AMIS: Development and Application of a GIS/Multicriteria Corridor Evaluation Methodology

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This paper describes the design and evolution of a GIS-based corridor route planning methodology called Analytic Minimum Impedance Surface (AMIS). A local State Highway Agency (SHA) requested an analytic methodology that would facilitate choice of a route corridor for a section of a proposed Interstate highway connector in the southeastern U.S. The SHA's specification demanded a robust, quantitative methodology that would both provide comparative information about pre-selected corridors and/or aid in the selection of corridors based on user-defined path inputs or endpoint location specifications. Additionally, the methodology was required to structure and incorporate useful input from a range of stakeholders including SHA employees from various divisions with separate but necessary remits, such as Design and Environmental, and other transportation professionals from the public and private sectors.

Figure 1 shows an enlargement of the study area and displays current road connections. The problem domain is located in a complex karst landscape possessing a variety of landforms and geologic characteristics. Much of the study area is dissected by a dense network of streams and steep gradients and cliffs are common. Although this area is mainly rural, containing large sections of a National Forest, several pockets of development in the study area. The area falls within the Appalachian Regional Commission's designation and exhibits a series of sub-par socio-economic indicators. In view of the significant recent social and economic impact of auto manufacturing and subcontracting transplants along Interstate corridors in neighboring regions, the potential economic impacts of this major new road link were considered extremely important. Among the key environmental concerns in the region were the future of the karst caves used for recreation while in the northern section several rare avian species are found, including the recently reintroduced red-cockaded woodpecker.

A foundational assumption was that a well designed decision support methodology for participants in such a process should (i) assist them determine criteria of significance, (ii) assess the importance of each criterion and (iii) allow them to quantify tradeoffs between each pair of criteria. It was not intended to form a rigid *a priori* framework to be imposed on participants. A formal system with such properties is termed a Decision Support System or DSS [1]. A DSS where the decision criteria have spatial dimensions is termed a Spatial Decision Support System, or SDSS [2]. A SDSS was developed based on the concept of the least cost path. However, the notion of cost, or its spatial equivalent of *impedance*, was treated as a complex, multidimensional and not necessarily monetarily-based variable. This impedance variable was composed of the sum of a number of individual impedance elements. Each of these elements consisted of an attribute with a location. The GIS was used to sum the value of all impedance elements for every cell in the corridor study area. The result was a continuous geographic surface that summarized scores pertaining to routing preferences and obstacles. This surface could be queried to provide combinatorial scoring useful for exploratory corridor testing.

A rigorous spatial analytic framework, in the form of a raster-based GIS, Arc/View, was conjoined with a robust rational choice decision methodology, the Analytic Hierarchy Process or AHP [3] to create AMIS. AMIS combines system priorities, such as economic development and connectivity improvement, with varied but specific on-the-ground features, such as wetlands, schools, median incomes or areas where endangered species are located. Both the system priorities and features can be user-specified. Input is in both written and electronic data format, while the output is displayed on standard GIS software.

One important goal of formalizing the selection criteria was to increase stakeholder satisfaction. Decision theoretic literature contends that policy decisions are often based on invisible or surrogate criteria – that is, participants may not be offered a framework that permits articulation of their true goals, or in other cases, support or resistance for a project is couched in tactical terms. For example, specific locational choices may be protested although opposition is in reality formed in principle to the development's goals rather than its specific form. In many cases this has led SHA's to regard public input as problematic and negative. Predicated on the belief that broad stakeholder involvement is a critical and a highly desirable component of any transportation modeling system, articulating and clarifiying individual values and views is, therefore, of fundamental importance. Yet, in the absence of a formal, analytical framework for capturing and incorporating these values, competing and often fractious views render goal-setting intractable, or result in compromises which are viewed as unsatisfactory even by those who contributed to them. One of the major reasons for this outcome is that the weighting system is often not rendered explicitly, and participants are left wondering whose views have more weight, and why [4]. It is therefore helpful to structure the problem in such a way that participants feel they are making a genuine contribution to goal-setting, and that their individual voices all count [5]. Further, iterative adjustment of model parameters based on expert opinion usually produces more satisfactory outcomes. Previous experience with the application of multicriteria techniques to large-scale, complex and contentious public policy and environmental management problems supports this view [8].

AMIS was therefore built using iterative process that incorporated input from a variety of federal and local government SHA representatives, including Engineers, Planners and Environmental specialists. This process took place over a period of approximately six months, with sets of meetings being held to move through the design stages. Facilitation methodologies were employed at each of these meetings to maximize stakeholder input [9].

The multicriteria priority model was structured around these three data layers comprised of surface data elements (originally 69 of these), affinity groupings of the 69 data elements (5 total) and FHWA Purpose & Need categories (8 total). First the participants were asked to specify an exclusive membership for each of the 69 elements in a category called an *affinity grouping*. This required definition of five appropriate classes (see Table 1). Two classes of elements were identified. The first consisted of elements considered critical (a), and the second class of less important elements (b). Then the individual elements were each assigned a raw impedance score, α, from 1 to 10 points, or exactly 100 points. This discontinuous scale was chosen arbitrarily, with 1 point representing low impedance (high willingness to develop) and 10 points a high impedance (low willingness to develop). 100 point α values were reserved for "undevelopable" factors. Arithmetic mean impedance scores were then calculated for each element (see Table 2). The research team facilitated this process: however, the participants assumed full responsibility for defining and naming the affinity groupings, assigning elemental membership and classifying and weighting each element.

Originally it was planned to use a classical AHP hierarchical framework. However, methodological limitations forced a reevaluation. First, 69 data elements were considered to be too many to be effectively handled using classic AHP even with multiple hierarchical levels. Second, the requisite assumption that the preference differentials between elements at the same level of the hierarchy approximated one order of magnitude was not tenable [3,6,7]. In addition, at the second meeting, one participant suggested that 8 Federal Highway Administration Purpose and Need (FHWA P/N) criteria for road construction be taken into account explicitly [10] (Table 3). This suggestion was greeted with such strong consensus that the research team felt it should be addressed, although incorporating the FHWA P/N's into the methodology required a substantial revision to the proposed procedure. A hybrid AHP process was developed in which affinity groupings were combined with the P/N's and inserted into the second level of the hierarchy. Connecting the P/N's to individual elements was then accomplished by using the P/N's to weight the affinity groupings. This was achieved by performing a full set of pairwise comparisons between the five affinity groupings for each of the 8 Federal Highway Authority Purpose and Need (FHWA P/N) criteria specified above. The logistics of this procedure were somewhat lengthier than had originally been planned, nevertheless, the participants were expeditious with their judgments and the meetings concluded in a timely manner. Priority setting for each of the affinity groupings were then averaged to scale the raw elemental impedance scores. This produced a unique impedance score for each element that represents a combination of its individual raw impedance and the priority of its affinity grouping. This affinity group priority was determined both by pairwise comparison among other affinity groups within single FHWA P/N and also by the relative priority of the P/N's deemed applicable to this connector.

To generate the final Analytic Impedance Value (AIV, or ϕ) for each element a weighting process was used. To avoid affinity groupings with more elements potentially registering higher total impedances an *isotropic layer* approach was used. Each affinity grouping was considered to offer a maximum possible impedance which could be generated only if all of its constituent elements were present (Table 4). The summed elemental impedances were then fitted into this layer. Where there were few elements, such as in the "Socioeconomic" affinity grouping, each element represented a larger % of the affinity grouping's total impedance. In other groupings with many elements, some registered very small percentages of the sum impedance.

This process can be specified mathematically. Consider the preference matrix [1]. Here, each Purpose and Need category, represented by PN_i where i = 1 to 8, contains a specific priority ordering of the affinity groupings. The priority coefficients (β) that weight each affinity grouping within PN_i are given by β_{ij}, where j = 1 to 5 for the five affinity groupings defined (see Table 1). Since AHP computation was employed for each P/N, for PN_i it is given that $\sum_{j=1}^{5} \beta_{ij} = 1$.

The complete matrix of 8 P/N's each comprised of 5 affinity grouping priorities was not used in this case. Instead the meeting participants were asked which P/N's applied to this highway. Three specific P/N's were identified and ranked through pairwise comparison for this project using AHP. To perform the AHP computations the Java-based web software HIPRE was used [11]. This offered an advantage over proprietary software such as *ExpertChoice* [12] in that being web-based and remote-site hosted it was accessible by all stakeholders at all times. Regardless of location, each stakeholder could view graphically the preference orderings generated by the AHP and even perform dynamic sensitivity analysis (see Figure 3). Password protection was used.

Combinatorial scoring was then employed to compute a scaling factor that was applied to each attribute. A second, independent AHP prioritization was performed on the three selected P/N's. This yielded:

$$\gamma_1 PN_1 + \gamma_2 PN_2 + \gamma_3 PN_3 = 1 \qquad 2$$

where γ_1 is the AHP-derived priority coefficient for the first P/N, γ_2 the coefficient for the second selected P/N and γ_3 applies to the final P/N.[1] The final weighting was computed on the basis of the following distribution: 65% from the "Legislation" P/N, 19.9% from the "Economic/social development" P/N and 15.2% from the "System Linkage" P/N (Figure 3). The affinity grouping priorities derived by AHP were then multiplied by the appropriate scaling factors. Substituting for PN_1, PN_2 and PN_3 from the matrix 1, the β coefficients were resolved. Each affinity grouping therefore possessed an affinity grouping (category) impedance multiplier (termed σ), representing a relational impedance (Table 4). To interpret σ, consider for example all of the elements in the affinity grouping "Dirt and Rock" sum to give about 1/6 of the impedance of all the elements in the "Regulatory Practices" affinity grouping. But all of the possible elements in each group are unlikely to be spatially copresent in one location, so individual elemental impedances, termed Analytic Impedance Values or ϕ, must be computed.

With α and σ given, ϕ was computed as given in Equation 3. For the elements belonging to the SocioEconomic affinity group, for example, ϕ_{aSE} is the final Analytic Impedance Value for element

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[1] AHP could only be used here if five or fewer P/N's were identified. In this case since only three were judged significant, all other γ =0.

a, α_{aSE} is the raw impedance score for element *a* and σ_{SE} represents the AHP-derived affinity group total impedance for the "SocioEconomic" affinity group.

$$\phi_{aSE} = \left(\frac{\alpha_{aSE}}{\sum_{i=1}^{n} \alpha_{iSE}} \right) \bullet \sigma_{SE} \qquad 3$$

To give some idea of the range of ϕ values the element with the highest impedance, $\phi = 7138.8$ units, was *Four F National Properties*. This element was assigned the highest raw score and since it belonged to the "Regulatory" affinity group it also received the highest categorical impedance rating. Every participant felt that such properties (National Historic Register) were very difficult and expensive to acquire, and even if legally and economically feasible, the acquisition process often faced significant and widespread community opposition. Therefore they felt that the Four F properties should be avoided when planning this road corridor. The lowest ϕ was assigned to element *Slope Categories 0-5%* in the "Dirt and Rock" affinity group ($\phi = 175.0$). This reflected a rather low level of impedance assigned to engineering concerns in this case. The final ϕ value for each data element was then ready for input into the GIS.[2]

The GIS database for AMIS was constructed to the same resolution as the underlying terrain data, USGS 30 meter digital elevation models (DEMs). This was selected to simplify data conversion and also to approximate an absolute minimum width for an interstate highway corridor. Although a larger cell size//ould have depicted the actual right of way required for a highway corridor more accurately, it would also have meant that the effective scale of the data would be reduced with concomitant accuracy loss. The 30 meter size was therefore selected as a necessary compromise. Data for the GIS came from a variety of sources within the state and federal government. (see Figure 3 and 4 for examples). All of the vector data was converted to raster grids within Arc/Info. The integer value of each grid cell was taken directly from the calculated AHP values for that data layer. For cell A, where *n* elements are present, net cellular impedance μ_a is given by:

$$\mu_a = \sum_{i=1}^{n} \phi_i \qquad 4$$

Once all the raster layers were completed, Arc/Info then added the values of all cells in the corridor study area. The result is an impedance surface, representing the sum of all the calculated costs on a per-cell basis (Figure 5). Using Avenue scripts within Arcview, the routing function is invoked with a button which then allows the user to specify where the route should terminate. Arcview then determines the least cost route to that cell and draws it onscreen as a graphic element (Figure 6).

AMIS offers both process and analyses advantages over more traditional, unstructured methods of corridor selection. First it encourages the explicit incorporation of specific systemic goals in the initial stages, such as FHWA Purpose and Need categories. This opens a discussion that helps clarify the goals of route planning. Second, the formalized approach to priority-setting reduces the potential for conflict and enhances the consensual strength of the outcome. Third, planning priorities can be customized for individual projects, or planning priorities can be mixed over different sections of the same route. AMIS could be used to solicit and incorporate public input on the relative importance of various cultural, natural, and tourism features of a locality. Even consideration of FHWA's Community Impact and Environmental Justice criteria [13] could be accommodated within the structure of AMIS.

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[2] Because of the hybridity of the process, classic measures of AHP consistency that gauge preference intransitivity cannot be applied meaningfully to the complete AMIS hierarchy [3,6,7].

FIGURE 1 Enlargement of Project Area Showing Current State and Federal Highways

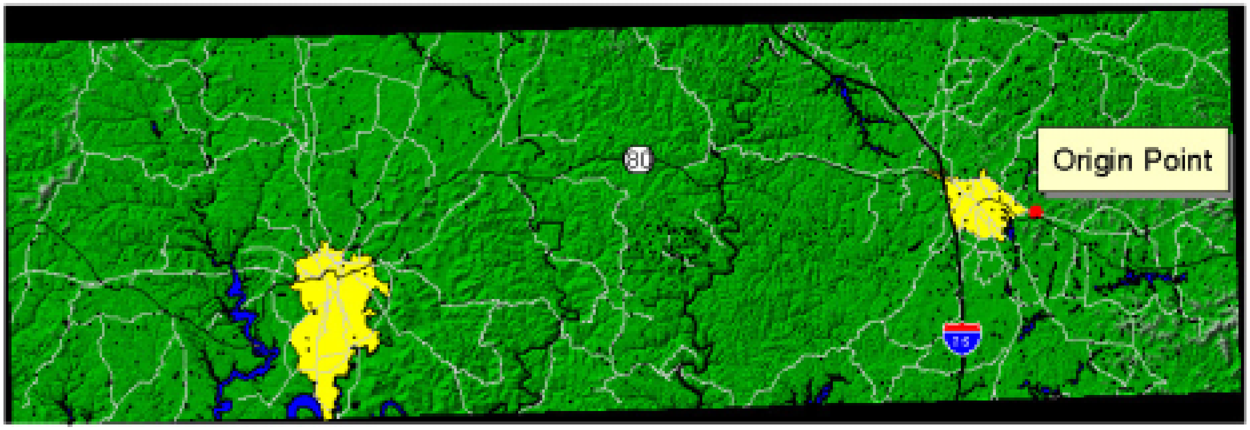


TABLE 1 Original Criteria Grouped by Affinity

Environmental	Man-made public features	Dirt and rock	Socioeconomic	Regulatory practices
Unique habitat	Hospital	Oil and gas wells	Land value	Picnic area
Large viewshed	Water tank	Mine	Poverty rate	National properties register
Archaeological feature	School	Strip mine	Median income	State park
Historic feature	Public Water Supply	Quarry	Population growth rate	Wild and scenic river
Streams	Airport	15-25% Slope	Community impact	Public campground
Wetland	Sewage treatment	10-15% Slope		Wildlife management area
Prime farmland	Church	5-10% Slope		Endangered species
Fish hatchery	Pumping station	Slope		National forest
Springs	Cemetery	Slope		Superfund site
Sink holes	Pipeline	Rock base		Close to natural attractions
Known caves	Golf course	Mixed/unknown base		National park
Underground fuel tank	Powerline	Soil base		Military installation
High probability of caves	Armory	Soil classification		
EPA project sites	Railroad			
Low probability of caves	Power plant			
Tire dump	Water filtration			
Landfills	Radio tower			
Hazmat	Dams			
	Electric substation			

TABLE 2 A Sample of Original Raw Impedance Scores for Individual Elements

Element	α (raw impedance score)
Four F Property (National Register)	51.9
National Park	46.8
Endangered Species	36.1
Military Reservation	33.3
Superfund	31.5
Wild and Scenic River	24.8
25%+ Slope	24.5
Threatened and Endangered Habitat	24.4
National Forest	23.7
State and Local Forest	19.7
State Park	18.6
Historical Feature	18.5
Dams	13.9
EPA Project Sites	13.9
Wetland	12.7
Public Water Supply	12.2
Railroad	12.1
High Probability of Caves	11.9
Campground	11.6
BREAK IN DATA: ELEMENTS EXCLUDED TO SAVE SPACE	
Electric Substation	5.2
Pipeline	5.1
Population Growth Rate	4.9
Powerline	4.6
Mixed/Unknown Base	4.4
Radio Tower	4.3
Soil Base	4.1
10-15% Slope	4.1
Strip Mine	4.1
Rock Base	3.9
Soil Class	3.8
Bridge Crossing	3.5
5-10% Slope	3.1
Golf Course	2.9
Low Probability of caves	2.5
0-5% Slope	1.8

EQUATION 1 PRIORITY COEFFICIENTS FOR FHWA P/N's.

$$\begin{array}{c} PN_1 \\ PN_2 \\ PN_3 \\ PN_4 \\ PN_5 \\ PN_6 \\ PN_7 \\ PN_8 \end{array} = \begin{array}{ccccc} \beta_{11} & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} \\ \beta_{21} & \beta_{22} & \beta_{23} & \beta_{24} & \beta_{25} \\ \beta_{31} & \beta_{32} & \beta_{33} & \beta_{34} & \beta_{35} \\ \beta_{41} & \beta_{42} & \beta_{43} & \beta_{44} & \beta_{45} \\ \beta_{51} & \beta_{52} & \beta_{53} & \beta_{54} & \beta_{55} \\ \beta_{61} & \beta_{62} & \beta_{63} & \beta_{64} & \beta_{65} \\ \beta_{71} & \beta_{72} & \beta_{73} & \beta_{74} & \beta_{75} \\ \beta_{81} & \beta_{82} & \beta_{83} & \beta_{84} & \beta_{85} \end{array} \tag{1}$$

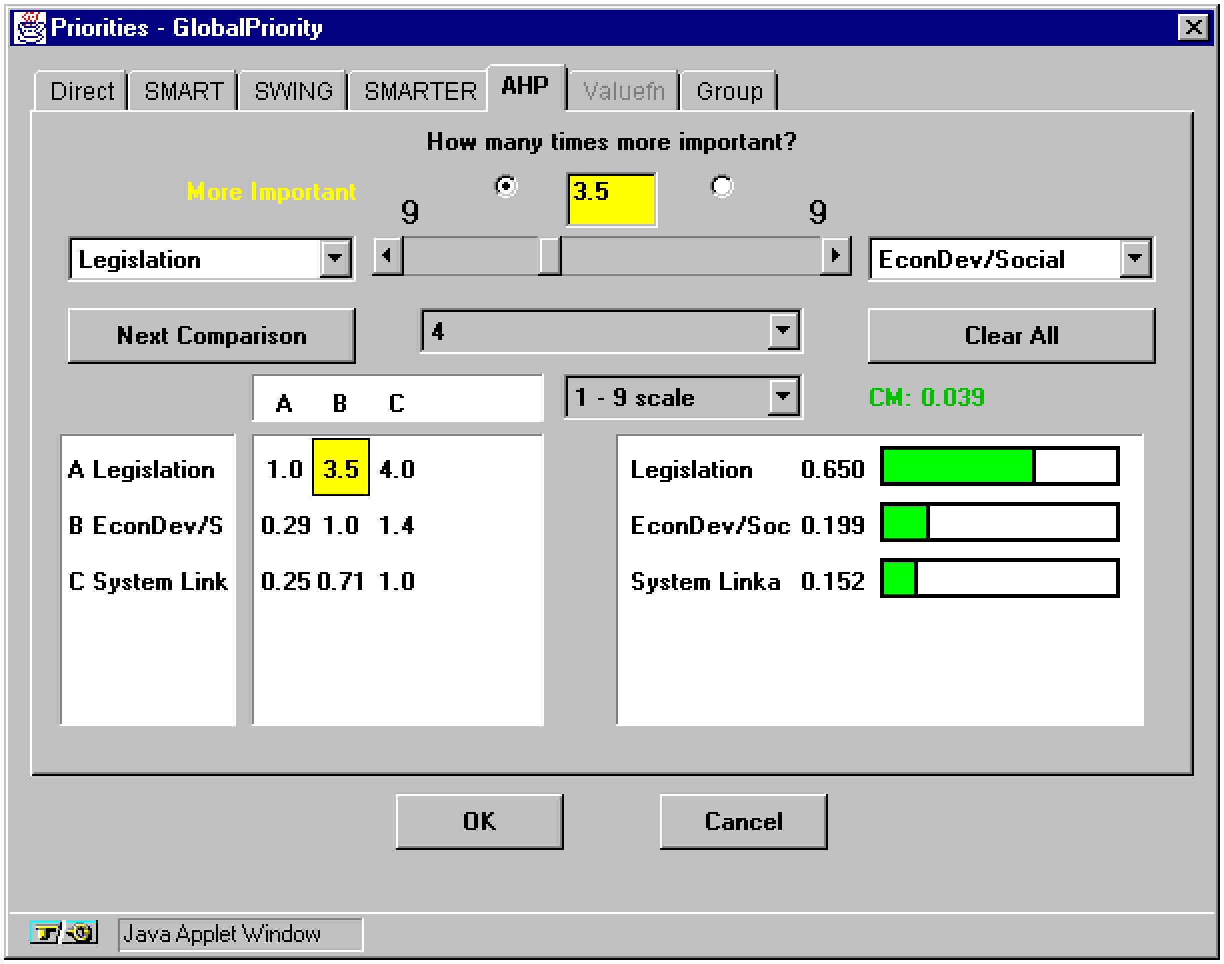
TABLE 3 Federal Highway Administration Purpose and Need Criteria

System Linkage
Capacity
Transportation Demand
Legislation
Social Demands or Economic Development
Modal Interrelationships
Safety
Roadway Deficiencies

TABLE 4 Affinity Grouping Impedance σ

Affinity grouping	Impedance multiplier σ (arbitrary units)
Environmental features	184
Man-made features	109
Dirt and rock	80
Socioeconomic	142
Regulatory Practices	485

IGURE 2 Example Output from HIPRE Showing FHWA P/N System Prioritization for this Interstate Connector



How many times more important?

○ 3.5 ○

Legislation

EconDev/Social

4

1 - 9 scale

CM: 0.039

	A	B	C
A Legislation	1.0	3.5	4.0
B EconDev/S	0.29	1.0	1.4
C System Link	0.25	0.71	1.0

Legislation	0.650
EconDev/Soc	0.199
System Linka	0.152

FIGURE 3 Sample Point Locations in Study Area

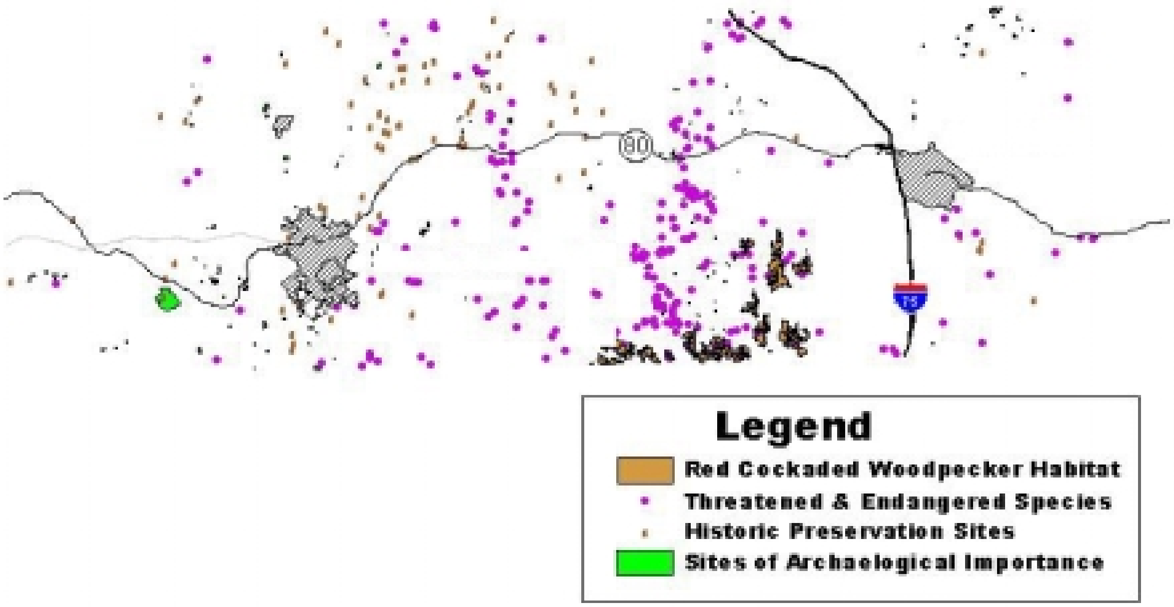


FIGURE 4 Area Coverage of National Forest

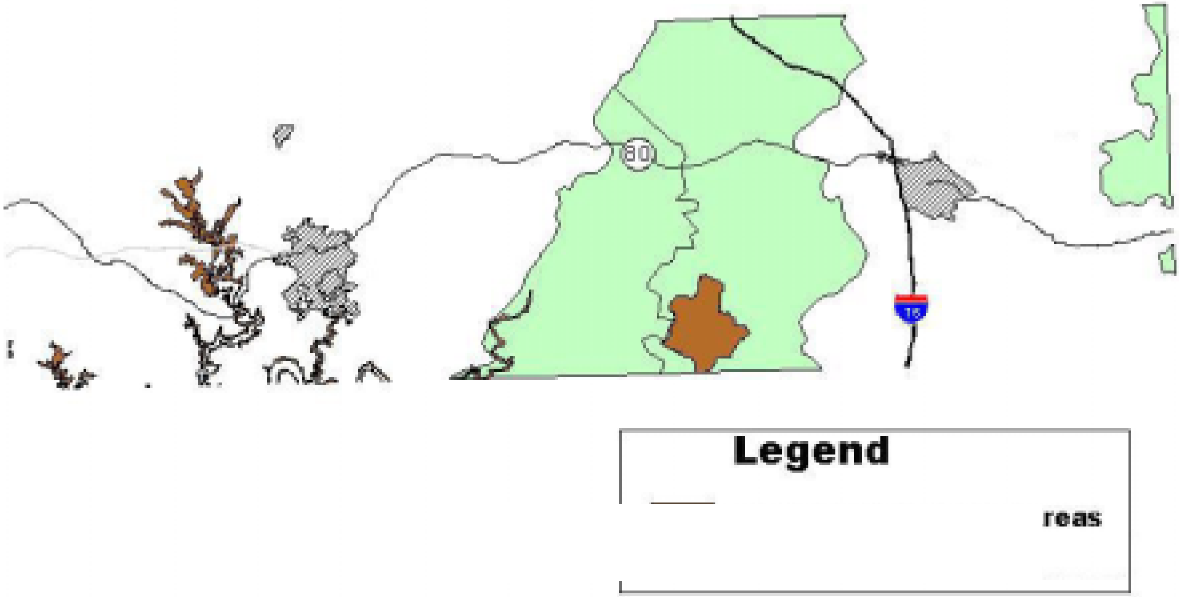


FIGURE 5 General Form of the Isocost Surface with User-Specified Origin

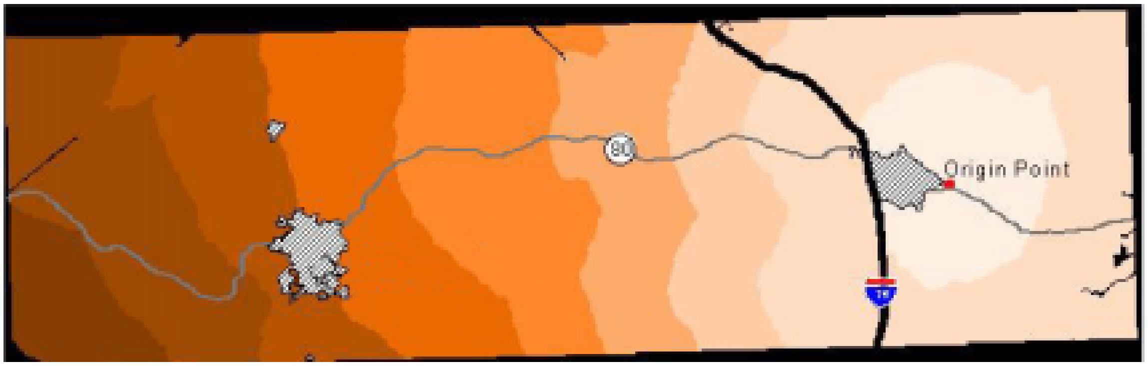
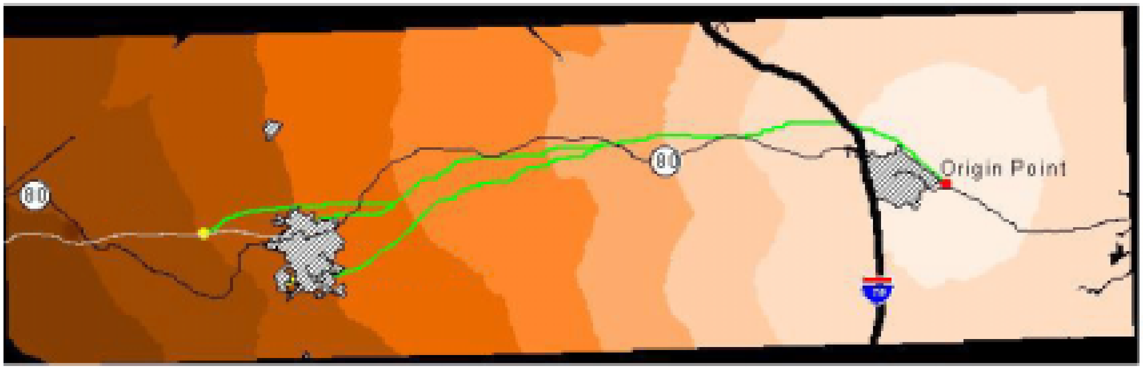


FIGURE 6 AMIS Routings from One Origin Point to Three Separate Destination Points



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