Accumulated Surfaces & Least-Cost Paths: GIS Modeling for Autonomous Ground Vehicle (AGV) Navigation

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(ABSTRACT)

The Geographic Information System (GIS) is a crucial part of any land navigation system. Autonomous ground vehicles should have access to stored geographic data and the ability to manipulate it for routing purposes. Since there is no human interaction involved in operating these vehicles, data that a human driver would use to make decisions must be stored in the GIS. The data which represent the earth's surface become a series of factors and constraints which translate to friction in terms of mobility. Factors need to be weighted appropriately, but require a sensitivity analysis before designating these weights. Constraints do not require any weight because they represent absolute barriers which cannot be traveled upon. All GIS layers are incorporated into the raster environment, so that an accumulated surfaces can be built on which a least-cost path can be located. The sensitivity analysis allows generation of many routes which can be field tested for the appropriate weight selection for each factor. Ultimately, the entire process would select an optimal path and output closely spaced waypoints which the vehicle can follow.

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Chapter 1 – Introduction

1.1 – Geographic Information Systems (GIS)

Geographic Information Systems (GIS) are defined as "a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes" (Burrough 2000). GIS can be applied to virtually any information that has a geographic relationship. Traditionally geospatial technologies have been heavily rooted in land management and defense applications. As GIS has matured throughout the years it has diversified into areas such as retail, telecommunications, biology, crime prevention, utility management, transportation, emergency services, hazard management, civil engineering, and social/medical studies. GIS/GPS tracking systems surround us every day. Most public transit systems, commercial shipping, airlines, railways, police vehicles, and snow plows are tied into automatic vehicle tracking (AVL) systems. Without AVL, businesses like Wal-Mart could not run as efficiently, forcing the customer to pay the difference in their distribution costs. Snow plows and salt levels would not be monitored in real-time, which cause delays in snow removal. GIS has also found its way into many other technologies such as the Internet, GPS, mobile phone and location-based services such as OnStar®. OnStar® is a subscription service that allows a vehicle to be monitored at the customer's discretion, equipping it with antitheft and accident reporting. Subscription services like these can also access the internet via your car or smartphone which can be utilized to provide you with

information on nearby gas stations, entertainment, or hotels. GIS and GPS are
working their way into these technologies providing additional capabilities and
efficiencies to their users.

1.2 – GIS Applications in Unmanned Systems

Current research is being conducted by the defense industry on how to
automate and program vehicles so they can drive autonomously. The defense
industry has many uses for this technology that range from reconnaissance
missions to simple transporting of resources and supplies to remote areas. As
part of this effort, the Defense Advanced Research Projects Agency (DARPA)
held a race for autonomous vehicles in March 2004 to encourage development of
the technologies that support these vehicles. The race consisted of navigating
through terrain between Barstow, California and Las Vegas, Nevada. Several
teams entered the race including a team of mechanical engineers and
geographers from Virginia Tech. The Virginia Tech team implemented a simple
GIS tool to interact with the navigation system which helped the vehicle to make
several successful qualifying runs. GIS will continue to play a critical role in the
development of future autonomous vehicles.

1.3 – Trends in Unmanned Systems Research

The National Defense Authorization Act of fiscal year 2001 set a goal for
the Armed Forces to achieve significant advancement in this area within the next
two decades. By 2010 the authorization wants one third of operational deep

strike force aircraft to be unmanned, and by 2015 one third of all operational

ground vehicles need to be unmanned (106th Congress, 2000). Many

autonomous ground vehicles (AGV) do not operate totally devoid of human

interaction. Albus makes note of four incentives why researchers should

continue testing and studying these vehicles and systems (2004).

"First, it is a problem domain for which there is a large

potential user base, both in the military and civilian sectors. This

translates into research funding.

Second, it is a problem domain where physical actuators and

power systems are readily available. Wheeled and tracked

technology is mature, inexpensive, and widely deployed.

Third, it is a problem domain for which the technology is

ready. The invention of real-time LADAR imaging makes it possible

to capture the 3-D geometry and dynamics of the world. This has

broken the perception barrier. The continued exponential growth

rate in computing power per cost has brought the necessary

computational power to economic viability. This has broken the

cost barrier. Cognitive modeling and intelligent control theory has

advanced to the point where engineering of intelligent systems is

feasible. This has broken the techno logy barrier.

Fourth, autonomous driving is a problem domain of

fundamental scientific interest. Locomotion is perhaps the most

basic of all behaviors in the biological world. Locomotion is

essential to finding food and evading predators through out the animal kingdom. The brains of all animate creatures have evolved under the pressures of natural selection in rewarding successful locomotion behavior. It is therefore, not unreasonable to suspect that building truly intelligent mobility systems will reveal fundamental new insights into the mysteries of how the mechanisms of the brain give rise to the phenomena of intelligence, consciousness, and mind" (adapted from Albus, 2004).

In 2004, the Joint Unmanned Systems Test, Experimentation and Research (JOUSTER) program was created by Virginia Tech and its partners to establish facilities where and standards by which unmanned technologies could be studied. "JOUSTER is a partnership between Virginia Tech, the Institute for advanced Learning & Research (IALR), and the Virginia International Raceway (VIR). JOUSTER is affiliated with the National Unmanned Systems Experimentation Environment (NUSE[2]), the Army's research, development, and Engineering Command (RDECOM), and the Department of Defense (DoD) Joint Robotics Program (JRP).

Together, these groups are establishing facilities to support unmanned aerial, ground, surface, and underwater vehicle experimentation over a wide variety of terrain and weather conditions" (JOUSTER, 2004)

1.4 – Research Purpose

Humans are intelligent creatures able to take in large amounts of information from five different senses (Sight, Hearing, Smell, Taste, and Touch). We use our senses to make complex decisions that enable us to do all sorts of things from cooking supper to driving down the road. These types of activities are rather simple and often taken for granted. Machines are approaching the

Figure 1.4.1 – GIS and AGV Navigation
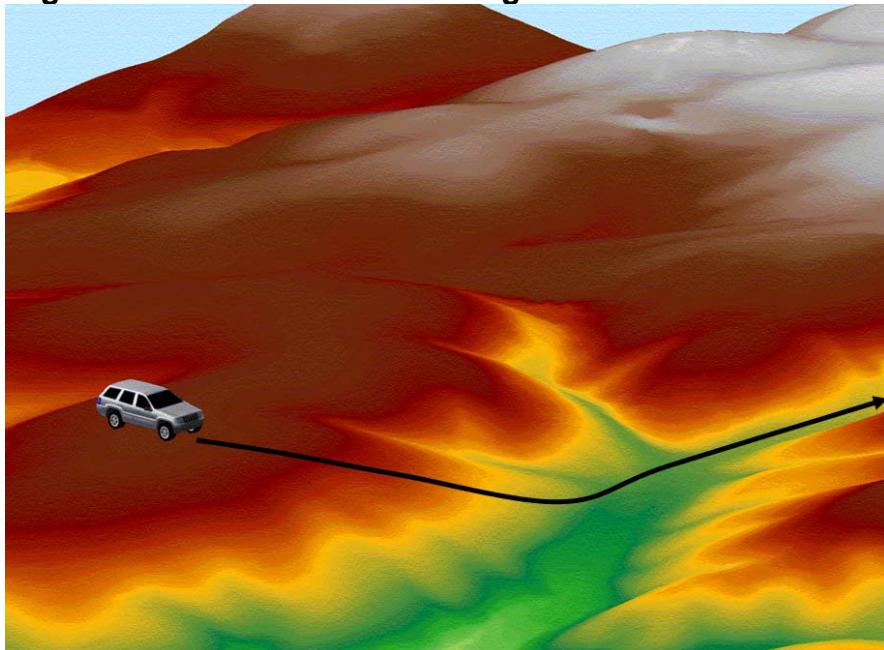
capacity to begin doing these types of things, but complete autonomy still remains to be seen. For an autonomous vehicle to be truly intelligent it must access knowledge about its environment so it can navigate. How can vehicles do this and what is the role of GIS? My paper will address this question through a few objectives.

Humans have been using various tools for navigation for a long time. The advancement of technologies has provided new tools to provide us with answers on how to get from point "a" to point "b". Technology has greatly advanced navigation instruments making autonomous vehicle research possible. Vehicle sensors or machine vision can identify obstacles in a limited area, but cannot plan for what may lie a mile ahead. GIS is a solution to this problem. Without a terrain database there is no way to navigate efficiently or develop long term routing. The first objective is to establish how GIS can handle navigation. What makes accumulated surfaces work well for autonomous vehicle navigation? The focus of this research is to examine accumulated surfaces and least-cost paths as a means of global route planning and long term guidance in autonomous vehicle navigation. The accumulated surface is a raster dataset containing values which calculate cost as travel occurs across the surface. They are ideal for road planning making them quite appropriate for route planning of all-terrain vehicles. However, building an accumulated surface can be difficult because of the number of factors one must consider.

The second consists of a number of options for building accumulated surfaces and least-cost paths. These options will be discussed as they produce different results that are vital to navigation. The third objective is to determine what inhibits travel of these autonomous vehicles. The inputs that are used by the GIS will determine the behavior of the vehicle. Finally, the fourth objective is to establish a set of parameters for input data which will need to be picked in order to produce a reliable model. Weights for deciding to navigate a vehicle up

a 5% grade versus one at 10% are unknown. These questions will be answered by developing a theoretically solid model and running it many times, varying the weights for costs of travel, and mapping the numerous paths to examine their suitability and accuracy in the field. The quality of my results weighs heavily on these last two objectives.

Chapter 2 - Literature Review & Related Research

2.1 - A Brief History of Navigation

There once was a time when ancient seafarers had to rely on their five senses in order to navigate the oceans. It wasn't until the second millennium B.C. that the first navigational instrument was used (Cotter, 1981). The device was called a sounding pole used by the Egyptians to measure water depth ensuring that the ship would not hit bottom. It wasn't until the 12th century that the compass and chart or map appeared, and the 16th century marked the first use of the log (Cotter, 1981). These were essential tools in obtaining an ability to perform "dead reckoning navigation". This type of navigation occurs when the driver is "flying blind" from a known point and measures direction, speed, and distance. Eventually, instruments like the quadrant and sextant were developed to measure the altitude of stars which aided in charting known points (Cotter, 1981). Since the 16th century technology has come a long way. In 1964 the United States Navy built the Navigation Satellite System (N.N.S.S.), a TRANSIT Doppler System made up of seven satellites that were used to update the inertial navigation systems of submarines (Weil, 2002). It wasn't until 14 years later that Navigation Satellite Tracking and Ranging (NAVSTAR) was put into operation by the United States Department of Defence (Weil, 2002). This was the first Global Positioning System (GPS) to provide a three dimensional position, velocity, and time for any receiver located on land, sea, or air. Most instruments of early navigation seemed to have been replaced, but the one that remains still heavily

used is the map. While computers have allowed us to automate mapmaking and increase accuracy we consistently use it to guide us through our environment.

2.2 – Autonomous Robots and Navigation

"Intelligent systems" is an area of technology that is on the rise thanks to research in neurosciences, cognitive psychology, artificial intelligence, robotics, and intelligent machines (Albus, 2004). With the advances of computer technology it is expected that, within the next 25 years, a small network of PCs can process as fast as the human brain (Kurzweil, 1999). James Albus of the National Institute of Standards and Technology notes that applications and capabilities of autonomous vehicles in both civil and military systems have exceeded past expectations. Autonomous vehicles are largely being researched by the defense industry for reconnaissance, weapons deployment, and search and rescue type situations (figure 2.2.1). JOUSTER was recently involved in a

Figure 2.2.1 – Mine Detection and Location
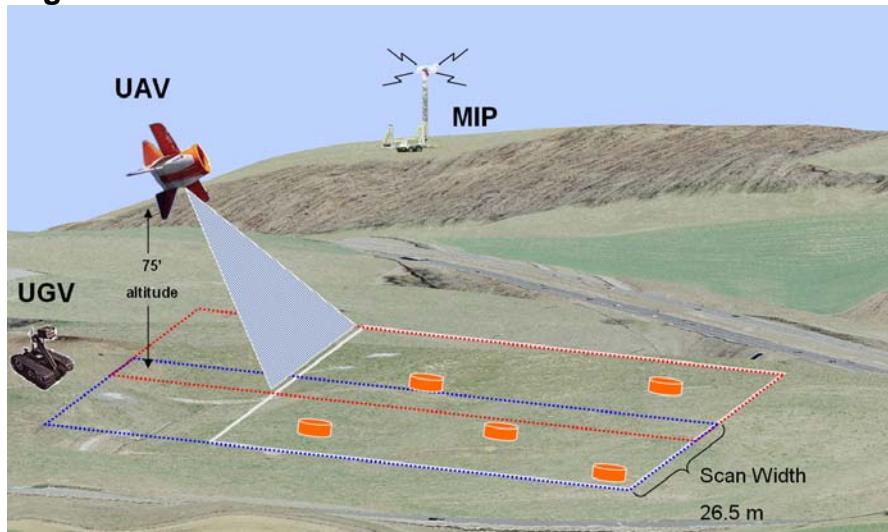
9

mine detection and location test that consisted of using an unmanned ground vehicle (UGV), an unmanned aerial vehicle (UAV), and a mobile instrumentation platform (MIP). The UAV would digitally scan for mines located on the ground and would wirelessly communicate that information back to the MIP which would send that on to the UGV. The UGV used the location information gathered by the UAV to further investigate for mines.

Some examples in civilian industries would include mining, farming, and construction to name a few. In farming the University of Illinois has been using machine vision to identify rows of corn to aid in proper navigation for harvesting (figure 2.2.2) (Peterson, 2004). Carnegie Mellon University has seen potential in

Figure 2.2.2 – Farming

Figure 2.2.3 – Golf Course Mowing

Figure 2.2.4 – Underwater

Figure 2.2.5 – Aerial

using autonomous systems for golf course maintenance creating savings in labor costs (figure 2.2.3) (Baard, 2004). Unlike water and air vehicles, which navigate through space or a medium such as water offering little chance of running into an obstacle, autonomous ground vehicles (AGVs) operate on a surface that is full of obstacles (figure 2.2.4 and figure 2.2.5) (Penland, 2003).   Navigation of AGVs becomes an issue and they require more caution and more sensors to safely navigate obstacles.

Some basic sensors that are pretty standard on AGVs are bearing-only lasers, time-of-flight lasers, an inertial measurement unit (IMU), encoders, and a differential GPS receiver (figure 2.2.6). The bearing-only lasers are usually mounted high on the vehicle and are intended to recognize reflective markings that are artificially placed in an environment. For example, mining vehicles travel

Figure 2.2.6 – 2004 Virginia Tech DARPA Grand Challenge Vehicle (Cliff)
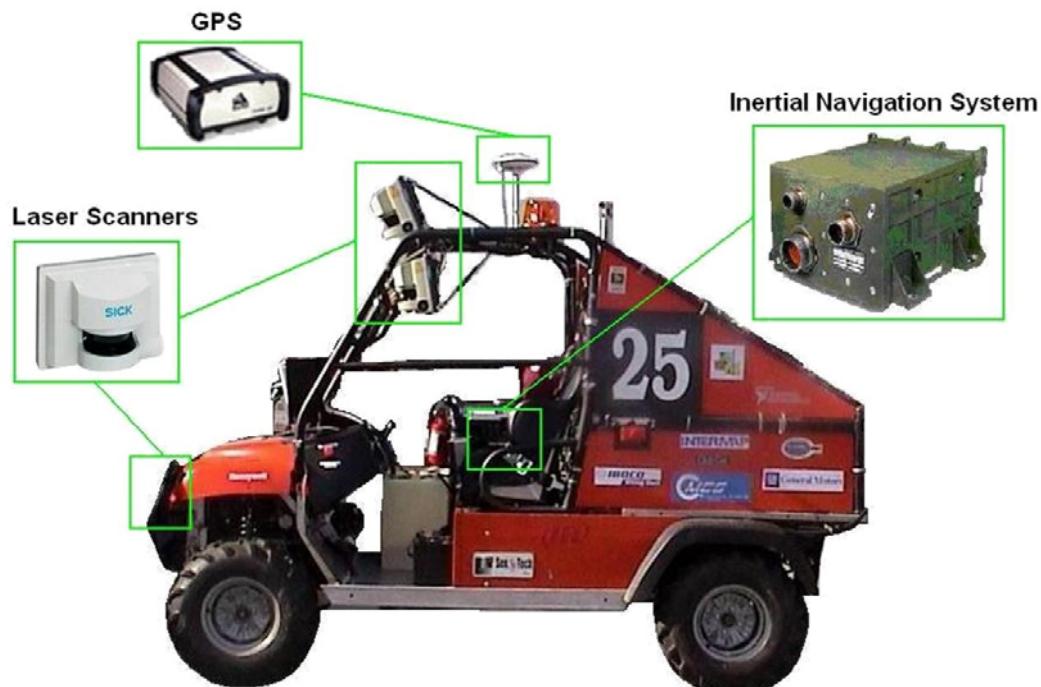
(Virginia Tech, 2005)

only a few routes over and over again. These lasers can recognize routes

marked with reflective markings on the ground. Time-of-flight lasers are pointed

forward on the vehicle and each may have different heights to provide specific

range and bearing data. An IMU measures vehicle heading, tilt, and

acceleration. This information assures orientation and safe operation. Encoders

provide information on speed and steering angles and are fitted to the wheels of

a vehicle.   The GPS can be used to calibrate the steering encoder, but they also

can provide positions so that on board computers can reference GIS data for

navigation. Many of these sensors are dependent on the conditions of the

environment. Dust, heat, cold, humidity, vibration, and GPS satellite visibility can

disable any one of these devices (Madhavan et al, 2003).

There are two types of mapping systems in AGVs. The local map is built

from data gathered by the previously mentioned sensors. The GIS is commonly

referred to as the global map. As the vehicle navigates, signals and sensors

from the local system should georeference with the maps contained in the global

system. Each map can be overlaid on top of the other in order to compare

differences between the two. In this manner, the data existing in the global

system can then be updated with the most recent information from the local

system. An example of such a system was used by Army Research Laboratory's

Demo III Experimental Unmanned Vehicle programs. A series of tests conducted

by the Army were completed in the winter of 2002-2003. The vehicles used were

driven 550 kilometers in rough terrain in desert, woods, fields of grass, dirt roads,

and the urban environment. Day, night, clear, cloud, rain, and snow, these

vehicles saw it all. No moving objects were contained in the test and the vehicles were independent without human assistance 90 percent of the distance (Albus, 2004).

2.3 – Movement and Routing: Vector and Raster Approaches

Movement and route analysis have various uses. In the raster environment, uses include HAZMAT modeling, roadway planning, and even bus route planning that employ accumulated surfaces and least-cost paths (Berry, 2004) (Berry, 2002) (Yu et al, 2003)   Route analysis or network analysis can many times be considered a vector problem, but raster software can also solve many of these problems. Most raster analysis software contains a built in set of tools or commands that can develop procedures for delineating watershed boundaries, valley bottoms, flow direction, buffers, cost surfaces, least-cost paths, and flow accumulation.

Modeling surface flow often creates thoughts of modeling rainfall accumulation on streams, but it can model just about anything that flows across the terrain. An example of a topographic use is easily explained by Berry's article "Migration Modeling Determines Spill Effects" (2004). If a tanker transporting oil crashes along a highway it would be invaluable if hazmat or emergency services could automatically simulate the flow of spilled material from a given location. Given the mechanical properties of oil and the characteristics of the affected terrain an estimated travel time can be established in a grid. This surface flow could tell you where the majority of the oil would flow and how fast.

Furthermore, the surfaces generated using these operations do not always have to be topographic in nature, but can be demographic. A demographic approach to surface modeling can model the number of bus riders for any given bus stop (2002).

Map 2.3.1 – Bus Ridership
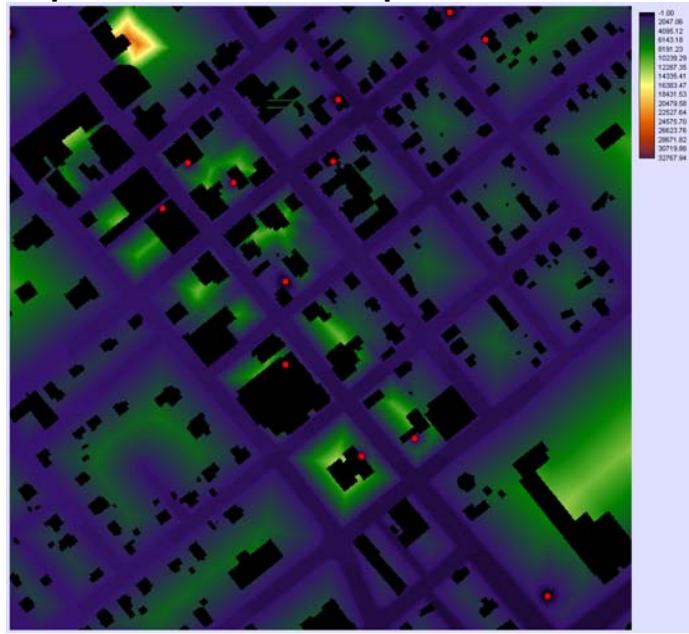
Berry mentions that by mapping the number of riders in each grid cell and accumulating the surface from the bus stops it can provide a surface on which ridership could be measured (map 2.3.1). Points along the route or between stops will have steep slopes because of the large saturation of riders. From the accumulated surface a least-cost path can be calculated from each cell showing which stop the riders will be more likely to use (Berry, 2002).

Common vector uses for routing often apply to street route planning for in car navigation systems. In car navigation is a technology that has seen large growth within the last few years and autonomous navigation systems are expected to significantly rise as well (Croswell, 2004). The difference between the two is quite large, but they both are intended to have similar goals of guiding a vehicle. Commercial and consumer interest have made in car navigation systems a standard in many of the vehicles sold today. Companies like Tele

Atlas™ and NAVTEQ™ provide real-time services that grant access to a national traffic database and update GIS data provided on their navigation systems. It's good to have a set of maps to guide a vehicle, but it's even better to have information such as accidents, construction, or congestion that could provide a more optimal route under changing conditions in real time. The ability to provide real-time traffic information and offer several path finding options such as shortest distance, shortest time, or even no toll routes based on the current vehicle's location is a tremendous advantage to the driver. These systems don't even require the driver to look at the screen because most of them give audible directions on a turn by turn basis and recalculate if the vehicle gets off course (Tele Atlas North America Inc., 2002).

Another route planning tool is MapQuest™, a web-enabled GIS that provides free road map directions to its users. In my experiences MapQuest™ does a pretty good job at locating the fastest route from "a" to "b". They've implemented what is referred to by Marc Smith, MapQuest's ™ Chief Technical Developer, as a "Double Dijkstra" which is a slightly modified version of Dijkstra's original shortest path algorithm (Robinson, 2004). The basic Dijkstra algorithm requires two or more nodes and searches possible routes for the shortest result based on specific weights of the edges that connect them. All nodes are connected to each other by these edges. The edges contain weight which could be cost, distance, or time. In a network of nodes the shortest path is the result of the lowest sum of weights between two nodes (Street, 2004).

For example, let's say that there are five nodes that are all connected (figure 2.3.1). Each node is connected by a road that contains a weight represented by time in minutes. We want to travel from node "a" to node "f". The source node or starting location of the shortest path to each node is "a". The arrows represent the direction of travel between the edges. The numbers near the arrows represent the weight or in this case travel time. Figure 2.3.2 shows the algorithm pointing to red nodes with a total time from node "a". As these red nodes are found not to have any other edges coming into them such as node "b", they are coded orange. This orange means that the lowest cumulative time has been assigned to that node. Searches continue for other nodes (c, d, e, and f) until the algorithm establishes that all nodes have been assigned the shortest cumulative time (figure 2.3.3). Figure 2.3.4 shows the final result and the shortest times between all nodes. The shortest path from "a" to "f" is 63 minutes

Figure 2.3.1 – Dijkstra Step 1
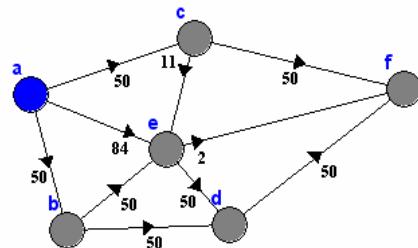
Figure 2.3.2 – Dijkstra Step 2
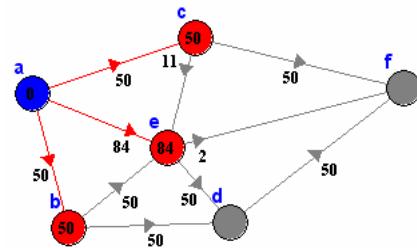
Figure 2.3.3 – Dijkstra Step 3
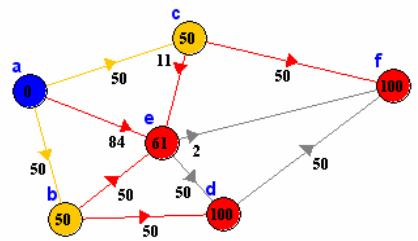
Figure 2.3.4 – Dijkstra Step 4
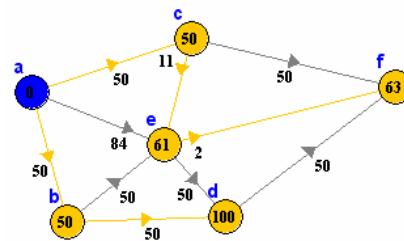
and the path follows through nodes "a", "c", "e", and "f". Geographically, it appears that the shortest path from "a" to "f" may follow nodes "a", "c", "f" or "a", "e", "f". This may be true for distance, but the level of service on those routes is low resulting in much longer travel times (figure 2.3.2) than that of figure 2.3.4 (Street, 2004).

This is all well and good if I were driving down the road, but what about an all-terrain unmanned or autonomous system? The major difference in these systems is how these vehicles are used. The common everyday driver typically drives on the road and is interested in how to navigate roads. The vehicle is fixed to a road which is easily represented by a line in the vector environment. Therefore, GIS software is used to attribute the lines in a roads database in order to provide the best possible route under certain scenarios. However, autonomous vehicles are being developed for all-terrain military uses. This application not only requires a GPS and road maps, but it also needs terrain and land cover maps at a reasonable resolution and the additional sensors and procedures to deal with the act of driving.

The vector approach falls far short in planning to traverse off-road terrain. Raster data illustrate numerical and geographic patterns best for elevation (Berry, 2002). In off-road applications, the use of elevation data is necessary and the vector model is not reasonably implemented. Instead using a raster environment for route planning is much more suitable, as it does not restrict the ability to travel over a continuous surface.

2.4 – Raster Terms & Definitions

<u>Accumulated Surfaces</u>

Accumulated surfaces are raster models that allow you to calculate a least-cost path from point "a" (start) to point "b" (target). The term "accumulated" implies that there is a building up of numbers or values, and this is exactly what happens. The cost for a cell in an accumulated surface is a value that represents a cumulative cost from the target. So, to travel across four cells in a row with the first two cells each having a value of one and the second two cells each having a value of two, the accumulated cost to travel through the four cells is six; this value is stored in the start cell. Under simple isotropic conditions (figure 2.4.1) the values must increase the further away you get from the point of origin. Isotropic conditions are defined by Merriam-Webster as "exhibiting properties (as velocity of light transmission) with the same values when measured along axes in all directions" (2004). In an isotropic surface, the only friction considered is

Figure 2.4.1 – Accumulated Surface

34	32	30	28	26	24	22	21	20	20	19	18	17	16	16	16	17	18	19	20	20	21	22	24	26	28	30	32	34
33	31	29	27	25	23	21	19	18	18	17	16	15	14	14	14	15	16	17	18	18	19	21	23	25	27	29	31	33
32	30	28	26	24	22	20	18	16	16	15	14	13	12	12	12	13	14	15	16	16	18	20	22	24	26	28	30	32
32	30	28	26	24	22	20	18	16	14	13	12	11	10	10	10	11	12	13	14	16	18	20	22	24	26	28	30	32
31	29	27	25	23	21	19	17	15	13	11	10	9	8	8	8	9	10	11	13	15	17	19	21	23	25	27	29	31
30	28	26	24	22	20	18	16	14	12	10	8	7	6	6	6	7	8	10	12	14	16	18	20	22	24	26	28	30
29	27	25	23	21	19	17	15	13	11	9	7	5	4	4	4	5	7	9	11	13	15	17	19	21	23	25	27	29
28	26	24	22	20	18	16	14	12	10	8	6	4	2	2	2	4	6	8	10	12	14	16	18	20	22	24	26	28
28	26	24	22	20	18	16	14	12	10	8	6	4	2	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
28	26	24	22	20	18	16	14	12	10	8	6	4	2	2	2	4	6	8	10	12	14	16	18	20	22	24	26	28
29	27	25	23	21	19	17	15	13	11	9	7	5	4	4	4	5	7	9	11	13	15	17	19	21	23	25	27	29
30	28	26	24	22	20	18	16	14	12	10	8	7	6	6	6	7	8	10	12	14	16	18	20	22	24	26	28	30
31	29	27	25	23	21	19	17	15	13	11	10	9	8	8	8	9	10	11	13	15	17	19	21	23	25	27	29	31
32	30	28	26	24	22	20	18	16	14	13	12	11	10	10	10	11	12	13	14	16	18	20	22	24	26	28	30	32
32	30	28	26	24	22	20	18	16	16	15	14	13	12	12	12	13	14	15	16	16	18	20	22	24	26	28	30	32
33	31	29	27	25	23	21	19	18	18	17	16	15	14	14	14	15	16	17	18	18	19	21	23	25	27	29	31	33
34	32	30	28	26	24	22	21	20	20	19	18	17	16	16	16	17	18	19	20	20	21	22	24	26	28	30	32	34

distance.

Friction Surfaces

Friction surfaces contain no cumulative values, but contain costs from which the accumulated surface is created (figure 2.4.2). Friction surfaces are a

Figure 2.4.2 – Friction Surface

4	3	3	2	2	1	1	1
4	2	1	2	2	1	2	2
1	1	5	1	3	1	4	5
5	4	3	2	1	5	5	5

significant factor in developing more realistic accumulated surfaces. Friction surfaces are matrices that add resistance to travel within the matrix. As a few sources put it, friction is:

> "the attributes of the cells through which distance accumulation take place" (Burrough and McDonnel, 2000)
>
> "costs of travel (functional distance) ..." (DeMers, 2002)
>
> "… a value greater than 1 by which you multiply the base cost of movement in order to arrive at the actual cost of movement."
>
> (IDRISI Kilimanjaro, 2003)

Different friction layers can be combined into one to perform an anisotropic type of modeling. Anisotropic is opposite of isotropic, therefore cost values are not equal on axes of all directions. Some frictions that can aid in anisotropic modeling are wind, slope, fuel consumption, monetary expense, risk, or any other variable you want to use to inhibit travel (figure 2.4.3). Data that the military

collects for mobility modeling include slope, land cover, hydrography, and roads (Edwards, 1988). These are the most obvious and probably influence navigation the most. When multiple frictions are used they create an anisotropic accumulation. Generally, this type of accumulation is best for modeling real world situations in which travel is complex and involves many decisions. To get good results from a GIS model it must contain all the factors that would play a role in the vehicle's ability to travel.

The most efficient means of travel, the least-cost path, is the vehicle's guide between the origin and destination. It is critical that the accumulated surface represent near real conditions or costs. Real conditions can be modeled best with anisotropic surfaces or algorithms. There are different types of algorithms used for routing and not all of them are appropriate for this application. For example, Yu, Lee, and Munro-Stsiuk's study of least-cost algorithms focuses on roadway planning and notes that few successes have been made in applying these to off-road vehicle navigation (2003). The reasoning behind their statement is that the algorithms used for road planning often

Figure 2.4.3 – Isotropic (left) vs Anisotropic (center and right)
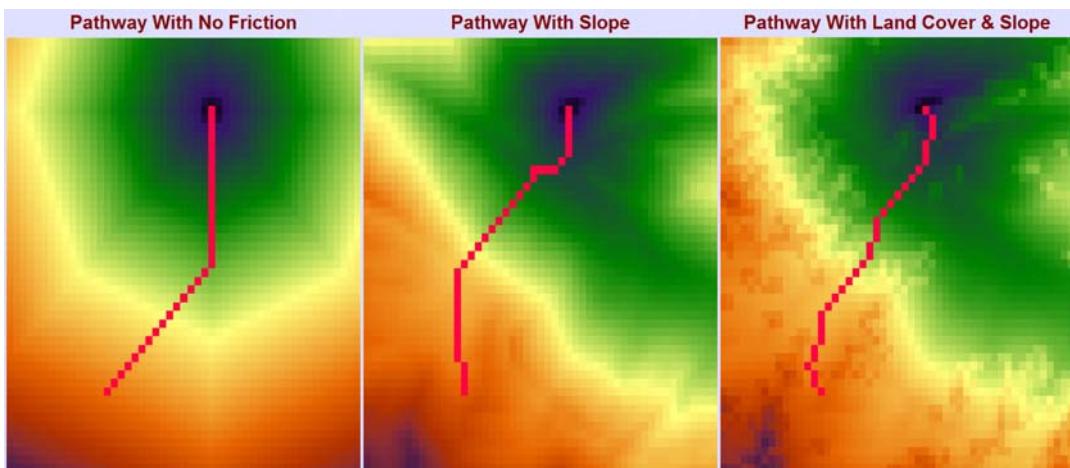
consider bridging and tunneling features. In addition, they are designed to examine slope direction in addition to slope which can create a "zigzagging" path that may be fine for road building, but difficult for navigating a vehicle. They refer to these algorithms as anisotropic because they consider slope direction. The danger is in tipping a vehicle with a path that "zigzags". The surface may provide too much tilt and vehicle testing on slope needs to be completed before

Map 2.4.1 – Difficulties Across Slope
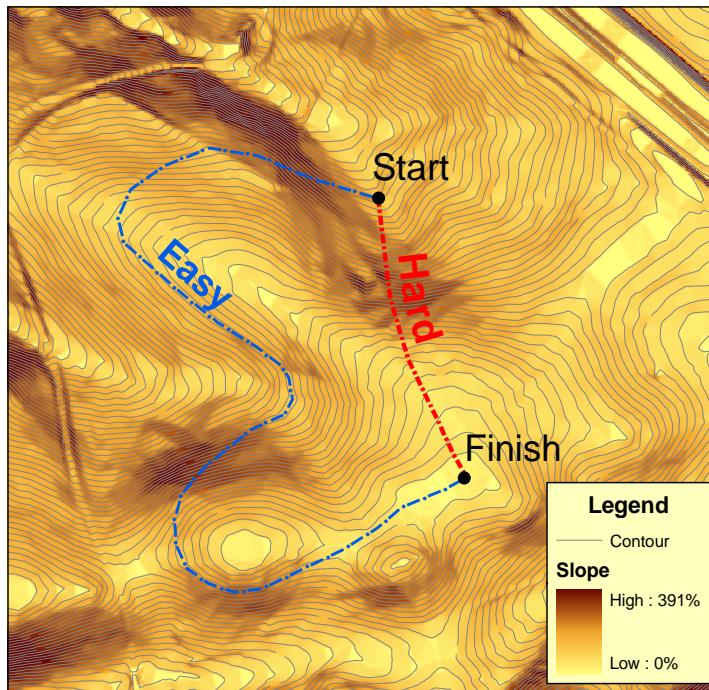
implementing such a routing algorithm. Conventional isotropic algorithms assume the maximum value of slope for the cell and don't consider the direction across multiple slope cells, which could ease travel (Yu et al., 2003). In the real world, travel up a slope of 25 percent could be lessened if traveled diagonal to the slope's magnitude (map 2.4.1). Isotropic algorithms do not always provide the best solution, as paths taken perpendicular to contours are steepest. If you rotate the path to an angle at either side of the perpendicular, the slope is

reduced until it reaches zero when it becomes parallel to the contour which could

be beneficial. Non-gradient slope direction may lessen gradients, but in the

application of the vehicle navigation it also could also cause a vehicle to roll over

due to sharp switchbacks on steep terrain. The *Rook's* pattern algorithm doesn't

examine diagonal values during accumulation and inserts a calculation based

only on direct neighboring cells. A larger pattern of cells such as the Queen's

and Knight's (figure 2.4.4) considers more angular movement (Yu et al., 2003).

Figure 2.4.4 – Rook's, Queen's & Knight's Patterns

| **Rook's** | **Queen's** | **Knight's** |
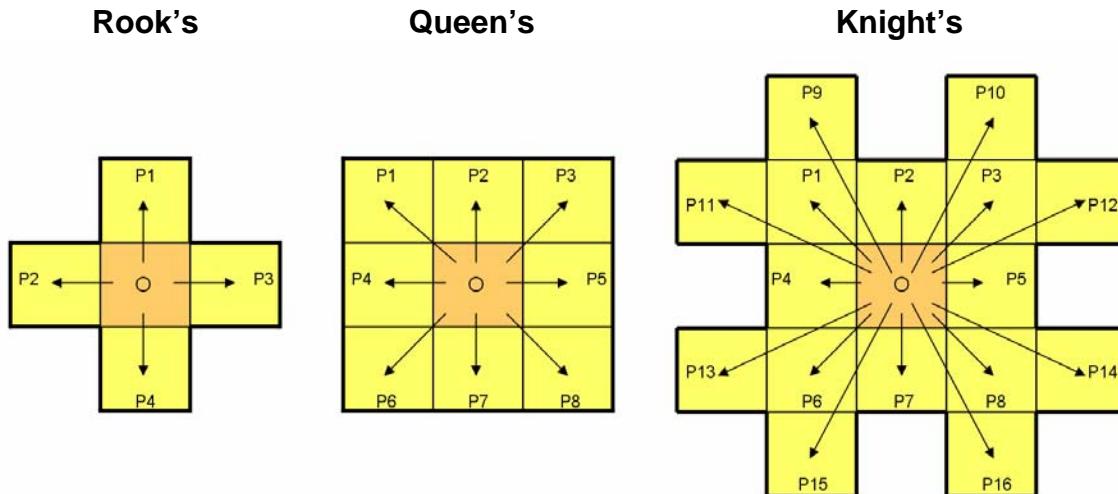
Using a pattern such as this with consideration of slope direction makes

switchbacks possible, lessening the gradient to be climbed. For example the

Queen's formula for an isotropic accumulation as stated by Yu would have two

parts. Equation 2.4.1 accumulates direct neighbors and equation 2.4.2

accumulates diagonal neighbors taking into account longer distances between

cell centers along a diagonal in a rectangular grid. Yu explains that $CC_{(O, Pi)}$ is

the accumulated cost from cell O to P_i. C_O and C_{Pi} are the costs for moving

between the individual cells, and µ represents cell width. CC_O is the accumulated

cost at cell O (2003). However, isotropic accumulations limit routes for an autonomous vehicle because the aspect of a slope is ignored. If vehicle limitations are known an anisotropic approach would be best. Instead of every cell's containing maximum slope values the direction travel across the slope is considered. The cost for moving through high slope is much heavier than that of low slope, but going down steep slope is more preferred than going up.

Equation 2.4.1 – Direct Neighbors

$$CC_{(O,P_i)} = \frac{(C_O + C_{P_i})}{2} \mu + CC_O \quad \text{where } i = 2,4,5,7$$

Equation 2.4.2 – Diagonal Neighbors

$$CC_{(O,P_i)} = \frac{(C_O + C_{P_i})}{2} (\text{SQRT } 2) \mu + CC_O \quad \text{where } i = 1,3,6,8$$

2.5 – Accumulation Algorithms

There a few basic types of algorithms that have been used for routing applications. The most popular algorithm is the Dijkstra algorithm. This algorithm accumulates all cells with a distance equal from the origin to the target. The accumulation process starts from the target and works its way outward (figure 2.5.1). In reference to figure 2.5.1, the pink cell is the starting point and the purple cell is the ending point. From the starting point each cell is examined in order of distance from the start and will iteratively search for the next closest cell. For every cell traveled from the starting point cost increases until the ending point is found. The cells in dark cyan represent cells of lower cost than those that are brighter. This type of accumulation works well with barriers because it

Figure 2.5.1 – Dijkstra
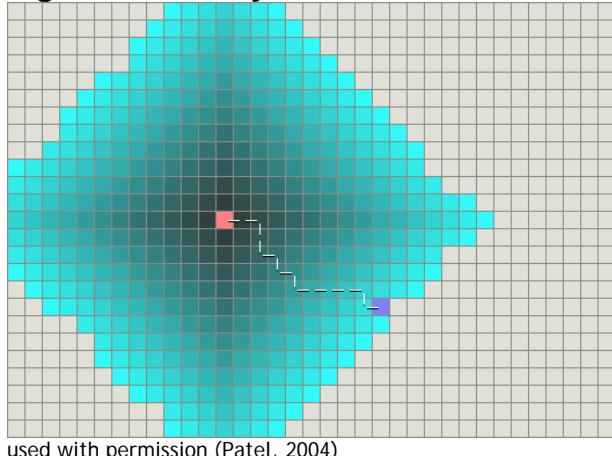
Figure 2.5.2 – Dijkstra with Barrier
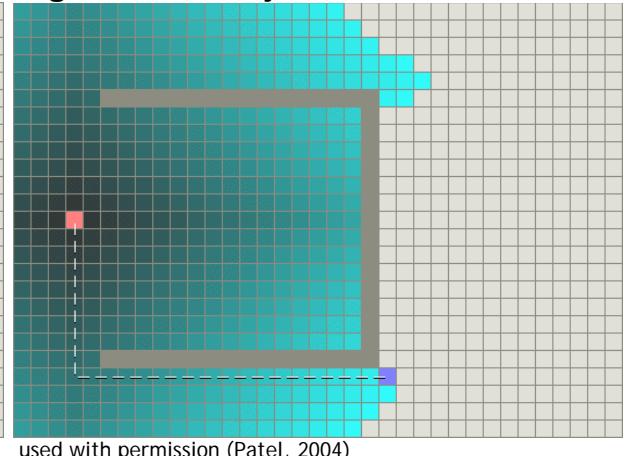
accumulates a large area and favors cells closer to the starting point (figure

2.5.2). It guarantees the shortest path, but accumulates many cells to do this.

Another algorithm called the Best First Search (BFS) algorithm accumulates in a

heuristic manner which searches for a path very quickly by accumulating a small

number of cells (figure 2.5.3). The heuristic trades off a bit in quality of the

solution for faster run times. BFS uses an idea of how far it is from the start point

to the end point. Because of this estimate it selects cells closer to the end point

for accumulation before it selects the cells near the start point. In figures 2.5.3

Figure 2.5.3 – BFS
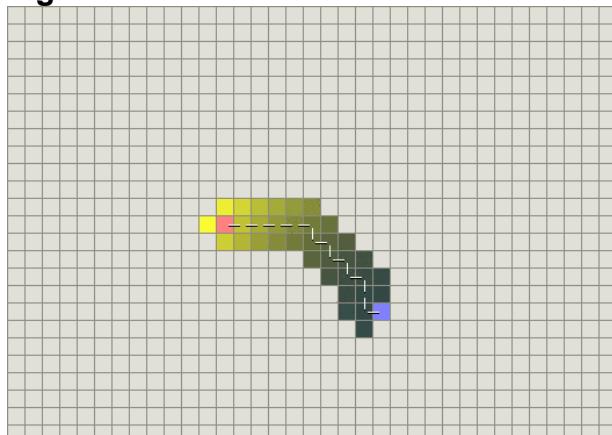
Figure 2.5.4 – BFS with Barrier
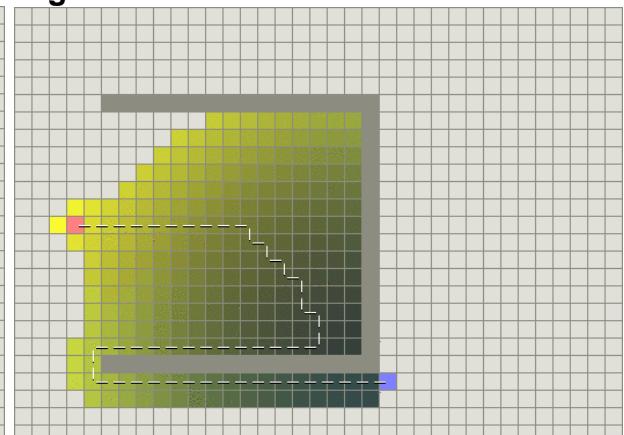
and 2.5.4 cells closer to the end point appear darker because they contain a lower heuristic value than those near the start. In this manner fewer cells are accumulated before it finds a solution resulting in fast calculations, but it does not guarantee the optimal result like Dijkstra. While fast, it also does not prove very useful for barriers (figure 2.5.4). Because it favors cells closest to the target, heuristic estimates result in unwanted backtracking when using the BFS algorithm.

The A* algorithm, a combination of the Dijkstra algorithm's reliability and the performance of the BFS could be most useful. Furthermore, A* will guarantee the shortest path. It is considered an admissible heuristic algorithm because it never over estimates the distance or cost from a cell to the end point. A* begins by searching adjacent cells from the starting point (figure 2.5.5). All of the directly adjacent cells and the starting point are put in the open list and the starting point is considered to be the parent of the others. The open list is just a list of cells that need to be considered for the least-cost path. Cells that are barriers are ignored and kept out of this list. Since the starting point is the parent it can be dropped from the list and sent to a closed list which verifies the first cell in the least-cost path. Next, one of the

Figure 2.5.5 – A* Step 1

= open list = closed list = barrier
= starting point = ending point
(figure adapted and modified from Lester, 2004)
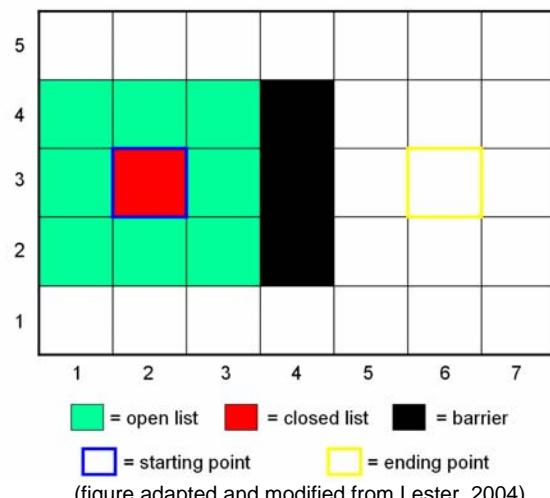
adjacent cells must be added to the closed list. To do this a simple equation is used (equation 2.5.1) to find "g" the cost for the cell represents the cell width of 100 feet. The diagonal width is 141 feet and will be used for diagonal movement because it is calculated as the square root of two (1.41) times the horizontal or vertical width. The other calculation needed is "h" the heuristic estimate. This can be completed in a variety of ways. The *Manhattan* method is simple, but creates an inadmissible heuristic like the BFS and doesn't guarantee the least-cost path (equation 2.5.2). Instead the *Diagonal Shortcut* method guarantees the best least-cost path (equation 2.5.3). You can see in figure 2.5.6 that after implementing these equations to calculate costs for the adjacent cells the lowest "F" value is the next cell added to the closed list. Now there are two cells adjacent to the current cells that contain the lowest "F" value. It is computationally faster to pick the last one added to the open list (Lester, 2004). No matter which is picked they will both result in paths of similar accumulative cost. Also, keep in mind that barrier cells are

Equation 2.5.1 – A* Calculation for Cost

$$f = g + h$$

f = total cost for travel through a cell

g = the cost for moving across the grid to the starting point

h = estimate of the cost to the end point

Equation 2.5.2 – Manhattan

$$h = 10*(\text{absolute of } (currentX-targetX) + \text{absolute of } (currentY-targetY))$$

Equation 2.5.3 – Diagonal Shortcut

xDistance = absolute of (currentX – targetX)

yDistance = absolute of (currentY – targetY)

If xDistance > yDistance then
   h = 141*yDistance + 100*(xDistance - yDistance)

Otherwise do this:
   h = 141*xDistance + 100*(yDistance - xDistance)

Figure 2.5.6 – A* Step 2 **Figure 2.5.7 – A* Step 3** **Figure 2.5.8 – A* Step 4**
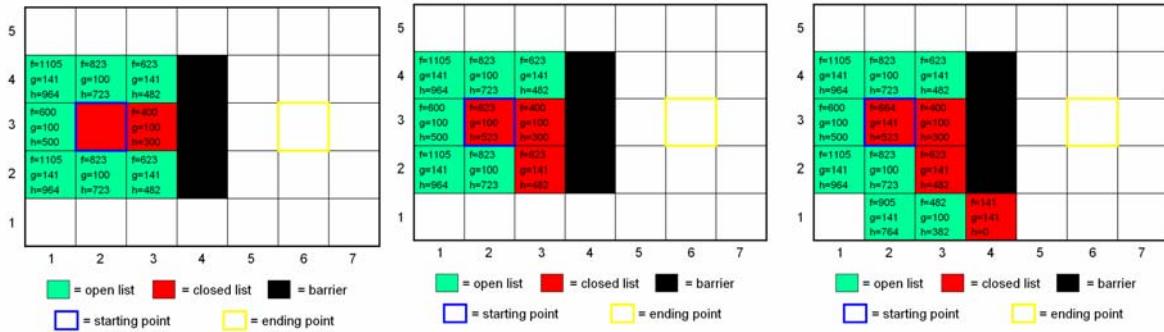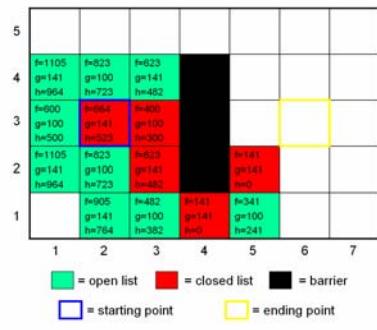
Figure 2.5.9 – A* Step 5 **Figure 2.5.10 – A* Step 6**
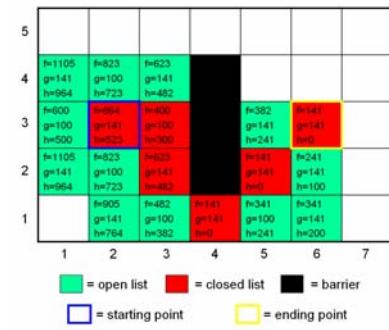
(figures modified from Lester, 2004)

totally ignored and are never put into the open or closed list. This process is

repeated with the *Queen's* pattern (as seen in figures 2.5.6 – 2.5.10) for each cell

added to the closed list until the end point is added to the open list or the open

list becomes empty in which case there is no least-cost path. Once the end point

is put into the open list it is sent to the closed list and the least-cost path can be

traced back to the start point.

While most commercial off the shelf (COTS) GIS products may not use

the A* algorithm, for example, IDRISI Kilimanjaro and ArcGIS™ Spatial Analyst

always accumulate an entire surface between two points, the ability to

accumulate part of a surface does exist in GIS software through creating a buffer

or masking the surrounding origin and target locations. By doing this you are

expecting the result to fall within the cells that fall between the two points, which

is similar to the operational assumptions of the A* algorithm. However, while this heuristic approach decreases computation time, it also eliminates possible better solutions that may fall outside the buffered region. For instance, if you use a buffering option and later the vehicle's local sensors find an unmapped obstacle such as a washed out bridge and it cannot find a viable alternate route within the buffered area, the model will need to accumulate a new surface to reroute itself around the obstacles, and likely backtrack a great deal in following the new route. If you compound the time for each instance in which this occurs it may be less efficient than running the accumulation across the entire grid allowing all the routing options to be studied. The alternative of running an accumulation for the entire grid eliminates this problem, but increasing your resolution means you increase the computation time.

For instance, halving a grid cell means you increase your calculations by a factor of four. Also, computation time is dependant on your hardware, software, and data types (byte, integer, float) it is difficult to try and predict how much longer a given calculation may take. For instance, ArcGIS™ depends on random access memory (RAM) capabilities and requires you to save your results to disk after the calculation is complete (ArcGIS, 2004). If processing time is an issue and you have little processing power resulting in longer computation times you may want to buffer out what you believe to be less useful data. On the other hand, if you've got great on board computers and can process large grids very quickly you may want to accumulate the entire grid. The risk with this is that it

still could have been faster to buffer out less useful cells however you protect yourself from having to accumulate another grid.

Over an accumulated surface it is possible to move in eight directions from any cell except in edge conditions. As described earlier (equations 2.5.1 and 2.5.2), movement perpendicular from a cell is calculated as 1.0 times the friction value. Movement to cells diagonal from the destination is calculated as 1.41 times the friction value (figures 2.5.6 – 2.5.10). A feature image marks all the values as unknown except for the target (destination) cell where growth will originate at zero. A second image used to calculate accumulated values stores the friction values that contain relative and absolute barriers. For example, IDRISI Kilimanjaro has two modules that accumulate cost called *cost push* and *cost grow* (Eastman, 2003). *Cost push* starts at a point of origin and moves directly outward pushing away and distributing accumulated values (figure 2.5.11). The algorithm makes a pass from the target to every corner of the image, which leads to a total of four possible passes. Eastman likes to explain the accumulation values like a pushbroom pushing dirt, and each pass will push previously examined values onto the next cell (Eastman, 1989). If there are not any absolute barriers within the image it is possible that the algorithm may only need two passes to properly accumulate

Figure 2.5.11 – Cost Push

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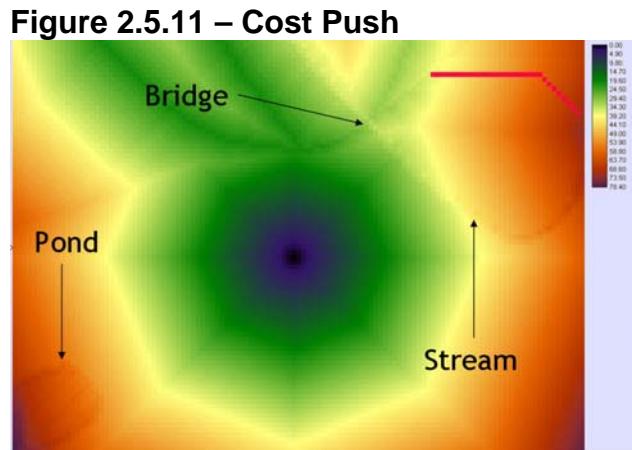
cost. Absolute barriers will at least require a third pass because they block the accumulation process on a portion of the image. The results of every pass are not stored in separate images and overlaid at the end. Instead, each pass is processed and overlaid on a row by row basis and then a square root of the values is taken before being stored. Tests have proved this algorithm to work rather quickly in most cases, however there are two distinct disadvantages to using this algorithm. The first is that it cannot work with network oriented data such as streams, trails, and roads. The second limits the use of establishing absolute barriers throughout the surface. These barriers that normally prohibit movement are assigned a very high cost instead of an infinite, so it is still possible that movement may occur across them. Reasons for both of these problems stem from the lack of passes required to properly accumulate the surface. Because network layers can be complex in nature (i.e. interconnected line formations and "web like") the maximum number of passes may not be enough. Likewise, absolute barriers may require many more passes for proper accumulation, so the algorithm was not written to accept negative cost values, which typically indicate these barriers (IDRISI, 2003) (Eastman, 1989).

Figure 2.5.12 – Cost Grow

On the other hand, the *cost grow* (figure 2.5.12) algorithm allows absolute barriers to be assigned infinite cost and

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work with network type data. This function also gives the option of setting a

maximum search distance to output a buffer. Instead of pushing through the

image two to four times it is more complex and makes multiple passes. Unknown

cells are given a value of distance plus 1.0 times the friction value for direct

neighbor cells and 1.41 for diagonal neighbors. For every cell that equals growth

from the target, a single pass must be made accumulating the values. As a result

of multiple passes this process can take significantly longer to run. The result is

that costs for this algorithm are directly related to relative and absolute barriers

rather than a function of distance (IDRISI, 2003) (Eastman, 1989).

2.6 – Historical & Current Methods of Terrain Analysis

Since the late 1980's, United States military research has developed

methods for acquiring a terrain knowledge database (Edwards, 1988). Data

layers that have been deemed necessary include topography, land cover, roads,

hydrography, soils, and cultural features. All of these have a direct relation to

vehicle mobility. Typically, these layers have been compiled through stereoscopic

imagery on a layer by layer basis. By using stereoscopic imagery, mass points

are compiled for DEM development. Mass points are point features that contain

an elevation estimate as determined by a stereoscopic compiler. Elevation can

also be attributed to the features being collected (buildings, bridges, roads,

streams, etc.) resulting in a complete 3D terrain model. Implementation of such a

3D model for vehicle navigation would include not only the route planning

process, but also updates in the database as obstacles and features are

encountered. Local obstacles are determined by a perception system that involves a charged coupled device (CCD) TV camera and a multispectral laser scanner. As obstacles are found, rerouting takes place by using the vehicle's current position and locating a new path to the target (Edwards, 1988). The papers found indicate the general concepts of this update and rerouting only. There is no mention of how the GIS conducts route planning through the 3D terrain model.

Advances in technology and software developments have made it easier to collect the data needed to produce a similar model. Light detection and ranging (LiDAR) is maturing and becoming much cheaper for aerial surveys of land cover and topographic terrain. LiDAR is classified as an active sensor that sends millions of light pulses toward the earth. The pulses are timed from the moment they leave the sensor, reflect, and re-enter the sensor (Campbell 2002). Because light has a constant speed and the carrying aircraft is equipped with inertial Global Positioning System (GPS) the sensor is capable of gathering geographic elevation data with a vertical error of about 15 centimeters, an accuracy suitable for this type of application. Since the commercialization of remote sensing and digital orthophotography technologies has begun, there has been a competitive market for providing affordable imagery at high resolutions. LiDAR can provide surface elevations of the ground as well as delineate tree canopies and some cultural features. The combination of imagery and LiDAR also provides an excellent means of digitizing roads and water bodies. As an alternative to LiDAR, stereoscopic imagery can be used to delineate contour

lines as well as attribute elevation data to features contained within the stereo imagery.

2.7 – Trafficabilty of Terrain

Trafficability is a common measure of the ease in travel across terrain (Slocum, 2003). This measure can be assigned to each cell in a grid. It can be a very important factor in vehicle mobility if it can be appropriately computed. As humans we visually assess the terrain we are driving through and typically scan for obstacles such as wet or soft soil. Most drivers would attempt to drive around these features or alter the manner in which we would handle a vehicle on this type of surface. As a driver enters a muddy area the driver would no longer want to stop or accelerate very quickly for fear of getting stuck or sliding out of control. Behaviors such as scanning the terrain from side to side and altering driving patterns due to terrain changes can be adapted from human behaviors and implemented in autonomous vehicles.

The US Army Engineer Research & Development Center, Topographic Engineering Center developed a trafficabilty analysis engine to provide any geographic location with a prediction between 0.0 and 1.0. A value closest to 1.0 is always the best. The outcome can also be associated with a confidence interval for the point depending on availability of all geographic data. If some data does not exist at a certain location the confidence is much lower. All geographic data can be further tweaked with the effects of current weather conditions. Since all vehicles are not equal and perform differently under certain

situations the engine can be adjusted for various types. The topography module constrains slope outside the allowable maximum slope for a given vehicle and uses a formula to classify the acceptable slope values. The soil and vegetation module uses a look up table to identify the characteristic for each vegetation or soil type to assign the appropriate trafficablity value. Modules for weather, roads, land use, hydrology and off limits areas also exist. Each module combines its trafficability values to output a final result. The current model weights all its layers equally, but it is clear that this should not be the case. Missing topographic data for a flat area is not as important as the soil data for a flat area. Future testing will shed light on the importance of each layer (Slocum, 2003).

2.8 – Summary of Literature Review & Related Research

The literature suggests that there is a capacity for further development of autonomous vehicle research. There is certainly a consensus that the technologies and tools are available. Secondly, GIS has already been implemented and does not pose as an obstacle. Thirdly, it is also quite clear that raster modeling is the main method for deriving routes for off-road navigation. In addition, the layers most commonly used as forces of cost consist of elevation data or slope, land cover, roads, hydrography, soils, and cultural features. It seems that most of these layers can also be combined into a trafficability analysis, which outputs a layer that also could be used to produce cost for travel. Nevertheless, a few things still remain unclear. One area that is very obscure is the manner in which local map data is referenced with global map data. While

papers claim that it is done it is not described in much detail. This area is critical

to the technology, but will not be addressed in this study since this is an entire

study in itself. On the other hand, the literature also seems to lack a documented

procedure for creating these raster maps, and modeling the effect of certain

parameters on least-cost paths. It is important to understand how each input is

used to provide the best route achievable by a given dataset and the GIS. My

intent is that the results of the study will aid in filling that gap.

Chapter 3 - Methodology

3.1 – Data Concerns: Selecting a Study Area

   The topography of the study area can be a concern if the right data is not available. Variation in topography and land cover is much harder to accurately represent at 30 meters than at 5 meters. An area with extreme variation in elevation might be problematic due to the resolution of a DEM and its ability to represent accurate height or slope measurements. Chang and Tsai studied the effect of DEM resolution on slope and found that, as cell size increases for areas of varying relief, accuracy will decrease (Chang and Tsai, 1991). Since, least-cost path discrepancies will be more like to occur in the terrain of western Virginia a small cell size would be more desirable than the current 10 or 30 meters that is available from United States Geological Survey (USGS) DEMs.

   While one meter resolution LiDAR imagery is available for Wytheville, VA and will soon be available for the JOUSTER test site at the Virginia International Raceway (VIR), neither site is possible for this research. The Wytheville site is on private land, and the JOUSTER site does not have LiDAR imagery available at this time. Because the Virginia Tech main campus has been mapped at a one foot contour interval, that dataset is suitable to create an elevation model with one meter resolution. Access to this information was granted by Virginia Tech's University Site & Infrastructure Development Department. The study area selected makes use of Virginia Tech's College of Agriculture & Life Sciences' land that lies on the western portion of campus near US 460 and the Huckleberry

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Map 3.1.1 – Study Area

Campus Data

Slope Weighting (Test1)

Road Weighting (Test2)

"Aerial Imagery © 2002 Commonwealth of Virginia. The data contained herein are the property of the Commonwealth of Virginia. Distribution of any of these data to anyone not licensed by the Commonwealth is strictly prohibited."

0   375   750   1,500

Meters

N
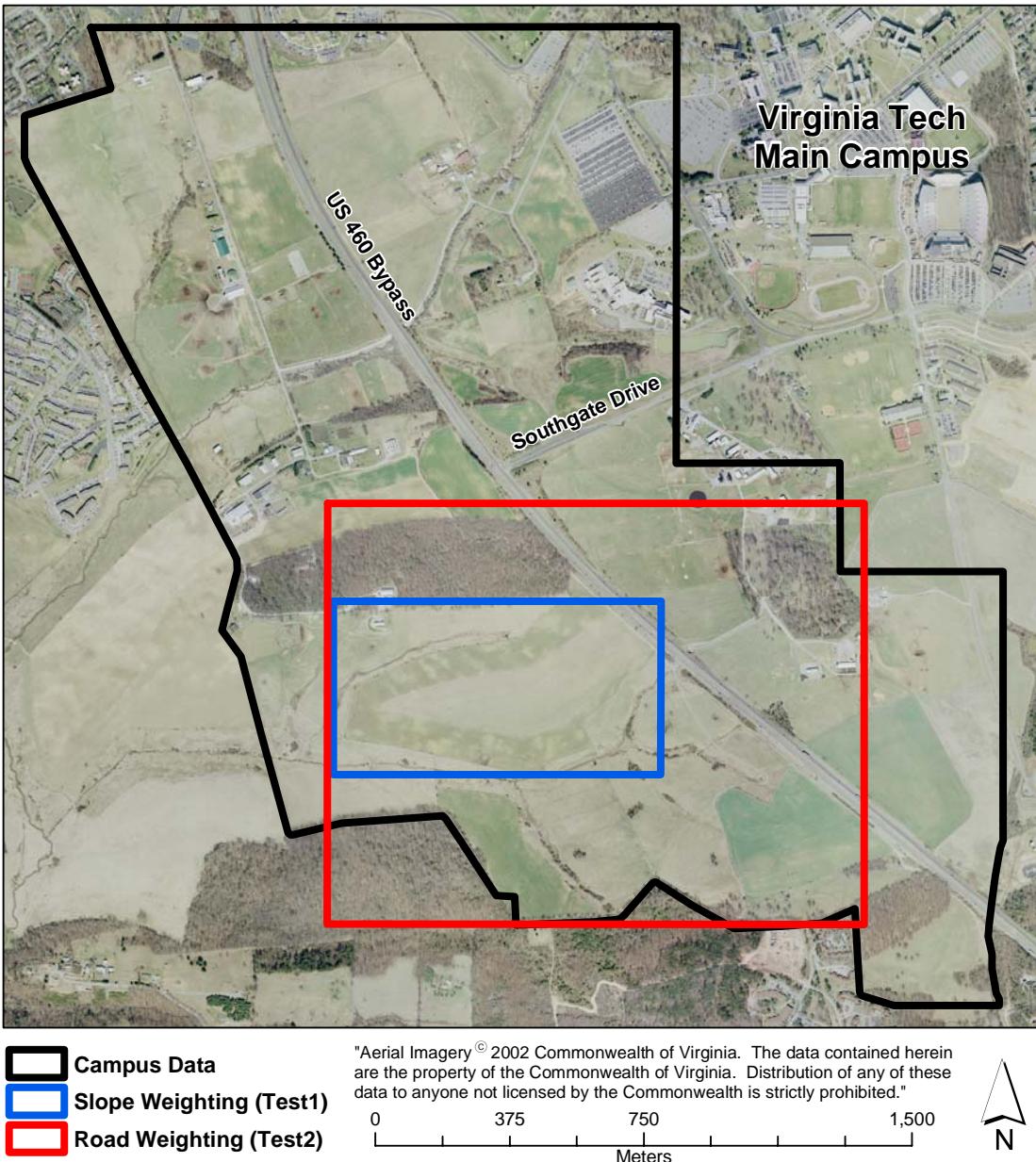
Trail (map 3.1.1). While much of this area contains fence lines and some farm animals, the terrain and proximity to campus will work quite well for this study. The size of the study area will be large enough to illustrate a significant amount of navigation. The ideal size would be large enough to model variation in terrain, but small enough to check paths by foot.

3.2 – Data Concerns: Errors and Conversion in Modeling

Source data for any GIS should be as free from error as possible. Errors

may consist of missing data and erroneous values. Common errors in DEMs are

peaks (figure 3.2.1) and pits (figure 3.2.2), which indicate extreme high and low

points, but do not reveal the true nature of the surface because of sensor

malfunction or misinterpretation. Systematic errors or artifacts may be present

and should be noticeable by abrupt changes in elevation values (figure 3.2.3). As

in all geographic studies, knowing one's study area will improve the chances of

noticing errors in the data (DeMers, 2002). Another way to introduce error into a

GIS model occurs during conversion from DEM into a derivative such as slope,

aspect, or hillshade layer. These layers are very useful for analyzing and

visualizing, but if there are already errors in the elevation data you may increase

them. Most data has a certain amount of uncertainty which must be accepted.

On the other hand, most of the major errors that occur in data conversion are in

the user's ability to match data to an application. Berry notes that different

algorithms create different slopes and a user should become familiar with

calculations being generated (Berry, 2003). A common formula used for

calculating slope uses the *Rook's* pattern and examines only the direct neighbors
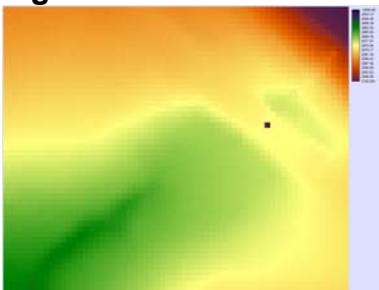
Figure 3.2.1 – Peak   **Figure 3.2.2 – Pit**   **Figure 3.2.3 - Artifact**
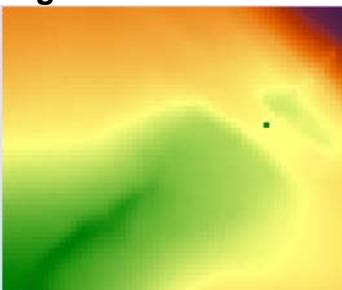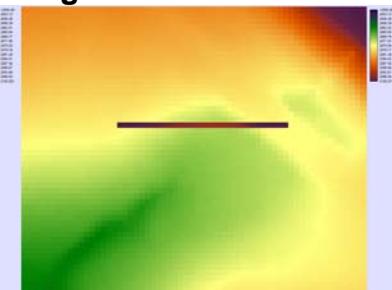
Figure 3.2.4 – Rook's Slope   **Figure 3.2.5 – Queen's Slope**
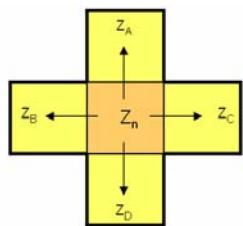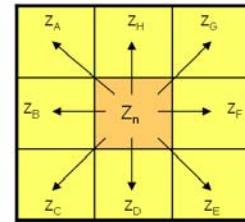
Equation 3.2.1 – IDRISI (dZ/dX) Equation 3.2.3 – Horn Method (dZ/dX)

$dZ/dX = (Z_A - Z_D) / 2 * \text{cell width}$ $dZ/dX = (Z_A + 2Z_B + Z_C) - (Z_G + 2Z_F + Z_E) / 8 * \text{cell width}$

Equation 3.2.2 – IDRISI (dZ/dY) Equation 3.2.4 – Horn Method (dZ/dY)

$dZ/dY = (Z_B - Z_C) / 2 * \text{cell width}$ $dZ/dY = (Z_A + 2Z_H + Z_G) - (Z_C + 2Z_D + Z_E) / 8 * \text{cell width}$

Equation 3.2.5 – Slope as Percent

$\text{Slope in \%} = \text{SQRT}(\text{SQR}(dZ/dX) + \text{SQR}(dZ/dY))$

of the cell in question. For cell n the tangent of the column or x is expressed in

equation 3.2.1 and the tangent of the row or y is expressed in equation 3.2.2.

IDRISI Kilimanjaro uses this type of formula in the module *Surface* (IDRISI,

2003). Other slope algorithms use a *Queen's* pattern to incorporate indirect

neighbor cells that would influence slope calculations as well (figure 3.2.5).

ArcGIS™ Spatial Analyst uses equations 3.2.3 and 3.2.4 which were developed

by Horn to calculate the tangent of x and the tangent for y (Horn, 1981). After

both tangents are found the squares of the two are summed, and the square root

of the sum will provide gradient as a percent (equation 3.2.5).

Another issue is the representation of linear features. Linear features such

as streams cannot simply be added to the cost surface without examining the

feature's width. When linear features are converted from vector to raster they

often create diagonal grid cells. If the new streams layer is only one cell wide an

Figure 3.2.6 – Buffering Linear Barriers
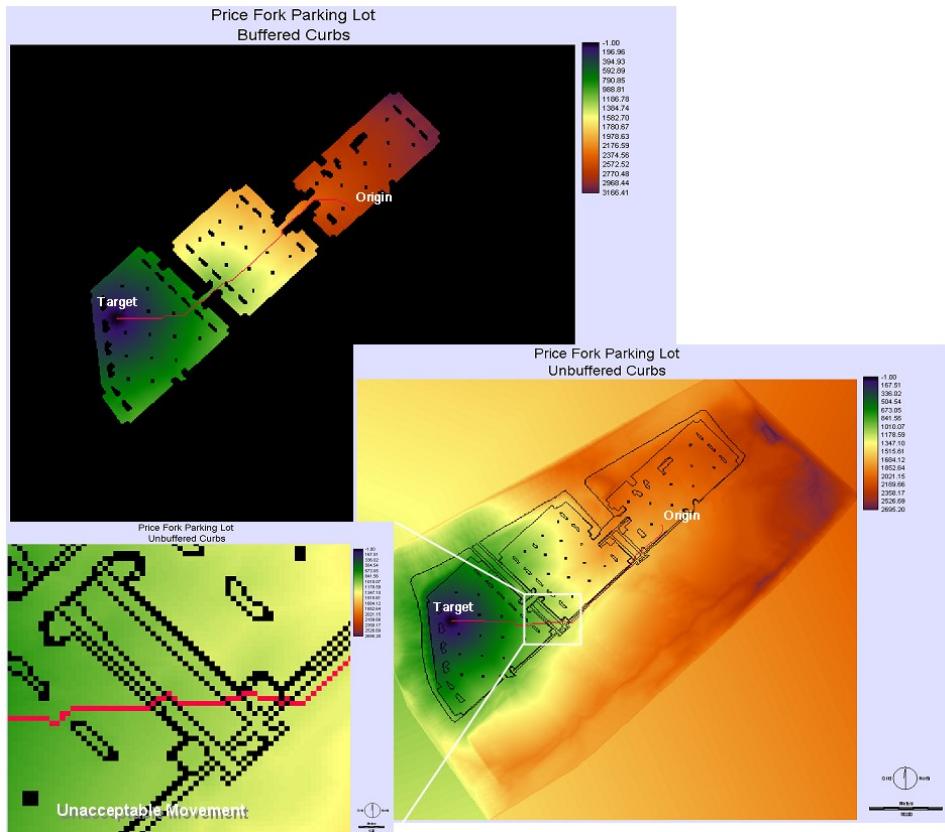
illegal movement can be made through it (figure 3.2.6). If the model is to

represent near realistic conditions then this should not be permitted. In order to

prevent this, a buffer of the feature should be added into the feature layer before

it is incorporated into the cost surface. Depending on the resolution of the raster

that extra buffer may restrict travel in areas that may be acceptable, but it

ensures that the stream acts as a barrier.

3.3 – Data Description & Preparation

The features for this study were extracted from three inch resolution

stereo images collected by EarthData International in 2002 (for details on the

collection, see Appendix A). EarthData International compiled and delivered

planimetric data to Virginia Tech in CAD format. The CAD layers that are helpful for creating the elevation model are contours and spot elevations. Contour data required interpolation into raster format before proper slope information could be derived. There are two ways this can be done and each should be looked at before further modeling is done. The first method that could be used is by using ArcGIS™ Spatial Analyst to convert features to rasters with a linear gradient descent algorithm. All cells that contain a contour line receive the value of the contour line. If no contour line intersects a cell the algorithm query's the direct and indirect neighbors using an eight cell neighborhood and the slope is interpolated based on the two steepest slopes found. Between the highest and lowest contour the steepest slope interpolation occurs to assign a value. The major drawback of this approach is that concave and convex features are chopped off because contours don't address the highest and lowest parts of the terrain (Liu, 2004). A second option, generating a triangulated irregular network (TIN) may solve this problem. The reason this may be true is that the high and low portions of the topography can be represented by added masspoints and breaklines. Masspoints and breaklines can be generated for concave and convex areas in the terrain that will lead to a more accurate raster generated from a TIN. For this reason, the TIN approach was selected. Furthermore, the final elevation grid will need to be converted to slope. The algorithm in ArcGIS™ will be used for this process since it uses a nine cell neighborhood (Queen's Pattern) rather than a five cell neighborhood (Rook's pattern).

Thus, the first step in terrain data development was to create a Triangulated Irregular Network (TIN) from which to interpolate a raster DEM. The important features used to model terrain obstacles to autonomous vehicle movement in the TIN were: slopes over 15%, highways, curbs, guard rails, parking lot islands, fences, and vegetation. Retaining walls, streams, water bodies, building structures, agricultural tanks, and trenches were used in the obstacles layer, but also enhanced the TIN by acting as breaklines. A few layers such as gravel roads, paved roads, parking lots, and fence gates encourage vehicle maneuverability and were used to create a *catalyst* layer. Fence gates were the only features that did not exist in the Virginia Tech CAD data so they were mapped using six inch resolution imagery from the Virginia Base Mapping Program (VBMP) accessible through the university library (see Appendix B).

All obstacle features mentioned earlier were examined against high resolution imagery available from VBMP. Some features which are polygons in reality are represented as lines within the CAD format. These were imported into ArcGIS™, examined, and then edited for feature connectivity. This is important when converting polylines to polygons within ArcGIS™ because all unclosed line features are purged from the new polygon layer because topologically they are not polygons. After basic examination and vector editing was complete each vector layer was converted to raster and matched to the same one meter resolution as the elevation and slope rasters.

3.4 – Factors & Constraints

Finally, the most important issue is to determine the optimum values to assign the input layers such as slopes and roads. We can likely assume that forests, water bodies, streams, and steep slopes are barriers that do not need a cost because they are a type of constraint. Constraints limit the alternative under consideration and provide simple yes or no solutions (IDRISI, 2003). On the other hand, factors enhance or detract from suitability, but never restrict or assure suitability. Weighting a factor such as slope is a way of ranking the severity of influence slope has on modeling the best route. In addition to slopes, roads need to be weighted as well. Different slopes should be weighted appropriately within the vehicle's operating capacity and must produce sensible routes. Exponentiation of the slope and road values in the final friction surface is a way to achieve this. It would be nice to have as many constraints and factors as possible to provide the best solution, but sometimes unavailability of data can be an issue. For modeling a route through complex terrain, it is absolutely necessary to have good elevation data and land cover information such as forest cover, streams, bodies of water, roads, and cultural features such as buildings fences, etc. Other types of data that would prove helpful would be soil, ground surface types, and real-time moisture content. This type of information is not always available, and may not be required for all situations. Soil and ground moisture have more to do with trafficability and enhancing vehicle performance. For now this study is focused on the basic routing abilities and not tweaking vehicle performance.

3.5 – Weighting Factors & Constraints

Each rasterized obstacle layer was fused together into one layer that represents absolute barriers for traveling across the study area. For constraining features, slopes over 15% or water bodies large enough to act as absolute barriers to vehicles, costs will be assigned as infinite. Absolute barriers contain absolute costs, a friction that is so high it would be faster or easier to move around them. For features modeled as factors, relative barriers cause some type of friction for moving through a cell, but do not prohibit travel. Trafficable slopes are relative barriers and should be assigned incremental costs. Roads act as a catalyst for travel and should have the lowest cost possible to encourage movement along them when practical to the direction of the target from the origin. To address the issue of how trafficable slopes and roads should be weighted, a sensitivity analysis will be performed in order to choose the most appropriate cost weights. A sensitivity analysis is a simulation that goes through many iterations, changing the parameters for inputs on every iteration. The process shown in figure 3.5.1 starts with dividing slope into trafficable and nontrafficable (step 1). Step 2 shows all obstacles being combined to generate a map representing all barriers. This map then covers the exponentiated values for slope (step 3). The exponentiation operation generates different exponential slope costs to produce various routes, each of which can be compared quantitatively with an ideal route found in the field. The resulting data will determine which weights and routes make sense. Step four is an overlay that uses the barrier map to cover intersecting areas from the exponentiated slope maps. Finally, accumulation and

Figure 3.5.1 – Slope Weighting Flowchart

Legend:
- Red: Data Preparation Process
- Yellow: Exponentiation Process
- Blue: Accumulation Process
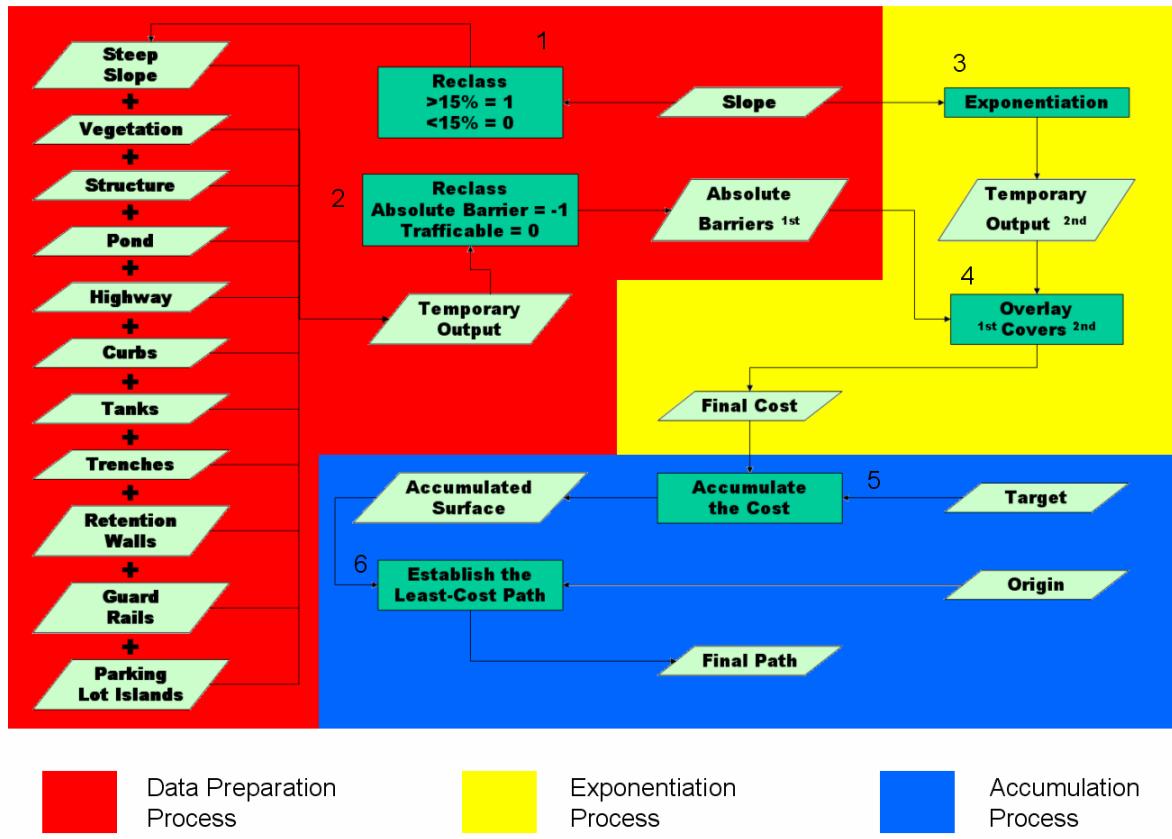
Figure 3.5.2 – Road Weighting Flowchart

Legend:
- Red: Data Preparation Process
- Yellow: Multiplication Process
- Blue: Accumulation Process
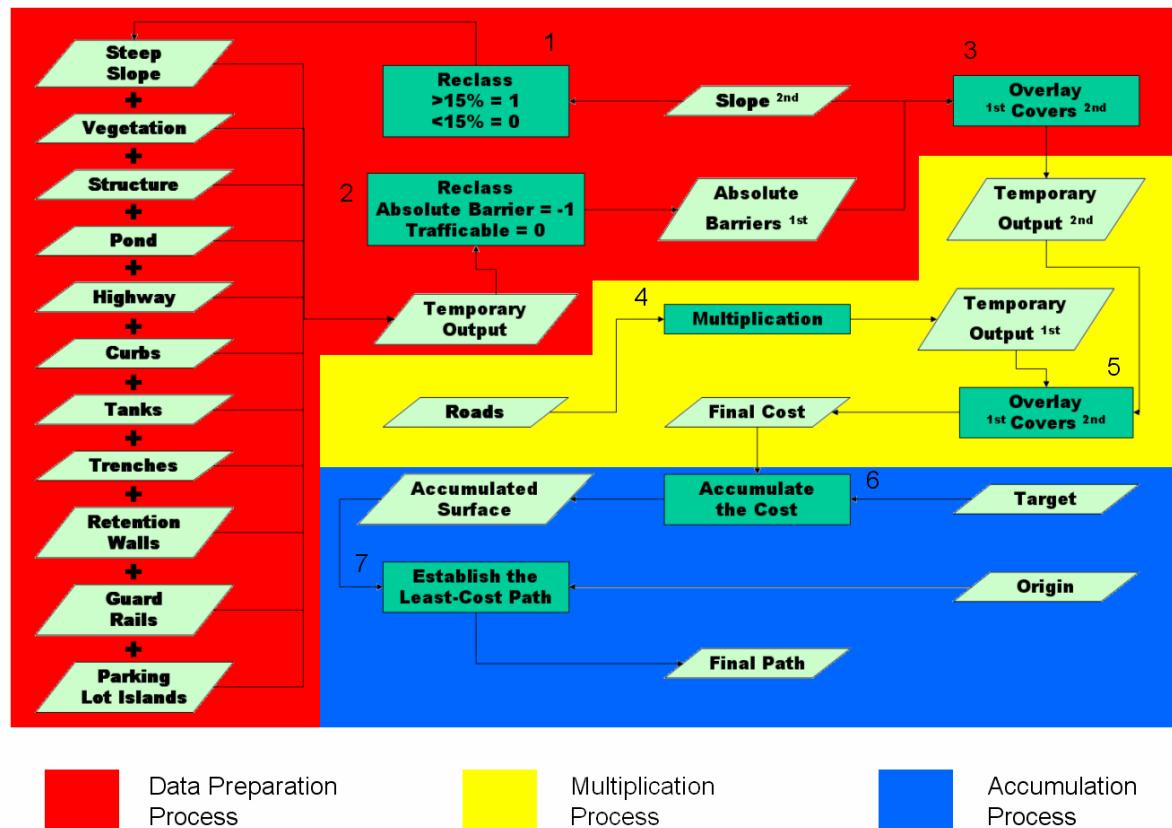
least-cost paths for each exponentiation are generated in steps five and six. The process for incorporating roads is similar, except that all road values in the study area are overlaid on the combined slope and barriers map (figure 3.5.2). Since roads are not measured in percent like slope a value of one is given to them and the multiplication operation is used to create a range of outputs.

Absolute barriers (E.g. forest, water, steep slopes) and network oriented data (E.g. trails or small roads) are presently making *cost grow* algorithm the best choice to build the accumulated surface. After performing the accumulated surface operation the IDRISI Kilimanjaro module called *pathway* delineates the least-cost path. *Pathway* identifies the smallest accumulation or summation of numbers between point "a" (the origin) and point "b" (the target) that results in a least-cost path. Several computed paths will be examined on foot in the field via GPS to ensure that the model is reliable. The GPS will contain a map of barriers to aid in fielding interpretation for creating the shortest path on foot. It would be best to get permission to drive an autonomous vehicle on the GIS proposed routes, as the path that is optimal for vehicle routing will always be dependent on the mechanics of a vehicle. This would be useful in determining if a vehicle could navigate rough terrain faster than taking smooth ground at higher speeds. As that was not practical for this research, the foot travel approach will be used instead.

3.6 – Route Measurements

Sinuosity: Sinuosity will be measured to determine the directness of a computed route. Sinuosity is a value of one or greater that implies to what degree a linear feature meanders or curves. Many times this measurement is used when studying geomorphology and river channels. Rivers which run through valleys often meander because the water does not contain enough force to push straight through the geology. Therefore, it flows where there is the least amount of friction. Likewise, the autonomous ground vehicle does not have enough power to drive over fifteen percent slope forcing itself to move around these slopes. Meandering paths are not very direct and should be avoided if

Figure 3.6.1 – Sinuosity Example
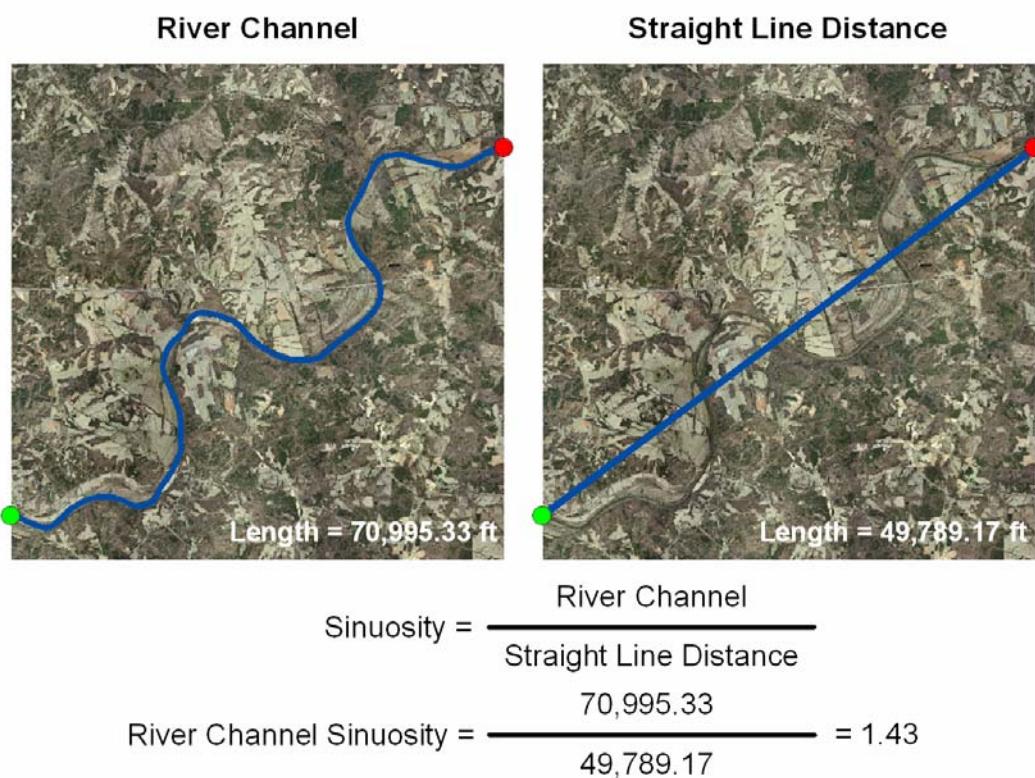
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possible. A simple VBA script can be written in ArcGIS™ to allow you to make this calculation fairly quick for multiple features in a shapefile. Otherwise, it can be done manually by calculating length for a set of features and using the equation described in figure 3.6.1.

Length: The path should be as direct as possible. Obviously, there is no maximum or minimum length that should be expected. However, shorter routes are preferred over longer routes. Simple VBA scripts provided in ArcGIS™ allow you to make this calculation fairly quickly for multiple features in a shapefile.

Slope: The path should also be on the flattest possible ground to avoid overturning the vehicle and to avoid slow ascents and descents due to steep terrain. Slope will be extracted by ArcGIS™ for every cell and then minimum, maximum, and mean values will be joined to each least-cost path. Mean slope from each path will aid in judging difficulty of travel through one route from the next.

When the model is finished locating the least-cost paths, each path will be measured by its sinuosity, length, and mean slope to aid in determining the most efficient path. The fastest path should show lower sinuosity and lower slopes than the alternatives. All will be compared to the values for the walked route using the walk as the ideal.

3.7 – Tests Performed at the Virginia Tech Site

Slope Weighting (Test 1):

The first step in determining the appropriate weight for slope is selecting

an area where slope has obvious variation, but is not too difficult to interpret.

Using IDRISI Kilimanjaro a subset of the study area was extracted that contained

a rye field with a significant amount of slope (map 3.7.1). Using a Trimble

Map 3.7.1 – Slope Map for Test 1
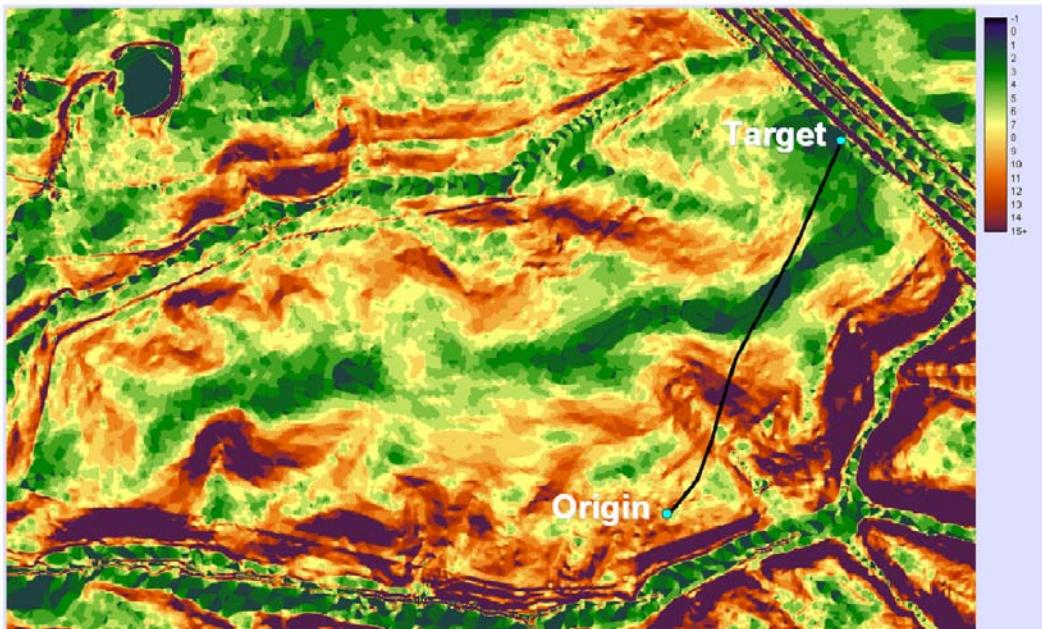
GeoExplorer® XT GPS, I located one origin and a target location between which

to build the routes. Slopes over 15% were present between the two points, so

absolute barriers would most likely influence the routes produced by the model.

While in the field I walked from the origin point to the target point in a path that I

perceived as the most direct had I been able to drive the vehicle. This path

would be used to compare with the routes produced by the sensitivity analysis.

In the sensitivity analysis slope was run through a module in IDRISI Kilimanjaro

called *Scalar* that used the exponentiation function to manipulate the original

values. Exponentiations of 0.1-2.0, not including 0, were completed to produce

twenty routes. The reason I have chosen this range is that values above one will

increase the magnitude between steep slopes and flat slopes, making steeper

slopes far less desirable for the route. Values less than 1, but above 0 decrease

the magnitude between steep slopes and flat slopes, making steeper slopes only

slightly less desirable for the route. For instance, a slope of 2 percent at an

exponentiation of 0.1 provides a friction of 1.07. At 1.0, the cost is 2.0, and at 2.0

the cost is 4.0. A steeper slope of 10 percent at an exponentiation of 0.1

Figure 3.7.1 – Slope Converted to Cost

	Exp. 0.1	Exp. 1.0	Exp. 2.0
2% Slope	1.07	2	4
5% Slope	1.17	5	25
10% Slope	1.26	10	100
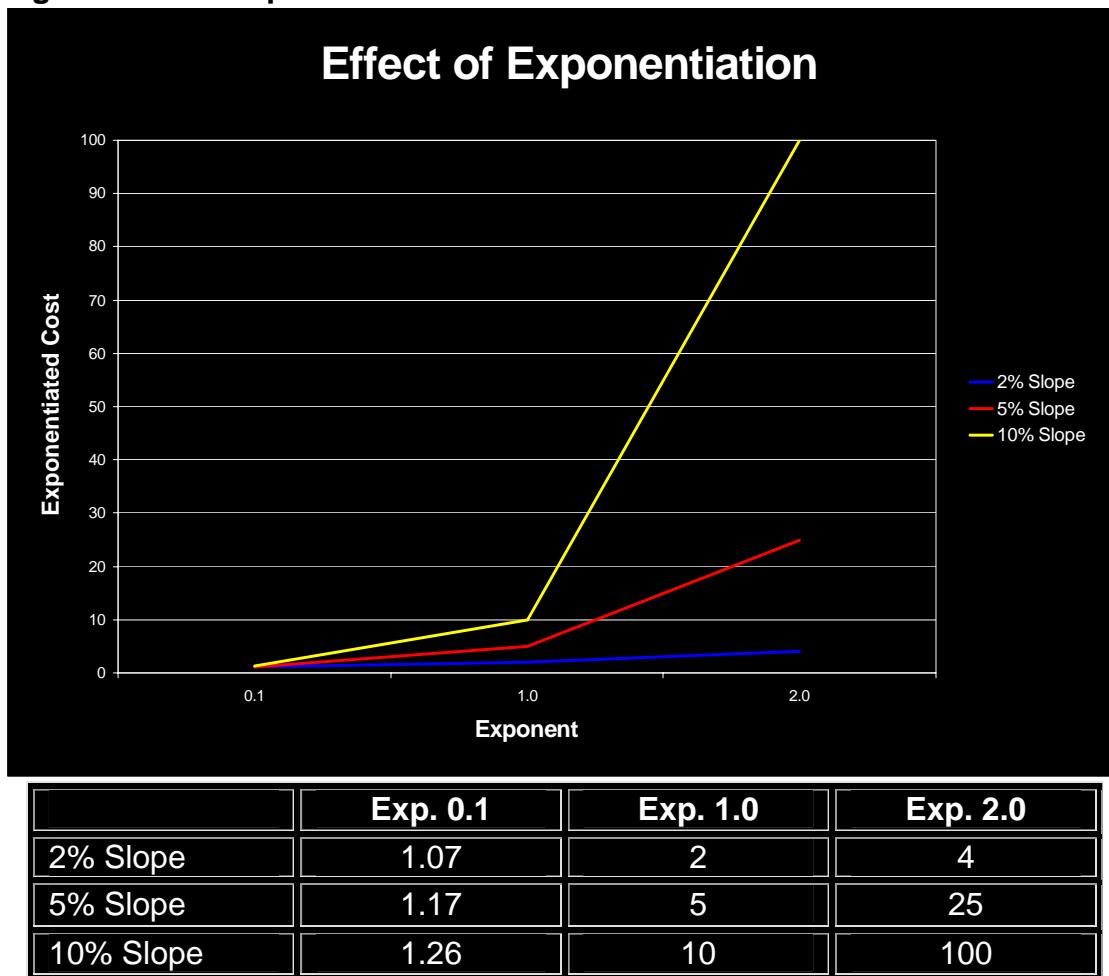
provides a friction of 1.26, at 1.0, 10.0 and at 2.0, a cost of 100.0 (figure 3.7.1).

Zero is not useful in this instance because any positive number that uses a base

of zero produces an answer of one consequently converting the entire map to

values of one, making slope irrelevant to the model.

Road Weighting (Test 2):

For road weighting, another test site within the study area was selected. A

slightly larger subset was extracted that contained part of the rye field, a

significant length of gravel road, and a cow pasture. Absolute barriers included

fencing, slopes over 15%, streams, and thick vegetation. The second test used

the slope exponentiation of 0.1 from the Slope Weighting (Test 1) results to

isolate the best weight for roads. Using the Trimble GeoExplorer® XT GPS I

located one origin in the rye field and a target location in the cow pasture (map

Map 3.7.2 – Road Map & Exponentiated Slope
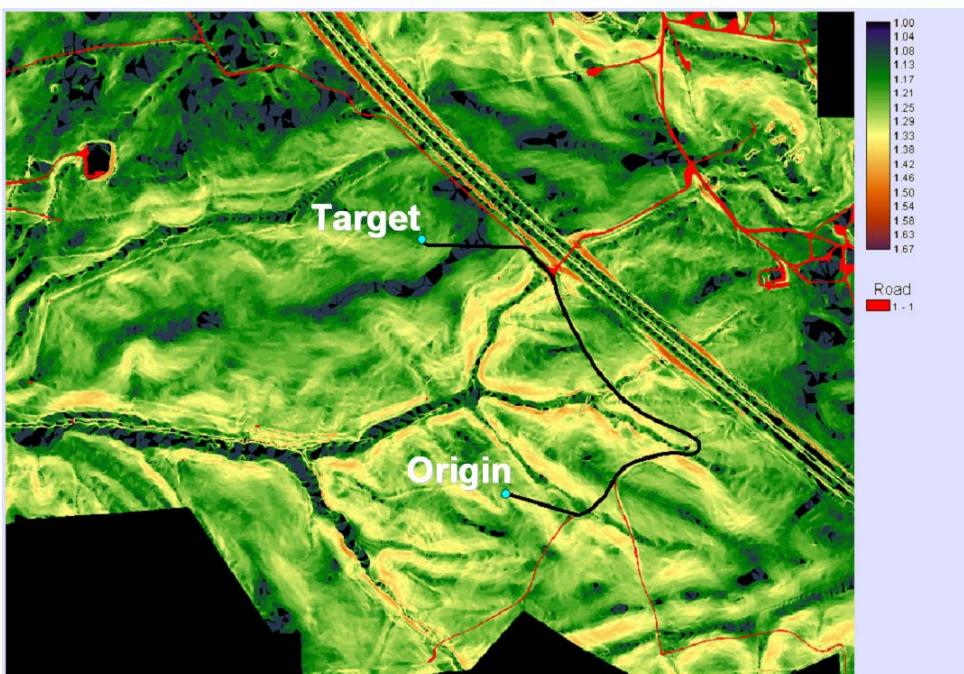
3.7.2). Selection of these two points forced the test to use the road as a medium of travel for the majority of the route. Once again I walked from the origin point to the target point in a path that I perceived as the most direct had I been driving the vehicle. Again, this path would be used to compare the routes produced by the sensitivity analysis. In the sensitivity analysis the road layer was run through a module in IDRISI Kilimanjaro called *Scalar* that used the exponentiation function to manipulate the original values. Multiplications of 0.1-2.0 were completed on the road layer which had an initial value of 1. Values lower in the range decrease the chance for movement off the road onto slope. Likewise, higher values increase the possibility of travel off road.

3.8 – Summary of Methodology

Up to this point, chapter two addressed almost all of the objectives stated in chapter one. Chapter 3 has placed importance on issues surrounding the data used for analysis, and it also discussed objective four to establish a set of parameters for input data. The methodology used in this chapter produced various least-cost paths which will allow me to assign appropriate weights or parameters to the accumulation model. Since there is little to no literature in this area, nor a formula or equation that tells me how much influence a certain slope has on this autonomous vehicle, this process is absolutely necessary to assign numeric value to friction layers. Generally, vehicle performance degrades as slope increases, but vehicle testing is necessary on various slopes in order match the right mechanical performance with the right exponentiation.

Chapter 4 – Results and Analysis

4.1 – Slope Weighting (Test 1) Results

      Once the model was complete for Test 1, I examined the results to see if they made sense and exported each accumulated surface and the resulting path to ArcGIS™. After getting all the data into ArcGIS™, I started examining which exponentiations significantly changed the route. From the range of 0.1 to 2.0, five paths were picked to illustrate different benchmarks the model made in locating the path. These five paths came from the 0.1, 0.5, 0.6, 1.0, and 2.0 exponentiations (figures 4.1.1 and 4.1.2). The path that I determined in the field as the most efficient path, which I recorded using GPS, was overlaid with the five paths. The most similar path of the five selections to the field derived path was path 0.1. This path has the highest mean slope over the entire route, but also is the shortest and least sinuous (figure 4.1.3). Paths continue to develop more sinuosity and less mean slope as exponentiation increases (figures 4.1.4-4.1.7). Path 2.0 has the lowest mean slope, but also travels over the longest distance and contains the highest measure of sinuosity (figure 4.1.7). This test also reveals that there is a direct correlation between mean slope, length, sinuosity and the paths' exponentiation. As the exponentiation increases, the length and sinuosity consistently increases, but mean slope decreases. These four characteristics determine the efficiency of a route and the performance of the vehicle. Since the vehicle can operate on slopes no steeper than fifteen percent,

Map 4.1.1 – Slope Test with Photo

Legend

Path
- ——— 0.1
- ——— 0.5
- ——— 0.6
- ——— 1.0
- ——— 2.0
- ▪▪▪▪ GPS Route
- ▉ Absolute Barrier

Target

Origin

Path	MeanSlope	Length	Sinuosity
0.1	5.34	423.82	1.08
0.5	5.02	443.07	1.13
0.6	5.5	528.67	1.35
1.0	3.33	544.85	1.39
2.0	3.33	552.6	1.41
GPS Route	6.3	395.01	1.01

0   35   70   140

Meters

N
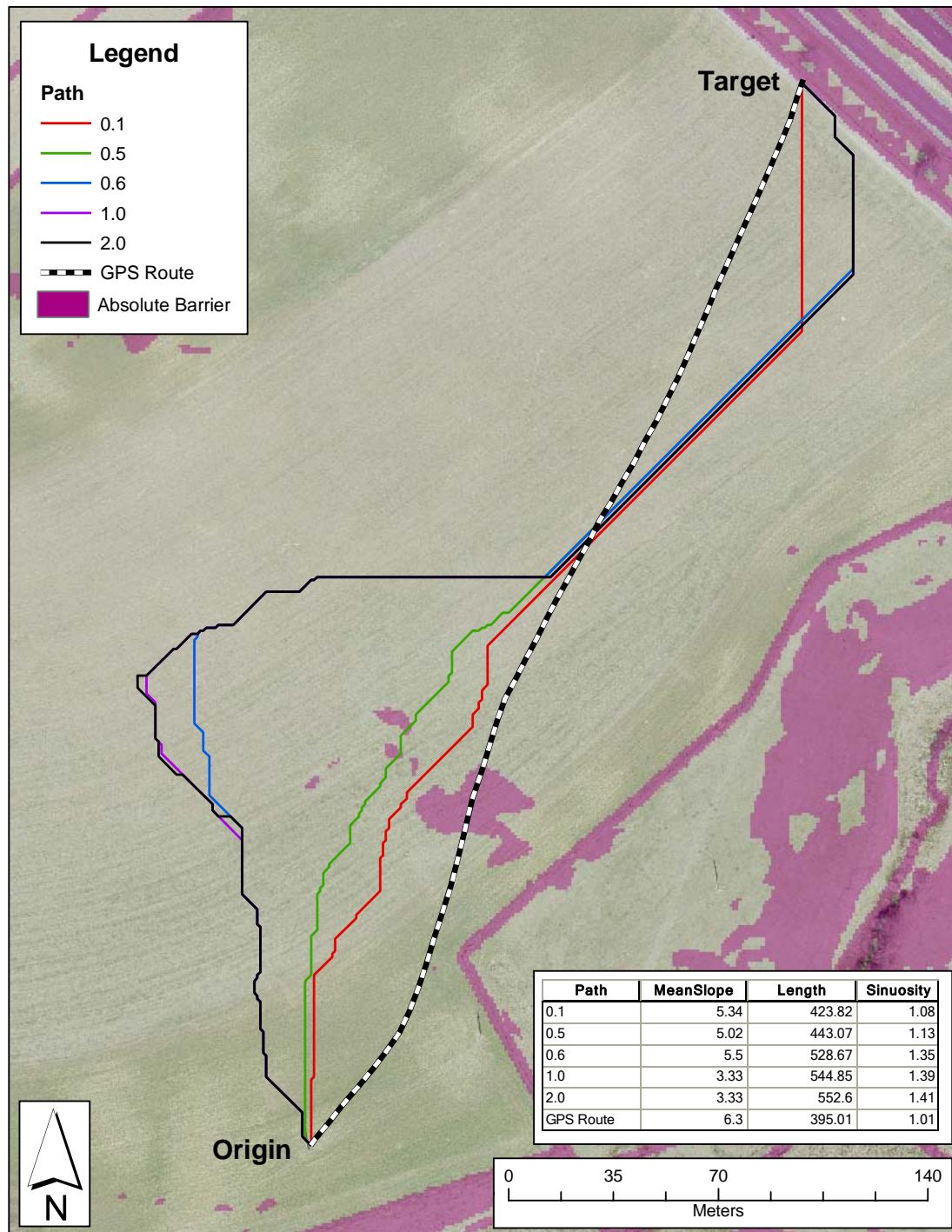
Map 4.1.2 – Slope Test with Barriers

Legend

Path
- 0.1
- 0.5
- 0.6
- 1.0
- 2.0
- GPS Route
- Absolute Barrier

Percent Slope
- High : 70%
- Low : 0%

Target

Origin

Path	Length	MeanSlope	Sinuosity
0.1	423.82	5.34	1.08
0.5	443.07	5.02	1.13
0.6	528.67	5.5	1.35
1.0	544.85	3.33	1.39
2.0	552.6	3.33	1.41
GPS Route	395.01	6.3	1.01

0   35   70   140
Meters

N
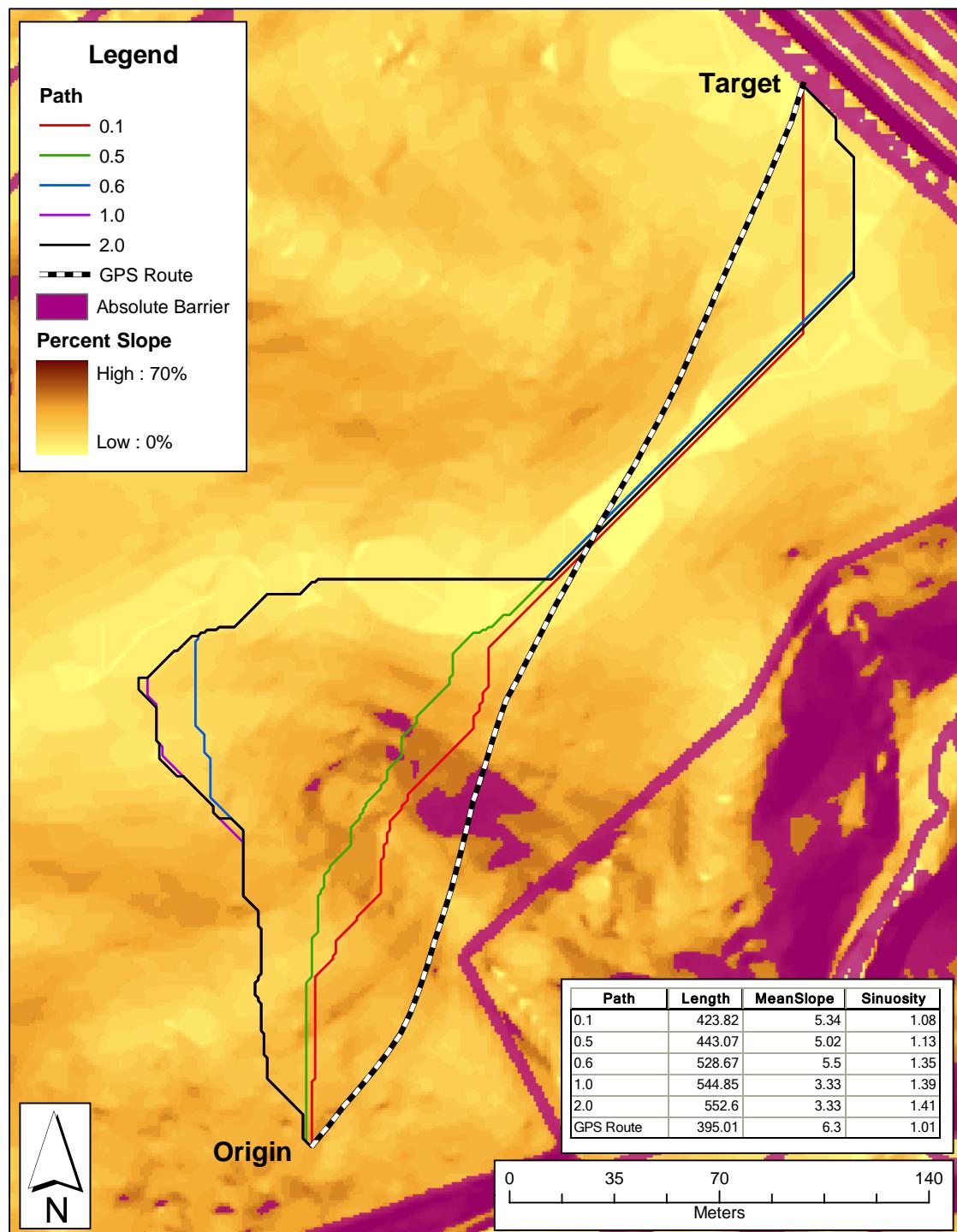
Map 4.1.3 – Results for the Slope Exponentiation of 0.1

Accumulated Surface Exponentiation of 0.1

Path 0.1

Path Statistics

Cell Count = 357   Mean Slope = 5.34
Min. Slope = 0   Sinuosity = 1.08
Max. Slope = 14   Length = 423.82

Path
High : 791.84
Low : -1.00
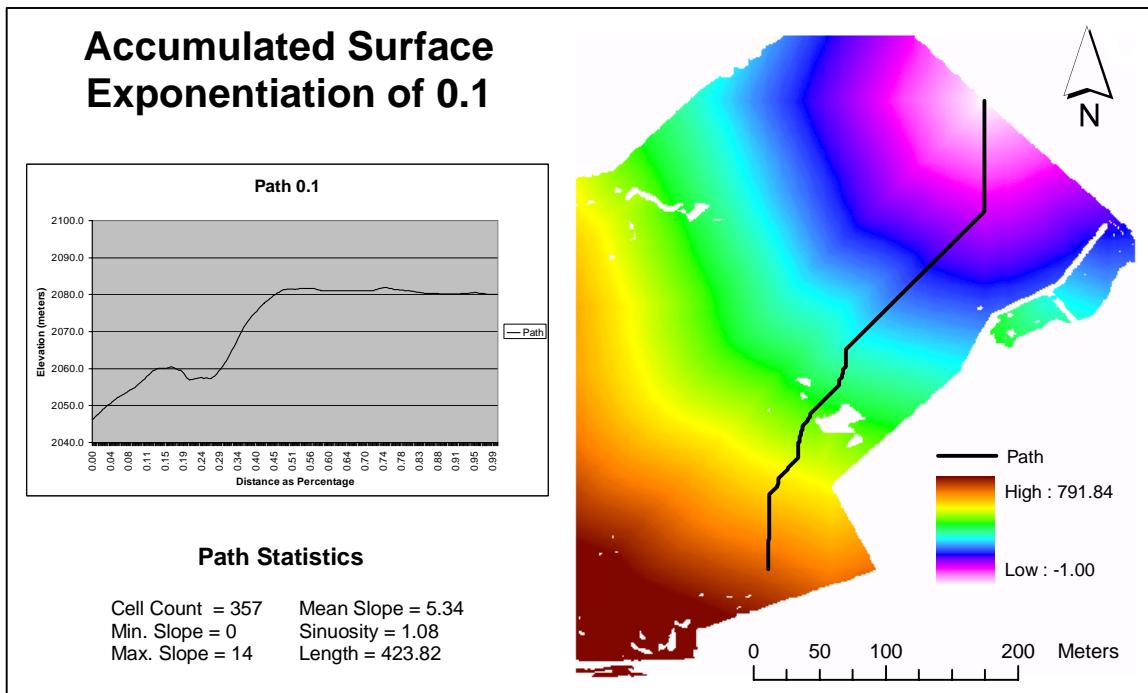
Map 4.1.4 – Results for the Slope Exponentiation of 0.5

Accumulated Surface Exponentiation of 0.5

Path 0.5

Path Statistics

Cell Count = 363   Mean Slope = 5.02
Min. Slope = 0   Sinuosity = 1.13
Max. Slope = 15   Length = 443.07

Path
High : 1212.54
Low : -1.00
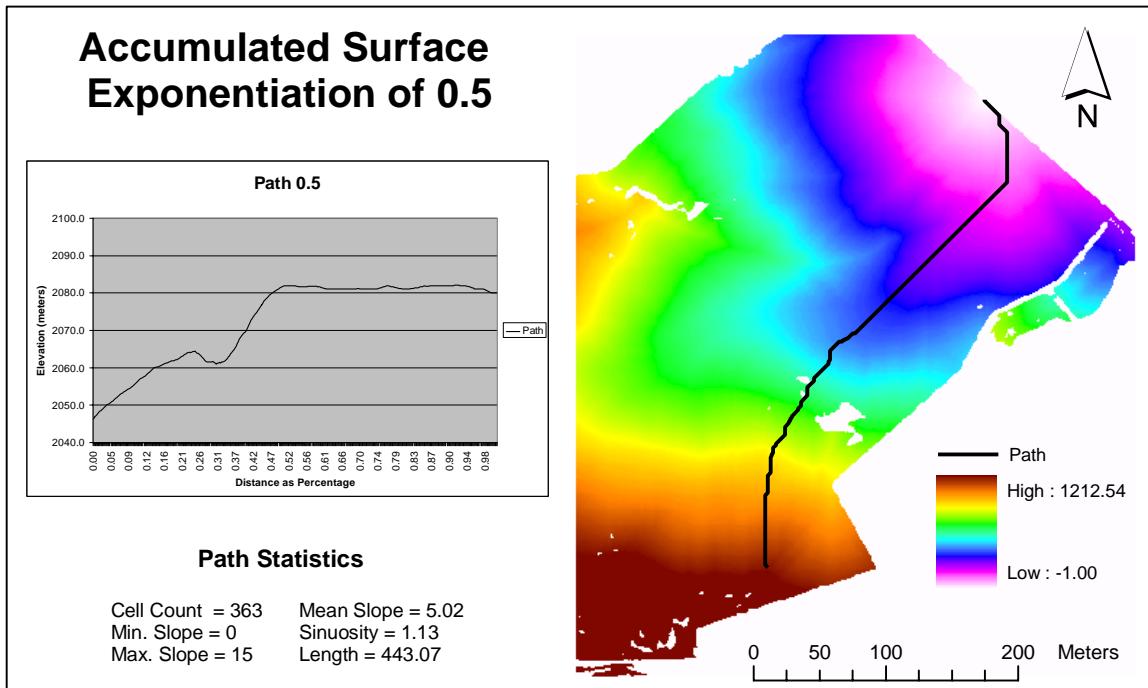
Map 4.1.5 – Results for the Slope Exponentiation of 0.6

Accumulated Surface Exponentiation of 0.6

Path 0.6

Elevation (meters) vs Distance as Percentage

— Path

Path Statistics

Cell Count = 454   Mean Slope= 5.50
Min. Slope = 0   Sinuosity = 1.35
Max.Slope = 11   Length = 528.67

Path
High : 1347.71
Low : -1.00

0   50   100   200   Meters
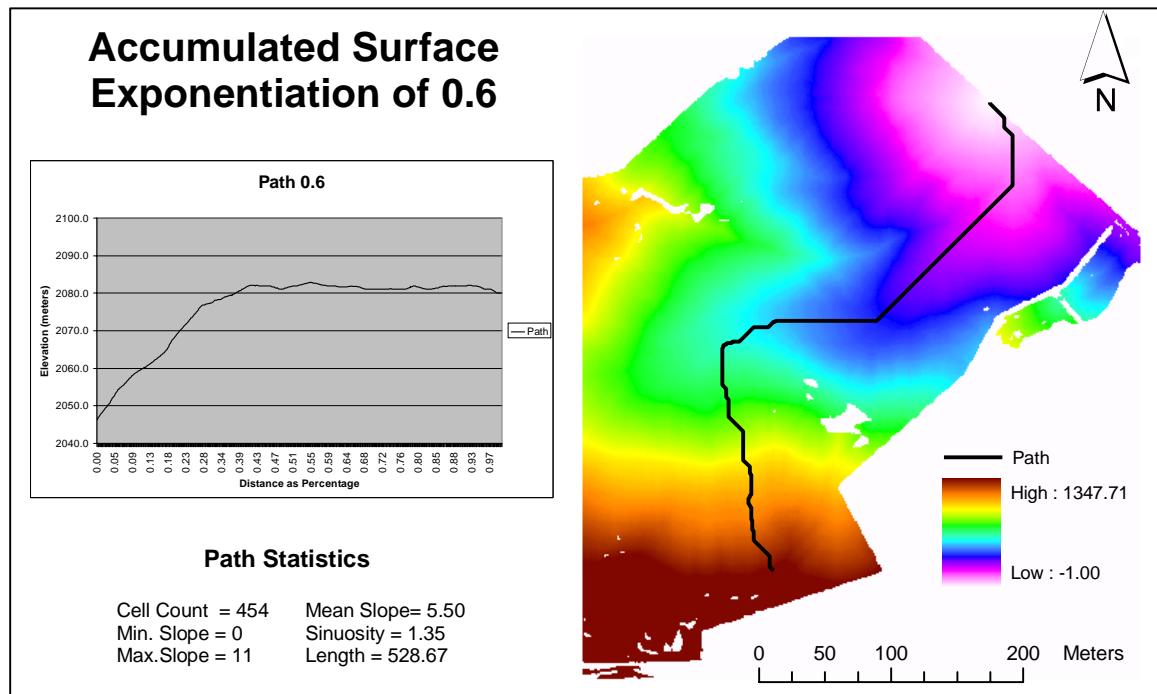
Map 4.1.6 – Results for the Slope Exponentiation of 1.0

Accumulated Surface Exponentiation of 1.0

Path 1.0

Elevation (meters) vs Distance as Percentage

— Path

Path Statistics

Cell Count = 459   Mean Slope = 3.33
Min. Slope = 0   Sinuosity = 1.39
Max. Slope = 11   Length = 544.85

Path
High : 2170.35
Low : -1.00

0   50   100   200   Meters
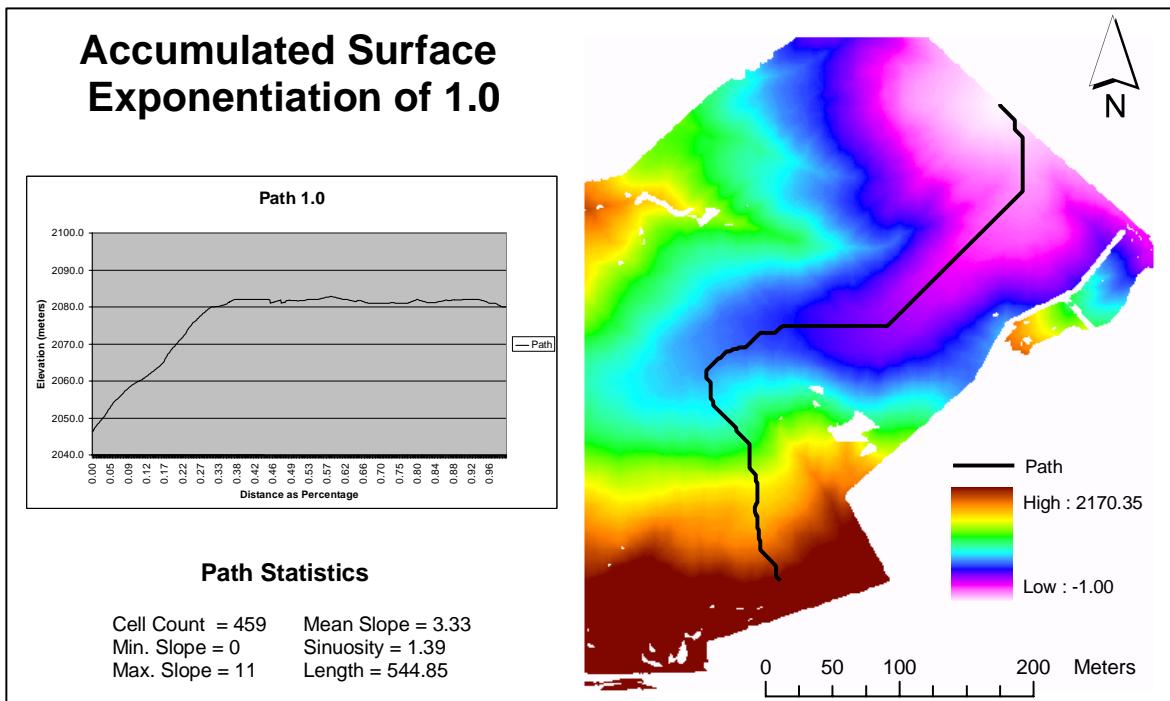
Map 4.1.7 – Results for the Slope Exponentiation of 2.0

Accumulated Surface Exponentiation of 2.0

Path 2.0

Path Statistics

Cell Count = 468   Mean Slope = 3.33
Min. Slope = 0   Sinuosity = 1.41
Max. Slope = 11   Length = 552.6

Path

High : 9281.44

Low : -1.00

0   50   100   200   Meters
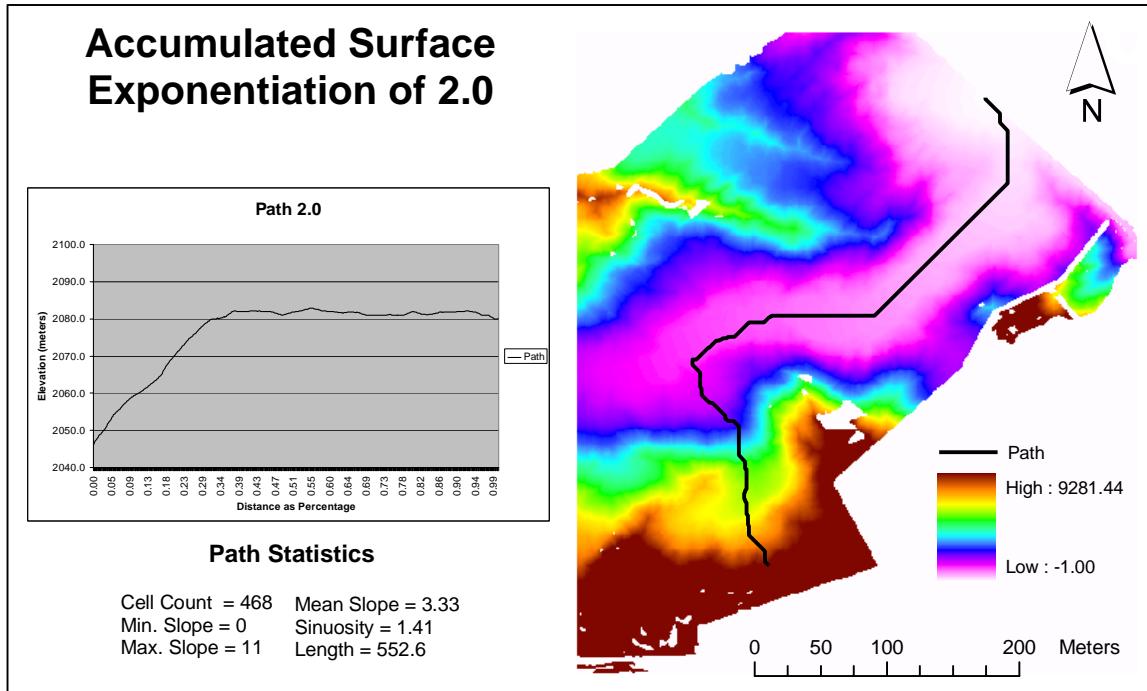
and slopes greater than this amount are excluded from the analysis as

constraints, path 0.1 is trafficable and the most direct route leading me to believe

that this is the most appropriate exponentiation to use for weighting slope's cost

in the model. There was nothing in the field work to indicate that the path could

not be driven, therefore this exponentiation was used to perform Test 2, which

incorporates the roads layer.

One other consideration is the artificially discrete separation between

slopes that are trafficable and slopes that are barriers. The result from the

exponentiation of 0.1 traverses the most difficult slopes of any route. Since

anything higher than 15% is classed as a barrier and is not trafficable, 15.1% is

not trafficable. You would think that the vehicle performance would degrade as

you approach the 15% benchmark. Therefore an error in the DEM could

potentially misrepresent slope allowing a path to travel on a slope over 15%. Ideally, more detail should go into consideration of this factor and constraint issue, but little vehicle performance testing has yet been done on slopes.

4.2 – Road Weighting (Test 2) Results

The paths generated in test 2 were then visually and statistically examined to determine their suitability. A macro file was used to export each accumulated surface and its resulting path to ArcGIS™. Once again, after getting all the data into ArcGIS™ the paths were studied to conclude which values created significantly different routes. Of the twenty results, five paths were selected to demonstrate where the major differences occurred between the origin and the target. These five paths resulted from the multiplication of 0.1, 0.7, 0.8, 1.0, and 2.0 against the original road value of one (figures 4.2.1 and 4.2.2). The GPS route that I determined in the field to be the most efficient or direct path was overlaid with the five selected paths. The most similar paths of the five selections were paths 0.7 and 0.8 (figures 4.2.3 and 4.2.4). In the results of Test 1 the mean slope of the paths increased as the exponentiation decreased and overall length and sinuosity increased as exponentiation increased. In this test roads are a very favorable factor in maximizing the vehicle performance and efficiency on a path. Because road following is the desired result, the overlay operation illustrated in figure 3.5.1 in chapter 3 is completed with a cover option. The cover option permits the first image to overwrite the values of the second

Map 4.2.1 – Road Test with Photo

Path	MeanSlope	Length	Sinuosity
GPS Route	8.1	1069.82	2.26
0.1	5.34	1147.25	2.42
0.7	8.17	1134.97	2.39
0.8	8.36	1110.7	2.34
1.0	8.17	1100.32	2.32
2.0	8.24	1107.05	2.34

Legend

Path
— 0.1
— 0.7
— 0.8
— 1.0
— 2.0
▬▬ GPS Route
█ Absolute Barrier
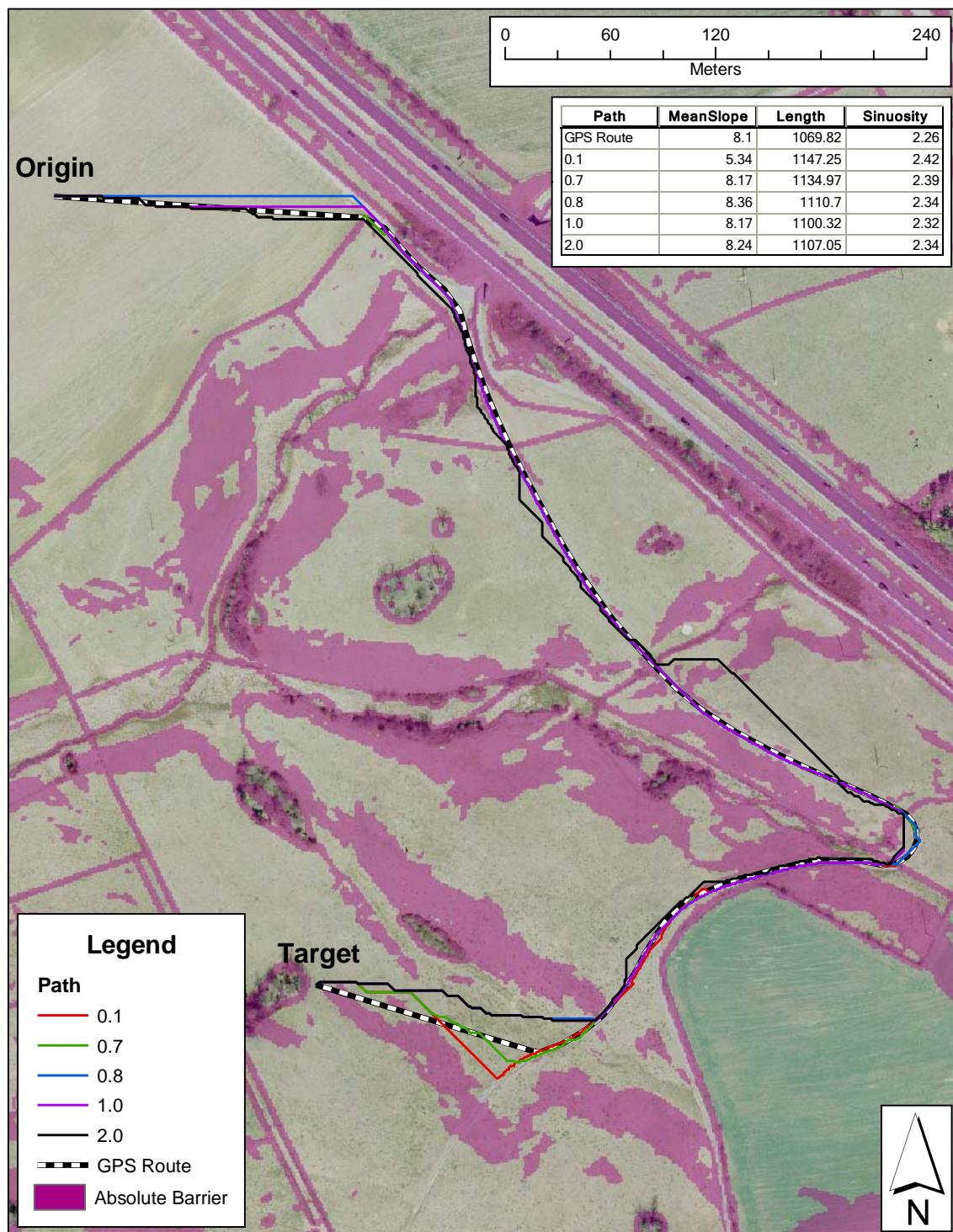
Map 4.2.2 – Road Test with Barriers

Path	MeanSlope	Length	Sinuosity
GPS Route	8.1	1069.82	2.26
0.1	5.34	1147.25	2.42
0.7	8.17	1134.97	2.39
0.8	8.36	1110.7	2.34
1.0	8.17	1100.32	2.32
2.0	8.24	1107.05	2.34

Legend

Path
- 0.1
- 0.7
- 0.8
- 1.0
- 2.0
- GPS Route
- Absolute Barrier

Percent Slope
High : 166%

Low : 0%
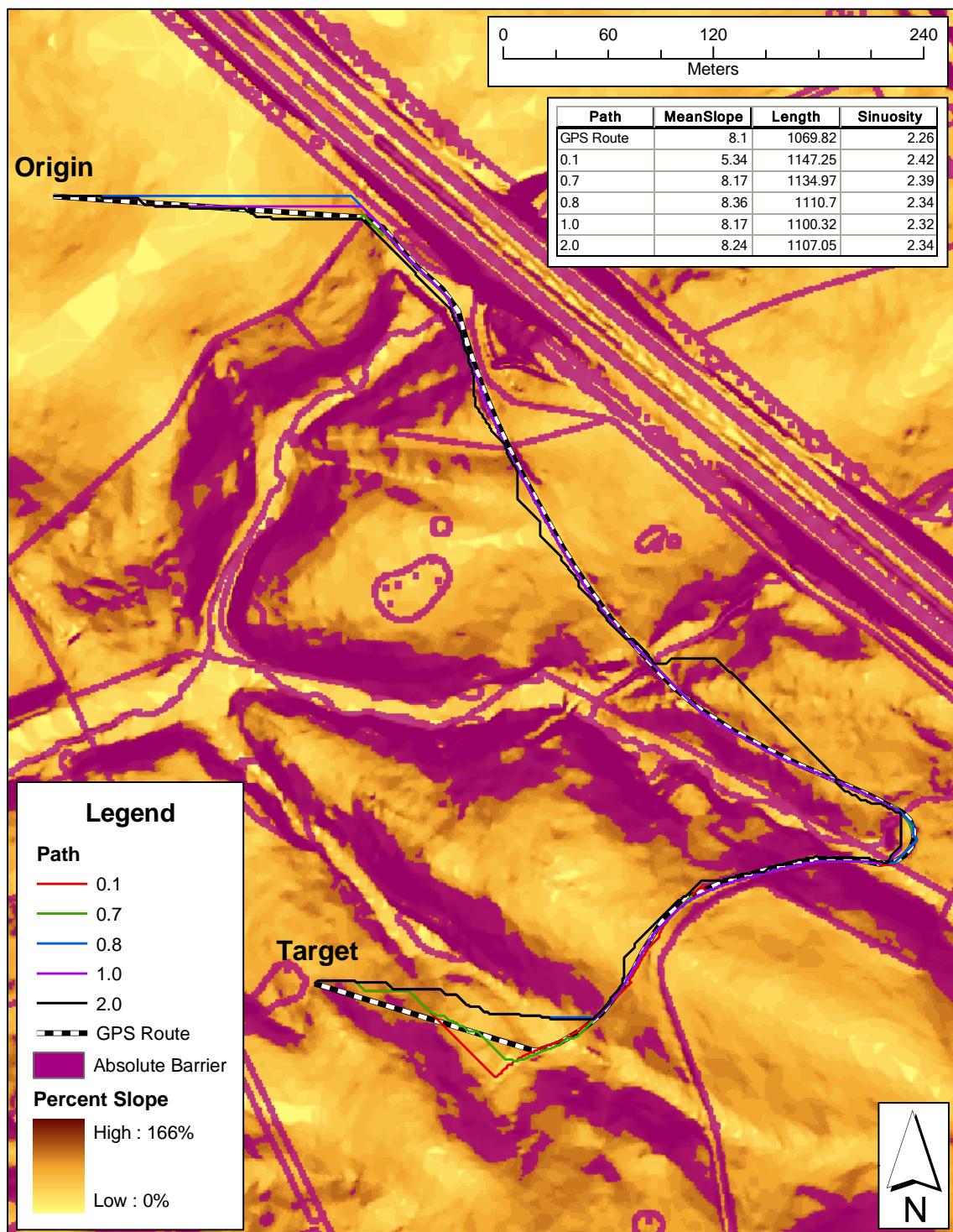
Map 4.2.3 – Road Results for Multiplication of 0.7

Accumulated Surface Multiplication of 0.7

Path 0.7

Path Statistics

Cell Count = 954 Mean Slope = 8.17 On Road = 69.0%
Min. Slope = 0 Sinuosity = 2.39 Off Road = 31.0%
Max. Slope = 28 Length = 1134.97
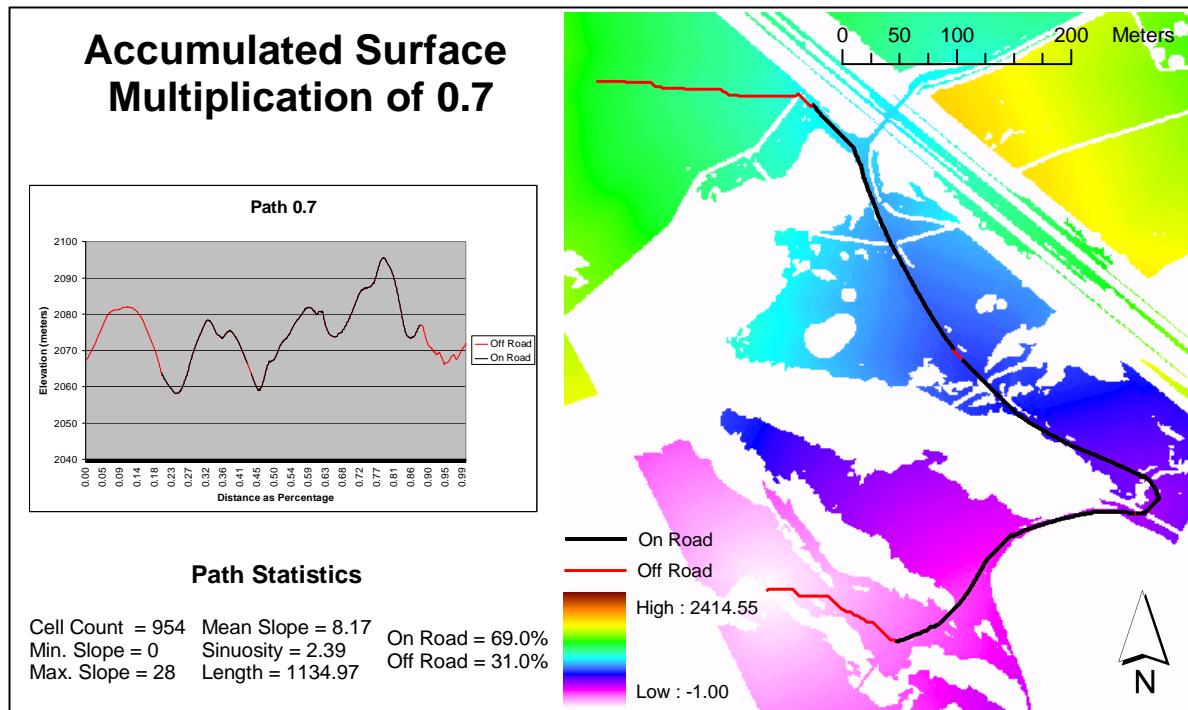
Map 4.2.4 – Road Results for Multiplication of 0.8

Accumulated Surface Multiplication of 0.8

Path 0.8

Path Statistics

Cell Count = 955 Mean Slope = 8.36 On Road = 69.2%
Min. Slope = 1 Sinuosity = 2.34 Off Road = 30.8%
Max. Slope = 28 Length = 1110.70

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image everywhere except where 0 values are contained. These 0 values are all

non-road areas. Therefore, the resulting paths do not show the same

relationship between mean slope, length, sinuosity, and the multiplication value

since the road layer's value completely negates the slope values contained on

the road. The assumption is that all roads, no matter what slope, are designed to

be driven on by any vehicle therefore providing a faster surface than off road

surfaces. The results do lead to an exponentiation that provides for getting on

and off the road in the best manner, and also retains its road following capability.

As mentioned before paths 0.7 and 0.8 provide the best routes for getting on and

off the road. However, path 0.7 leaves the road for a few meters where it should

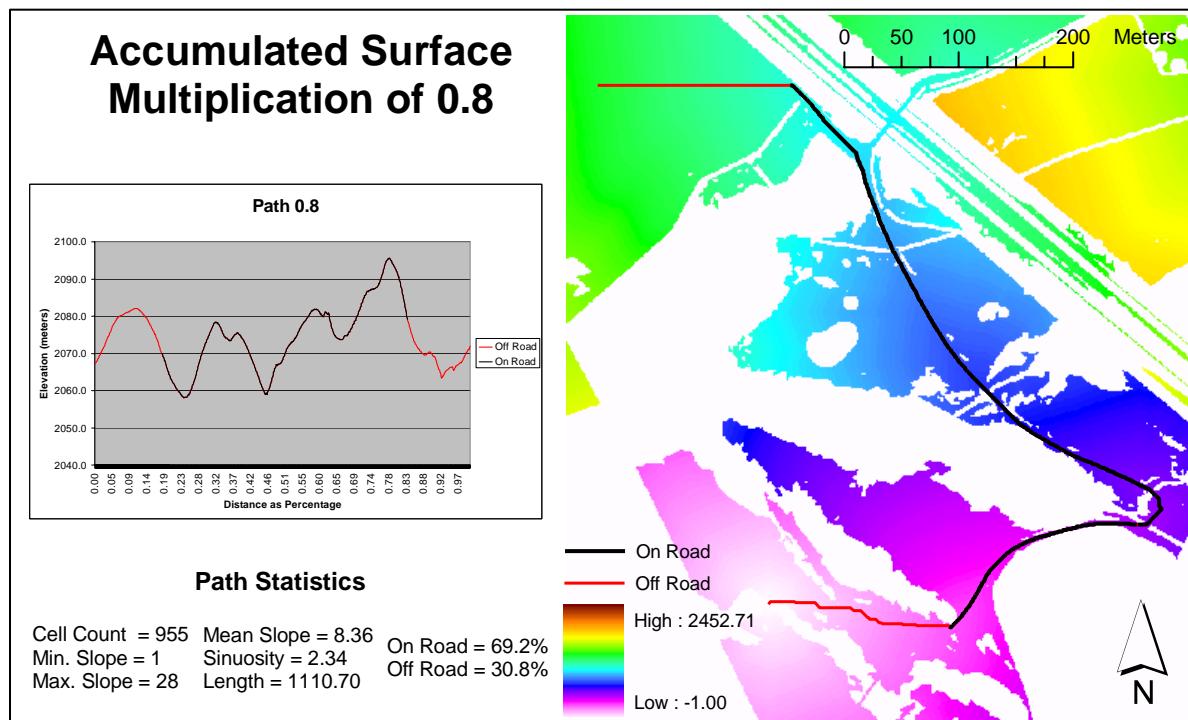continue to follow the road. It does this in two instances, and the reason it

happens is because the slope is so low off the road that it moves to that cell until

it finds another cell with higher cost forcing it to move back on road. Path 0.8 has

much better road following capability and does not leave the road until it

becomes more efficient to travel off road to the target. One thing that I did notice

about this path is that it becomes a bit "zigzaggy" on a sharp turn. If there is no

visible obstacle, which there is not, it should be smoothed out in some manner.

After analyzing the results for this test, a better alternative would be to extract the

center line for roads and to pull coordinates between the points, where the path

enters and leaves the road feature. This would eliminate the road following

concern and ensure that the vehicle drives down the middle of the road rather

than the side.

4.3 – Pros & Cons of the Cost Grow Algorithm

An advantage of this *Cost Grow* algorithm is that it can accumulate a huge area and *Pathway* can be rerun with many different origins. This is important if the local mapping system on a vehicle finds an obstacle or series of obstacles that cause it to deviate from the plan to an alternative path. This permits the GIS to run the much faster algorithm in *Pathway* and recalculate a new path. When done on the fly the pathway algorithm alone is much faster than having to reaccumulate another surface and then calculate a new path.

However, there is a drawback to this method of routing. The accumulation

Figure 4.3.1 – Grid Processing Times
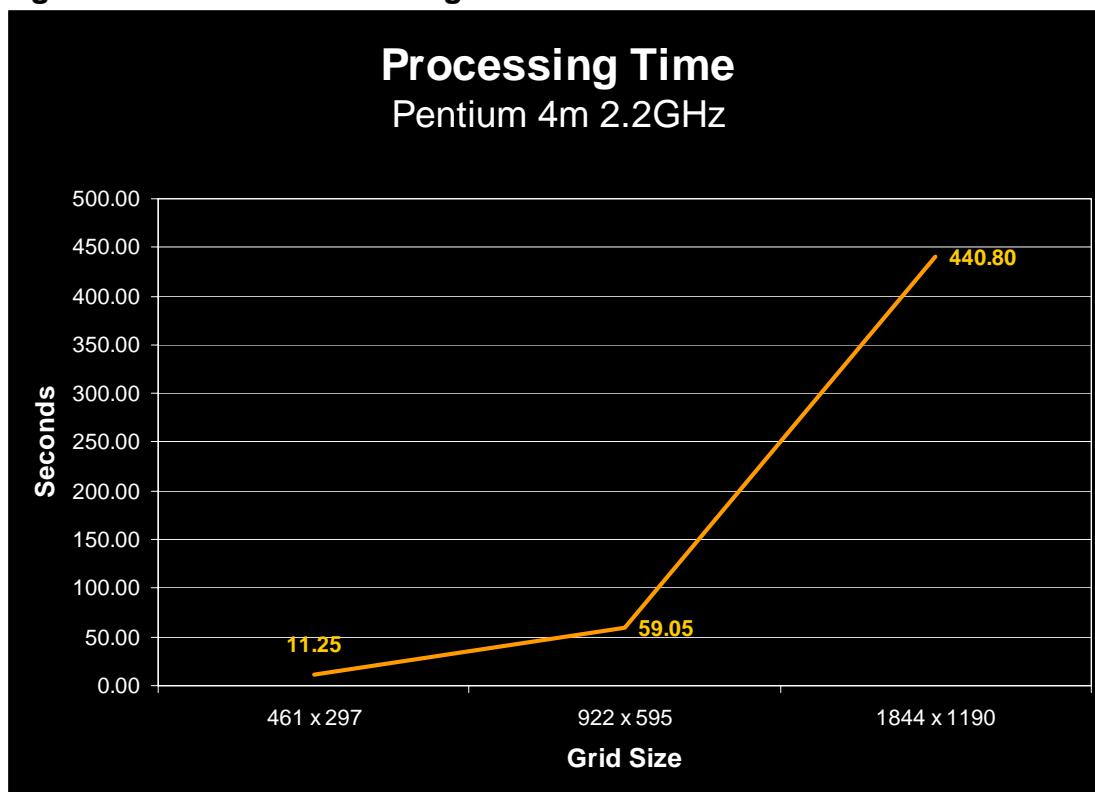
process gets longer as the grid size increases. I completed a short test with this algorithm using a 461 x 297 grid. The run time for accumulation was 11.25 seconds on a Pentium 4m 2.2 GHz processor. I halved every cell creating a finer grid at 922 x 595 and it took 59.05 seconds. Finally, I ran the algorithm on an 1844 x 1190 grid which ran for 7 minutes 20.8 seconds (figure 4.3.1). Obviously, this algorithm has longer start up times with larger grids. This could be an issue when using a computer that is not equipped with proper processing power for the application. Outside of boosting the computer's performance, there is another option that can be implemented in the accumulation process. As mentioned earlier in this study, a possible solution to speeding up the process would be to accumulate a selected portion of the study area. Usually when working with a large area the outer edges of the accumulated surface are useless for travel. Much of this area can go unprocessed. Accumulating only within a user defined buffer between the origin and the target will narrow the area of possible travel. Many times this makes sense, however once the accumulation occurs the eliminated areas are not searched for possible routes. The user must pick an appropriate width keeping in mind the entire study area. On the other hand, if you incorporate the A* algorithm into the GIS you would not need to figure out how far you need to buffer. As you can see back in chapter 2, the A* heuristic estimate of distance to the target takes care of this and eliminates the need for accumulating many additional cells outside of the least-cost path.

4.4 – Summary of Results

Overall, the route I mapped on foot is not going to be the least-cost path. If you look at test 1 and test 2, neither of the results comes precisely close to matching this path. This path is intended to be used as a good path to shoot for because it is a viable path that I perceived as a direct route. The major influence for choosing the 0.1 path was sinuosity and length. These two measures indicate how direct the path is between the points. As the exponentiations get closer to 1.0 the magnitude of cost greatly increases which over emphasizes slope as a friction. On the other hand, test 2 had to be handled differently. Using the exponentiation of 0.1 as the standard input for slope the most appropriate road input was determined to be 0.8 as a multiplication for the initial value of 1.0. The selection of this result does not rely on sinuosity since sometimes roads are sinuous in nature. However, they do expedite travel and consistent road following is a concern. Routes that jump on and off a road are not wanted. Most of the routes are guilty of this up to a multiplication of 0.7 where it only occurs once. The resulting path from the multiplication of 0.8 is the only path to stay completely on the road once entering it, and it continues until it is forced off road toward the target.

Literature does not address how vehicle routing occurs with use of a GIS. The results for weighting both the slope and road layer are only good for a vehicle that contains the same constraints as described in the study. While a vehicle that can overcome these constraints can perform adequately it may

perform better if the model was altered to fit its own limitations or constraints. The model can easily accommodate these changes by mapping new absolute barriers. If such an adjustment were made, the sensitivity analysis should still be run since new spatial locations are available which may alter the cost for travel between the origin and target.

Chapter 5 - Conclusion

5.1 – Recent Trends and the Objectives of this Research

Technology is always changing and providing us with various new tools and instruments that make navigation easier. These instruments they have allowed us the capability to automate information and decision making for autonomous vehicles. Literature suggests that the ability to incorporate local sensor information with global mapping information is possible giving an opportunity to develop real-time GIS enhancement and automatic rerouting.

There is little published research on navigating autonomous ground vehicles with a GIS. The papers that have been found do not mention commercial off the shelf software (COTS) such as ArcGIS™ or IDRISI Kilimanjaro and tend to approach the issue by writing their own software from scratch, a process that can be quite daunting, and perhaps unnecessary. Another reason why this area is not well documented may lie in who is interested in this technology. The defense industry funds much of this work which must remain unpublished for security reasons or the competitive nature of the industries that support the military. Furthermore, my experience in this research leads me to believe that the geospatial aspect has been overshadowed by larger, more immediate issues. There is a focus on standardizing the mechanics of unmanned systems so that the communication and physical structures of the vehicles are more reliable. Vehicle reliability is a major weakness of these systems. In looking at what happened to the vehicles in the DARPA Grand

Challenge, Carnegie Mellon University's Red Team's GPS navigation system was not precise enough causing them to veer off course. Scianautics 2 lost GPS connectivity and wrecked into boulders. Team Digital Auto Drive (DAD) drove across a sand pit, but lacked enough traction or finesse to escape. The Golem Group didn't have enough power to climb a hill. Virginia Tech's "Cliff" had laser range finder problems which engaged brakes during acceleration causing a CVT (controlled variable transmission) belt to break (Kohn, 2005).

Autonomous research seems to have been a high risk area in which only a select few have begun to research. Historically this has been due to immature technologies and monetary expense, however this has changed within recent years and the needed technologies are not only becoming capable but also affordable. Likewise, geospatial technologies have also been limited in the past because of expense or manpower to collect appropriate data needed for guidance and route planning. But within recent years, photogrammetric and LiDAR technologies have improved enough to make high quality data available and affordable for educational institutions to do this research. As autonomous vehicle research continues to grow and mature, GIS modeling will become a standard for addressing the numerous geographic issues that surround it.

5.1.1 Objective 1: Accumulated Surface as a Solution

Accumulated or cost surfaces have been widely accepted as a viable medium for modeling travel across space. While many examples don't have anything to do with overland navigation, most are network oriented problems that have similar goals of finding a route of travel for whatever purpose.

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5.1.2 Objective 2: Algorithm or Software Options

Many options exist and need to be considered when modeling routes for a vehicle. ArcGIS™ Spatial Analyst and IDRISI Kilimanjaro provide their own set of algorithms to measure cost given that the correct data can be fed into them. Then there is always the ability to customize the software with an algorithm such as the A* which may speed up performance and still provide acceptable results.

5.1.3 Objective 3: Determining Sources of Friction

A large factor in the quality of the result is determining the geographic features in the real world that make it cumbersome to navigate a vehicle. Features that act as absolute barriers in this study consisted of a variety of urban features as well as forest, water, and high slope. Trafficable slope was identified as a factor that had variable cost, and roads were identified as a feature that was catalytic for travel. These layers are quite obvious and can be mapped at a useful scale for any geographic location.

5.1.4 Objective 4: Establish Parameters for Input Data

Accurately weighting sources of friction for driving in the all-terrain environment is not easy. Weights for each input are virtually unknown. The sensitivity analysis is a very good method for tweaking weights until a favorable result is found. The sensitivity analysis is more elaborate than triall and error in that is an automated process. Each outcome can be mapped and the most advantageous result explains what parameters should be used. This approach produces good paths which are perfectly acceptable, but sometimes they are not always the most optimal.

5.2 – Future Work

        While the techniques in this paper provide respectable results, there is much that still needs to be researched. There is the issue of aspect on slope that has not been addressed in this model (map 4.2.1). The current model ignores the aspect of a slope. As mentioned earlier, others such as Yu, Lee, and Munro-Stsiuk have addressed this issue by compiling their own least-cost path algorithms. However, I believe this could still be accomplished by using a series of aspect grids as a means to refine a route produced by my current model. There needs to be some kind of balance between slope costs and aspect cost. Aspect gives insight on the direction across which slope is traveled. For instance slopes over 15% were totally eliminated from travel, but these areas may be made trafficable if taken at angles non-perpendicular to the calculated slope. No matter which approach is used, it's important to consider the vehicle's stability on all slopes so it doesn't end up tipping over and rolling down a hill.

        Secondly, all data was converted to a one meter resolution which is somewhat finer than needed. Yet, it is also clear that a ten meter grid may be too coarse to navigate a one meter by two meter vehicle. Resolutions such as this might not be appropriate as they could hide obstacles. It is also quite clear that a higher resolution lets you see more detail (figure 5.2.1). However, research is needed to identify at what point does more detail become overdone and stop providing useful results. It might be safe to assume that a grid cell size near the vehicle size would be a good rule of thumb, but there is no proof of what

Figure 5.2.1 – Grid Resolution

1 Meter   **2 Meter**
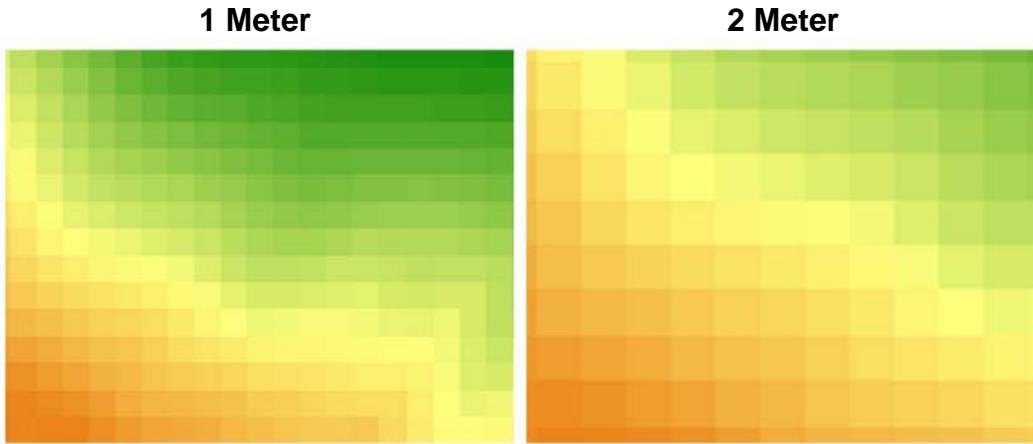
is the most suitable cell size. A valuable study would consist of examining the

effects of resolution for producing these least-cost paths for vehicle navigation. If

a more coarse resolution could be used and produce useable results it could

significantly reduce computation time and data storage.

Another area to investigate is route smoothing or generalization. The

advantage of this would be to create a good output that makes graceful

movements when traveling at higher speeds. Sometimes the path a model

computes is certainly navigable, but, because of the nature of raster databases,

45 degree and 90 degree turns appear in the route, and at higher speeds the

path itself might pose a problem (figure 5.2.2). Use of spline or line

generalization algorithms might help in producing a smoother route, but this is a

process that would be external of the accumulation or least-cost path generation.

Ultimately, this would be a final process that refines the path and always ensures

its compatibility with the models factors and constraints. You would not want to

smooth a line and find out that a portion of the smoothed line travels directly into

an absolute barrier. Most likely local sensors or machine vision systems would

Figure 5.2.2 – Route Smoothing
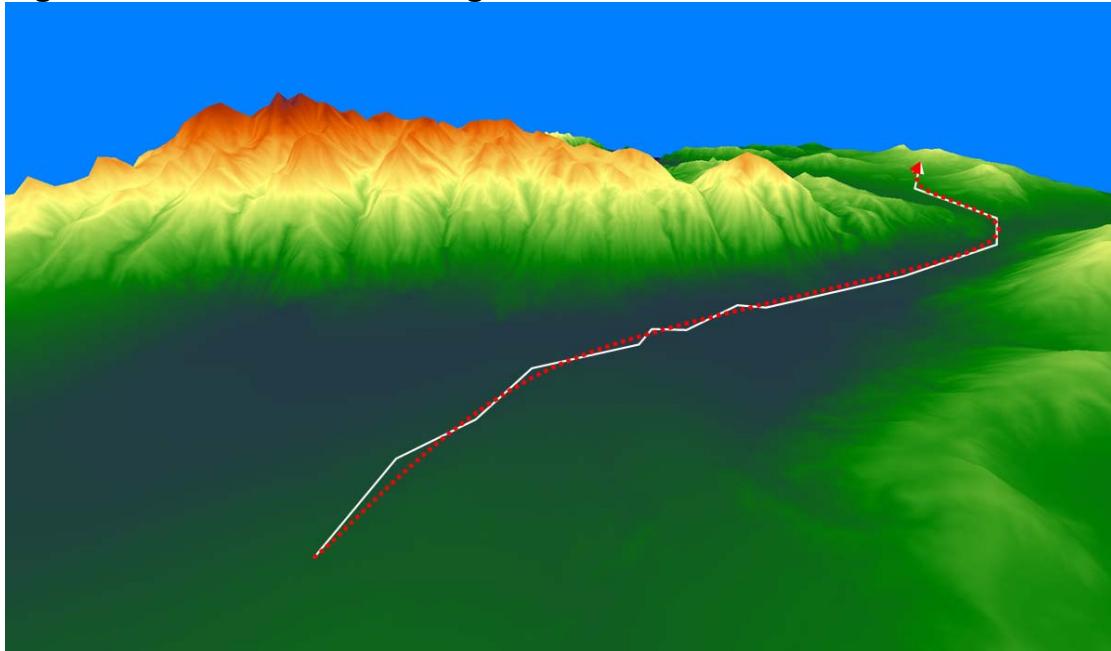
adjust and recalculate the route, but it is something that could easily be avoided if the smoothed route is checked against the final friction surface.

Fuzzy logic is an area of GIS that can be used in making a decision about uncertain or vague datasets. The trafficability analysis engine mentioned in section 2.7 used a confidence interval to aid in making decisions about mobility. You can take it one step further by assigning a confidence interval to an entire route based on potential vulnerabilities along a route. Say there are three routes generated to get from one point to another. The first route crosses two bridges along the way. The second crosses only one bridge, and the third crosses no bridge and travels much further than the other two routes. The region these routes travel through are susceptible to flash flooding, so bridges have potential for being inaccessible. The highest confidence interval would be associated with the long route that does not travel over bridges. The second highest confidence interval would be associated with the route using only one bridge. Two bridges

Map 5.2.1 – Fuzzy Logic
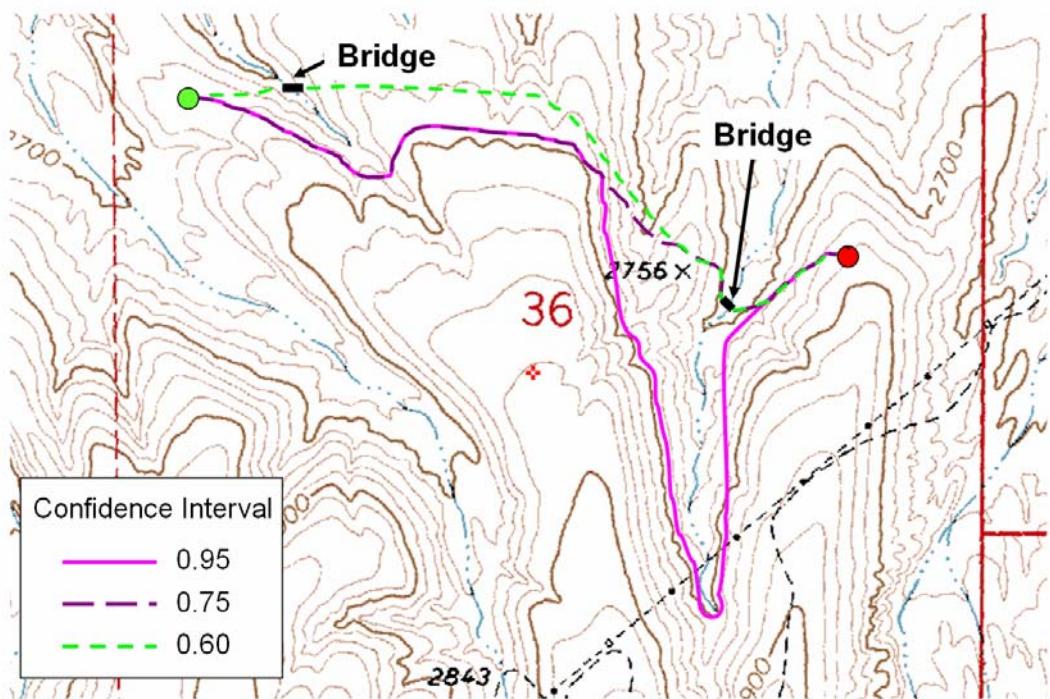
offer two chances at finding a barrier; therefore this route would have the lowest confidence interval.

5.3 – Summary

Overall, the results of this study show that weights selected for slope and land cover factors have very different results, and a weight should be selected based on specific mechanical limitations for a vehicle. According to Virginia Tech's Grand Challenge team, Cliff has a constraint on 15% or greater slopes. If it were another vehicle like a Hummer H1 the model would need to be adjusted to its limitations. Assuming that Cliff can operate in all other situations the results are useful. My results also reflect no vehicle performance test on any resulting path.   If the situation permits, paths should be tested by the vehicle before making a final decision on which exponentiation to use for weighting factors.

Unfortunately, the study areas used had some restrictions and this could not be done to help validate results.

Using computers to model something a human might do easily is not a simple task. Computers do what they are programmed to do. They are not intelligent and we need to pre-plan for nearly every scenario before the computer encounters it. While the best path from a GIS model works very well, routing algorithms do not assure optimal results. You might not be able to model the optimum path in every scenario. GIS models rely on data that is assumed to be correct. Until real-time GIS data is implemented with all the factors necessary for navigation, it may be impossible to assure finding the optimal path, but we should always be able to find a good path.

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Appendix A: 2002 Virginia Tech Main Campus Metadata

(adapted from Rempel, 2002)

Aerial Flight:

Date Flown: 2/16/2002

Film: Color, Agfa X-100

Scales: 1"=250' and 1" = 660'

Altitudes: 1,500" and 3,960'

Endlap: 60%

Sidelap: 30%

Deliverables:

Aerial Triangulation Report

1 Set of 9'x9" color contact prints

1"=50' plan with 1' contours in 3D digital map data files in AutoCAD.dwg R14 on

CD

1"=100' plan with 2' contours in 3D digital map data files in AutoCAD.dwg R14 on

CD

Mylar plots of 1"=50' plan with 1' contours

Mylar plots of 1"=100' plan with 2' contours

Color TIFF images with TFW at .25 ft gsd (pixel) on CD

Color TIFF images with TFW at .5 ft gsd (pixel) on CD

Methodology:

Aerial Photography

EarthData International acquired new color aerial photography for the area

indicated by the client. The aerial camera used was a Wild RC30 camera system

with a six-inch focal length. The camera was equipped with a high resolution,

distortion free lens and forward motion compensation. The photography was

flown at 1500' and 3960' above mean terrain to achieve the photo scales of

1"=250' and 1"=660' respectively with 60% forward endlap and 30% sidelap.

Ground Control

The ground control for this project consisted of 28 paneled points (11 existing

control and 17 new control points) and was the responsibility of Virginia Tech.

Horizontal and vertical values were established for all points using accepted

survey methods. Control panels were set in accordance with recommendations

from EarthData. The horizontal datum was referenced to Virginia State Plane

NAD83, South Zone and the vertical datum was referenced to mean sea level

NAVD88. The working units for this project was US Survey Feet.

Aerial Triangulation

Fully analytical aerial triangulation was performed to extend the ground control

and establish orientation parameters for each exposure. A final bundle

adjustment, using ISBBA software, was performed on the entire block of

photography. The results were checked to make certain that they conform to National Map Accuracy Standards with respect to scale and RMSE.

Digital Data Capture

Planimetric and topographic data was captured by highly experienced photogrammetric technicians, using Zeiss P3 Analytical Stereoplotting Systems. The planimetric features captured conform with those normally collected for 1"=50' scale mapping. Digital terrain model (DTM) points and breaklines were collected from which 1' contours were generated. The contours were generated in real-time by the stereoplotter operators and spot elevations were added as required.

CAD/Edit

CAD/Edit technicians generated final contours, performed extensive quality control checks, and translated the map data to 3D plan and contour files and 3D DTM and breakline files. The digital data files were delivered on CD-ROM in AutoCAD, V.14.0, .DWG format.

Digital Ortho Mosaic

For this project the 1"=660' scale color aerial photography was used to produce the 1"=100' scale color orthophoto mosaics. The orthophoto mosaics were spatially corrected throughout the image area, allowing for the direct and accurate referencing of vector data to the image. The images were scanned at

14 microns, and the final orthophotos had a ground pixel resolution of +/- 0.5',

and a spatial accuracy of +/- 2.5'. The individual orthophoto sheets conformed to

the tile coverage of the 1999 photo mosaic sheets.

Statement of Accuracy:

The mapping conforms to National Map Accuracy Standards. Ninety percent of

all well-defined planimetric features are plotted to within 1/40 inch of their true

coordinate position. No well-defined feature is in error by more than 1/20 inch.

Ninety percent of all contours on unobscured ground are within 1/2 of the contour

interval and the remaining 10% are not in error by more than the contour interval.

In areas where the ground is obscured, contours are represented by dashed

lines indicating that these lines may not be to standard accuracy. They are

plotted as accurately as possible making full use of spot elevations and ground

surveys. Ninety percent of all spot elevations are correct within 25% of the

specified contour interval and none are in error by more than 50% of the contour

interval.

Point of Contact:

Harold Rempel, Project Manager

EarthData International, 7320 Executive Way, Frederick, MD 21704

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Appendix B: Virginia Base Mapping Program (VBMP)

Local Government Product Deliverables

Quick Reference VBMP Product Specifications

(adapted from Virginia Geographic Information Network, 2005)

Conformance to Standards: VBMP digital orthoimagery meets or exceeds accuracy requirement for:

    o Class 1 mapping standards in conformance with Virginia Map Accuracy Standards (1992) and

    o ASPRS (1990) Accuracy Standards for Large-scale Maps, **Class 1.**

Method of Collection: Traditional Aerial Photography Film exposed with a 6" focal length aerial photography Camera. Airborne GPS was used onboard the aircraft. Image scans were produced from the Photographic film.

Imagery Type: True Color (24 bit)

Orthophotography Extent: Orthoimagery for the Virginia Base Mapping Program (VBMP) was developed over the entire land area of the Commonwealth. The State boundary was buffered by a minimum of 1000'. Land areas adjacent to the Atlantic Ocean and Chesapeake Bay were buffered by 1000' or the extent of man-made features extending into the bay (with the exception of the Chesapeake Bay Bridge Tunnel(s)).

Time Period of Collection: Spring of 2002, leaf-off conditions

Orthophotography Scale and Tile Size: Orthoimagery for the Virginia Base Mapping Program (VBMP) was developed at one of three scales depending on population/housing density and local options:

Resolution	Imagery Scale	Flying Height	Ortho Tile Size
½ foot	1"=100'	3,600 feet	2,500' x 2,500'
1 foot	1"=200'	7,200 feet	5,000' x 5,000'
2 foot	1"=400'	14,400 feet	10,000' x 10,000'

Product Orientation:

Horizontal

Datum: NAD 83/93 (HARN)

Vertical Datum: NAVD 88 vertical datum with NGS Geoid 99 model used in derivation of orthometric heights.

Coordinate

System: Virginia State Plane North and South zones

Units: US Survey Feet.

Vita

Christopher Wayne Stahl was born in Johnstown, Pennsylvania on December 4, 1979. He is the older of two sons raised by Larry and Joanne Stahl. In 1999 he received his Associates of Applied Science in Geographic Information Systems from Cambria County Area Community College. In 2001, he completed his Bachelors of Science in Regional Planning at Indiana University of Pennsylvania. While at Indiana University of Pennsylvania he worked at the University's Spatial Science Research Center as a Research Assistant on various GIS projects. Before graduating he was hired at BAE Systems in Pittsburgh, PA as a Photogrammetric Editor. In November of 2001, Southern Alleghenies Planning & Development Commission had hired him as a GIS/Transportation Planner in Altoona, PA.

In August 2003 he was offered a Graduate Teaching Assistantship to pursue a Master's Degree in Geography at Virginia Tech. In 2004 he began a Graduate Research Assistantship through the Joint Unmanned Systems, Test, Experimentation, and Research (JOUSTER) which is run by Virginia Tech's Department of Mechanical Engineering. Christopher was awarded a 2005 A.B. Massey Award in recognition of superior performance and professionalism while a graduate student, and also was a recipient of a 2005 research award in recognition of outstanding achievement from Virginia Tech's Sigma Xi Chapter. Following graduation, Christopher will be moving near Washington DC to pursue a career in geospatial intelligence and research under the US Department of Defense.