Design of Routing Networks Using Geographic Information Systems: Applications to Solid and Hazardous Waste Transportation Planning

M. HADI BAAJ, SULEIMAN A. ASHUR, MIGUEL CHAPARROFARINA, AND K. DAVID PIJAWKA

Geographic information systems (GIS) represent a technology with considerable potential for important applications in transportation engineering. This paper focuses on the applications of GIS technology in the transportation routing area. Two case studies are presented: the first focuses on the design and analysis of different Arizona statewide waste tire collection transport networks corresponding to different percentages of total annual waste tires collected. The second case presents ongoing Environmental Protection Agency-sponsored research on the transportation routing and risk management of hazardous waste shipments across the U.S.-Mexico border region. Both routing applications take advantage of the efficiency and productivity of GIS technology and have been implemented on the GIS software TransCAD.

This paper focuses on the applications of Geographic Information Systems (GIS) technology in the transportation routing area. This is demonstrated via two case studies implemented on the GIS platform TransCAD. The first section presents a general overview of geographic information systems and its applications in transportation engineering, an extensive literature review of GIS applications in the transportation routing area, and a brief description of TransCAD. The second section presents the first case study: the design of Arizona statewide waste tire collection networks using data provided by the Arizona Department of Environmental Quality (ADEQ). The problem definition and application significance are revealed, the solution approach is reviewed, and application results are presented. The third section presents the second case study: ongoing Environmental Protection Agency (EPA)-sponsored research focusing on the transportation routing and risk management of hazardous waste shipments across the U.S.-Mexico border region. The interest of EPA in this research study is a direct result of the recent North America Free Trade Agreement (NAFTA). This paper then concludes with an overview of results and directions for further research.

GEOGRAPHIC INFORMATION SYSTEMS

Overview of GIS Systems

GIS is a computerized data base management system for the capture, storage, retrieval, analysis, and display of spatial data. A GIS contains two broad classifications of information: geocoded spatial data and attribute data. Geocoded spatial data define objects that have an orientation and relationship in two- or three-dimensional space. Each object is classified as either a point (such as an accident or a signal location), a line (for example a highway), or a polygon (number of people living within a block) and is tied to a geographic coordinate system. These objects have precise definitions and are clearly related to each other according to the rules of mathematical topology. Moreover, a GIS contains the same attribute data that are found in traditional data bases. Attributes associated with a street segment might include its width, number of lanes, construction history, pavement conditions, and traffic volumes. GIS is preferred over a traditional data base because data attributes are associated with a topological object (point, line, or polygon) that has a position somewhere on the surface of the earth (*1,2*). Spatial considerations are fundamental to most transportation activities. A transportation system network representation consists of nodes, links, and entities distributed in two- or three-dimensional space. Events happen within this system at a point (an accident or a signal location), along a segment (vehicle volumes or pavement deficiencies), or within a geographical area (the number of people living within two blocks of a bus stop or working in an industrial park).

GIS Applications in Transportation Planning

GIS applications can be expected in traditional areas of the highway agency responsibility, namely: pavement management; traffic engineering; planning and research; bridge maintenance; and field office support (*3*). A wide range of prototype and even fully operational GIS applications were identified by a research team from the University of Wisconsin in planning, management, and engineering (*4*). GIS software was used by the Saskatchewan Department of Highways and Transportation to build a regional highway network using their corporate highway data base including traffic count data (*4,5*). A second planning application used the overlay and routing GIS functionalities for hazardous material routing. The overlay GIS function was used to generate estimates of the population within a specified distance of each link in the highway or rail network. This enabled the inclusion of the population exposure in an objective function for route selection (*4*). Other planning applications include evacuation planning, planning for hazardous material release inci-

M. H. Baaj, Department of Civil and Environmental Engineering, American University of Beirut, Beirut, Lebanon. S. A. Ashur and M. Chaparrofarina, Department of Civil Engineering, Arizona State University, Tempe, Ariz. 85287-5306. K. D. Pijawka, School of Planning and Landscape Architecture, Arizona State University, Tempe, Ariz. 85287-2005.

dents, development of new traffic analysis zones from census tracts, and development of new urban highway networks (*4*).

GIS Applications in Routing

GIS is a powerful tool in the analysis and design of transport routing networks. Its graphical display capabilities allow not only visualization of the different routes but also the sequence in which they are built, which allows the understanding of the logic behind the routing network design. A GIS adds a degree of intelligence and sophistication to a transportation data base that has been previously unknown. For a segment on a road, a GIS system knows what routes cross it and whether there is an actual physical intersection. It knows the position of roadside features along the segment and can tell which census blocks are to the right and left of the segment or within any distance of it. Rather than being limited to textual queries, it is possible to perform geographic queries in a straightforward, intuitive fashion. For example, a GIS with the appropriate routing algorithm and data can easily compute and display the route that will result in the minimum population exposure to a shipment of hazardous materials. With the route drawn on the computer screen, the analyst can see immediately how the logic of the model has bypassed certain population centers. The analyst can create a detour by pointing to a road segment and deleting it from the network and then watch the routing algorithm redraw the path. Similarly, the analyst can ask a series of geobased questions and obtain the answers quickly in an easy-to-understand, color-coded display on the screen, hard copy, or disk file.

The interaction between the transportation system and its surrounding environment makes GIS technology ideally suited for hazardous materials-routing design, risk analysis, and decision making. GIS combines information on the transport network, social and demographic factors, weather conditions, topography and geology to assess the likelihood of a spill and its probable consequences. GIS can also be integrated with sophisticated mathematical models and search procedures to analyze different management options and policies.

GIS has been used in the risk analysis of hazardous materials transportation in Arizona (*6*). The main objective of that research was to assess the risk and vulnerability of transporting hazardous materials and waste on the Arizona highway system. A general GIS system called Geographic Information Management System (GIMS) was used. The risk assessment model used was based on four factors: accident rate by segment, shipment frequency by highway segment, population density along the routes, and response time. Each component was evaluated and presented on the GIS map. Although this study was one of earliest and most basic research studies in this area, it lacks a strong modeling of risk assessments and routing evaluations.

A second study aimed to assess the best routes for transporting hazardous materials in an area of about 609 km^2 (235 mi^2) in France (*7*). To assess alternative routes, the transport risk was calculated based on the multiplication of the accident probability by the number of exposed people. The minimum risk route from one origin to a destination was determined using Dijkstra's shortest path algorithm. Different risk values were assigned to different segments of the transportation network based on the type of material transported, its packaging aspects, accident probability (which varies with vehicle and route characteristics, such as road classification, bridges and tunnels, and so on etc.), transportation operational aspects (such as speed limit), law enforcement and weather conditions, and the environmental surroundings along the routes (such as population density, sensitive buildings such as schools and hospitals, general land use, and, in particular, sensitive environmental zones such as water resources areas). An output of the study was a GIS software called INGRES. Although the level of detail in this study was comprehensive, it was specific for the area of study. In addition, the economical component was not considered in this study (e.g., risk profile and the tradeoff between cost and risk).

A third study developed a first-generation GIS-based system for hazardous materials transport routing and risk management (*8*). The system, called HAZ-TRANS, currently under development, can be run using a stand-alone microcomputer. It is designed to accommodate future data collection and model enhancements. This system was used to highlight the conflicts presented by routing decisions, namely, between economic and safety concerns, and among potentially affected populations. Two applications were analyzed: first to minimize trip distance and second to reduce population exposure. It was found that a relatively small increase of about 10 to 15 percent in trip distance will achieve a reduction of 40 percent in population exposure.

TransCAD

TransCAD is a GIS software package for the planning, management, operation, and analysis of transportation systems and facilities (*9*). It can be used for any application that requires digital mapping, spatial analysis, and data retrieval and maintenance. It can analyze all types of geographic and spatial data with extended capabilities for transportation data. In addition it is ideal for many different transportation applications such as highway or transit planning and operations, facility management and inventory systems, accident reporting and analysis, pavement management, maintenance planning, demand modeling and forecasting, market analysis, environmental impact assessment, regulatory and policy analysis, distribution planning, routing and scheduling, and emergency management (*9*).

The reason for selecting TransCAD as the GIS software platform for both routing applications discussed in this paper is that it includes a battery of procedures tailored for transportation applications. Such procedures geocode data, build networks, find shortest paths, create service districts, and perform polygon overlay processing. The first application demonstrating the design of statewide waste tire collection networks uses the "SHORTEST-PATH" and "VEHICLE-ROUTING-PROBLEM" procedures of TransCAD applied repetitively to the GIS-coded map of the state of Arizona. The second application assessing the risk of transporting hazardous waste across the U.S.-Mexico border region uses the "K-SHORTEST-PATHS" procedure of TransCAD applied repetitively to the GIS-coded map of the U.S.-Mexico border region (*10,11*).

ARIZONA WASTE TIRE COLLECTION NETWORK DESIGN

Application Definition and Significance

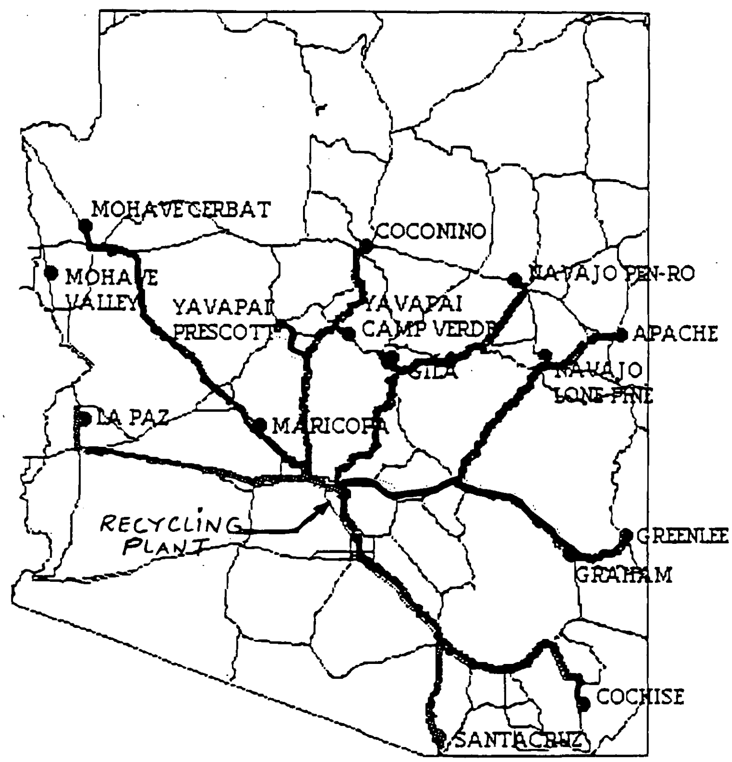
A waste tire processing facility has been operating in the state of Arizona since 1990. As part of the incentives given to the operating company to start business in the state, Arizona guaranteed to the company that for the first 2 years of operation, all waste tires disposed in the state's county landfills would be processed at its facility. Thus, there was a need for the state to contract with a hauler to transport the waste tires from each waste tire collection site (WTCS) to the waste tire processing facility (WTPF). There are 15 approved WTCS and 1 WTPF in operation in Arizona as shown in Figure 1 (*12*).

The Arizona Department of Environmental Quality (ADEQ) was interested in identifying the optimal network for the collection of waste tires from all the 15 participating WTCS (100 percent demand satisfaction) to the WTPF and its corresponding total annual hauling cost. This information is useful and necessary to ADEQ so that it can use it as a base to compare the hauling bids with, and to better negotiate its contract with, the selected hauler. In addition, ADEQ was interested in obtaining a plot of the total annual hauling cost versus the number of waste tires collected because it increases from 13,678 megagrams/year (15,080 tons/year) (the number generated by the largest WTCS of Maricopa County, representing 75.2 percent of the total annual waste tires disposed) to 18,187 megagrams/year (20,052 tons/year), the total number generated by all 15 participating WTCS. This involves the design of different routing networks corresponding to different percentages of the demand satisfied. This is useful to ADEQ in decision making under budgetary constraints that may affect the amount of funding allocated for the waste tire hauling program. Thus, given a certain maximum funding allocation for tire hauling, ADEQ can then determine the corresponding total number of waste tires that could be collected for processing and the collection network configuration.

The study objectives were to (*a*) design with the aid of the GIS TransCAD the statewide tire collection network and determine its total annual hauling cost; (*b*) provide ADEQ with a plot of the total annual hauling cost versus the percentage of total tires hauled for processing; and (*c*) demonstrate and test the use of TransCAD in the design of collection networks. The data for this study were obtained from ADEQ's tire manifest data base. By law, at each WTCS, any disposer of waste tires is required to fill a manifest indicating the date of disposal and number and size (large or small tires) of the disposed tires. Such manifests are collected by each county authority and are delivered to ADEQ. Thus, ADEQ is capable of maintaining a waste tire data base indicating the number and sizes of tires disposed daily at every WTCS.

Solution Methodology

The waste tire collection network configuration can be either a direct network, an indirect one, or a composite network. In a direct



Annual Number of Disposed Tires in Arizona's 15 WTCS (in Tons/year)

Mohave Cerbat = 793; Mohave Valley = 793; Coconino = 801; Yavapai Prescott = 577; Yavapai Camp Verde = 424; Navajo Pen Ro = 224; Gila = 250; Apache = 91; Navajo Lone Pine = 133; La Paz = 101; Maricopa = 15,080; Greenlee = 13; Graham = 200; Cochise = 424; Santa Cruz = 148. TOTAL = 20,052 Tons/year.

FIGURE 1 Arizona's 15 waste tire collection sites (WTCS) and waste tire processing facility (WTPF). (Also shown is the direct network generated by TransCAD satisfying 100 percent of total demand).

network, all collection trips are performed directly between each WTCS and the WTPF. Thus, there are as many routes as there are WTCS, and each hauling route operates independently with its own fleet of trucks. This network can be easily designed with repetitive application of the SHORTEST-PATH procedure of TransCAD.

In an indirect network, a hauling truck can travel not only between one WTCS and the WTPF but among several locations and the recycling plant. This is suitable for the case of disposal sites with a minimal annual number of tire deposits, which does not justify the expensive cost of direct line hauling. This mode of operation follows that of a multiple-origin-single-destination traveling salesman problem (TSP). Such a network is configured with repetitive application of TransCAD's "VEHICLE-ROUTING-PROBLEM" procedure.

A composite network is one involving a direct network between a subset of the WTCS and the processing facility and an indirect network between the complimentary subset of WTCS and the processing facility. For the case of Arizona, one WTCS (namely, that of Maricopa County) produces 75.2 percent of the total number of annually disposed tires, and the combination of the remaining 11 WTCS produces 25 percent. Thus, the composite network was perceived to consist of one direct haul line between Maricopa County's WTCS and the WTPF and an indirect network between the remaining 11 WTCS and the WTPF (*13*). For this application, a simplifying assumption was made that 1.61 km (1 mi) costs $1 to operate (such costs include fuel, maintenance, driver wages, and depreciation but exclude the fixed costs of acquiring the trucks). Also all fleet sizes were assumed to be the same, consisting of 18.14-megagram (20-ton) trucks.

Results of Application

Computational results using TransCAD indicate that it costs approximately $145,000/year to operate the direct line serving Maricopa County's WTCS (75 percent of total demand satisfied). To serve 80 percent of the demand, there are many possible combinations of WTCS other than Maricopa County's WTCS, which account for approximately 5 percent more of the demand satisfaction. Using TransCAD, the best network configuration (whether it is a direct, indirect, or composite one) is determined for each possible combination. The combination of WTCS whose optimal network configuration has the lowest annual hauling cost is selected as the one corresponding to the given percentage of demand satisfaction. Figure 2 shows the plot of the total annual hauling cost versus the percentage of demand satisfied. As shown in Figure, as the percentage of demand satisfied increases from 75 to 100 percent, the total annual hauling costs increases from $145,000 to $280,000 (a 93 percent increase in the annual cost for a 33 percent increase in demand satisfaction) (*13*).

HAZARDOUS WASTE SHIPMENTS IN THE U.S.-MEXICO BORDER REGION

Application Definition and Significance

Under a 1988 Mexican environmental law, any hazardous waste generated by U.S. companies (Maquiladoras operating in Mexico's border region) must be returned to the U.S. for treatment and disposal. According to the EPA, only 40 percent of the hazardous waste generated in Mexico returns to the U.S. Moreover, in 1992, only 10 percent of the companies in the Mexican states of Baja and Sonora requested official shipments of hazardous waste to the U.S. Most of this waste was either stored in Mexico or was treated in small recycling firms. Currently, there is no complete data base providing information on the pattern of shipments of waste from these industries as well as the shipment routes to disposal facilities. Furthermore, it is widely expected that the amount of hazardous waste will increase substantially as a result of the North American Free Trade Agreement (NAFTA) and the resulting accelerated relocation of U.S. industries to Mexico. In addition, NAFTA's proposed regulations will render illegal dumping very difficult in Mexico (*14*); the permit process for regulating hazardous waste has progressed since 1988.

The goal of the ongoing EPA-sponsored research is to develop an analytical framework for assessing the transportation risk of shipping hazardous waste in the border region using the GIS technology. The research addresses two overriding and major issues; the first issue concerns the lack of a current comprehensive data base that tracks the amounts of hazardous shipments, determines their risks to population and the environment, and identifies the patterns of shipments (their origins, destinations, and transport routes). The second issue is the growing need for a risk assessment model that can assist in determining the transport risks involved and can serve as a valuable tool for formulating different management scenarios aimed at transportation risk reduction and equity (*14*). The research objectives are to: 1) develop a risk assessment model/framework implemented

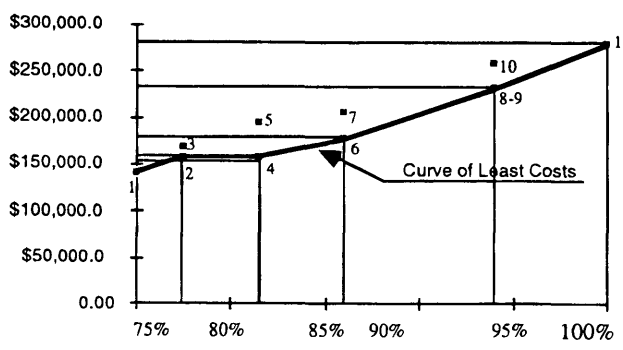


FIGURE 2 Annual hauling costs versus the percentage of demand satisfied.

on the GIS platform TransCAD; 2) test the model; and 3) develop methodologies that can be applied to the U.S.-Mexico border region.

The aims of the framework are to assess the risks of transporting hazardous waste in the U.S.-Mexico border and to examine different transportation and other related scenarios that will facilitate decision making and planning to reduce the impacts of transportation accidents. The framework will be tested and demonstrated by applying it to a specific geographical area along the U.S.-Mexico border region, namely, the Arizona-Sonora area. This area was selected because of the availability of data and because the risks of shipping hazardous waste were considered a dominant environmental and public safety concern (*14*).

Solution Methodology

The following tasks were proposed to achieve the goals of the research:

1. *Literature Review of Risk Assessment Models*: This task has been completed, and results were summarized in the preliminary report sent to EPA (*14*).
2. *Data Collection and Analysis*: This task has been completed. It involves the collection of several data for implementation on the GIS software TransCAD:
   a. Hazardous waste shipment data: These data include the quantities, types, and routes that are used in the shipment of hazardous waste from U.S.-owned industrial plants in the Mexican State of Sonora to the state of Arizona in the U.S. Moreover, these data need to be confirmed through the manifest copies available from the EPA.
   b. Land Use Data: These are data on sensitive properties and population densities in the U.S. and Mexico.
   c. Truck Accident Data: These data are necessary to calculate the probability of accidents of trucks carrying hazardous waste shipments.
3. *Development of Solution Framework*: This ongoing task considers computer modeling by establishing a TransCAD-implemented data base of Arizona and Sonora highways with different attributes (such as length of road segments, speed limits, type, and population along the route), applying the risk assessment model to the GIS map, and developing the necessary computer algorithmic analysis programs (Database IV, FORTRAN, and so on). The use of TransCAD's K-SHORTEST-PATHS procedure will be instrumental in the identification of many alternative routes for every pair of hazardous waste origin-destination.
4. *Development and Analysis of Different Management Scenarios*: A major contribution of this study is to identify the impacts of different risk management scenarios. There are two sets of scenarios; the first set of scenarios focuses on changes in the demand pattern (and amounts) such as: (*a*) dumping some/all of the waste in Mexico; (*b*) the partial closure of the border between California (or Texas) and Mexico; and (*c*) the construction of new recycling facilities in Sonora and/or Arizona. The second set of scenarios focuses on impacts of routing of hazardous waste under different preferences (such as minimum cost, minimum risk, risk equity, or a combination thereof).

CONCLUSIONS

GIS is a powerful technology in the analysis and design of transport routing networks. The key contribution of GIS technology is that it adds a major degree of intelligence and sophistication to a transportation data base that is inherently geographical in nature. The interaction between the transportation system and its surrounding environment makes GIS technology ideally suited for solid and hazardous waste routing design, risk analysis, and decision making. GIS technology combines information on the transport network configuration, social and demographic factors, weather conditions, topography, and geology to assess the likelihood of a hazardous spill and its probable consequences. GIS can also be integrated with sophisticated mathematical models and search procedures to analyze different management options and policies. Two case studies were presented to demonstrate the usefulness of GIS technology in the design of routing networks. The first case dealt with the design of many Arizona statewide waste tire collection networks corresponding to different percentages of the demand satisfied. The second case reviewed ongoing research examining the routing and risk management of transporting hazardous waste across the U.S.-Mexico border region.

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