University of Redlands

**Trail Analyst Extension:
Multidimensional Segmentation of Transportation Networks to Support
Multimodal Travel**

A Major Individual Project submitted in partial satisfaction of the requirements
for the degree of Master of Science in Geographic Information Systems

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ABSTRACT

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by
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Transportation planners have usually disregarded unimproved roads and trails. However, in applications such as disaster relief, emergency evacuations, and recreational hiking and treks there is a need to consider all possible paths on a transportation network. These previously ignored travel routes differ from paved roads in their increased susceptibility to the effects of weather and limits on particular transportation modes. The transportation planning system used by the client was upgraded from one that considered only paved roads to one showing an integration of roads, off-road vehicular trails, and footpaths. The Trail Analyst Extension was developed as an extension to a commercial GIS software package to provide a suite of tools to: 1) augment the location of trails with additional attributes, such as, elevation, water hazards, and meteorological events to better facilitate seasonal planning; 2) construct a transportation network that includes the trails and unimproved roads, as well as paved roads; and 3) segment the transportation network edges according to user-defined constraints. The Trail Analyst Extension provides planners a means to tailor routes based on recent meteorological conditions and varying modes of transport.

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List of Acronyms

DEM	Digital Elevation Model
DIME	Dual Independent Map Encoding
DLG	Digital Line Graph
DRG	Digital Raster Graphic
GIS	Geographic Information System
GIS-T	GIS - Transportation
GPS	Global Positioning System
Hazmat	Hazardous Materials
IDW	Inverse-Distance-Weighted
MARS	Multivariate Adaptive Regression Splines
NASA	National Aeronautics and Space Administration
SEE	Standard Error of Estimate
SUV	Sport Utility Vehicle
TIN	Triangulated Irregular Networks
USGS	United States Geological Survey
VORTAL	Variational Optimization of Random Trees ALgorithm

1. Introduction

Wildlife nature tours are becoming very popular with a wide variety of individuals and groups. Tour operators are required to adapt their offerings to account for the varied needs of groups with physical conditions ranging from the extreme adventurer to the physically handicapped and elderly. The challenges faced with designing an itinerary that accommodates the physical needs and desires of this diverse customer base may be mitigated through the use of a Geographic Information System (GIS).

Businesses scheduling wildlife-nature tours and expeditions have to take into account numerous factors when creating an itinerary. Recent weather conditions or climatic events may render a road or hiking trail unusable. The presence of wildlife within a geographic region will increase the desirability of travel on paths that traverse a specific area for customers. The same wildlife areas may need to be avoided by support groups carrying supplies and additional equipment to minimize incursions into sensitive areas. Age, physical fitness, equipment load, and the use of pack animals will change the type of trails that are usable and the speed with which they can be traversed. The presence of vehicular routes will determine what part of the trip is accomplished via motorized vehicle before starting off on foot or horseback.

The client currently offers excursions on paved roads for large groups by bus. Smaller groups are transported by sport utility vehicle (SUV). In an effort to expand their business the client intends to offer off-road excursions via SUV, horseback and hiking. The client utilizes a GIS to assist in the planning of vehicular tours. This system is woefully inadequate when applied to the planned expansion of services. The new system expands on the capabilities of the existing in two directions. The first expansion is in the addition of road grade and climate to the existing travel routes. A road that can be traversed by a four wheel drive SUV may not be suitable for a bus. The same road may not be usable by the SUV during certain months of the year. A guide using the current system to plan an excursion must supply the terrain and climate knowledge to the planning process. The new system will add this level of intelligence and remove the need for the operator to provide this expertise.

The second expansion is in the types of routes that may be defined. The current system allows for highways and paved local roads with varying number of lanes. The new system allows for unpaved roads and off-road vehicle paths such as a SUV or cart trail. The new system allows for non-vehicular travel by including foot paths and trails. The addition of off-road routes also requires the inclusion of water hazards that may render the route impassable under certain conditions. These water crossings or fords have characteristics that differ from bridges. A bridge may be unaffected by an increase of six inches in the level of a stream while a ford may be rendered impassible by the same condition.

The client operates a small business in Fresno County, California. Over the past five years, they have offered tours to large and small groups on the roads within the Sequoia and Kings Canyon National Parks. All excursions are limited to paved roads.

The owners are expanding the tour offerings to include off-road travel as part of an overall strategy of growth.

The client expected the delivery of a utility set that would allow their staff to perform the basic tasks of expedition planning within the expanded environment with minimal increase in time. There was preference as to the specific technology utilized to provide the guides with the new capabilities beyond the need to utilize the existing database of roads and bridges that is currently in use. Based on their experience with the existing system, the client insists on a user interface that would allow the guides to have direct access to the underlying records describing the new features.

1.1. Problem Statement

The problem addressed by this project is to devise a tool or set of tools that would allow trip planners to quickly generate a route tailored to an individual tour group and taking into account recent local climatic conditions. It was decided that augmenting a vector based transportation network with environmental data traditionally only available in raster format would address this need.

1.2. Trail Analyst Extension

The Trail Analyst Extension was developed to solve the problem described in Section 1.1. The Trail Analyst Extension is an extension of the ArcGIS Desktop and works with ArcMap 9.2. The interface and functions supplied by this extension are described in Section 4.

2. Background and Literature Review

GIS has been applied to transportation problems from its beginnings. In the early stages raster math was utilized to aggregate a variety of continuous surfaces. The resulting “cost-surface” was then analyzed to determine the least-cost-path of travel. Later developments lead to the transition to vector-based transportation networks consisting of nodes and links. These constructs permitted more sophisticated behavior modeling including one way edges and restricted turns at links. Each approach brings it own unique strengths and weaknesses (Corbett, 2001; Goodchild, 2000; Grieco & Rajé, 2003; Hägerstrand, 1970). The challenge addressed by the Trail Analyst Extension is to bridge the gap between these methodologies to combine their strengths and reduce their weaknesses.

2.1. Cost Surface Approach

The development of a cost surface is generally accomplished by adding two or more raster layers. These various layers attempt to account for the effects of elevation, vegetation cover, surface composition, a wide variety of additional factors that may influence travel within a region. By weighting each contribution, the cost to move between two points is determined. The path with the least cost best meets the design goals.

Least-cost-path models have been in use since the 1960s (Goodchild, 2000). These models sometimes considered the cost of travel across terrain as an average value for a general area. The level of generalization was often driven by the cost and availability of technology. As technology storage and processing costs decreased the level of generalization has also decreased. Brannan (1992) incorporated the variable cost of travel across slopes ranging from -40% to $+40\%$ as well as the differences resulting from changes in terrain surface. The resulting equations for calculation of a cost surface greatly improved the accuracy of the path selection.

Tobler (1993) was also interested in the development of surface cost models that accounted for the varying costs associated with hilly terrain. Based on empirical evidence gathered by others, Tobler developed an equation that calculated the velocity of a traveler on a slope. With this formula a cost surface may be quickly developed. One of the most important observations that Tobler made within this work is the need to combine network models with continuous cost surfaces. The ability to combine information from these two sources was beyond the computation capabilities of both the hardware and software of the early 1990s.

Marble and Machovina (1996) felt that Tobler’s model was too simplistic and did not take into account factors that effect travel across terrain as much as, or more than, slope alone (Machovina & Marble 1996). Water features are mentioned as a prime example as something that can impede or speed travel. When a traveler encounters a lake with no means of water borne transport available, the lake becomes an obstacle that must be traveled around. The same traveler may utilize a dry or shallow river bed as an easy path that increases their rate of travel through regions of dense underbrush.

A common problem encountered in the grid-based cost models of the 1990s is in the area of spatial aggregation. Most studies conducted during this timeframe attempted to model the behavior of an individual walking across terrain using small scale elevation data. It is easy to understand how contour maps with 20 meter by 20 meter grid sizes or 50 meter contour lines do not work for this level of analysis (Machovina & Marble, 1996). The combination of computational power, data storage capacity, and accessibility of large scale elevation data necessary to carry this analysis to the next stage did not become available to researchers until the mid to late 1990s.

The next advance in the area of least-path cost analysis that is directly applicable to this project occurred when Lee and Stucky (1998) incorporated viewsheds into the analysis. Viewsheds were included as high or low-cost elements of the surface depending on the traveler's purpose. If the traveler's intention is to stay hidden from some areas then the viewshed is allocated a high cost. If the viewshed area contains scenery of interest, then the cost values are reduced for this area. Lee and Stucky developed four different traveler scenarios to test and prove their model. An interesting result of their study was the positive correlation between the scenic traveler and the typical least-cost path. The inclusion of scenic traveler's preferences in relation to viewsheds complimented the results of standard least-cost path analysis. The primary drawback to Lee and Stucky's work is in their failure to include terrain features other than a digital elevation model.

The identification and inclusion of cost values associated with specific applications has taken place in the area of canals (Collischonn & Pilar, 2000) and highways (Fischer, 2003; Yu, Lee, & Munro-Stasiuk, 2003). The inclusion of these factors is more in the way of tuning of the cost surface than a modification or extension of the basic methodology used to develop paths.

Balstrom (2002) took a different approach by first developing a friction-based cost model and ending with a vector network of least-cost paths. Balstrom included cost values for various terrains using a digital elevation model (DEM) and empirical data gathered at the study site. One of the major limitations that Balstrom encountered was the inability to account for slope in more than one direction. Utilizing a common grid approach only one value may be captured for a given cell. The value assigned to the cell is typically either that of the steepest slope or the slope in the direction of travel. This limitation is of concern when conditions arise that make it desirable or necessary for a traveler to change their direction of travel. If no consideration is given to the variations in traveling uphill versus along a slope or downhill, then the results of such a model must be suspect.

This limitation was also encountered by Wood and Wood (2006) while developing a caloric cost model for pedestrian travel across terrain. Wood and Wood found that most GIS tools eliminate all negative slope conditions. This led to the statement that since "there are no downhill slopes, it really is possible to walk to school uphill both ways" (Wood & Wood). Rather than accept what they perceived as the limitations of existing tools, Wood and Wood developed a new raster grid approach. This approach calculated eight different slope values for each cell on the travel grid. The value used for calculation of the cost of travel was determined by the direction of travel. Using this system travel cost was adjusted for the degree of positive or negative slope encountered.

Strobl (2007) included the procedure for starting with a transportation network, converting it to a cost surface, and then combining the cost surface with other surfaces. This approach allowed network travel to be adjusted by traditional cost surfaces and for off-network travel to be considered.

The approach taken by Wood and Wood appears to be similar to that used in MODFLOW. MODFLOW is the USGS finite-difference ground-water flow model developed in the 1970s and 1980s (Hill, 2002). MODFLOW uses a 3D view and computes the flow of water across each of the six surfaces that surround a cell. These six values form the basis for interpolating the flow rate for any direction within the 3D space (Pollock, 1994). It is easy to see that this algorithm could be modified to handle the eight adjacent cells within a 2D grid.

2.2. Vector Network Approach

A survey of existing geographic data processing systems was conducted by Nagy and Wagle in June of 1979. They reviewed the Laboratory of Computer Graphics and Spatial Analysis at Harvard University (ODYSSEY); Nordbeck's and Rystedt's Mapping System (NORMAP); Dual Independent Map Encoding (DIME); Experimental Cartographic System (ECS); Semiautomated Cartographic System (SACARTS); Wildland Resource Information System (WRIS); Canada Geographical Information System (CGIS); Storage and Access of Network Data for Rivers and Drainage Basins (STANDARD); Geo-Data Analysis and Display System (GADS); and NIMS. The only system setup to address network related problems was GADS. GADS had "been subjected to limited operational testing by municipal agencies interested in the optimal reconfiguration of police beats and school districts" and "for solving certain network-related (as opposed to area-related) problems." This system review and a referenced IBM Research Laboratory article by P.E. Mantey entitled "Transportation planning applications of the geo-data analysis and display system" (1974) are among the earliest references to the use of GIS in transportation analysis.

The current GIS representation of a transportation network has its origins in the U. S. Bureau of the Census DIME files. Developed for the 1970 census, this network was a collection of nodes and links. This collection of nodes and links provided "the ability to institute checks of logical consistency". This structure also provided a solid foundation for the development of algorithms necessary to find the optimal or shortest path through a node and link structure (Goodchild, 2000).

The use of GIS to determine the shortest travel distance between two points is common. Internet GIS service providers such as MapQuest and Expedia.com offer easy access to systems that utilize known networks (interstates, highways, and roads) and common maximum speed limits to deliver travel directions and estimated times. By using the speed limits to estimate the cost of travel across a route segment, a least-cost-path is developed over the network between the two travel points.

The National Aeronautics and Space Administration (NASA) sponsored research into methods of analyzing transportation network topologies and determined that:

GIS's ability to integrate a variety of different data layers into a software environment in order to manipulate and analyze the spatial relationships is of

great value for transportation planners ... The ability to do network analysis in a GIS context offers several advantages, such as being able to define highly accurate service areas or to relate network decision-making with environmental, land use, and other planar variables. (Kuby, Tierney, Roberts & Upchurch, 2005)

This suitability has been recognized and exploited by numerous parties and is one of the key reasons for the development of the field currently referred to as GIS-T (GIS – Transportation).

The study of transportation networks generally takes two divergent views. A large group of professionals and research has focused on the planning, creation, and maintenance of transportation networks. Significant research has been focused on the study of hazards (weather, landslides, and seismic events) and their impact on the transportation network. The purpose of this study has been focused on prevention. Planners and emergency response groups often develop hazard matrices to assess the potential impact of catastrophic events on individual elements of a transportation network. Most of these efforts gage success by throughput. However, the “objective of transportation systems is improving individual accessibility. ... Accessibility, not throughput, is why transportation systems exist” (Miller & Wu, 2000).

In an effort to improve accessibility and mitigate the impact of weather some jurisdictions are attempting to provide real-time advice to transportation network users. One approach in use is to “improve traffic operations under adverse environmental conditions, travelers information may be furnished through roadside warning systems, web-based application, and interactive telephone systems” (Pisano & Goodwin, 2002).

The second view of transportation networks is in the optimal routing of an individual traveler on the transportation network. This view also addresses hazards but from a different perspective. If a potential hazard exists in the immediate future, or if a real hazard exists that may impact a traveler, how do we gain and use that knowledge?

One source of information regarding travel hazards is the Internet. Travelers may locate up-to-date information regarding road construction and weather-related road conditions on the Internet. This information has been made available from a variety of online sources, including the Wisconsin Department of Transportation (Peng & Beimborn, 1998). Real-time traffic information is also available from sites like mobile.inrix.com using a subscription service. These sites provide subscribers with mobile web access to views showing major transportation arteries with their current traffic condition color coded and, optionally, their current average speed. Traffic incidents are also displayed to pinpoint causes of congestion. These sites may also provide real-time alternate routing to avoid these high impact areas.

The fact that “weather events can cause slick pavement, lower traffic speeds, increase speed variability, reduce roadway capacity, increase delay, escalate crash risk, disrupt access to roads (e.g., lane obstruction, flooding), and damage road infrastructure” emphasizes the need for “road operating and maintenance agencies [to have] road weather observations, forecasts, and decision support tools” (Pisano, Pol, Afelor, Goodwin & Stern, 2005). This need is even more critical to transportation organizations that handle explosive, chemical, nuclear and other hazardous materials.

Recent research within the Washington DC Metropolitan area focused on the “ability to reroute a vehicle carrying hazardous materials (hazmat) given real-time information [this] is crucial to avoid unexpected delay or adverse weather that could lead to increased risk of accident” (Kim, 2006). Kim was able to use real-time climate feeds to “quickly provide updated routing instruction to hazmat trucks in real-time considering current traffic and weather conditions, emulation of the real-time road weather advisory system in a GIS environment, and a methodology for integrating and using publicly existing real-time information.” This real-time ability to react to changing weather conditions is a significant step in the inclusion of climate in transportation route planning.

A different approach has been taken by Knoblock (2004). In an effort to supply travelers with route modifications based on real-time weather conditions, Knoblock created tools to query the Yahoo Weather information. These updates were forwarded to the travelers if they indicated potential problems for their travel plans. This notification provided a more proactive approach to responding to weather conditions that developed after the initial planning process.

The final area of research into transportation networks and the computation of travel costs and route optimizations is a methodology called VORTAL. The Variational Optimization of Random Trees ALgorithm (VORTAL) computational methodology proposed by de Smith (2003) takes components of the cost surface and carries them into the realm of vectors. VORTAL uses a series of triangles to define the space between the origin and destination. The vertices of the triangle are selected at random. Each triangle is evaluated and a path is developed to travel across the triangle. The path is found by generating three trees with branches extending out from each vertex. When two of the trees have branches that are close they are joined. A tree is extended from the junction until it encounters the tree from the third point. After all trees are joined a “tension” process is executed. This process involves removing points along the three converging paths to simplify them. This is similar to pulling each path from the two ends. After each path has been simplified further optimization is performed by moving the point of intersection of the three paths until the movement does not result in an overall shortening of the three paths. As each successive triangle is solved, the path from origin to destination is identified. Optimization routines follow the initial definition until the final solution is obtained. Gradients and other travel cost values can be applied to each triangle to account for factors traditionally defining the cost surface. Development of VORTAL is reported to be continuing.

2.3. Proposed Solution

The client requires a customized fusion of network analysis and grid-based least-cost-path data sources. Within the study area, travel is dependent on recent weather conditions which must be addressed. Travel costs will have to be calculated for each path segment to account for grade, surface condition, and climate. Current network analysis tools are optimized to support this established set of networked paths after appropriate travel cost values are applied. The Trail Analyst Extension was created to bridge the gap between the traditional cost surface and network analysis tools. This toolset will extract information from raster files, segment a transportation network into homogeneous segments, assign climatic attributes, and calculate travel cost values for each segment.

3. Data

The datasets used in this project were collected from government sources available to the public. These datasets were formatted to be compatible with the clients existing data standards and placed in a personal geodatabase (Appendix A).

3.1. Source Data

All data used to prepare the geodatabase are listed in Table 3-1.

Table 3-1 Table of Data

Dataset	Description	Source and Date	Data Model
DEM	Digital Elevation Model	USGS NED, 2006	Raster
RoadsTrails	DLG Roads and trails	USGS SDTS, varied	Polyline (vector)
Lakes	Lakes	USGS, 2005	Polygon (vector)
Streams	Rivers and streams	USGS, 2005	Polyline (vector)
DRG	Digital Raster Graphics (Mosaics)	USGS, varied	Raster
Maintained_Roads	Roads	NPS, 2003	Polyline (vector)
Maintained_Trails	Trails	NPS, 2004	Polyline (vector)

The road and trail network is one of the key components of this project. The National Park Service is currently in the final stages of updating their road and trail network data. When this new dataset is released to the public it will replace the data used within this project. Due to the lack of availability of this dataset within the timeframe of this project, the USGS Digital Line Graph (DLG) dataset was selected as the most complete data source available. Some of these data required additional preparation due to inconsistencies and lack of attributes. Figure 3-1 shows the study area and its overlap of DLG quadrangle boundaries. Quadrangles shown in grey were not available from the USGS for this project. Road and trail features within these quadrangles were digitized using the Digital Raster Graphic (DRG) mosaics and ArcMap 9.1.

The Maintained_Roads and Maintained_Trails datasets were utilized to provide name attributes to approximately one-third of the final RoadTrails features. The remaining features were given fictitious names using the OBJECTID field and a name generator (e.g., Un-named 4236). This was deemed satisfactory until the National Park Service released their updated dataset.

Figure 3-1 Quadrangles with DLG Transportation Data
USGS DLG Transportation data not available for quadrangles in grey

The Streams dataset was used in conjunction with the RoadsTrails dataset to generate point features identifying potential fords. This ford dataset was processed to remove all points that did not represent a water crossing hazard. The remaining points were assigned attributes to indicate the typical water level during the three assigned climatic conditions. The Streams dataset was developed by the USGS from 1:100000 DRGs. This is a lower level of accuracy than the 1:24000 RoadsTrails dataset, but was deemed acceptable for this use.

Hypsographic DLG data (1:24,000 contours) was available for this area from the USGS. This data was not used at the client's request. All elevation data was obtained from the DEM to remain consistent with the client's current practices.

3.2. Database Design Considerations

The Trail Analyst Extension works from an enterprise and/or personal geodatabase. This flexibility allows individual users to share data and, when desired, keep portions of the

data separate. Trip planners may have developed transport mode profiles that are unique to their expeditions and are kept within a personal geodatabase. The feature classes and domains utilized by the Trail Analyst Extension were required to be compatible with the client's legacy system. To accomplish this goal, no datasets or fields were deleted and no definitions were changed.

The RoadsTrails feature dataset is compatible with the client's legacy system. The addition of the new trail features required extensions to the domain containing valid values for surface width. The new values continue the legacy scheme and do not affect how legacy applications utilize these values. The inclusion of the environmental factors also required the addition of new attributes to this dataset. These attributes contain measures of grade, snow depth, ice, and depth of ford crossings under various rainfall conditions.

The Fords feature dataset is a new addition to the client's GIS system. This is a point feature class with attributes describing the typical water depths experienced under a variety of conditions. The RoadsTrails feature dataset has a corresponding set of fields to hold water depth values for features that are fords.

The Transport mode table is another new addition to the client's GIS system. This table stores individual transport mode descriptions. Each description provides the detailed travel characteristics necessary to determine if a road or trail segment may be traversed given a set of climatic conditions and the corresponding speed of traversal.

The data required by the Trail Analyst Extension increased the size of the enterprise database by approximately 475 MB. The majority of this increase is due to the addition of the DEM, Solar, Ice and Snow rasters. The total increase is approximately 475MB. The additional vector data sets and fields add less than 4MB to the size. The largest potential increase would result from adding the DRGs to the database. If the client elects to add these data it will take an additional 8.31GB of disk space.

3.3. Data Accuracy Considerations

The Trail Analyst Extension relies heavily on the positional alignment between the RoadsTrails dataset and the DEM. Most of the DLGs obtained from the USGS appeared to have accurate registration of the road and trail features to the contour lines and corresponding DEM. One of the DRGs (Lodgepole, Figure 3-1) was a provisional series USGS map and appeared to be misregistered. The DLG for Lodgepole appeared to be shifted 43 meters east of its proper location (Figure 3-2). This apparent misalignment was verified using a GPS unit (Section 5) and by verifying the positional alignment of the DRG with respect to the DEM.

The apparent improper registration of the DLG (the RoadsTrails dataset) results in elevation values interpolated from the DEM that yield misleading grade signatures. Figure 3-3 illustrates the grade signatures observed with the GPS-altimeter, interpolated from the original USGS data, and interpolated from the adjusted USGS data. It is clear that the adjusted feature exhibits grade characteristics that are closer to the actual trail than does the apparently misregistered feature.

Possible sources of this apparent misregistration were investigated. The possibility that the apparent shift was caused by a datum error was researched. Using the

National Geodetic Survey North American Datum Conversion tool provided by National Geodetic Survey, National Oceanic & Atmospheric Administration (2007) with the southwest corner of the Lodgepole quadrangle as input returned a value of 83.581 meters for the total datum shift between NAD83 and NAD27. This value is almost twice the offset that was measured on the provisional quadrangle. This was discarded as a possible source of the apparent misregistration. We have not determined the reason for this shift at this time.

Figure 3-2 USGS DLG Registration Error

Figure 3-3 USGS DLG Registration Grade Impact

A shift in the elevation along the entire feature was also seen when the interpolated DEM candidate vertices were compared to the Global Positioning System (GPS) gathered information. The elevations interpolated from the DEM showed a decrease of approximately 17 meters in elevation at every point. If an adjustment was made to the interpolated data it followed the GPS data with a higher degree of accuracy (Figure 3-4). This elevation offset was not important to the Trail Analyst Extension analysis since the changes in elevation, and subsequently the calculated grade, were unaffected by this offset.

Figure 3-4 USGS DLG with Adjusted Elevation

4. Methodology

The approach used in the creation of the Trail Analyst Extension can be summed up in the phrase “divide and conquer”. Each trail and road feature is examined from the viewpoint of fords, climate and grade. If a significant change, as defined by the user, in any of these environmental conditions occurs the feature is segmented. The end result is a set of individual segments that have a common collection of environmental attributes.

4.1. Segmentation Overview

As an example consider a road that goes from A to E (Figure 4-1). The length of the road is 12 miles. A and E are at the same elevation but there is a hill between the two. A traveler leaving A will travel 2 miles on level ground before reaching the hill. The hill is a steady 4% grade three miles to the top. The traveler then proceeds six miles down a 2% grade before traveling the final mile to get to E. The Trail Analyst Extension will segment this road into the smaller pieces listed in Table 4-1 Segmentation Results.

Figure 4-1 Segmentation Example

Table 4-1 Segmentation Results

Segment	Length	Grade
A-B	2 miles	0%
B-C	3 miles	4%
C-D	6 miles	-2%
D-E	1 mile	0%

Each road and trail feature is constructed of vertices connected by lines. The location of the vertices determines the shape of the line. The Trail Analyst Extension inserts candidate vertices on the line between these vertices based on a user defined maximum sampling distance. If two vertices are more than the maximum sampling distance apart and are less than twice the maximum sampling distance, then one candidate vertex is inserted on the line midway between the two vertices. The placement of the candidate vertex at the midpoint rather than at a fixed distance from the starting

vertex was selected to provide a more uniform series of points to be used to represent the feature. The elevation for these points is then calculated using the DEM.

The formula used to determine the number of candidate vertices to be inserted between any two adjoining vertices is

$$n = \sqrt{(P1_x - P2_x)^2 + (P1_y - P2_y)^2} / SD \quad (4-1)$$

where n is the number of candidate vertices; $P1$ is the starting vertex; $P2$ is the ending vertex; and SD is the maximum sampling distance. After the number of candidate vertices is determined they are equally spaced in a straight line between the two vertices. After the candidate vertices are placed, the entire set of points (vertices and candidate vertices) is evaluated against the environmental criteria.

Figure 4-2 shows a sample road that was constructed from four vertices (A-D). Using the original vertices, the road could be segmented at C to provide two features (A-C and C-D) with common grade attributes.

Figure 4-2 Segmentation – Initial Evaluation

Figure 4-3 shows the insertion of candidate vertices at a maximum distance of 10 meters. Three candidate vertices were inserted between A and B, three between B and C, and one between C and D. A significant grade change at B2 is now evident.

The next step is to remove candidate vertices that are not needed. A candidate vertex is determined to be needed when it is to become a new vertex that will separate two segments. If a candidate vertex has a value that falls within the user specified range of the preceding and following points, it is not required and is removed. The final collection of points contains all of the original vertices and new vertices (candidate vertices) that will become the start and end of the new segments.

Figure 4-3 Segmentation – Insert Candidate vertices

The final step is to create the new segments. Figure 4-4 shows the final segmentation results using B2 (renamed C) as a new vertex. Each new segment will have an environmental value that differs from any adjoining segment by at least the user supplied break value. All original vertices will be contained within the new segments to preserve the original line shape. Since the new segments are, essentially, subsets of the original feature it may be desirable to retain the original naming convention. The Trail Analyst Extension – General Tab (Figure 4-7) includes fields to incorporate a user defined string into the segment names. The naming convention allowed is

<original name> <string1> #<string2>

where *original name* is the name of the source line; *string1* and *string2* are user supplied strings; and # is the segment number starting with 1. If the user elected to provide “_Ford_” as *string1* and nothing as *string2* the name for the first three John Muir Trail segments would be:

John Muir Trail

John Muir Trail_Ford_1

John Muir Trail_Ford_2

This naming convention allows tracking of the original segment and the reason for the segmentation if desired. No naming convention is enforced as requested by the client.

Figure 4-4 Sample Point – Final Results

4.2. Raster Interpolation Overview

Raster surfaces are generally constructed from a set of sample points to represent a continuous surface. The surface is constructed using spatial interpolation. O’Sullivan describes spatial interpolation as “the prediction of exact values of attributes at unsampled locations from measurements made at control points within the same area” (O’Sullivan, 2003, p. 220). A grid is constructed and all grid points are interpolated from the known sample points. A great deal of literature addresses the process of creating the raster grid from these known sample points (e.g., Longley, Goodchild, Maquire, & Rhind, 2005; O’Sullivan & Unwin, 2003).

The Trail Analyst Extension starts with a raster grid that is already constructed and interpolates the value of a point on the grid. The normal rules for the selection of an interpolation algorithm address a collection of sample points and how to determine the

best interpolation method to create a raster grid. An example of this is the six criteria proposed by Slocum, McMaster, Kessler, and Howard (2005, p. 281). Since these rules do not apply to this situation we follow the advice of O’Sullivan and Unwin when they said “there is no universally best scheme. It is up to the analyst to make sure that the method chosen is suited to a particular problem” (2003, p. 231).

The method chosen for the first version of the Trail Analyst Extension is Inverse-Distance-Weighted (IDW). Refer to Section 7 for a discussion on alternative algorithms. IDW was used by the SYMAP computer program in the early 1960’s and was instrumental in pioneering the development of spatial analysis systems (O’Sullivan, 2003, p. 228). IDW interpolates a value for a point by summing the weighted values of its neighbors. The weighting used is reflective of the distance from the point to be interpolated. The number of neighbors considered may vary and is controlled by a radius or limited to a constant number. The weighting is often assigned the value of the inverse distance but may be derived from the inverse of the distance raised to some value. In our case we utilize the inverse distance according to the formula

$$X = \sum_{i=1}^m \left(\frac{1/d_{ij}}{\sum_{i=1}^m 1/d_{ij}} z_i \right) \quad (4-2)$$

where X is the unknown point; d_{ij} is the distance from the known point z_i to the unknown point; m is the number of points (four for our purposes); and z_i is the known point.

4.3. Ford Segmentation Process

River and stream crossings, or fords, may be impossible to traverse for certain modes of transport during periods of rain or flood. This is factored into the transportation analysis process by segmenting the road or trail at the ford. The new segment is labeled as a ford with attributes defining the water depth under various conditions. The mode of transport definition table includes entries regarding the depth of water that may be crossed. The combination of these elements allows planners to factor in fords and recent rainfall when creating an expedition.

4.3.1. Ford Creation

Fords are point features where roads and trails cross rivers. These crossings may occur where a structure exists to allow a crossing unaffected by water level such as a bridge or culvert. When no such structure exists and travel may be limited due to water level a ford should be created.

Potential fords may be created in a variety of ways including using the ArcToolbox Intersect (Analysis) and ArcToolbox Feature to Point (Data Management) tools. The Intersect tool will take as input the road, trail, and streams and return a multi-point output file. The second tool will take the multi-point output file and return a point output file. The point output file can be used to identify the location of possible fords. The final dataset can be generated by eliminating all points where no water crossing hazard exists and adding the required attributes listed in Appendix A.

The final step in the ford creation process, independent of the method used to create the point features, is the integration of the fords with the road and trail features. Using the ArcToolbox Integrate (Data Management) tool with the roads, trails, and fords features ensures that the feature crossings are truly coincident. This is accomplished by inserting a new vertex at the point of intersection or by moving an existing vertex if one is within the user specified distance parameter. The point features produced by the ArcToolbox tools are placed close to but not on the intersection of the roads, trails, and streams. The example shown in Figure 4-5 shows an offset of 0.000051 meters. This offset may result from the rounding of the coordinates of the intersection point that occurs during the point feature creation. The Trail Analyst Extension requires the point to be on the intersection to function properly. The Integrate tool ensures the accurate placement of the point and also inserts a vertex into all line features (roads and trails) at the point where they are coincident with the point features (fords). This coincident vertex is critical when determining if a ford is located on a specific road or trail.

Figure 4-5 Ford Prior to Integrate

4.3.2. Ford Segmentation User Interface

The ford segmentation interface is found in the Trail Analyst Extension form (Figure 4-7). The form is accessed through the Trail Analyst Extension toolbar shown in Figure 4-6.

Figure 4-6 Trail Analyst Extension Toolbar

The *General* tab of the Trail Analyst Extension form (Figure 4-7) provides the user with the means to identify the input line feature set (roads and/or trails) and the output feature set along with the segmentation naming convention.

A screenshot of the 'Trail Analyst Extension' dialog box. The 'General' tab is selected. It contains fields for 'Input Trail Features' and 'Output Trail Feature Class', each with a folder icon. Below these is a 'Segment Naming Convention (optional)' section with 'Original Segment Name' and a '#' symbol, followed by an example: 'Original Segment Name '_sub' # 'DEM' the first new segment for trail 'Muir Grove' is named Muir Grove_sub1DEM'. There is also an 'Input Feature 'Name' Field' dropdown. At the bottom is an 'Option Status' section with checkboxes for 'Grade Option', 'Ford Option', 'Climate Option', '[DEM]', '[Area Solar]', '[Snow Surface]', and '[Ice Surface]'. 'Process' and 'Cancel' buttons are at the bottom right.

Figure 4-7 Trail Analyst Extension – General Tab

The Trail Analyst Extension – Ford tab (Figure 4-8) provides access to the remaining required inputs. The ford feature set and associated fields are identified on this form. After identification of all required parameters the *Process* button starts the segmentation process.

The image shows a software dialog box titled "PreProcessorParameters". It has a blue title bar with standard Windows window controls (minimize, maximize, close). Below the title bar are five tabs: "General", "Grade", "Ford", "Climate", and "Parameters". The "Ford" tab is currently selected and highlighted. The main area of the dialog is light beige and contains several input fields. At the top is a text box labeled "Ford Features" with a folder icon to its right. Below this are four dropdown menus, each with a label and a downward arrow: "Feature 'Ford' Field", "Feature 'Normal Depth' Field", "Feature 'Rain Depth' Field", and "Feature 'Flood Depth' Field". At the bottom right of the dialog are two buttons: "Process" and "Cancel".

Figure 4-8 Trail Analyst Extension – Ford Tab

4.3.3. Ford Segmentation Algorithm

The algorithm used for the ford segmentation is shown in Figure 4-9.

Figure 4-9 Ford Segmentation Algorithm

The Trail Analyst Extension uses map units for many calculations. As with other ArcToolbox tools this requires the map units to be in feet or meters. Utilizing a map unit of decimal degrees will cause unpredictable results.

Road and trail features are processed one at a time. Each vertex is examined to determine if it is coincident with a ford. If the two points are coincident a segment of approximately one map unit in length is created from the original feature (Figure 4-10). This results in three segments being created unless the ford is coincident with either the starting or ending vertex. If the ford is coincident with one end of the feature then two segments are created.

Figure 4-10 Ford Segmentation Example

Each segment is assigned with all the fields and field values of the original except for the name field. The name field is derived using the user supplied parameters. The new ford feature is labeled as a ford and the ford attributes for water depth are assigned using the coincident ford as the source.

4.4. Climate Segmentation Process

Rain, snow, and ice are often encountered along the roads and trails within this study area. Climatic events such as storms may change travel conditions days before an expedition is planned. The Trail Analyst Extension handles these events through the climate segmentation process.

The primary input is an area solar radiation surface. This surface is generated using the ArcToolbox Area Solar Radiation (Spatial Analyst) tool. The output from this tool is a raster surface corresponding to the total amount of solar insolation (direct and diffuse) occurring at each cell. The raster surface has units of watt hours per square meter (WH/m^2). The calculations are based on user supplied parameters that allow for timeframes ranging from less than one minute to more than one year. The timeframe selected must be coordinated with a variety of inputs including time intervals and the number of sample points. Refer to the ArcGIS Desktop Help sections on Solar Radiation for a complete explanation of all of the parameters involved (2007).

The area solar radiation surface is combined with local knowledge of recent climatic events and used to segment and attribute the road and trail network.

4.4.1. Area Solar Radiation Creation

The ArcToolbox Area Solar Radiation (Spatial Analyst) tool is used to create a raster surface with watt hours per square meter. This tool is computationally intensive and can take a quad processor approximately one month to create a raster surface for a 3,000 square mile area using a 10 meter resolution DEM. Alternative approaches are being considered and will be presented in Section 7.

The area solar radiation surface created for this study was generated using the Area Solar Radiation tool with the study area DEM as the primary input and March 17th as the single day to calculate. All default parameters were accepted except for the 'Sky Size'. The Sky Size value was changed to 2800 per ESRI's documented recommendations (ArcGIS Desktop Help, 2007).

4.4.2. Climate Surface Creation User Interface

The climate surface creation interface is found on the Trail Analyst Extension form (Figure 4-7). The form is accessed through the Trail Analyst Extension toolbar shown in Figure 4-6. The *Climate* tab takes you to the climate page (Figure 4-11). This page provides access to all of the climate surface creation and segmentation functions.

Figure 4-11 Trail Analyst Extension – Climate Tab

From the *Climate* tab you check the *Create “Snow” and “Ice” rasters* check box to get to the climate raster surface creation (Figure 4-12). The parameters used in the creation of the snow and ice rasters are listed and described in Table 4-2. The parameter names used were determined by discussions with the client. The client is confident that the parameter names convey their purpose in an unambiguous manner.

Figure 4-12 Trail Analyst Extension – Climate Tab (Create)

After identification of all required parameters, the *Process* button starts the climate surface generation process.

4.4.3. Climate Surface Creation Algorithm

The climate surface creation algorithm is a multi-step process that starts with finding the value of maximum solar radiation around the “Minimum Snow Elevation in Sun”. This is accomplished by performing the following steps

- 1- Create a MaskDEM raster surface where DEM cells having a value within 10 map units of the “Minimum Snow Elevation in Sun” are assigned a value of 1 and all others a value of 0.
- 2- Create a raster surface equal to Area Solar Radiation * MaskDEM.
- 3- Assign MaxR equal to the highest value in the raster surface created in step 2.

MaxR is assumed to be the watt hours per square meter required to melt all snow at this elevation.

Table 4-2 Create Snow and Ice Raster Parameters

Parameter	Description
Area Solar Radiation	Raster generated using the ArcToolbox Area Solar Radiation (Spatial Analyst) tool
DEM	Digital Elevation Model
Output Snow Surface (raster)	Raster output to be generated
Output Ice Surface (raster)	Raster output to be generated
Minimum Snow Elevation	Minimum elevation where snow is present (same units as DEM)
Elevation of Maximum Snow	Minimum elevation where the maximum snow fall has occurred (same units as DEM)
Maximum Snow Depth (m)	Maximum amount of snow on the ground in meters (should correlate with the Elevation of Maximum Snow)
Minimum Freezing Elevation	Minimum elevation where the temperature stays below zero degrees centigrade for a specified time period (same units as DEM)
Minimum Snow Elevation in Sun	Minimum elevation where snow is found on the sunniest side (same units as DEM)
Snow Level Breaks (cm)	Maximum variation in snow level before segmentation occurs (centimeters)
Max Snow Level Break (cm)	Maximum snow level to perform segmentation on. All snow depths in excess of this value will be treated as equal to this value (centimeters)

The next step is to calculate the estimated snow depth across the study area. The snow depth is calculated based on the elevation and solar values using the following criteria.

- 1- If the elevation is less than the Minimum Snow Elevation then the snow depth is zero (0.0).
- 2- If the elevation is greater than or equal to the Elevation of Maximum Snow then the depth is the Maximum Snow Depth.
- 3- If the elevation is greater than or equal to the Minimum Freezing Elevation then the depth is calculated using a straight line interpolation using the Minimum Snow Elevation, Elevation of Maximum Snow, and Maximum Snow Depth.

- 4- Otherwise the depth is calculated using the interpolation method of step 3 minus the amount of estimated snow melt. The amount of estimated snow melt is calculated starting with the amount of snow that melted on the sunny slope. This value is found using step 3 and the Minimum Snow Elevation in Sun. MaxR is assumed to be the solar value required to achieve the snow melt. The ratio of Area Solar Radiation to MaxR provides the multiplier to determine amount of snow melt for a specific location.

The following pseudo-code implements the above criteria:

```

EAboveSnowLine = Elevation - Minimum Snow Elevation
SnowRange = Elevation of Maximum Snow - Minimum Snow
Elevation
SnowMelt = ((Minimum Freezing Elevation - Minimum Snow
Elevation) / SnowRange) * Maximum Snow Depth
If elevation < Minimum Snow Elevation Then
    Depth = 0.0
ElseIf elevation > Elevation of Maximum Snow Then
    Depth = Maximum Snow Depth * 100
ElseIf elevation > Minimum Freezing Elevation Then
    Depth = EAboveSnowLine / SnowRange * Maximum Snow
    Depth * 100
Else
    Depth = (((EAboveSnowLine / SnowRange * Maximum Snow
    Depth) - (( 1 - ((Area Solar Radiation ) / MaxR)) *
    SnowMelt * 100

```

The ice surface is calculated using the snow surface. If the snow depth is equal to or greater than 3.0 cm, then ice is assumed to be present. If the snow depth is less than 3.0 cm then no ice is present. This is a simple algorithm for determining the presence of ice. Alternatives to this method are presented in Section 7.

4.4.4. Climate Segmentation User Interface

The climate segmentation interface is found on the Trail Analyst Extension form (Figure 4-13). The *Climate* tab takes you to the climate page (Figure 4-11). Additional parameters may be found on the Trail Analysts Extension Parameters tab (Figure 4-14).

Figure 4-13 Trail Analyst Extension – General Tab

Figure 4-14 Trail Analyst Extension – Parameters Tab (Climate)

Those parameters on the Trail Analyst Extension – Climate Tab and Parameters Tab that are used in the climate segmentation process are listed and described in Table 4-3.

Table 4-3 Climate Segmentation Parameters

Parameter	Description
Input Snow Surface (raster)	Snow surface created using <i>Create “Snow” and “Ice” rasters</i>
Input Ice Surface (raster)	Ice surface created using <i>Create “Snow” and “Ice” rasters</i>
Input Feature ‘Snow’ Field	Name of field (long integer format) in the input feature to contain the calculated snow depth
Input Feature ‘Ice’ Field	Name of field (long integer format) in the input feature to contain the calculated ice value
Snow Level Breaks (cm)	Maximum variation in snow level before segmentation occurs (centimeters)
Max Snow Level Break (cm)	Maximum snow level to perform segmentation on. All snow depths in excess of this value will be treated as equal to this value (centimeters)

After identification of all required parameters, the *Process* button starts the climate segmentation process.

4.4.5. Climate Segmentation Algorithm

The algorithm used for the climate segmentation is shown in Figure 4-15.

Figure 4-15 Climate Segmentation Algorithm

Road and trail features are processed one at a time. Candidate vertices (potential new vertices) are inserted between existing vertices based on the user specified maximum sampling distance (Section 4.1). The snow and ice surfaces are sampled at each of the vertices and candidate vertices (Section 4.2). As the set of points are sequentially examined, minimum and maximum snow levels and the ice value are examined and maintained. When a value exceeds the user specified break point the set of examined points is saved as a new segment and the review process continues until all points and lines are exhausted (Figure 4-16). All snow values equal to or greater than the user supplied *Max Snow Level Break* are considered to be equal in value. Implementation of this feature recognizes the fact that for most modes of transport once a certain snow depth is exceeded additional snow does not change the transport speed. An example of this is a hiker that may traverse snow up to a depth of 200 centimeters but cannot travel across snow with a greater depth without snow shoes or skies. If we were modeling a hiker with these additional tools we might set the *Max Snow Level Break* to a value of approximately 60 centimeters.

Figure 4-16 Climate Segmentation Example

Each segment is assigned with all the fields and field values of the original except for the snow value, ice value, and name fields. The name field is derived using the user

supplied parameters. The snow and ice values are calculated from the vertices making up the new segment.

4.5. Grade Segmentation Process

One of the most common impediments to travel encountered is grade or slope. Since this element is static in nature it is easier to incorporate into a transportation network. However, the labor involved in manually segmenting, attributing, and maintaining over 5,300 individual features comprising thousands of miles of roads or trails makes this cost prohibitive using standard methods. GIS analysts would have to extract approximately one-half million elevation points and perform the same number of grade calculations to determine where these features should be segmented. After segmentation each feature would have to be annotated with the appropriate attributes which would take hundreds of additional hours. The Trail Analyst Extension performs these operations during grade segmentation processing.

4.5.1. Grade Segmentation User Interface

The grade segmentation interface is found on the Trail Analyst Extension form (Figure 4-17).

Figure 4-17 Trail Analyst Extension – General Tab

The *Grade* tab takes you to the grade page (Figure 4-18) where the DEM is identified as well as the fields in the input feature required for processing.

Figure 4-18 Trail Analyst Extension – Grade Tab

Additional parameters may be found on the Trail Analyst Extension's Parameters tab (Figure 4-19, section 1). These parameters will generally remain unchanged once they have been defined for a specific region. The user may elect to use the Grade Window or Standard Error of Estimate (SEE) segmentation algorithm (Figure 4-19, section 2) and set the appropriate formula parameters.

The screenshot shows the 'Trail Analyst Extension' dialog box with the 'Parameters' tab selected. The 'Grade' section contains sliders for 'Sample Distance (map units)' (10), 'Grade Breaks (%)' (2.0), 'Smoothing Window (wide)' (120), and 'Smoothing Window (narrow)' (40). A red circle with the number 1 is placed next to the 'Grade Breaks (%)' slider. The 'Climate' section has sliders for 'Snow Level Breaks (cm)' (60) and 'Max Snow Level Break (cm)' (240). The 'Standard Error of Estimate' section has a slider for 'First pass error' (5.0) and a checkbox for 'Use SEE' which is unchecked. A red circle with the number 2 is placed next to the 'Use SEE' checkbox. The 'Process' and 'Cancel' buttons are at the bottom.

Figure 4-19 Trail Analyst Extension – Parameters Tab

The parameters used in the grade segmentation process are listed and described in Table 4-4.

After identification of all required parameters, the *Process* button starts the grade segmentation process.

4.5.2. Grade Segmentation Algorithm

The algorithm used for the grade segmentation is shown in Figure 4-20.

The initial steps in the grade segmentation processing differ from the climate segmentation only in the use of the DEM rather than the ice or snow surfaces. After inserting candidate vertices and interpolating the elevation value for all points, the next step is to apply a smoothing function. The need for this function was determined through

analysis of the initial results discussed in Section 5. The function selected uses a user defined value (*Smoothing Window (wide)* and *Smoothing Window (narrow)*) to define the extent of the averaging function. The user supplied *Wide – Min. Width* value determines which of the two smoothing windows is used for a specific feature. For each point on the feature segment the smoothed DEM value is calculated to be the average DEM value of all points on the segment that fall within the smoothing widow. The criterion for evaluating the inclusion of each point is based on the linear distance along the line, not the spatial distance between each pair of points.

Table 4-4 Grade Segmentation Parameters

Grade Tab	
Parameter	Description
DEM	Digital Elevation Model
Feature ‘Grade’ Field	Name of field (float format) in the input feature to contain the calculated percent grade value
Feature ‘Surface Width’ Field	Name of field (long integer) in the input feature containing the surface width data
Parameters Tab	
Sample Distance (map units)	Maximum sampling distance
Grade Breaks (%)	Maximum change in grade allowed before segmentation occurs (applies when Grade Window algorithm is selected)
Smoothing Window (wide)	Distance (in map units) to use in calculation of running average smoothing algorithm for ‘wide’ surfaces (as determined by Wide – Min. Width parameter)
Smoothing Window (narrow)	Distance (in map units) to use in calculation of running average smoothing algorithm for ‘narrow’ surfaces (as determined by Wide – Min. Width parameter)
Wide – Min. Width	Minimum width defining a ‘wide’ surface used to determine the Smoothing Window parameter
First pass error	Maximum error acceptable during the first pass of the grade segmentation algorithm (applies when SEE algorithm is selected)
Use SEE	Use the SEE algorithm if checked, Grade Window algorithm if unchecked

Figure 4-20 Grade Segmentation Algorithm

The next step is dependent on the user selection for *Use SEE* checkbox. If the user has elected to use the SEE algorithm, then each point along the line is sequentially added to the new segment until an unacceptable error (standard error of estimate) level is reached. As each new point is added to the segment collection, the least-squares-fit line is calculated using

$$slope = m = \frac{n \left(\sum_{i=1}^n X_i Y_i \right) - \left(\sum_{i=1}^n X_i \right) \left(\sum_{i=1}^n Y_i \right)}{n \left(\sum_{i=1}^n X_i^2 \right) - \left(\sum_{i=1}^n X_i \right)^2} \quad (4-3)$$

where $X_i Y_i$ is a point in the collection; n is the number of points; and m is the slope. We can then calculate the intercept of this line using

$$intercept = b = \frac{\sum_{i=1}^n Y_i - m \left(\sum_{i=1}^n X_i \right)}{n} \quad (4-4)$$

where X_iY_i is a point in the collection; n is the number of points; m is the slope; and b is the intercept. Using the slope and intercept the standard error of estimate can be calculated using

$$S_{yx} = \sqrt{\frac{\sum_{i=1}^n (Y_i - Y'_i)^2}{n - 2}} = \sqrt{\frac{\sum_{i=1}^n (Y_i - Y'_i)^2 - \frac{\left[\sum_{i=1}^n (X_i - X'_i) (Y_i - Y'_i) \right]^2}{\sum_{i=1}^n (X_i - X'_i)^2}}{n - 2}} \quad (4-5)$$

where S_{yx} is the standard error of estimate; X_iY_i is a point in the collection; $X'_iY'_i$ is a calculated value; and n is the number of points.

If S_{yx} exceeds the user supplied value *First pass error* then the line is segmented. If S_{yx} is less than the *First pass error* the next sequential point is added to the collection and all values are recalculated. This process continues until all points have been addressed.

Each segment is assigned all the fields and field values of the original except for the grade value and name. The name field is derived using the user supplied parameters. The grade value is calculated using the slope formula.

If the *Use SEE* checkbox is not checked, then the Grade Window segmentation algorithm is used. Starting with the first point the grade is computed to each sequential point along the line. As the grade is computed the minimum and maximum grade values are identified. When the difference between the minimum and maximum grade values exceeds the *Grade Breaks (%)* parameter, a line segment is constructed using the starting point, the point where the grade was exceeded minus one, and all vertices (as opposed to candidate vertices) between the two. The process continues from the end point of the new segment and continues until all points are processed.

Each segment is assigned all the fields and field values of the original except for the grade value and name. The name field is derived using the user supplied parameters. The grade value is calculated using the slope formula.

4.6. Transport Mode Creation

The Transport Mode table contains the descriptions of all modes of transportation utilized in the planning process. The modes can vary from a casual hiker to a SUV or tour bus. The forty-two fields included for each mode specify the surfaces that may be traversed and the speed of traversal. The fields are listed and described in Appendix A.

4.6.1. Transport Mode Creation User Interface

No user interface is provided for entry of transport mode records. Records may be entered using standard ArcGIS or database utilities.

4.6.2. Transport Mode Algorithm

The Transport Mode table contains speed parameters for a multitude of conditions. To determine the speed for a specific surface the grade is examined (Figure 4-21). Using the grade and speed parameters in the table, the speed for the desired grade is interpolated.

Figure 4-21 Speed vs. Grade

An example of this interpolation using the transport mode parameters shown in Table 4-5 and calculating the speed on a 5% grade is:

$$\text{Speed on 5\% grade} = 65 \text{ mph} - ((65 \text{ mph} - 50 \text{ mph}) * (5\% - 4\%) / (8\% - 4\%))$$

$$\text{Speed on 5\% grade} = 61.25 \text{ mph}$$

Table 4-5 Speed Interpolation Example Parameters

Parameter	Value
SpeedOnFlat	65 mph
Grade1	4%
Grade1Speed	50 mph
Grade2	8%
Ice	1.0
IceSpeed	15.0

Once the speed has been calculated any required adjustment factors are applied. If the feature surface is not a paved road than a surface multiplier must be applied. The appropriate multiplier is obtained from the transport mode record using the feature surface composition.

If the segment is on ice then the flag for travel on ice on the specific feature surface is examined. The speed is adjusted if the transport mode supports travel on ice. The adjustment is made by multiplying the speed by the *IceSpeed* parameter.

Continuing the example speed interpolation from above, we can factor in travel on ice as:

$$\begin{aligned}\text{Speed on 5\% grade on ice} &= \text{Speed on 5\% grade} * \text{IceSpeed} \\ &= 61.25 * 0.15 \\ &= 9.2 \text{ mph}\end{aligned}$$

If ice is not present than the snow depth is examined. If the snow depth is greater than zero than the flag for travel on snow on the specific feature surface is examined. The speed is adjusted if the transport mode supports travel on snow. The adjustment is made by multiplying the speed by a value interpolated using the *SnowMinDepth*, *SnowDepthRange*, and *SnowSpeed*. If the surface snow depth is in excess of the *MaximumSnowDepth* then travel is not possible.

If there is no ice or snow than no climate adjustment is required.

4.7. Travel Cost Calculation

The Trail Analyst Extension – Travel Time utility takes as input the pre-processed (segmented) road or trail feature set, transport mode, and recent climate conditions. Each feature is examined and the travel time calculated for each direction.

4.7.1. Travel Time User Interface

The Trail Analyst Extension – Travel Time form (Figure 4-22) is accessed through the Trail Analyst Extension toolbar shown in Figure 4-6.

Figure 4-22 Trail Analyst Extension – Travel Time

The parameters used in travel time calculations are listed in Table 4-6.

Table 4-6 Travel Time Parameters

Parameter	Description
Input Trail Features	Input road and trail feature dataset
Transport Parameters	Transport mode table
Primary Transport Mode	Primary transport mode
Secondary Transport Mode (optional)	Secondary transport mode
Primary Mode Preferred	<p>Checked – primary mode speed to be used on all routes wide enough even if speed is zero</p> <p>Unchecked – secondary mode to be used is primary speed is zero</p>

Parameter	Description
Recent Rain Level (optional)	List of three possible settings for the recent rain level including normal, rain, and flood
FromTo Travel Time	Field in output dataset to be set to travel time for segment in from-to direction
ToFrom Travel Time	Field in output dataset to be set to travel time for segment in to-from direction
Mode Used	Field in output dataset to be set to mode of transport used in travel time calculations
Width	Field in input dataset containing surface width
Surface Type	Field in input dataset containing surface type
Predominant Soil	Field in input dataset containing predominant soil type
Grade	Field in input dataset containing grade
Speed Limit	Field in input dataset containing speed limit value not to be exceeded
Snow	Field in input dataset containing snow depth
Ice	Field in input dataset containing ice value
Ford	Field in input dataset containing text indicator identifying fords
Normal Depth	Field in input dataset containing ford normal water depth
Rain Depth	Field in input dataset containing ford rain water depth
Flood Depth	Field in input dataset containing ford flood water depth

4.7.2. Travel Time Algorithm

The algorithm used for travel time calculation is shown in Figure 4-23.

Figure 4-23 Travel Time Calculation Algorithm

Road and trail features are processed one at a time. The first step in the process is to determine if the feature is a ford. If it is a ford then a determination is made as to whether it may be crossed based on the user supplied *Recent Rain Level (optional)* (default value is *Normal*), the ford water depth, and the *MaxFordDepth* of the primary and secondary transport modes.

If the ford is crossable it is assigned a travel cost of 2 minutes for both the from-to and to-from fields. This value was selected by the client as being a reasonable value for most water hazards. If the ford is impassable then a cost of -1 is assigned to the feature.

The next step is to determine if the primary transport mode is capable of traversing the feature. The width of the feature, presence of ice, and snow depth are evaluated against the primary transport mode parameters to make the determination. If the primary mode cannot traverse the feature then the secondary mode is evaluated. Once the mode is selected the speed for the feature surface is determined using the procedure described in subsection 4.6.2.

The final step uses the calculated speed and the feature length to arrive at the from-to and to-from travel times. The final travel times are used to update the feature in the geodatabase.

4.8. Methodology Summary

Using the “divide and conquer” strategy the Trail Analyst Extension takes an input feature dataset and segments the components into a collection of features with environmental attributes. This process is accomplished in a series of steps that are autonomous in nature. The client may elect to include or exclude fords, snow, ice and/or grade. The initial segmentation may be based on grade alone with other environmental factors being added for the winter months. Flexibility has been designed into the Trail Analyst Extension to provide the client with the ability to tailor the process to their needs.

5. Results

The implementation of the Trail Analyst Extension required the selection of an algorithm capable of segmenting a road and trail feature set that would model the real world as closely as possible. The output of the algorithms being evaluated had to be compared against a “ground truth” that was as close to the real world as feasible given the budgetary and time constraints of the project. A section of the Generals Highway in Sequoia National park starting one-half mile south of Ash Mountain National Park Headquarters and ending one-half mile south of Hospital Rock was selected as the focus area for this detailed study.

Data was gathered using a Garmin GPSMAP 60CSx handheld GPS unit with a Titan III Universal GPS Antenna. This combination was able to acquire and hold a lock on nine to twelve satellites within the study area. The GPS receiver and an internal altimeter provided position and elevation data at a sampling rate of one sample every second. Testing indicated that the positional accuracy of the GPS was approximately ± 10 feet. The altimeter demonstrated a sampling repeatability of ± 5 feet during testing. This unit was utilized to gather “ground truth” for the test area.

The altimeter was calibrated on April 23, 2007 at benchmark GT0114 (N $36^\circ 27.617$, W $118^\circ 52.317$, altitude 1032.7 feet) located approximately 8 miles from Hospital Rock. Data was gathered between April 23 and April 25, 2007. The Generals Highway was traversed from south to north at an average speed of approximately 15 miles per hour. Each traverse required approximately 24 minutes to complete. A total of eight passes were made over the three day period.

The goal of the grade segmentation algorithm was to model ground truth using the minimum number of segments consistent with accurate representation in order to keep maintenance efforts and computational requirements as low as possible.

5.1. Smoothing Algorithm Results

The first phase of testing consisted of calculating elevation data using a 1/3 arc second (9.267 meter) DEM along the Generals Highway. This was accomplished using portions of the Trail Analyst Extension program. Candidate vertices were inserted with a maximum sampling distance of 10 meters. The elevation was calculated from the DEM at each vertex using an IDW interpolation with the four nearest neighbors and no exponent on the distance. The data were plotted against the GPS-Altitude (“ground truth”) and are shown in Figure 5-1.

The figure shows the general agreement between the two datasets while also demonstrating the local variations within the USGS data. This local variation is the result of accumulated modeling error. The Trail Analyst Extension uses data that are generalizations of reality. The processing performed by the Trail Analyst Extension creates a further generalization of reality. Each time generalization occurs, error is introduced. The challenge is to remove the accumulated modeling error while retaining the significant features of the data. In this case the significant features are the grade changes and feature length.

Figure 5-1 Profile of Generals Highway 1
Collected by GPS and Altimeter vs. Calculated using USGS DLG and DEM

A smoothing algorithm was applied to the USGS data to remove the accumulated modeling error. A running average using a window of ± 120 meters was used to produce the results shown in Figure 5-2. The resulting data come closer to replicating the GPS-Altimeter than the raw data. The significant grade changes are retained while removing most changes that are not found in the GPS-Altimeter data. There are numerous alternatives for the smoothing algorithm and future work in this area is recommended in Section 7.

After the smoothing algorithm was developed it was incorporated into the grade segmentation program. The first segmentation algorithm developed used the Grade Window algorithm described in Section 4.5.2. The results of the Grade Window algorithm without using the smoothing algorithm are shown in Figure 5-3. A *Grade Breaks (%)* setting of 2.5% produced 981 segments to represent the variations in grade for this section of Generals Highway.

Figure 5-2 Profile of Generals Highway 2
 Collected by GPS and Altimeter vs. Calculated using USGS DLG and DEM then smoothed

Figure 5-3 Profile of Generals Highway 3
 Calculated using USGS DLG and DEM vs. Processed using Grade Window segmentation with a Grade Break value of 2.5%

The observed vertical shift resulting from the processing of the USGS DLG/DEM data (Figure 5-3) was investigated and found to be an artifact of the Grade Window segmentation algorithm. The segmentation process occurs where significant grade variations occur along the feature. This segmentation process removes some of the more significant peaks and valleys found in the input data resulting in a generalized grade value that returns a decreased change in elevation along the segment length (Figure 5-4, bullets 1-4). The change may be positive or negative depending on the characteristics of the input data. When the smoothing algorithm is run against the input data prior to segmentation, peaks and valleys are decreased or removed. Using these smoothed data as input to the segmentation process results in a generalization that has a greatly reduced vertical shift (Figure 5-5). In the examples shown, the vertical shift is reduced from approximately 8 meters to less than 2 meters.

Figure 5-4 Grade Window Segmentation Algorithm Vertical Shift Example
Calculated using USGS DLG and DEM vs. Processed using Grade Window segmentation with a
Grade Break value of 2.5% vs. Processed using Smoothing Algorithm and Grade Window
segmentation with a Grade Break value of 2.5%

The results obtained by the Grade Window with the smoothing algorithm are shown in Figure 5-5. The settings used in this test were the same as those in Figure 5-3 with the exception of enabling the smoothing algorithm. The total number of segments produced by this run was 492. With the smoothing algorithm the number of segments

was reduced by 50% while obtaining a higher degree of accuracy in representation based on visual examination.

Figure 5-5 Profile of Generals Highway 4
Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and Grade Window segmentation with a Grade Break value of 2.5%

5.2. Grade Window Algorithm Results

The Grade Window algorithm produced a collection of attributed segments that closely resembled the USGS DLG that was used as the input feature as shown in Figure 5-5. The next step in testing this algorithm was to determine a recommended *Grade Breaks (%)* setting that would retain a reasonable level of accuracy while minimizing the number of individual segments required to represent the original feature. A series of runs were made using *Grade Breaks (%)* ranging from 2.5 to 15.0 in increments of 2.5. The number of segments generated showed a steady decline as expected (Table 5-1).

Table 5-1 Grade Breaks Parameter vs. Segments Generated at Given Grade Percentages

Grade Breaks (%)	Segments
2.5	492
5.0	276
7.5	171
10.0	118
12.5	87
15.0	58

The results from this test were evaluated using visual examination and demonstrated acceptable performance below a *Grade Breaks (%)* value of 10.0 (see Figure 5-6). When the parameter was set to 10.0 or above the results were skewed by short peaks such as the one found on Generals Highway between 500 and 700 meters.

Figure 5-6 Generals Highway Grade Window (2.5% – 15.0%)
Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and Grade Window segmentation with Grade Break values of 2.5% - 15.0%

The study rejected all values above 7.5 and focused on the range between 2.5 and 7.5 as shown in Figure 5-7.

The section between 5,000 and 6,000 meters was enlarged to obtain a better view of the relative accuracy of the three settings (see Figure 5-8). This shows the slight deterioration of accuracy between 5.0% and 7.5%. The fidelity shown by the 7.5% setting was judged to be sufficient for analysis purposes.

Figure 5-7 Generals Highway Grade Window Smoothed (2.5% – 7.5%)
 Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and Grade Window segmentation with Grade Break values of 2.5% - 7.5%

Figure 5-8 Generals Highway Grade Window (from 5000m to 6000m)
 Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and Grade Window segmentation with Grade Break values of 2.5% -- 7.5%

5.3. Standard Error of Estimate (SEE) Results

The use of a least-squares-fit line formula coupled with a decision guided by the resulting standard error of estimate (SEE) is a statistically sound approach to minimize error. The least-squares-fit line formula determines the slope of a line estimating the trend of a collection of points with the least amount of error. The SEE provides an accurate measure of that error. The combination provides the slope of a segment and where that segment should end.

Initial testing of the SEE algorithm used *First pass error* values ranging from 5 to 50. These numbers represent the maximum average elevation error acceptable for a least-squares-fit line. The numbers are in map units which, in this case, are in meters. The results indicated that *First pass error* values 5 and over do not provide a sufficient level of accuracy (Figure 5-9).

Figure 5-9 Generals Highway SEE (5 – 50)
Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and SEE segmentation with a First Pass Error value between 5 and 50

As expected, the number of segments generated using *First pass error* values from 1.0 to 50.0 showed a steady decline (see Table 5-2).

Table 5-2 SEE First Pass Error vs. Segments

First pass error	Segments
1.0	298
2.0	235
3.0	201
4.0	179
5.0	160
10.0	120
15.0	94
20.0	80
25.0	74
50.0	58

The next series of tests used *First pass error* values ranging from 1 to 5 (Figure 5-10). The test results show that values 1 and 3 follow the source data at various points but neither value tracks over the full extent. The disturbing entry is the value 2. Given the relatively good performance of 1 and 3 we would expect 2 to also track the source data. The fact that 2 has results that deviate approximately the same as values 4 and 5 shows an inconsistency in this process.

Figure 5-10 Generals Highway SEE (1-5)
Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and SEE segmentation with a First Pass Error value between 1 and 5

5.4. Grade Window and SEE Algorithm Comparison

A visual comparison was made between the Grade Window and standard error of estimate (SEE) algorithms to determine which should be the default choice. Figure 5-11 shows a comparison between the Grade Window using a value of 7.5 and 171 segments and the SEE using a value of 1.0 and 298 segments. Both algorithms show acceptable performance. The Grade Window algorithm is visibly better and requires less than 60% of the segments to represent the original data. Based on this comparison the Grade Window algorithm was selected as the default. Additional algorithms and testing are recommended in Section 7.

Figure 5-11 Generals Highway Algorithm Comparison
Calculated using USGS DLG and DEM vs. Processed using Smoothing Algorithm and Grade Window segmentation with Grade Break values of 7.5% vs. Processed using Smoothing Algorithm and SEE segmentation with a First Pass Error value of 1.0

5.5. Ford Segmentation Results

The grade segmentation capabilities of the Trail Analyst Extension are supplemented by additional features including the ford segmentation function. The ford segmentation algorithm proved capable of creating a representative segment within an existing feature that held the ford water depth attributes and supported the travel time calculations. This feature became an impassable obstacle for transport modes that were incapable of

crossing a water hazard with the depth of the ford. This obstacle resulted in routes that circumvented the hazards. Workflow analysis indicated that it may be desirable to add new ford features after the initial segmentation process. To accommodate that possibility, the segmentation algorithm was modified to identify any existing ford segments and prevent duplication.

5.6. Climate Segmentation Results

The climate surface creation algorithm was able to generate a raster surface showing snow depths within the study area. An analysis of the snow surface showed major snow accumulations occurring within expected regions. A more detailed analysis, including reference to ground truth, was not possible with the information available. The ice surface algorithm is an area that needs further research and development (Section 7). The climate segmentation algorithm proved capable of segmenting the input feature according to the raster information provided. Enhancements using this capability are discussed in Sections 6 and 7.

5.7. Summary of Results

The Trail Analyst Extension was able to calculate ice and snow surfaces; segment roads and trails based on these surfaces; and assign attributes that were used to develop travel cost values. The Trail Analyst Extension also inserted fords and assigned attributes to the resulting features representing the water crossing. Roads and trails were segmented based on grade derived from a DEM and values assigned. Finally, the Trail Analyst Extension was able to use these values to calculate travel times for a variety of user defined transport modes. The resulting feature set supported transportation modeling within the ArcGIS Network Analyst.

6. Discussion

The initial design philosophy envisioned for this project was to segment roads and trails according to data extracted from raster surfaces. These surfaces are traditionally used for least-cost-path analysis. These data were to be assigned to individual features and ultimately used to develop travel cost values. This design has proven effective with little change. The most significant difference between the initial design and the implementation is in the modularization of the segmentation algorithms. The initial design anticipated having all segmentation occurring within an integrated set of algorithms. Programming and workflow considerations led to the final design allowing each function to be independently controlled and initiated.

6.1. Interpolation Algorithms

One of the major challenges anticipated at the start of this project was in the extraction of elevation information from a DEM. The positional accuracy of the road and trail features in respect to the DEM suggested that significant fluctuations in elevation may be seen in areas that were actually a constant grade. The location of roads and trails within this mountainous area often meant that a positional shift of ± 5 meters could result in an elevation change of ± 25 meters (see Figure 6-1).

Figure 6-1 Middle Fork Trail

The Trail Analyst Extension currently uses an inverse-distance-weighted (IDW) algorithm that factors in the four nearest neighbors from the DEM. The inclusion of only the four nearest neighbors as opposed to the more common nine nearest neighbors was an attempt to localize each point along the road or trail. This localization was expected to retain any significant elevation changes while minimizing the effects of positional displacement. The extracted data required the use of a smoothing algorithm as discussed in Section 5.1. This combination of IDW and smoothing algorithm is achieving acceptable results. Section 7 addresses alternative algorithms that should be explored.

6.2. Grade Segmentation Algorithms

The Grade Window segmentation algorithm was developed as a simple, intuitive approach to identifying segmentation points that has achieved outstanding results within this study area. The results obtained using the statistically sound straight line regression formulas to achieve a least-squares-fit line have been disappointing. Straight line regression provides the optimal solution for a line estimating the trend of a collection of points. Increasing the collection one point at a time until an error threshold is reached would seem to be a sound approach. The alternative (Grade Window) approach takes the starting point and draws a straight line from that point to the last point in a collection. The minimum and maximum grade values determine the value used to decide if the threshold is reached. The second approach ignores the aggregate effect of all points in the collection unlike the least-squares-fit line approach. One would expect a widely used methodology that includes all points to be able to produce more accurate results than an ad-hoc method like the Grade Window algorithm.

A more advanced statistical approach would be to use the Multivariate Adaptive Regression Splines (MARS) methodology. This approach is capable of handling large wildly scattered data. When adapted to this problem it becomes a two pass process similar to the standard error of estimate (SEE) approach. Other than the two pass process, the most significant difference between SEE and MARS is that MARS looks at the entire dataset each time it evaluates a segment. With the SEE algorithm, you look at a subset of the data and determine if the standard error of estimate indicates that a break should be made. With MARS you look at the subset and you look at the remainder to determine if the combined impact of the segmentation on the entire dataset indicates that a break should be made.

With MARS, a first pass is made with the standard error of estimate set to a value low enough to result in the generation of approximately twice as many segments as desired. To determine if segmentation is desired, a standard error estimate is generated for the entire dataset from the least-squares-fit line. As each potential segment is examined the standard error or estimate for all resulting segments are examined and a decision is made based on a comparison of the aggregate errors. A second pass is made to determine if any segment break points should be eliminated. An aggregate standard error of estimate is generated based on the removal of a single segmentation break point. This calculation is performed for all identified break points. The break point with the least negative impact on the standard error of estimate is deleted from the potential segmentation point set. This removal process continues until the desired standard error of

estimate and number of segments is reached. In Section 7 we recommend additional research within this area.

6.3. Solar Area Radiation Surface Creation

Where accurate interpolation of the DEM is key to the grade segmentation, the solar area radiation surface is key to the climate segmentation. This surface provides an accurate measure of the total energy the sun delivers to each raster cell within the study area.

The focused study area consisted of approximately 62 square miles. The ArcToolbox Area Solar Radiation (Spatial Analyst) tool required two days to create a solar radiation surface for this area. Studies indicate that a quad-processor server dedicated to this effort would require one month to process the full 3,000 square mile study area.

During the initial stages of this project the proposed approach to this aspect of the overall problem was to create a set of hillshades. The hillshades would then be combined to generate a surface reflecting the aggregate amount of sunlight seen for all points within the study area. This approach would be similar to the Multidirectional Oblique Weighting (MDOW) hillshade technique. The resulting surface was to be used the same way that the application currently uses the current solar surface.

Since the release of ESRI's ArcMAP version 9.2 and the included ArcToolbox Area Solar Radiation (Spatial Analyst) tool we have the opportunity to utilize the more accurate solar surface produced by this tool as a baseline for checking other methodologies. Further research into this area is recommended.

6.4. Ice Surface Creation

The current model for the creation of the ice surface needs to be improved. One alternative approach is suggested by Seville and Metcalfe's (2005) research:

Building a generic model of conditions that result in road closures from snow and ice may be possible by comparing the conditions of the most frequently occurring road closures. If the correlation between weather conditions and key geographical features (altitude, slope, etc.) is strong, it may be possible to use generic conditions for all roads with possible adjustment factors for roads at higher altitudes or with other easily measured variations in conditions. ... The minimum and maximum temperatures on days when ice was formed were compared with those for days when ice did not form on the road. Statistical analysis revealed that for ice to form the maximum temperature must remain below 10°C and minimum temperature must fall below 2°C. As these closure criteria are specific to the Desert Road (relative to weather conditions in Waiouru), this type of analysis would need to be carried out individually for different areas. Hence, it is suggested that this analysis focus on those sections of road that have been regularly affected by snow and ice in the past. (Section 3.5)

The viability of this methodology on mountain terrain needs to be researched. Further study may be beneficial if the method proves valid outside the desert region.

Elements that may have to be considered include the effect of terrain and wind conditions on the relative temperatures found at ridgelines, hillsides and valley floors; the effect of differing ground covers and vegetation; and the seasonal variations resulting from the shade of trees and shrubs.

6.5. Potential Trail Analyst Extension Uses

The Trail Analyst Extension may prove useful to post disaster responders and planners. The Kashmir earthquake (a.k.a. South Asia earthquake or Great Pakistan earthquake) of 2005 is an example of a situation that where the Trail Analyst Extension may be helpful. Landslides in the mountainous regions impeded access by blocking roads. The earthquake caused an estimated 3.3 million homeless in Pakistan (Wikimedia, 2007). The Trail Analyst Extension could be used to quickly segment a transportation network based on raster surfaces of known or suspected slide areas and grade. The resulting network may provide relief personnel with information regarding available routes for supply trucks, buses, and emergency response vehicles.

7. Future Work

This project has identified several topics that may improve upon the results obtained in this paper or may expand the scope of work into beneficial areas. The first of these is in the area of interpolation. The Trail Analyst Extension may use a DEM, area solar radiation surface, ice surface, and snow surface. The interpolation requirements for the DEM are more demanding and have a greater impact on the results than the others. It may prove beneficial to investigate alternative algorithms including IDW using nine nearest neighbors and/or an exponent on the distance. Kriging, Natural Neighbor, and Spline techniques should also be considered. An alternative approach may be found using triangulated irregular networks (TIN). These surfaces may yield additional information applicable to the grade segmentation process.

The smoothing function utilized in the grade segmentation algorithm may have to be adjusted or even eliminated based on the results of the interpolation findings. These study areas need to be coordinated to isolate the optimal combination for use with the grade segmentation algorithm.

To further complicate this study, the grade segmentation algorithm must be considered. One option that should be explored is the use of the Multivariate Adaptive Regression Splines (MARS) statistical approach. This approach may perform best using the interpolated data without a smoothing function being applied. If a smoothing function is required it may differ from the function that has proven effective with the Grade Window segmentation algorithm.

The next area that may benefit from additional research is in the area of the climate surfaces. The current version of the Trail Analyst Extension uses the ArcToolbox Area Solar Radiation (Spatial Analyst) tool to generate the initial surface. The ice and snow surfaces are derived from this initial surface. The Area Solar Radiation tool is designed to work with a relatively small area such as a residential neighborhood. It is not designed to be used with a 3,000 square mile study area. The processing time required to prepare the solar area surface makes this tool impractical for some projects. It may be possible to use a hillshade as the starting point for the Trail Analyst Extension climate processing. This should reduce the processing requirements from weeks to hours. The hillshade will probably prove to be less accurate than the solar area surface but may prove to be useful. The climate surfaces may also benefit from the addition of a better climate model for the prediction of ice.

The final area of future work that is proposed is in the extension of the Trail Analyst Extension to include areas of interest. An area of interest would be used by the planner to influence the travel route. An area may be identified as a likely location to find a rare animal or species of tree. These areas would be used as attractors when the route is determined. Other areas may be identified as containing a hazard that should be avoided. Weightings would allow the planner to determine how much influence these areas of interest would exert on the route.

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Appendix A – Database Design

The Trail Analyst Extension works from an enterprise and/or personal geodatabase. This flexibility allows individual users to share data and, when desired, keep portions of the data separate. Trip planners may have developed transport mode profiles that are unique to their expeditions and are kept within a personal geodatabase. Refer to Appendix A Table 1 for a list of the geodatabase contents.

Appendix A Table 1 Database Contents

Dataset	Description	Source and Date	Data Model	Attributes
DEM	Digital Elevation Model	USGS NED, 2006	Raster	Surface elevation
RoadsTrails	Roads and trails	USGS SDTS, varied	Polyline (vector)	(refer to Appendix A Table 2)
Streams	Rivers and streams	USGS, 2005	Polyline (vector)	Length, FLOW, PNAME, STATECODE, HYSNUM
Fords	River crossings	Developed	Point (vector)	Name, normal depth, rain depth, flood depth
Transport	Modes of transportation	Developed	Table	Name, MinWidth (see Table 3-# for others)
Lakes	Lakes	USGS, 2005	Polygon (vector)	Name, STATECODE, WRCBLAKES, AREA
Solar	Area Solar Radiation	Developed	Raster	Watt hours per square meter
Ice	Ice Surface	Developed	Raster	Ice (1) or no ice (0)
Snow	Snow Surface	Developed	Raster	Snow depth (cm)

The RoadsTrails feature dataset is compatible with the client's legacy system. The addition of the new environmental attributes has increased the number of fields as shown in Appendix A Table 2.

Appendix A Table 2 Roads/Trails Field List

Field Name	Description	Data Type	Domain
OBJECTID	Unique feature identifier	Object ID	
Shape	Feature shape	Geometry	
Name	Name	Text	
Number	Numeric identifier (optional)	Double	
Condition	Condition of feature surface	Long Integer	Condition
MinShoulderWidth	Minimum shoulder width	Long Integer	Minimal Shoulder Width
Moisture	Subsoil moisture level	Long Integer	Subsoil Moisture
Plasticity	Surface plasticity	Long Integer	Plasticity
PredomSoil	Predominant soil type	Long Integer	Predominant Soil
SurfaceType	Surface type	Long Integer	Surface Type
SurfaceWidth	Surface width	Long Integer	Surface Width
TerrainType	Terrain type	Long Integer	Terrain Type
Ford	Text flag set to “T” if it is a ford	Text (length = 1)	
NormalDepth	Water level during normal conditions	Float	
RainDepth	Water level during typical rain	Float	
FloodDepth	Water level during flooding	Float	
Grade	Percentage grade of road surface	Float	
Snow	Depth of snow (cm)	Long Integer	

Field Name	Description	Data Type	Domain
Ice	Integer flag set to 1 if ice exists or 0 if no ice	Long Integer	
Shape_Length	Length of feature	Double	

The domains and values used by the RoadsTrails feature class are shown in Appendix A Table 3. These domains were implemented to ensure backwards compatibility with the legacy data and applications.

Appendix A Table 3 Roads/Trails Domains

Domain Name	Coded Values
Condition	1 – (G) Good 2 – (P) Poor
Minimal Shoulder Width	1 – (A) $\Rightarrow$ 2 m 2 – (B) 1-2 m 3 – (C) $\leq$ 1 m
Subsoil Moisture	1 – (M) Moist 2 – (W) Wet 3 – (D) Dry
Plasticity	1 – (H) High 2 – (L) Low 3 – (NA) Not Applicable
Predominant Soil	1 – (G) Gravel 2 – (S) Sand 3 – (C) Clay
Surface Type	1 – (C) Concrete 2 – (B) Bituminous 2 – (N) Natural Surface
Surface Width	1 – (A) $>$ 7.2 m 2 – (B) $6.4 \leq 7.2$ m 3 – (C) $5.5 \leq 6.3$ m 4 – (D) $4.6 \leq 5.4$ m 5 – (E) $3.6 \leq 4.5$ m 6 - (F) $1 \leq 3.5$ m 7 – (G) $<$ 1 m
Terrain Type	1 – (F) Flat 2 – (U) Undulating 3 – (H) Hilly 4 – (M) Mountainous

The Fords feature dataset is a new addition to the client's GIS system. The addition of the new water depth attributes has increased the number of fields as shown in Appendix A Table 4.

Appendix A Table 4 Fords Attributes

Field Name	Description	Data Type
Name	Name of the ford	Text (no length requirement)
NormalDepth	Depth of water during "normal" conditions.	Float
RainDepth	Depth of water during rainy conditions	Float
FloodDepth	Depth of water during extreme rain or flood conditions	Float

Note: The unit of measure for ford depths is user definable but must match the unit of measure used in the transport mode table.

The Transport mode table is a new addition to the client's GIS system. This table stores individual transport mode descriptions. Each description provides the detailed travel characteristics necessary to determine if a road or trail segment may be traversed given a set of climatic conditions and the speed of traversal (refer to Appendix A Table 5).

Appendix A Table 5 Transport Mode Table Fields

Field Name	Description	Data Type
Name	Name of the transport mode	Text (no length requirement)
MinWidth	Minimum width required for passage	Long Integer
SpeedOnFlat	Speed on flat paved surface	Float
Grade1	Maximum grade where speed is equivalent to flat surface	Float
Grade1SpeedUp	Speed traveling up surface with grade between Grade1 and Grade2	Float

Field Name	Description	Data Type
Grade1SpeedDown	Speed traveling down surface with grade between Grade1 and Grade2	Float
Grade2	Second grade break	Float
Grade2SpeedUp	Speed traveling up surface with grade between Grade2 and Grade3	Float
Grade2SpeedDown	Speed traveling down surface with grade between Grade2 and Grade3	Float
Grade3	Third grade break	Float
Grade3SpeedUp	Speed traveling up surface with grade between Grade3 and MaxGradeUp	Float
Grade3SpeedDown	Speed traveling down surface with grade between Grade3 and MaxGradeDown	Float
MaxGradeUp	Maximum grade travel is possible up hill	Float
MaxGradeDown	Maximum grade travel is possible down hill	Float
MinLoad	Maximum load with no effect on travel speed	Double
TypicalLoad	Typical load capacity	Double
MaxLoad	Maximum load capacity	Double
MaxLoadSpeed	Percentage of unloaded speed that can be obtained under maximum load	Short Integer
GravelSpeed	Percentage of speed that can be obtained on prepared gravel road surface	Short Integer
NGravelSpeed	Percentage of speed that can be obtained on natural earth gravel surface	Short Integer

Field Name	Description	Data Type
NSandSpeed	Percentage of speed that can be obtained on natural earth sand surface	Short Integer
NClaySpeed	Percentage of speed that can be obtained on natural earth clay surface	Short Integer
NGravelWetSpeed	Percentage of speed that can be obtained on natural earth wet gravel surface	Short Integer
NSandWetSpeed	Percentage of speed that can be obtained on natural earth wet sand surface	Short Integer
NClayWetSpeed	Percentage of speed that can be obtained on natural earth wet clay surface	Short Integer
SnowTravelOnC	Y if travel on a type C surface with snow is possible, N if not	Text (length 1)
SnowTravelOnB	Y if travel on a type B surface with snow is possible, N if not	Text (length 1)
SnowTravelOnNGravel	Y if travel on a natural earth predominantly gravel surface with snow is possible, N if not	Text (length 1)
SnowTravelOnNSand	Y if travel on a natural earth predominantly sand surface with snow is possible, N if not	Text (length 1)
SnowTravelOnNClay	Y if travel on a natural earth predominantly clay surface with snow is possible, N if not	Text (length 1)
IceTravelOnC	Y if travel on a type C surface with ice is possible, N if not	Text (length 1)
IceTravelOnB	Y if travel on a type B surface with ice is possible, N if not	Text (length 1)

Field Name	Description	Data Type
IceTravelOnNGravel	Y if travel on a natural earth predominantly gravel surface with ice is possible, N if not	Text (length 1)
IceTravelOnNSand	Y if travel on a natural earth predominantly sand surface with ice is possible, N if not	Text (length 1)
IceTravelOnNClay	Y if travel on a natural earth predominantly clay surface with ice is possible, N if not	Text (length 1)
SnowMinDepth	Minimum depth of snow that effects speed	Float
SnowSpeed	Percentage of speed while traveling on SnowMinDepth + SnowDepthRange	Short Integer
SnowDepthRange	Depth of snow (added to SnowMinDepth) over which SnowSpeed is interpolated	Float
MaximumSnowDepth	Maximum depth of snow where travel is possible	Float
IceSpeed	Percentage of speed possible on ice	Float
MaxFordDepth	Maximum depth of water that is passable (units are user definable but must match Ford attributes)	Float