materials might be divided into two factors:

1) The likelihood of various accidents occurring.

2) The damage caused by an accident that does occur.

Sometimes it is assumed that "reducing the risks" can be accomplished by reducing the probability of an accident occurring. However, we must clearly also include the possible consequences when attempting to reduce risk.

Consideration of various parameters in routing of hazardous materials has been a crucial issue. Using these parameters with equity is even more complex. The regulatory requirement (49CFR, Subtitle 3) in highway routing of hazardous materials include [8]:

- population densities
- the types of highways
- the types and amounts of hazardous materials
- emergency response capabilities
- the results of consulting with affecting persons
- exposure and other risk factors
- terrain considerations
- the continuity of routes
- alternative routes
- the effects on commerce
- delays in transportation and
- other factors the Secretary considers appropriate

Chemical Dispersion Modeling

Dispersion modeling is one of the tools that can be used to predict the spread of an air contaminant during an emergency response to an accidental release of hazardous materials. When a pollutant is released to the atmosphere, it is most concentrated near the source. For a gaseous pollutant, the concentration in the air near the source depends upon a chemical characteristic, vapor pressure, which is the tendency of a substance to evaporate to the

atmosphere. There are five main weather factors that determine how a given chemical will disperse in the atmosphere:

- Temperature - the higher the temperature, the faster the substance will evaporate from the source of the release to the surrounding air.

- Wind Speed - the higher the wind speed, the greater the rate of spreading out of the chemical plume downwind away from the release. The extent of the geographic area covered by a plume of the chemical is directly related to wind speed.

- Wind Direction - the direction of the wind will determine which geographic areas are affected by the plume of the chemical released to the atmosphere. Wind direction at the scene of a release is fickle. Localized wind can vary considerably in direction at any given time.

- Presence of an inversion - the stability of the atmosphere, refers to the degree of vertical mixing that occurs which will affect the degree to which the pollutant is diluted. In the most stable atmospheres - known as atmospheric inversions - there is a "lid" on the atmosphere that causes minimum mixing of the atmosphere close to the ground. This results in a more highly concentrated plume of the chemical that stays closer to the source of the release. Atmospheric inversions require special modeling considerations.

- Humidity - Some chemicals are soluble in water vapor; hence, the higher the humidity, the higher the concentration of the chemical in the atmosphere close to the ground.

The topography of the terrain downwind of the release affects the way that the pollutant is spread and distributed into the community. This consideration is referred to in models as ground roughness. In general, there are two extreme categories that need to be considered with regard to ground roughness:

- Obstructions - the presence of hills, buildings or other structures in the path of a plume of a chemical dispersing from a release will tend to keep a higher concentration closer to the source (with pockets of high concentration accumulating on the windward side of valleys or building walls). This condition is sometimes referred to as the "urban" condition.

- Flat terrain - a flat open terrain (e.g., the Great Plains" type of landscape) will carry the slug of chemical in the plume farther away from the source (affecting a greater area) and dilute it more (resulting in less dangerous concentrations). This is sometimes referred to as the "Rural" condition.

In addition to categorizing ground roughness as one of the two extremes described above, some dispersion models allow the input of specific ground roughness factors that are determined in the field.

The following chemical characteristics of the chemical involved in the release need to be considered in the running of the dispersion model:

• Chemical Identity - the specific identity of the chemical needs to be known and the chemical must be present in the database of the model. It is important to note that there are some substances that can not be modeled. Each dispersion software package has its own limitations on the database of substances that can be predicted by the model. For example, the ALOHA model utilizes a database of approximately 900 chemicals that are commonly involved in a release.

• Concentration - the concentration of the chemical at the source of the release must be known. In general, the substance that is being released will either be fully concentrated (e.g., the release of ammonia at 100%) or some dilution of the chemical (e.g. 33% sulfuric acid in a puddle evaporating to the atmosphere).

• Physical state - the chemical that is released to the atmosphere, if it is a liquid or a gas. This is a fundamental question that needs to be input into the model.

• Vapor pressure - this chemical characteristic determines how fast the substance evaporates to the atmosphere. This is not a specific parameter that needs to be entered into the model, as this characteristic is part of the model's chemical database.

• Toxicity and flammability limits - the modeler needs to know the concentration of the chemical that is deemed to be hazardous. This is the key judgment that needs to be made by the modeler and requires a knowledge of which standard to use - for example, "Immediately Dangerous to Life and Health," "Short Term Exposure Limit," "Lower Explosive Limit" or some combination of health and flammability standards. This will be the key input by the modeler and it determines the limit of what constitutes a "hazardous atmosphere" that will be predicted by the dispersion run.

In 1997, the Environmental Protection Agency (EPA) distributed a copy of the public domain chemical dispersion model, "ALOHA" to each LEPC (Local Emergency Planning Committees) in the nation which requested this software. The ALOHA dispersion model was designed by the National Atmospheric and Oceanic Administration (NOAA) specifically for predicting the geographic spread of a hazardous atmosphere resulting from accidental releases of hazardous materials.

Risk Analysis Models
Hazardous materials transportation decisions involve a number of decision-makers and require the consideration of multiple and sometimes conflicting objectives. Models found in the hazardous materials routing literature can be classified according to the number of criteria used to determine the best paths between origins and destinations. If only one criterion is used, the models are characterized as single-objective optimization problems, and the shortest path problem is used to find the best path connecting the origin-destination pair. When more than one criterion is used for routing of hazardous materials, the models are characterized as multicriteria

decision-making problems. Multicriteria routing models can be used to study tradeoffs between conflicting routing objectives.

The need to consider multiple criteria in the decision usually means that it is generally not possible to identify a single "best" route (i.e. a route that performs better than all other routes with respect to each criterion) [9]. Rather, the goal is to identify the set of "non-dominated" or "Pareto-optimal" routes so that trade-offs between different objectives can be represented explicitly. It is also important to note that the performance of the links in the transportation network with respect to each of the criteria may change throughout the day. For instance, accident rates are widely understood to be higher at night than during the day.

The need for multi-objective criteria has been focused while defining the arc costs in routing the hazardous materials [10]. Leonelli, Bonvicini, and Spadoni explain that if the minimization of risk is the sole criterion, then routes obtained are more than twice as long as the fastest alternative and so not feasible for financial reasons. In some cases the various objectives have been added, after combining them with weight factors whose values reflect the relative importance of each criterion; while in others they have been converted into constraints, after arbitrarily establishing threshold values for each of them. They argue that the weak point of these approaches to the routing problem consists in fixing the values of the weight factors or the thresholds; in fact, calculations have shown that different weights (or different threshold values) can produce different optimal routes, highlighting that the determination of the optimal path is strongly dependent on the decision-maker, who has to fix the value of weights and thresholds. They have simplified the costs in two basic categories: "truck operating cost TOC" (out-of-pocket expenses) and "risk-related costs." Based on these two categories, they have developed a computer model, which calculates the optimized route.

Sandia National Laboratories has software tools for Multiobjective Spatial Analysis (MOSA). MOSA can be used to discover, display, and compare a range of solutions that satisfy a set of objectives to varying degrees [11]. Researchers at Argonne National Laboratories (ANL) have developed the RISKCHEM Modeling System, which is composed of several previously developed chemical accident models. RISKCHEM is useful for evaluating the consequences and quantifying the risks associated with accidents that occur during the transportation of hazardous materials. While RISKCHEM has been shown to aid in the prediction of risk after an accident, it does not provide *a priori* route calculations that may serve to reduce the impact of accidents.

The tradeoffs associated with highway routing and risk minimization were addressed by T.S. Glickman and M.A. Sontag [12]. They also discussed whether routes that minimize the risk of incidents and accidents should be established as opposed to routes that have the lowest operating cost. Using computer software, the authors computed cost-risk tradeoffs and estimated the average cost of rerouting per fatality averted. Another finding was that minimum risk routes, on average, reduce population exposure about tenfold, but reduce risk only about sixfold because of the influence of other factors, such as road type and distance.

Probabilistic risk assessment models use the conditional probability of an accident and the magnitude of its consequence as the two parameters. These models differ in, a) how they

combine the two parameters to arrive at a risk; b) the levels of detail for data acquisition; and c) the methods of obtaining data and model parameters. Computer programs are also available to perform probabilistic risk assessment. Radtran, a program developed by Sandia National Laboratories, is one example of a program that performs probabilistic risk assessment for transportation of radioactive materials. Radtran provides outputs in the form of expected exposures to general population, maximum exposures and so forth. Its input requirements include information about the material being transported, the type of vehicle, and containment; information about the environment; and attributes of the transportation network.

Risk assessment process can also be characterized as 1) Bottom-up Risk Estimates and 2) Top-Down Risk Estimates [13]. In Bottom-up approach it considers the risks of each single shipment of a cargo along a specified route by a specified mode of transport, and then adds these to obtain the risk of the total traffic in hazardous materials in the area of concern. Whereas in Top-Down it uses aggregate historic data as a basis for estimating particular situation. In bottom-up risk assessment, routes are broken into segments and for every i^{th} segment for trip j, the fine-grain risk for that segment and trip, R_{ij}, is given by the following formula:

$$R_{ij} = P_{1ij} * P_{2ijk} * P_{3ijmn} * P_{4ijp} * P_{5ijp} * P_{6ij} * P_{7ijq} * N_{ij} \qquad (1)$$

where,

P_{1ij} = Probability of an incident in mode segment i based on road type and conditions, traffic levels, traffic hazards, congestion, and vehicle type. This is usually based on historic data for similar conditions or obtained through regression models.

P_{2ijk} = Probability of an incident resulting in an accident of severity class k. Historic data can be used in some cases, but only actual tests combined with models can be used for rare events.

P_{3ijmn} = Probability of release of cargo type, m, in an amount of spill of a size class n.

P_{4ijp} = Probability of release spreading by pathway p, e.g., air plume, water release, etc.

P_{5ijp} = Probability of ignition for a flammable or explosive material via the pathway p.

P_{6ij} = Probability of wind direction for an air release.

P_{7ijq} = Probability of damage to an area receiving the spill and the probabilities that an exposed person will die or be injured.

N_{ij} = Number of people exposed.

In this case probabilities are taken as independent probabilities. This means that errors in each term are also related multiplicatively, resulting in very high levels of error propagation. These probabilities could better be represented as conditional probabilities.

In the current United States Department of Transportation (USDOT) guidelines, the probability of a hazardous materials accident is computed as follows :

$$P(A)i = ARi \times Li \tag{2}$$

where:

$P(A)i$ = probability of a hazardous materials accident for route segment i.

ARi = accident rate per vehicle-mile for all vehicle types on Route Segment i.

Li = length (in miles) for route segment i.

In 1990, Harwood, *et al.* proposed a modification to equation (2). Their rationale was that having a truck accident does not necessarily mean a release of hazardous material. To remedy this, they proposed the following equation:

$$P(R)i = TARi \times P(R/A)i \times Li \tag{3}$$

where:

$P(R)i$ = probability of an accident involving a hazardous materials release for route segment i.

$TARi$ = truck accident rate (accidents per vehicle-mile for route segment i).

$P(R/A)$ = probability of hazardous materials release given an accident involving a hazardous materials-carrying truck for route segment i.

There are two reasons that render equation (3) more appropriate than equation (2) for hazardous materials routing analysis: (1) risk is based on truck accident rates rather than just the probability of an accident, and (2) risk is based on truck accident rates rather than all-vehicle types accident rates.

Glickman in 1992, used the same procedure in a more detailed analysis for risk assessment of transporting flammable liquids in bulk. He used the following equation in his analysis:

$$P(X) = P(A) \times P(R/A) \times P(X/A,R) \tag{4}$$

where:

$P(X)$ = probabilities of each of the possible outcomes X (i.e., spill, fire, and/or explosion. No threat components were considered).

P(A) = probability of a truck accident.

P(R/A) = probability of a truck accident involving a release.

P(X/A,R) = probability of an outcome X given a truck accident and a release.

The probabilities P(A) that a truck will have an accident on a given route segment i is estimated by multiplying the segment's length, in miles, by the estimated accident rate, measured in accidents per truck-mile.

$$P(A)_i = TAR_i \times L_i \tag{5}$$

The scientific community has also focused attention on the quantified risk analysis of hazardous materials transportation networks [14] and has extended to these particular risk sources the techniques of quantitative risk analysis (QRA) initially developed for fixed plants. The most common risk indexes used to perform a QRA for a major accident hazard plant, i.e. individual and societal risk, are used also in transportation risk analysis. The transportation route can simply be viewed as a linear risk source constituted by a great number of point risk sources. This consideration substantially increases the computational effort necessary to obtain the final risk measures. For this reason, instead of the individual and societal risk, other simplified risk measures are very often adopted, like the population living in a corridor along the route, or the frequency of occurrence of a hazardous release event, or a simple product of these two items. The type of the material has also been considered in some of the related work [15].

A criterion considered in existing approaches that could be very misleading is the assumption of static conditions [16], hence resulting in inefficient route selection and unnecessary risk exposure. Therefore, both the measures of risk and travel time should be assumed as random variables with probability distribution functions that vary over time. This is referred to as a stochastic, time-varying network analysis because the weights are time-varying random variables.

Application of GIS is widely used in risk analysis in transportation of hazardous materials. It helps in quantifying the risk and provides better accuracy in analyzing the risk considering various parameters. The Oak Ridge National Laboratory is supporting DOE in development of the Transportation Routing Analysis Geographic Information System (TRAGIS), a user- friendly GIS-based transportation and analysis model. Primary reasons for development of TRAGIS are to improve the ease of selecting locations for routing, graphically displaying the route calculated, and to provide for additional geographic analysis of the route.

Section 3
Methodology

Various methods used to estimate the risks of hazardous materials transportation include: (1) enumerative indices, (2) regression models, (3) network and distribution models, and (4) probabilistic risk assessment models [11]. In Enumerative Indices, the number of conditions is counted that exist in order to develop a risk rating score. Regression models attempt to use measurable parameters (such as average daily traffic, number of heavy volume intersections, number of signals, type of road, or road condition) in order to develop a value for the probability of an accident per million vehicle miles (or some other similar probabilistic form) for a specific vehicle type. Network and distribution models and probabilistic risk assessment models use the conditional probability of an accident and the magnitude of its consequences as the two parameters. Probabilistic risk assessment models differ in: (a) how they combine the two parameters to arrive at risk; (b) the level of detail for data acquisition; and (c) the methods of obtaining data and model parameters. These models are best suited for routing rather than risk identification. Some models use fault-tree analyses to develop probabilities, whereas others, use average accident rates by mode and vehicle. Atmospheric dispersion models for population exposure and simulations to determine spill behavior are two of many approaches that have been used to develop the magnitude of consequences.

The solution methodology relies on the development of a suitable risk assessment model. To select a suitable model, one may either choose an existing model (or a combination of existing models) from the literature, or develop a new risk assessment model.

After review of various risk models used in hazardous materials transportation and their advantages and disadvantages, the category of probabilistic risk assessment models was selected. This was made because of the flexibility of the model for the level of detail for data acquisition and the methods of obtaining data and model parameters [11].

In probabilistic risk assessment, risk is calculated as the product of the probability of occurrence of a hazardous waste accident (or incident) and the consequences of that accident. The outcome of the risk estimation process is the calculated risk associated with each link in the transportation network model. If the objective is to minimize the risk in a network, the calculated risk will be the input to the proposed routing model. Alternatively, if the objective is to minimize travel time or length, that will be the attribute of each route segment.

The methodology used in the system presented in this report takes the product of incident/accident probability and a linear function of population and distance as the magnitude of consequence. The system uses GIS technology provided by the ArcView GIS software to

perform some spatial analyses to assist the optimization procedure. The program code and flowchart (Appendix 1 and Figure 4), which is written in Avenue, calculates the score of each segment and adds them in the street table by making a new field. To make it more understandable and simple, the methodology of the system design can be categorized in three main components:

1. Data collection
2. Risk Analysis and Development of mathematical model
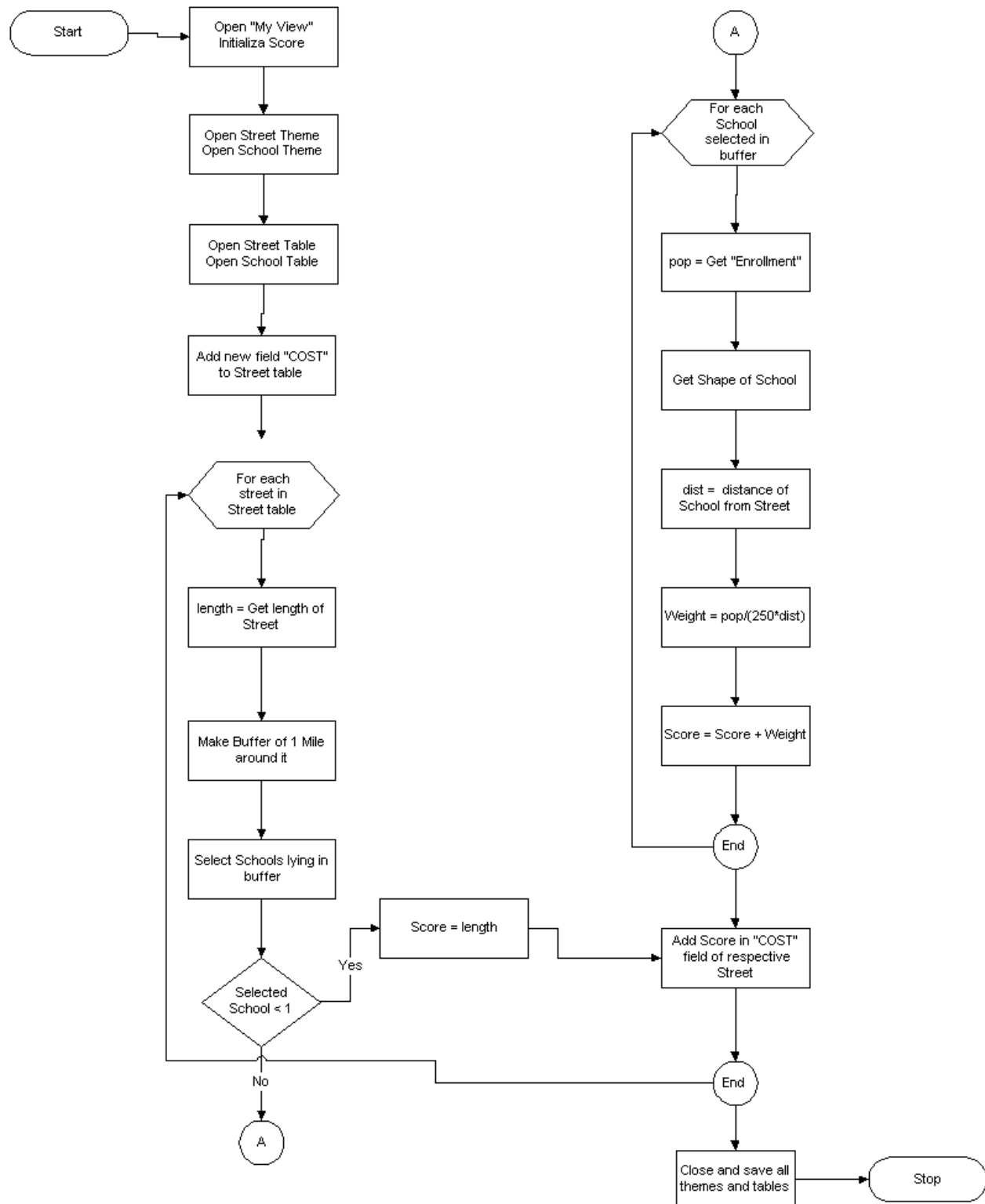3. Implementation using ArcView GIS

Figure 4. Flow chart for computer code written for GIS transportation route selection.

Data Collection

The input data required in the system include road segment data for Birmingham, Alabama (Jefferson County) obtained from 1995 TIGER files. This data includes all the streets and highways of Jefferson County and is not limited to the official designated truck routes, which are basically used for the transportation of hazardous materials. This example application is therefore most applicable for smaller vehicles that are not subject to the same restrictions as heavy vehicles. Obviously, the system could be easily modified to restrict the route selections to designated truck routes by entering specific data for the truck routes. The facilities included are schools, day care centers, retirement homes and hospitals, considered as most vulnerable to the impacts of such incidents. This project was a trial (proof-of-concept), therefore limited data has been utilized in order to come up with reasonable results which can easily be expanded in future versions by including extended and more accurate data.

The school data with details like type of school, enrollment and point locations are taken from a directory of Jefferson County Schools. The map of Jefferson County was available in ArcView GIS which is based on spatial data containing the geographic location of features on the Earth's surface, along with attribute information describing what these features represent.

Vulnerability Analysis and Scoring of the Route

Vulnerability of the facilities which lie along each segment of route corridor, is calculated as the linear relationship between the population of the facility and its distance from that road segment. Population of each school is the enrollment according to the different types of school (elementary, junior, high etc). The distance taken is the shortest distance from each facility to the route. The risk associated with the route is calculated taking the exponential probability function, which assumes the rate of accident as constant throughout the route. So the scoring or weight for the each segment of the route is the multiplication of the vulnerability of the facilities by the risk associated with that particular segment:

Scoring (of each segment) = Vulnerability of the facilities * risk of the road segment

Vulnerability of the Facilities

Table 2 shows an example interrelationship of the two parameters (population of the facility and its distance from the road segment). As shown, the relative risk becomes lower as the distance from the road increases and it becomes higher with increasing population of the facility.

Table 2: Relative Vulnerability of Facilities as a function of Distance and Population

Population:	Distance of Facility to Route (miles)			
	0.5	1	5	10
500	4	2	0.4	0.2
1000	8	4	0.8	0.4
5000	40	20	4	3

From Table 2 it is obvious that:

Population α Vulnerability, and
Distance α 1/Vulnerability

The relative linear function from Table 2 is therefore:

$$f(p,d) = p/(250)d \qquad (6)$$

Where, p is the population of the facility, d is the distance from the road link and 1/250 is a constant.

In case of schools, colleges and day care centers, timings of the day are also considered because the vulnerability becomes zero in off-hours for these facilities. For schools and colleges, the period of greatest vulnerability is between 7:00 am to 4:00 pm on working days, while for day care centers, this critical period is between 7:00 am to 6:00 pm on working day. At other times, the vulnerability is considered zero. The model vulnerability algorithm therefore considers different times of the day.

The total vulnerability, which can be assumed for graphic purposes as the radius of the circle around that facility on the route segment, is calculated from equation (5) by adding up the values (radii) of all the facilities lying in that route corridor. The expression can be written as:

$$r = \sum_{i=1}^{n} f_i(p,d) \qquad (6)$$

Risk on the route segment

For probability to have an accident, we use exponential distribution function. Exponential distributions describe the distance between events with uniform distribution in time.

$$f(t) = e^{\frac{-t}{t}} \qquad (7)$$

Where,

$e^{\frac{-t}{t}}$ is the probability of having no accident in time t

t is the distance between the occurrence of two events

Therefore,

$1 - e^{\frac{-t}{t}}$ is the probability to have an accident in time t, and

$$p = 1 - e^{\frac{-t}{t}} \qquad (8)$$

Or

$$p = 1 - e^{-lt}$$

Where

$$l = 1/t$$

$$l = \ln(1-p)^{\frac{-1}{t}} \qquad (9)$$

Here, l is the rate of an accident per unit time or length if we don't consider the speed. The rate of accident (per unit time or length if we ignore the speed) is multiplied by the length of the segment in order to get the total risk on that segment.

$$\lambda * L \qquad (10)$$

To get the cost (relative risk) of the segment, it is multiplied by the linear function of population and distance of the facilities. Because accident rate is assumed to be constant on all the segments, linear function is multiplied by the length of route segment to get the cost or risk of that segment. In cases where there are no facilities in the route corridor (buffer), the cost is taken as the length of the segment.
The score or weight of the route segment is given as:

$$\text{Score} = r * l * L \qquad (11)$$

In this model, it is assumed the rate of accidents throughout the road is a constant because detailed data was not available. Similarly, no dispersion model was used which could calculate the vulnerability of the facility and the area or distance affected by the incident. Therefore, for this example, the distance from the facility to the road segment has been considered as a straight line linear function for this application. Again, it is possible to easily modify the model to consider specific accident rates and relative dispersion conditions.

Working on ArcView GIS
To implement the mathematical model described above, ArcView GIS software was used. The data was imported in the software and is geocoded on the map of Jefferson county. The data

comprises the map of Jefferson county; road segments descriptions; locations and sizes of schools, day care centers, hospitals, retirement centers; and TSDFs and waste handlers. The themes were added in that order to maintain the visibility of each theme on the multi-layered display.

Network Analyst, an extension of ArcView was used. This system calculated the shortest route depending on the scoring given. In order to compare the results, two routes were calculated; one only considering the length of the route as the scoring, and second with the scoring calculated in equation (11) for each route segment. Using Avenue, ArcView's built-in object-oriented language, the score for each route segment was calculated using equation (11).

After creating a new field in street theme, scores or costs were added for the each segment. These scores are used to calculate the best route for the transportation of hazardous materials. The user can optionally calculate the shortest route and safest route to compare the results.

Section 4
Results, Case Study for Birmingham, AL

The case study examined in this research was a hazardous waste routing across Birmingham, Alabama, using a version of the Hazardous Waste Transport System (HWTS) outlined in the methodology. The goal was to route a hazardous product from an origin location to a destination location while minimizing the impact of the shipment if an accident should occur. As identified in the methodology, there are many features of interest to avoid when routing hazardous material, however, this case study addressed only schools located within the county.

To begin, the necessary data were gathered into the GIS (shown in Figure 5). The roadways for Birmingham, Alabama (Jefferson County) were from the 1995 TIGER files. The point locations for schools were taken from a directory of Jefferson County Schools and identified the different types of school (elementary, junior high, and high school).
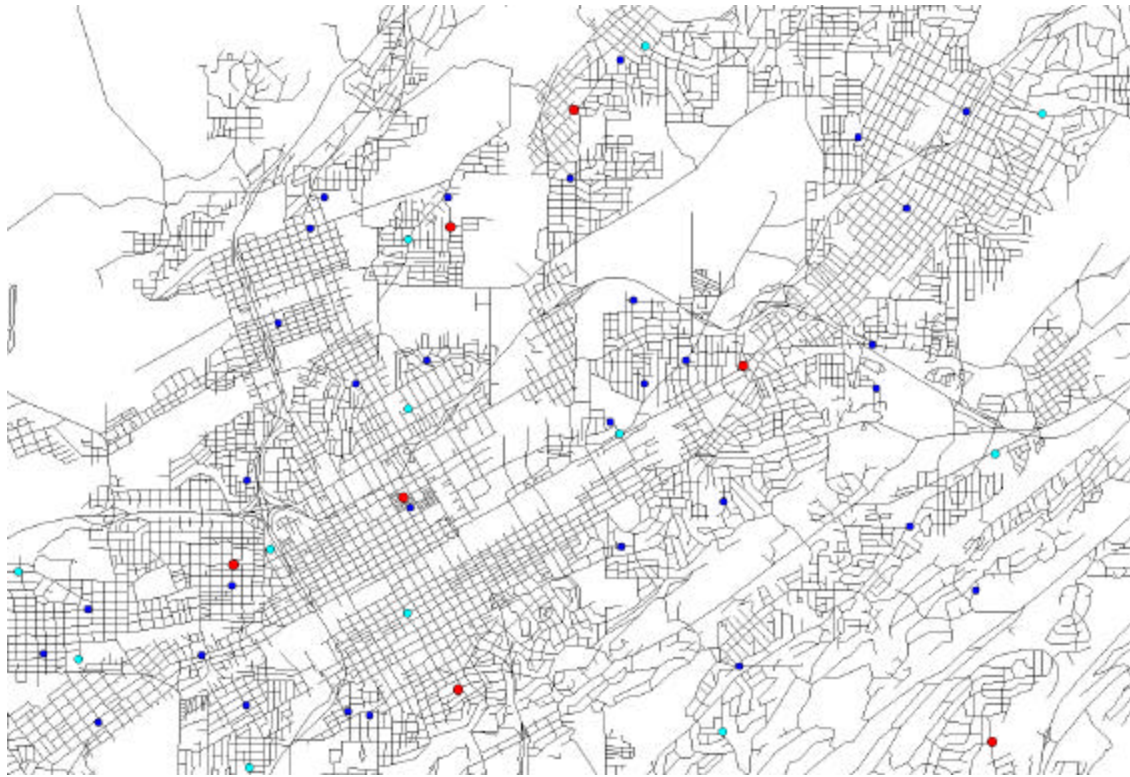

Figure 5. Birmingham area in Jefferson County, Alabama, showing street layouts and locations of schools.

After collecting the necessary data, the HWTS asks the user to specify the locations for the shipment origin and destination. The user provides this information by selecting the appropriate locations on the map. For this case study, this is shown and labeled on Figure 6.

With no regard for reducing the impact of the hazardous waste shipment in the community, the carrier would move the shipment on the shortest possible path between the origin and the destination. For this particular example, the path was 10.54 miles across town (see Figure 7). There are nine elementary schools, two junior high schools, and two high schools located within one-half mile of this route. Should an incident occur during this hazardous waste movement, this route places some school-aged children at risk of being exposed to harmful material.

Using the location of the schools and the roadway adjustment methodology presented in previous discussions, the HWTS was used to develop a new route that minimizes the potential impact on area schools. GIS was used in the HWTS to provide additional values for roadway segments falling within specified distances of area schools. These values were then included with the roadway segment distance to develop a new potential impact distance for the roadway segment. For this case study example, the student population of each elementary school was assumed to be 200, each junior high school was assumed to have 500 students, and each high school was assumed to have 2,000 students. The ring around each school in Figure 8 shows the hazardous waste routing impact zone. Each roadway segment that falls into this zone of influence was assigned a hazardous waste impact value based on proximity to the school.

Figure 9 shows that the shortest route intersects numerous school zones of influence, with potential serious consequences in cases of accidents. Using the combined roadway distance and impact score, a new route was developed that minimizes potential impact associated for a hazardous waste shipment. This new route is shown in Figure 10. Examining the two routes, the shortest path has a distance of 10.54 miles compared to the minimized impact route of 11.68 miles. However, with the combined distance and impact score, the route that initially had the shortest path is scored as 38.91 while the route that minimizes potential impact is scored as 32.40. This alternative transport route for a hazardous waste shipment therefore reduces the impact of a potential incident.
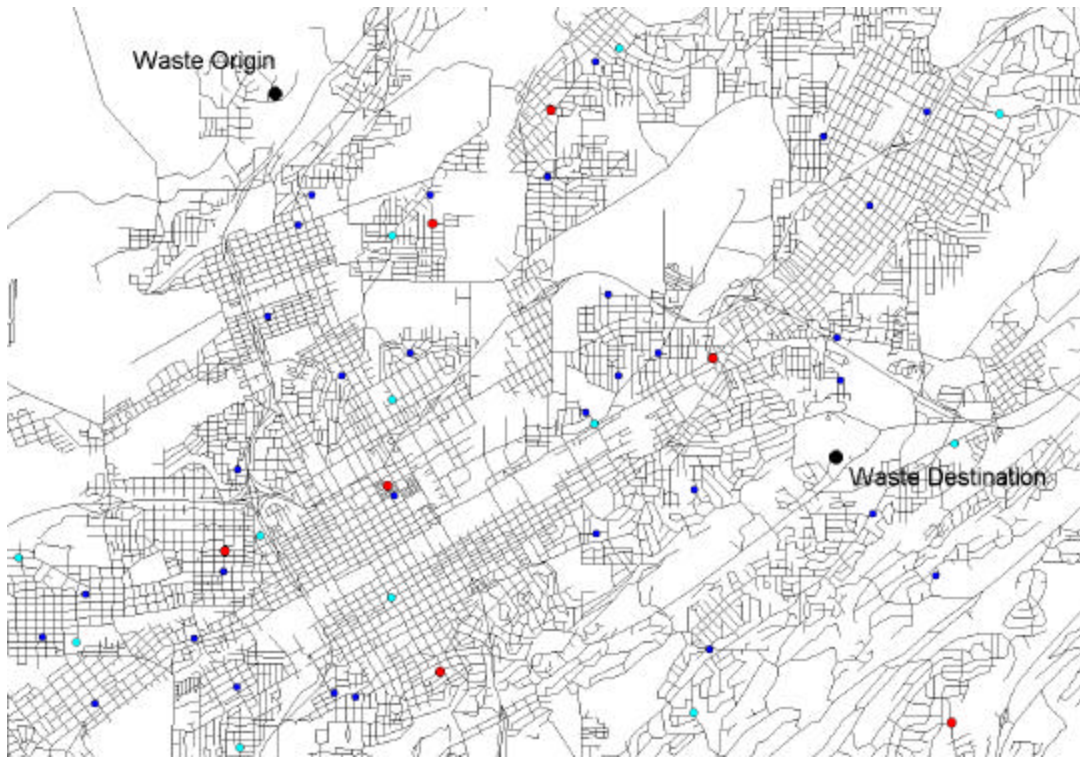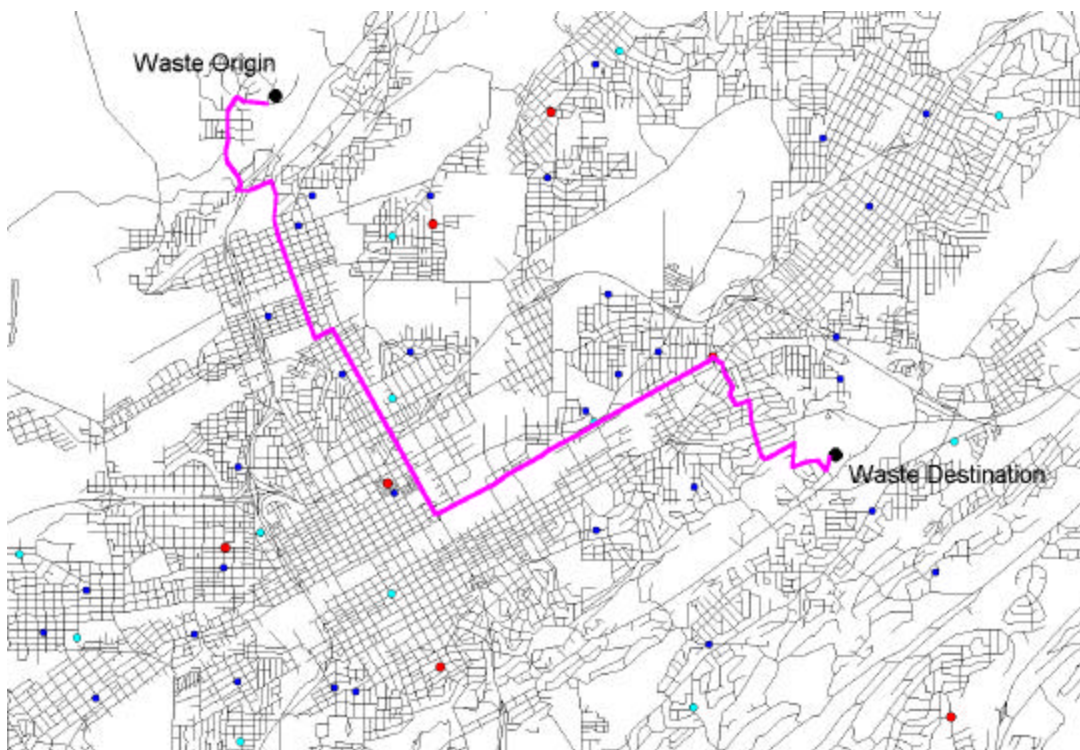
Figure 6. Example waste origin and destination.

Figure 7. Shortest route between waste origin and destination.
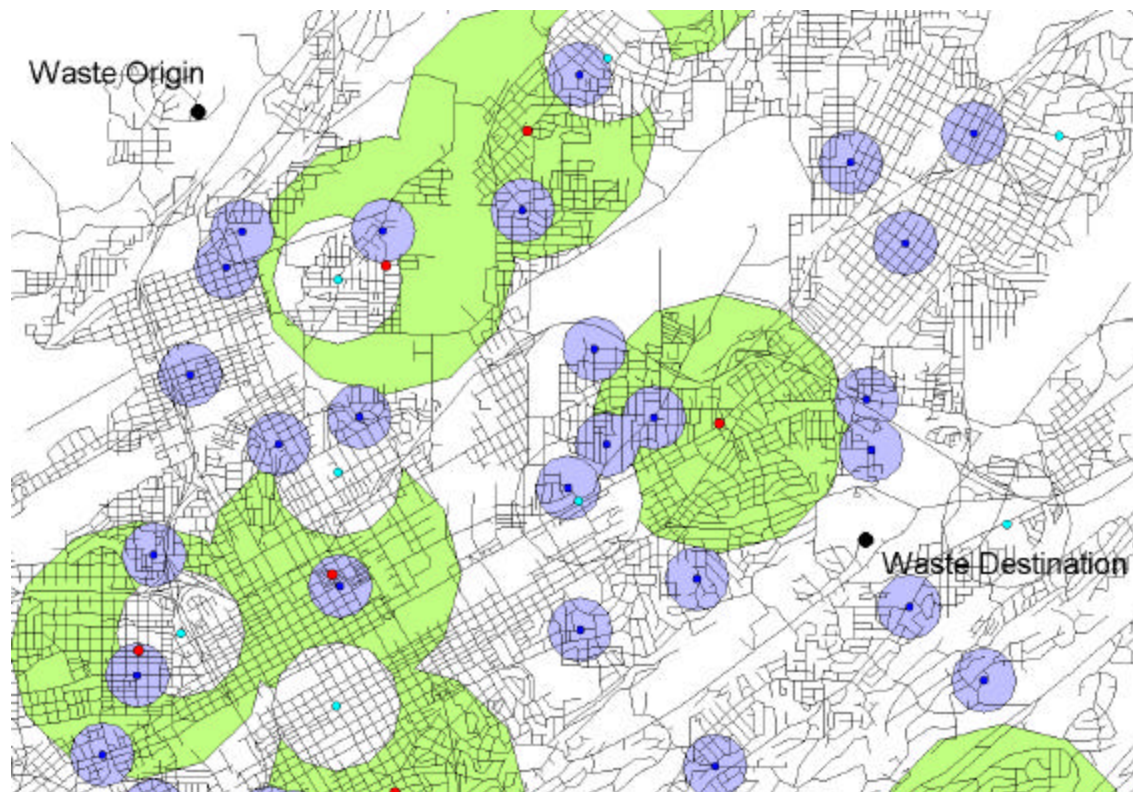
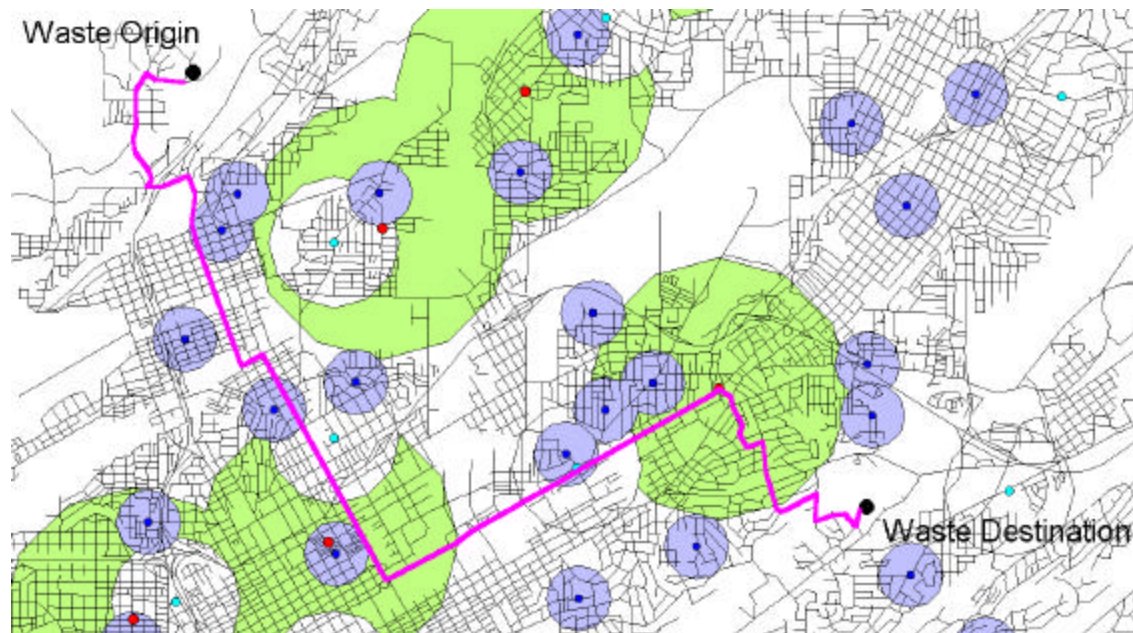**Figure 8. Critical zones around different schools.**

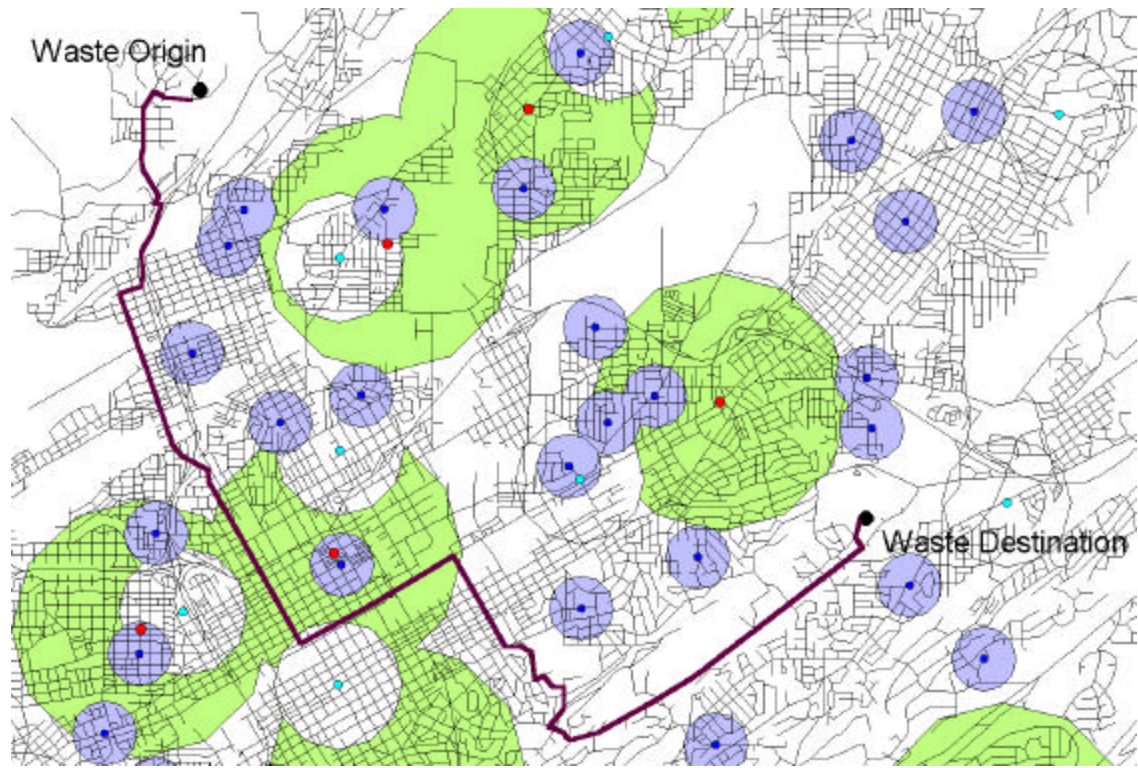**Figure 9. Shortest route intersecting critical zones surrounding schools.**

Figure 10. Best route minimizing intersections with critical zones around schools.

Section 5
Conclusions

This report presented the motivation, methodology, and example of a GIS-based Hazardous Waste Transport System (HWTS) that is intended to reduce the impact of potential incidents involving hazardous waste shipments across an urban area. The methodology included in the HWTS provides for the determination of transportation routes that attempt to minimize the impact of potential incidents by incorporating socio-economic considerations (locations and sizes of critical receptors) into the routing process. The case study of Birmingham, Alabama, demonstrates the use of the HWTS using school locations and size as the socio-economic considerations. As demonstrated in the case study, the shortest route for the shipment passes close to several schools. When the location of each school is considered in the routing equation, there is a small increase in total distance of travel, however, there is a larger increase in potential safety associated with the longer route.

The application of this research is transferable to any urbanized area where the transportation professionals have access to ArcView GIS software. The TIGER files that were used in the case study are available for every county in the United States and available form a variety of sources, both governmental and commercial. The socio-economic data used to identify potentially hazardous locations can be developed from local records or taken from a variety of commercial vendors offering business address software at a reasonable price. The HWTS software scripts written to perform the routing that incorporates socio-economic factors can be easily transferred.

Future Work
The results of this project include the original methodology for the HWTS, demonstrated through the case study provided. However, there are many areas where this research can be extended.

First, this research can be extended to include all pertinent socio-economic characteristics desired by the community, including other features to avoid during the routing and areas to travel in close proximity. Some feature that can be included in the list of avoidance locations, such as hospitals, day care centers, and retirement homes, can be included in the analysis. In addition, police stations, fire stations, and other emergency response units might be used as locations that provide a benefit for the hazardous waste shipment to travel near, as these facilities might be able to provide quick response and help organize evacuation plans for other people. If these factors are included in the analysis, further study is needed to determine the size and shape of the vulnerability function.

A second area of future research would be to develop a matrix of information about parameters and vulnerability functions for differing hazardous waste shipments. This would allow the

HWTS to provide differing optimal routes for liquid versus gas shipments, shipments that were highly corrosive versus highly toxic, etc, to improve the routing even more. What can be envisioned is a cubic matrix identifying time for the shipment (X), socio-economic variables and parameters (Y), and material being transported (Z) in a framework where the user of the HWTS enters these three variables (along with origin and destination) to generate the appropriate route for all possible instances.

The final, and probably most important, suggested area for future research is the validation of the model with local transporters in Birmingham. This study would be necessary to determine the actual route shippers use to transport materials to compare their route to the route generated by the HWTS. It is expected that many drivers automatically incorporate the trade-off between shortest distance and increased safety, however, a study of existing routes would allow for determination of the vulnerability intrinsic to the transporter and allow comparison to the model developed during this project.

Obviously, conducting these future research project would require a large amount of additional resources not available at the present time, however, they are included to identify areas where more research is needed in this important field.

Overall Conclusion
The development of the HWTS and the methodology to identify the optimal transportation route for hazardous waste shipments that balances shipment distance and safety for the residents of the community is an important step in reducing the severity of incidents associated with hazardous waste. The model developed in this project demonstrated the ability to generate an improved route based on incorporating safety concerns into the route choice decision, and although only a first step in a line of potential research projects, is a step in the direction of safety.

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Appendix 1

Program Code for Route Selection Process

```
'This program calculates the score of each route segment based on risk
analysis
' model explained then writes that score in street table.
' 0.5 mile is the size of buffer

theSize = 0.5
theView = av.GetProject.FindDoc("MyView")

theTheme = theView.FindTheme("newselstr.shp")
theFtab =theTheme.getftab
streetfield = theFTab.findfield("MILES")
theShape=theftab.FindField("Shape")
theGraphics=theview.getgraphics
thedpy=theView.GetDisplay
newsize = units.convert(thesize,#UNITS_LINEAR_MILES,#UNITS_LINEAR_DEGREES)

'Starts editing in street table and creats a new field.
if (theFTab.StartEditingWithRecovery) then
    theFTab.BeginTransaction
        f1 = Field.Make("COST",#FIELD_FLOAT, 15, 10)
    theTheme.EditTable
    theFTab.AddFields({f1})

    'Initializes the score.
        for each sam in 0..2
        _sc = 0
      _score = 0
      weight = 0
      listofgr={}
      h = -1

      'Creates buffer around each segment.
      for each x in theFTab
        h = h+1
        if (h=sam)then
          p = theFTab.ReturnValue(theShape, x)
          thebuffshape=p.returnbuffered(newsize)
          a=listofgr.add(thebuffshape)
          break
        end
      end
      for each m in a
        newg=graphicshape.make(m)
        theGraphics.add(newg)
      end
      theView1 = av.GetProject.FindDoc("MyView")
```

```
      theTheme1 = theView1.FindTheme("JSchools")
      theFTab1 =theTheme1.GetFtab
      myfield1 = theFtab1.findfield("Shape")
      myfield2 = theFtab1.findfield("Schools")
      myfield3 = theFtab1.findfield("Enrollment")
      theGraphics1 = theView1.GetGraphics
      thedpy=theView1.GetDisplay
      theunits=thedpy.getunits
      Distunits=thedpy.GetDistanceUnits
      distunits=theunits
      theVTab=theTheme1.GetFTab
      shapeList = {}

      'Gets the schools in the buffer.
      for each d in theGraphics1
        shapeList.Add(d.GetShape)
      end
      theTheme1.SelectByShapes(shapeList,#VTAB_SELTYPE_NEW)
      theBitMap=theVTab.GetSelection
      if (theBitMap.count<1) then
        _score = 0
      end
      cnt = theBitMap.count
      if (cnt > 0) then
        selrec = theBitMap.GetNextSet(-1)
        cnt= cnt-1
        for each i in 0..cnt
           selSchoolshape = theVTAb.ReturnValue(myField1,selrec)

           'Calculates the distance from the scool to the segment.
           dist = p.distance(selSchoolshape)
           newdist =
units.convert(dist,#UNITS_LINEAR_DEGREES,#UNITS_LINEAR_MILES)
           pop = theVTab.ReturnValue(myfield3, selrec)

           'Calculates the score for each school.
           weight= pop/(250*newdist*newdist)

           'Adds the score for all the schools in the buffer.
           _score=_score+weight
           selrec = theBitMap.GetNextSet(selrec)
        end
      end
      theTheme1.ClearSelection
      h=-1
      for each x in theFTab
        h = h+1
        if (h=sam)then
          leng = theFtab.ReturnValue(streetfield,h)

        'If there are no schools in the buffer, the scoreis equals to length
of segment.
          if (_score=0) then
              _sc = leng
```

```
                'Score of the schools is multiplied by the segment length.
            else
              _sc = (_score*leng)
            end
            theFTab.SetValue(f1,h,_sc)
            break
          end
        end
      theView.GetGraphics.SelectAll
      theView.GetGraphics.ClearSelected
    end
end

'Stops editing in the street table and saves edits.
saveEdits = TRUE
theFTab.StopEditingWithRecovery(saveEdits)
```