DETERMINING WHERE INDIVIDUAL VEHICLES SHOULD NOT DRIVE IN SEMIARID TERRAIN IN VIRGINIA CITY, NV

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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Abstract

This thesis explored elements involved in determining and mapping where a vehicle should not drive off-road in semiarid areas. Obstacles are anything which slows or obstructs progress (Meyer et al., 1977) or limits the space available for maneuvering (Spenko et al., 2006). This study identified the major factors relevant in determining which terrain features should be considered obstacles when off-road driving and thus should be avoided. These are elements relating to the vehicle itself and how it is driven as well as terrain factors of slope, vegetation, water, and soil. Identification of these in the terrain was done using inferential methods of Terrain Pattern Recognition (TPR), analyzing of remotely sensing data, and Digital Elevation Map (DEM) data analysis. Analysis was further refined using other reference information about the area. Other factors such as weather, driving angle, and environmental impact are discussed. This information was applied to a section of Virginia City, Nevada as a case-study. Analysis and mapping was done purposely without field work prior to mapping to determine what could be assessed using only remote means. Not all findings from the literature review could be implemented in this trafficability study. Some methods and trafficability knowledge could not be implemented and were omitted due to data being unavailable, un-acquirable, or being too coarsely mapped to be useful. Examples of these are Lidar mapping of the area, soil profiling of the terrain, and assessment of plant species present in the area for driven-over traction and tire punctures. The Virginia City section was analyzed and mapped utilizing hyperspectral remotely sensed image data, remote-sensor- derived DEM data was used in a Geographical Information Systems (GIS). Stereo-paired air photos of the study site were used in TPR. Other information on flora, historical
weather, and a previous soil survey map were used in a Geographical Information System (GIS). Field validation was used to check findings.

The case study’s trafficability assessment demonstrated methodologies of terrain analysis which successfully classified many materials present and identified major areas where a vehicle should not drive.

The methods used were: Manual TPR of the stereo-paired air photo using a stereo photo viewer to conduct drainage-tracing and slope analysis of the DEM was done using automated methods in ArcMap.

The SpecTIR hyperspectral data was analyzed using the manual Environment for Visualizing Images (ENVI) software hourglass procedure. Visual analysis of the hyperspectral data and air photos along with known soil and vegetation characteristics were used to refine analyses. Processed data was georectified using SpecTIR Geographic Lookup Table (GLT) input geometry, and exported to and analyzed in ArcMap with the other data previously listed.

Features were identified based on their spectral attributes, spatial properties, and through visual analysis. Inaccuracies in mapping were attributable largely to spatial resolution of Digital Elevation Maps (DEMs) which averaged out some non-drivable obstacles and parts of a drivable road, subjective human and computer decisions during the processing of the data, and grouping of spectral end-members during hyperspectral data analysis.
Further refinements to the mapping process could have been made if fieldwork was done during the mapping process.

Mapping and field validation found: several manmade and natural obstacles were visible from the ground, but these obstacles were too fine, thin, or small to be identified from the remote sensing data. Examples are fences and some natural terrain surface roughness – where the terrain’s surface deviated from being a smooth surface, exhibiting micro-variations in surface elevation and/or textures. Slope analysis using the 10-meter and 30-meter resolution DEMs did not accurately depict some manmade features [eg. some of the buildings, portions of roads, and fences], evident with a well-trafficked paved road showing in DEM analysis as having too steep a slope [beyond 15°] to be drivable. Some features had been spectrally grouped together during analysis, due to similar spectral properties. Spectral grouping is a process where the spectral class’s pixel areas are reviewed and classes which have too few occurrences are averaged into similar classes or dropped entirely. This is done to reduce the number of spectrally unique material classes to those that are most relevant to the terrain mapped. These decisions are subjective and in one case two similar spectral material classes were combined. In later evaluation should have remained as two separate material classes. In field sample collection, some of the determined features; free-standing water and liquid tanks, were found to be inaccessible due to being on private land and/or fence secured. These had to be visually verified – photos were also taken. Further refinements to the mapping could have been made if fieldwork was done during the mapping process.
Determining and mapping where a vehicle should not drive in semiarid areas is a complex task which involves many variables and reference data types. Processing, analyzing, and fusing these different references entails subjective manual and automated decisions which are subject to errors and/or inaccuracies at multiple levels that can individually or collectively skew results, causing terrain trafficability to be depicted incorrectly. That said, a usable reference map is creatable which can assist decision makers when determining their route(s).
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1 Introduction

Questions Addressed

1) What makes an area non-trafficable or "NoGo"?
2) In semiarid land trafficability analysis, what is needed to locate non-driveable terrain areas?
   a. What information is relevant for semiarid land trafficability analysis and which data must be included to do off-road semiarid terrain analysis?
   b. What factors need to be considered to assess vehicle trafficability in semiarid terrain?
3) How do you map the non-drivable areas in a semiarid environment?
   a. What methodologies are needed to locate and to map non-trafficable areas?
   b. Is there an order or order of precedence to these methodologies?
4) How do you assess terrain slope?
5) What is Terrain Pattern Recognition (TPR) and how can it be used in trafficability assessments?
6) What is Remote Sensing (RS), what does RS image data provide, and what kinds of imagery are most useful in trafficability analysis?
7) What are Geographical Information Systems (GIS) and how can they be used to determine and map trafficability in semiarid terrain?

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1.0 Introduction

This thesis investigated the terrain elements and vehicle characteristics that determine where vehicles should not drive off-road in semiarid areas. This study reviewed the factors that are obstacles in terrain to off-road driving, what makes them obstacles, methods of locating them remotely by their attributes, other’s findings, and terrain characteristics utilizing tools available and deductive analysis.

Obstacles are anything that slows or obstructs progress (Meyer et al., 1977) or limits the space available for maneuvering (Spenko et al., 2006). Knowledge of terrain elements and obstacles, identified by vehicle characteristics, was applied to assess the trafficability of a section of Virginia City, Nevada as a case-study. The Virginia City section was studied and mapped utilizing remotely sensed image data along with Digital Elevation Mappings (DEMs), and Geographical Information Systems (GIS) tools. Field validation was used to check materials classes derived from airborne hyperspectral data, Terrain Pattern Recognition (TPR) analysis of the area, slope analysis of 10-meter and 30-meter Digital Elevation Maps (DEMs), and the two NoGo mappings which used the two slope analyses separately with the hyperspectral materials classification.

The case study showed misclassification of terrain slope, inability to perceive some obstacles – such as fences and telephone poles, and assessed some areas as non-trafficable which were used as vehicle roads. These inaccuracies were found during field verification and attributed to known sensor characteristics and limitation in resolution, data fusion compatibility issues, and subjective human and computer decisions.
The NoGo trafficability map generated for Virginia City, NV was field checked and found to identify many obstacles a vehicle would face when off-road driving in a semiarid environment, however it did not identify all obstacles and misscategorized some drivable terrain.

Questions addressed:

1) What makes an area non-trafficable or “NoGo’’?

2) In semiarid land trafficability analysis, what is needed to locate non-drivable terrain areas?
   a. What information is relevant for semiarid land trafficability analysis and which data must be included to do off-road semiarid terrain analysis?
   b. What factors need to be considered to assess vehicle trafficability in semiarid terrain?

3) How do you map the non-drivable areas in a semiarid environment?
   a. What methodologies are needed to locate and to map non-trafficable areas?
   b. Is there an order or order of precedence to these methodologies?

4) How do you assess terrain slope?

5) What is Terrain Pattern Recognition (TPR) and how can it be used in trafficability assessments?

6) What is Remote Sensing (RS), what does RS image data provide, and what kinds of imagery are most useful in trafficability analysis?

7) What are Geographical Information Systems (GIS) and how can they be used to determine and map trafficability in semiarid terrain?
Relevance

Off-road semiarid driving is done by many people for a variety of reasons. It is often not possible to visually determine the degree of difficulty of a given route when in the field (Allen, 2002). Being able to identify hazardous areas in advance of an expedition will reduce travel time, maximize fuel economy, and save lives.

This research is to determine if successful off-road semiarid driving can be better assured using a trafficability map. Terrain trafficability maps help determine:

1) If the vehicle can successfully travel through the terrain at all.

2) Drivable areas, allowing a path to be planned which avoid hazards, meet goals, and improves survivability.

3) In the field, if questionable areas are actually drivable and in maneuvering decisions.

1) What makes an area non-trafficable or “NoGo”?

Vehicle

The vehicle is the key element that determines what is not trafficable. The vehicle is the key element with the exception of man-defined restricted areas. Vehicle types, weight, weight distribution, attributes, and abilities are factors in this determination.

Additionally, how the vehicle is driven also affects its off-road performance.

How the vehicle interacts with the terrain influences which areas should be avoided. Soil, vegetation, clay-rich soil, surface water and slope are factors involved in vehicle-
terrain interaction, with moisture and climate as primary influencers because they alter the physical properties of terrain.

**Obstacles**

For off-road semiarid driving, progress is forward motion on a chosen path (Spenko et al., 2006). Therefore, an obstacle is defined as anything that slows or obstructs progress (Meyer et al., 1977) or limits the space available for maneuvering (Spenko et al., 2006). Not all objects protruding out of the ground are dangerous obstacles (Jansen et al., 2005). Some objects may appear to be obstacles, such as bushes, but are actually conquerable.

In semiarid driving, one of the most common and demanding tasks in terrain trafficability analysis is the discrimination of true obstacles. Inability to distinguish between bushes and rocks leads to unnecessary detours around transversable vegetation and/or collisions with impassable rocks classified as trafficable vegetation (Kelly et al., 2006). Other obstacles, if approached at a fast enough speed, may be “jumped”. Examples are shallow ditches (Spenko et al., 2006) and small earthen berms.

There are five primary physical obstacle types to movement: 1) vegetation, 2) surface irregularities – known as microliefs, 3) surface water, 4) slopes steepness beyond vehicle capability, and 5) cultural features – manmade / man-altered (Rula et al., 1963).

Some of these only become an obstacle when influenced by weather or are found in large quantities.
2) In semiarid land trafficability analysis, what is needed to locate non-driveable terrain areas?

a) What information is relevant for semiarid land trafficability analysis and which data must be included to do off-road semiarid terrain analysis?

To determine non-drivable areas, many different sources of data are available. Digital Elevation Maps (DEMs) provide slope information, multispectral and hyperspectral imaged data are usable for materials classification, historical weather data provides seasonal and regional weather patterns, aerial photos will provide geographic and vegetation information, and other historical and current sources will contribute additional relevant information.

Approach

In the Virginia City case study, airborne hyperspectral data, Digital Elevation Mappings (DEMs), aerial black and white photos, and satellite-derived digital orthoquadrangles (DOQs) were used. The non-drivable areas were determined, identified, located, and mapped, with field validation done afterwards to check findings.

b) What factors need to be considered to assess vehicle trafficability in semiarid terrain?

Weather - Water

Weather influences the terrain. Moisture, in the form of precipitation, can cause major changes in trafficability by causing vegetation to become slippery when wet, slowing or halting movement (US Army, 1994). Even on dry, firm soil, a significant traction loss
can occur with as little as only 0.25 inches of rainfall (Moore, 1989). A large enough presence of water can reduce soil’s shear strength, causing it to become a muddy, sticky, and slippery - making it difficult or impossible to drive through (Barton et al., 2000) or climb slopes (Moore, 1989).

Flash flooding is not uncommon in semiarid areas. Semiarid soil is not accustomed to water absorption, and has a tendency to flash flood in some areas which are hazardous to driving because they block areas from being crossed without the vehicle getting slowed, stuck, buried, or swept away. Stoddard (2001) recommended that areas prone to flash floods should be avoided because even heavy military transport vehicles have been carried downstream during floods in water just two feet deep.

**Vegetation**

Vegetation is another obstacle when off-road driving. It can grow large and/or dense making some areas slow-going or impassable. Even in cases where vegetation can be pushed over by a vehicle, the resulting pile-up of vegetation may halt movement (U.S.Dept.of The Army, 1990).

**Soil**

The trafficability of soil is defined as a soil’s capability to permit the movement of a vehicle (Bassett and Meyer, 1968). Off-road driving vehicles are primarily affected by a “critical layer” of soil that exists within the first 15 inches in depth from the soil’s surface. Which parts of this first 15 inches that most directly relates to the chosen vehicle
is based on vehicle weight and soil type (Bassett and Meyer, 1968; Rula et al., 1963; US Army, 1994). Remote sensing is largely unable to reach and assess the soil beyond the top surface layer.

**Driving**

Vehicle performance in regard to obstacles is not always easily determined. The Vehicle’s approach to obstacles, its ground clearance, and its center of balance influence the outcome.

**Obstacles**

Some hazardous obstacles are easily detectable such as surface water and steep slopes. These areas should be avoided because the depth of water features is often very difficult to determine (US Army, 1997) and steep slopes can cause stalls, rollovers, and slideslip (Shoop et al., 2005; Stahl, 2005).

**Tracks**

Roads and tracks present in the area may be useful in supporting it as trafficable or non-trafficable\(^1\). Presence and level of success in crossing the terrain, derivable from the track pattern, can indicate areas as drivable, difficult, or NoGo.

\(^1\) Vehicle tracks, in semiarid environments, can last for tens to hundreds of years (Belnap and Warren, 2002).
Environmental Impact

Off-road semiarid driving damages the environment. Even a single vehicle pass changes the physical properties of the terrain for any vehicle which follow or crosses its tracks. The level of damage is influenced by the maneuvers done (Grahn, 1991; Hansen and Ostler, 2005; Rula et al., 1963; Rula et al., 1963; Affleck, 2005; Halvorson et al., 2001), the weather during drive-over (Affleck, 2005; Hansen and Ostler, 2005), and the vegetation present (Hansen and Ostler, 2005). Even single passes cause major environmental damage (Grantham et al., 2001; Hansen and Ostler, 2005; Lacey et al., 2001; Taylor, 2002).

3) How do you map the non-drivable areas in a semiarid environment?

a) What methodologies are needed to locate and map non-trafficable areas?

A systematic approach using a process of terrain exclusion was used to determine non-trafficable areas. By eliminating non-drivable terrain in each step, the following methodologies could be used to focus on the remaining terrain.

b) Is there an order or order of precedence to the methodologies?

Based on the writer’s observations, methodologies for terrain elimination are as follows:

- The first methodologies are the ones with the most concrete results of Go / NoGo.
- Then the more subjective assessments which involve more complex subjective decisions to decide Go / NoGo.
- Then known trafficable areas are included in the assessment to override the previous assessments.
Lastly, human-imposed restrictions are added as these have nothing to do with actual terrain trafficability but which must be excluded from consideration as areas for driving.

**Assessment Order**

1. Slope
2. Water
3. Vegetation
4. Soil for clays
5. Known trafficable areas – which will override areas deemed non-trafficable by other assessments
6. Other – (human-restricted areas, known hazards, etc..)

Note: Areas initially determined as non-drivable, based on degree of slope, were found with field validation to have drivable areas. This result was attributed to the DEM dataset spatial resolution limitations.

**4) How do you assess terrain slope?**

**Slope**

The maximum slope a vehicle can handle is influenced by its center of gravity, engine capabilities, tires or tracks, weight, and environmental factors (Rula et al., 1963). Slope steepness is primarily limited by the vehicle’s tire-terrain adhesion (Wong, 2001) and effective driving vector. The effective slope angle can be increased or decreased by adjusting the driving direction of the vehicle in reference to the slope. This can also change some of the dynamics of the effective slope angle. Laterally addressing a slope
can reduce its effective steepness; however, chances of rollover and sideslip increase (Shoop et al., 2005; Stahl, 2005); addressing a slope other than straight at the slope is not recommended (Sheppard, 1988).

Down slopes have an effectively greater load applied to them than up-slopes for both wheeled and tracked vehicles. On a downslope, deeper rutting occurs which effectively increases the slope angle, which in turn may hinder or prevent turning, causing the vehicle to overturn or stop in its tracks due to increased rolling resistance (Rula et al., 1963).

Suvinen (2006) found slopes became a limiting factor at 15-20° climbing uphill and 25-30° when descending, and on lateral inclines of greater than 8.5°, subject to the vehicles unique attributes, load size, soil type and the soil’s adhesion. Shoop et al. (2005) used a slope gradient of more than 30° to determine “NoGo” areas. In the Virginia City case study slopes of 15°+ were used as criteria to eliminate areas beyond vehicle abilities.

5) **What is Terrain Pattern Recognition (TPR) and how can it be used in trafficability assessments?**

**Terrain Pattern Recognition (TPR)**

Terrain Pattern Recognition (TPR) is a method of reading the physical expressions of the land’s surface to derive its underlying attributes. TPR may be useful in identifying areas susceptible to flash flooding by examining landforms and drainage patterns. Landforms are the physical expression of the land surface (U.S.Dept.of The Army, 1990). They are
terrain features formed by natural processes having a consistent and definable range of characteristics and composition. Landform types reflect similar subsurface terrain conditions. TPR is based on the fact that similar landforms under similar conditions contain the same combinations of element patterns. This allows an analyst to derive conclusions and gain an understanding of its physical properties and conditions once landform patterns are recognized. Much of the information needed to TPR does not exist and must be interpreted using airborne remotely sensed photos (Way, 1978; U.S. Dept. of The Army, 1990), maps, literature and other sources (U.S. Dept. of The Army, 1990).

Remote sensing can be used to indirectly infer information about the study area landform and its subsurface through inferential interpretation (Way, 1978). Stream erosion patterns, “drainage patterns”, usually provide an indication of the rock structure and composition and indicate whether the region is underlined by one of several rock types (U.S. Dept. of The Army, 1990). Many of these patterns are on such a large scale that they may be missed during conventional ground surveys. Studying and interpreting visual elements relating to a landforms origin, morphological history, and composition requires a systematic analysis (Way, 1978). This technique was applied to the case study area of Virginia City, NV.
Study area: Virginia City TPR

A drainage pattern trace of the Virginia City, NV area was made using two aerial stereo-paired air photos taken by the USGS on June 27, 1948. Drainage patterns are consistent with a medium to fine dendridic drainage pattern (see Appendix C).

Based on Way (1978), this pattern indicates the topography to be characterized by steep sideslopes and high amounts of desiccation reflecting the rock’s soft nature. Other attributes associated with the level of precipitation typical of Virginia City, NV are rounded ridgelines and the possibility of faint bedding planes being visible along hillsides. This terrain reflects rapid runoff. Soil coloration and tonal differences are based on different mineralogical compositions instead of differences in texture. The TPR pattern (see Appendix H) indicates depth of soil cover may range from little soil cover to coverage of a few feet, with greater soil cover depth to be found along the lower slopes and hills from which the materials have been removed and moved downslope by creep, frost action, and erosion.

6) *What is Remote Sensing (RS), what do RS image data provide, and what kinds of imagery are most useful in trafficability analysis?*

**Remote Sensing**

Remote Sensing is the collecting and storing of information without any actual contact with the object or area that is being investigated (Answers Corporation, 2009). There is no defined distance for remote sensing, the only criteria is that the sensor is not touching what is being measured/observed (Jensen, 2006).
Remote sensing tools are successfully used to map, assess, and analyze different terrain and landscape patterns (e.g. landforms, drainage, and cover types): terrain topography\(^2\), vegetation – location and attributes\(^3\), soil - composition and moisture\(^4\), water-features\(^5\), manmade features\(^6\), erosion\(^7\), land usage\(^8\), obstacle detection\(^9\), flash-flood zones\(^10\), patterns\(^11\), and changes\(^12\). The Virginia City, NV case study utilizes some of these abilities in its trafficability assessment.

Remote Sensors are usually measure reflected or emitted electromagnetic energy in Electromagnetic (EM) wavelength bands from the surfaces of materials (Appendix C). Measurements are made from airborne or spaceborne platforms. Sensor measurements are dependent on radiometric, spatial and spectral resolution.

The kinds of remotely sensed data which are most useful in trafficability analysis are:

- Multi-band spectral imagery (multispectral and hyperspectral)
- Digital Elevation Mapping (DEM)

\(^2\) (Koukoulas and Blackburn, 2005; Lefsky et al., 2002; Glenn et al., 2006)
\(^3\) (Verstraete and Pinty, 1991; Kemmouche et al., 2004; Breidenbach et al., 2008; Riaño et al., 2003; Xiao et al., 2002)
\(^4\) (Ben-Dor and Banin, 1990; Ben-Dor and Banin, 1995b; Ben-Dor and Banin, 1995a; Ben-Dor et al., 2002; Jackson and Schmugge, 1989; Csillag et al., 1993)
\(^5\) (Ben-Dor et al., 1997; Mounton, 2005)
\(^6\) (Michaelsen et al., 2006; Kim and Muller, 1996)
\(^7\) (Carlson and McDaniel, 1967; Stevens, 1988; Ben-Dor et al., 2003; Hunt Jr. et al., 2003; Glenn et al., 2006)
\(^8\) (Xiao et al., 2002; Hunt Jr. et al., 2003; Xiao et al., 2002)
\(^9\) (Kelly et al., 2006; Macedo et al., 2000; Manduchi et al., 2005; Puntambekar, 2006; Spenko et al., 2006)
\(^10\) (Foody et al., 2004)
\(^11\) (Michaelsen et al., 2006; Glenn et al., 2006)
\(^12\) (Michaelsen et al., 2006; Nelson et al., 2005; Rosin and Hervas, 2005; Glenn et al., 2006)
**Multispectral and Hyperspectral Sensors**

In multi-spectral and hyperspectral remote sensing, measurements are taken simultaneously across different wavelengths of the EM spectrum and represent the terrain at time of imaging. Both sensors assess bands of the EM spectrum, the fundamental definition difference is that a multispectral sensor measures tens of spectral bands (regions) while a hyperspectral sensor measures 100+ spectral bands (Stork et al., 2006; Hsieh and Landgrebe, 1998; Jensen, 2006). Hyperspectral sensing is a newer technique which delivers near-laboratory-quality reflectance spectra for each individual pixel, allowing the analyst to do identification utilizing well-known spectral absorption features (Goetz et al., 1985; Ben-Dor et al., 2002). These sensors depict find individual absorption features, which can be used to group terrain into classes or types (Ben-Dor et al., 2002) usable for trafficability assessments.

Pure substances show consistent spectral properties. There are few cases where pure substances exist in nature, most terrain cover is a mixture of material cover types (e.g.: soil with vegetation, water and soil, etc…). In remote sensing analysis, the main objectives are to determine what the majority cover type is of each pixel and locating similar pixels to be grouped into material class groups.

Pixels in remote sensing data of mixed terrain are often due to substances occupying the same space, (e.g. vegetation ground cover over soil) (Vaughan et al., 2001) and/or the resolution of the sensor used – presenting things within a specific distance from one another as a collective assessment in the form of a single pixel with one spectral signature.
that is a mixture of the materials collectively imaged. Studies to see if these mixed pixels are analyzable enough to distinguish separate components have been attempted with some success (Sabol et al., 1992).

In remote sensing and GIS, spatial resolution is a reference to the Ground Sample Distance (GSD) which describes how much of the Earth’s surface is collectively in a single pixel (Wikimedia Foundation, 2009). Frankin and Wulder separated spatial resolution into three categories: coarse as 250+ meters (m), medium 30-250 m, and fine as 1-30 m (Frankin and Wulder, 2002), though even finer resolution than 1 m is available.

Radiometric resolution is a measurement of how finely a system can distinguish or differentiate levels of intensity of intensity or reflectivity. While spectral resolution involves how many different wavelengths or spectrum are detected and differentiable (Wikimedia Foundation, 2009). Resolution affects the quality of analysis that is possible.

Each pixel of a multispectral or hyperspectral image has a spectral signature. The spectral response of a substance in specific spectral bands can be used to narrow down what a substance is or is not. No single spectral band separates all classes of surface cover from one to another with some EM regions being more helpful than others. Closely matching spectral signatures with positively identified spectra helps to determine what the terrain depicted within each pixel’s main components are. Numerous spectral bands are not necessarily required to determine a substance’s main composition (Ben-Dor et al., 2002). For example, when green shrubs and trees are present in enough density they are easily identifiable in their reflectance within the VIS / NVIS region due to their
distinct spectral signature (Salisbury and D'Aria, 1994). Step-by-step procedures utilizing only a limited number of select spectral bands can largely separate different cover classes (Pickup et al., 2000; Herold et al., 2005).

Remote sensing image data provides an overview of what is imaged that is more rapidly acquired and less invasive than field surveying methods. Remote sensing data is versatile and customizable. It can provide information about the materials, slope, and the topography imaged. Remote sensing is easily incorporated into combined GIS analysis which assesses terrain for material classification and trafficability.

In trafficability assessments, the remote sensing data that is the most useful are DEMs - for slope and topography, and hyperspectral and multispectral imagery - for classifying materials. Air photos are also very useful for identifying terrain topographic features and some materials classes.

**Digital Elevation Map (DEM)**

A Digital Elevation Map (DEM) is surface terrain that has been digitally represented using an array of individually identified points (Solé et al., 2004). Each point of the DEM corresponds commonly to an east-west (x), north-south (y), and elevation (z) coordinate (Raaflaub and Collins, 2006) representing a terrain ground-point position in three-dimensional space (Solé et al., 2004). Depending on the sensor used, the point represented may be an area average or be point elevations, the coarseness of both relate to the image’s resolution (Solé et al., 2004). Currently DEMs are made almost exclusively
from analyzed remotely sensed data (Jensen, 2006), typically radar and Lidar (Koukoulas and Blackburn, 2005). GIS applications can conduct slope and terrain analysis on these DEMs as well as generating 3-dimensional (3-D) terrain representations.

One of the primary limiting factors for off-roading vehicles is steep slopes (Rula et al., 1963), which can be found using a DEM and a GIS (ESRI, 2006). DEMs of 10-meter and 30-meter resolution were used in the Virginia City, NV case study.

**DEM Accuracy, Errors & Issues**

DEM generation commonly have “artificial” topographic features created by some points becoming overly elevated [dams / peaks] and in other cases, where points have no neighboring points with lower elevations, pits occur. Both of these features creating topographic slopes that do not accurately represent terrain. These errors need to be identified and removed. This can be done manually, though time consuming and labor intensive, or through more automated methods (Raaflaub and Collins, 2006).
Hammer et al. (1995) found that maps derived from 10-meter DEM data are more accurate than maps made from 30-meter DEM data and that slope classes derived from the 30-meter DEM commonly underestimated slopes on concaved areas and overestimated them on convexed regions. Soil surveys and 30-meter maps derived from the 30-meter DEM both overestimated all slopes except the steepest ones (Hammer et al., 1995). The Virginia City, NV case study also identified slope analysis problems with both the 10-meter and 30-meter DEM data used.

DEMVs are useful in visualizing and analyzing terrain, especially when used for slope, aspect, and hillshades (Stahl, 2005). It is noteworthy that Berry (2003) found different slope measurements were generated by different algorithms. Implying that slope accuracy by any or all algorithms may have inherent errors. Discrete computer-generated maps of slope classes needs to be verified with “ground-truthing”, done by field verification of the data (Hammer et al., 1995).

7) **What is GIS and how can it be used to determine and map trafficability in semiarid terrain?**

**Geographical Information Systems (GIS)**

The computer software and hardware applications that deal with the storage, processing, analysis, and display of spatial data are collectively known as GIS. Remote sensors typically acquire large amounts of spatial and spectral data that requires processing and analysis to provide useful information. GIS is able to compile, store, analyze, correct, and integrate these large quantities of information. They allow users to manipulate,
combine, and analyze spatially referenced geographic and remotely sensed data. They can create graphical depictions of what is imaged in various visual formats (Bonham-Carter, 1998).

GIS is used for enhanced processing, analysis, and creation of vegetation maps (Demers, 1991; Koukoulas and Blackburn, 2005), soil assessment and analysis (Altinbas et al., 2005; Eshel et al., 2004), topographic mapping (Sties et al., 2000) slope assessment (Hammer et al., 1995; Breidenbach et al., 2008), visualization (Koukoulas and Blackburn, 2005), water feature recognition, mapping and prediction (Frankenstein and Koeing, 2004; Semen, 2006), and conducting spatial calculations (Qiang et al., 2007).

In the field of remote sensing, these tools are also used to view, integrate, analyze, detect and/or correct anomalies, and spatially rectify data generated by remote sensors. GIS stores and provides access to multiple data sets simultaneously or in select groupings for analysis and display. These capabilities allow users to conduct analysis previously impossible or too time and/or labor intensive to be practical. It is these abilities that make GIS one of the best tools for determining the makeup and condition of a studied area for determining where not to drive. GIS can be used to determine the majority of terrain characteristics required to find most of the areas where one should not drive in semiarid regions.
Methodology for trafficability assessments using GIS

A systematic approach is required to most effectively identify terrain areas which are NoGo and slow-go (Rula et al., 1963). GIS can be used to conduct most of the analysis steps automatically, though human involvement is often used because current automated image recognition techniques are not equivalent to human abilities (Adams, 2003) and often users prefer to have some control over the process (Bateson and Curtiss, 1996).

Data Fusion

Using data from multiple sources can yield collectively more information than separately; this concept is known as data fusion (Kelly et al., 2006). Different sensors are able to characterize terrain features better in some ways than others while being unable to determine attributes which a different sensor can provide. Other data (botanical references for the area, mining mineral records, maps drawn from field mapping, etc...) created by non-remote sensors may also be complimentary to determining where not to drive. Using these for analysis in a GIS can yield better results, but may also inherit additional unwanted qualities due to collective errors caused by data fusion and problems with geo-registration of data.
**Data Fusion: Issues**

“The benefits of longer term data fusion eventually becomes drawbacks due to the effects of blur” (Kelly et al., 2006).

A major problem is that any two sources can be spatially distanced off by hundreds of feet, which poses problems when high resolution is a critical factor (Adams, 2003). In determining where not to drive, resolution and accuracy are critical, as shown in the Virginia City, NV case study. Fusion of data that is not spatially the same can and will distort the results, reduce overall accuracy, and affect a drivability assessment.

**Data Fusion: Mitigation of Issues**

To maximize the benefits of data fusion and minimize the problems associated with it, it is necessary to:

1) accumulate and use no more data then necessary.

2) exploit Signal Properties separately then merge the findings together.

3) have the data acquired oriented in the best possible way for your targeted results – possible if you have control of the sensor capturing the image (Kelly et al., 2006).
Analysis of spectral data with GIS

GIS can use data from a wide variety of sources. Known historical references of an area, information from other GIS sources - such as road and fence-line data files, and spectral data collected by remote sensors can be compiled and utilized in a GIS system providing a more accurate assessment of a region. Analysis using these multiple sources, examined collectively, or in select combinations can help the user determine where hazardous and off limit areas are. In a mapped trafficability assessment, the terrain will visually show areas that are hazardous and areas that should be good to drive. This in-turn allows a user to figuring out if the area is drivable by their vehicle and their best path.

By analyzing electromagnetic (EM) spectral signatures, slopes derived from DEMs, historical references (field studies and weather recordings, and topographic information about nearby terrain), and TPR of aerial photos general terrain characteristics can be deduced. These deduced features of drainage patterns, slopes, vegetation, standing water, buildings and roads, etc… can be used in assessing the terrain’s trafficability.

Different terrain features have unique spectral attributes which allows their identification to be easier in certain bands of the EM spectrum (Adams, 2003). Other cues like geometric shape, color, and texture can also aid in terrain and terrain features classification (Iagnemma and Dubowsky, 2002). These distinct attributes allow for identification, mapping, and analysis.
Once the different data sets are loaded into the GIS analysis can be conducted by the user. They can examine each of the data sets and filter them by distinct attributes, grouping them into class-types and then creating shapefiles of the NoGo areas. NoGo areas can collectively be unionized together and then known trafficable areas subtracted from it. This combined shapefile can then be visually shown in GIS on a map, image, or a 3-dimensional projection of the terrain.

Depending on the type and resolution of data available, a user can identify known or visible obstacles and mark them within the GIS database along with an indicator of their level of hazard. Areas such as privately owned land, country boundaries, and mine-fields are examples of man-imposed areas likely marked as NoGo regions regardless of their actual level of trafficability.

Remote sensing data is versatile and customizable. It is easily incorporated into combined GIS analysis which assesses terrain for material classification and trafficability.

The end trafficability product should provide a reference to decision-makers to allow them to make educated decisions regarding 1) if their vehicle is capable of driving in the terrain and 2) planning a path which accomplishes their goals while minimizing: fuel, risk, and waste of time.
2.0 Case Study Area: Virginia City, Nevada

Objective: Illustrate the process by which a map is created of where not to drive using only remote means and the validation procedures of the map.

1) Create a map of where not to drive in largely unimproved semiarid terrain using known vehicle characteristics and terrain data characteristics, derived from airborne remote sensing image data, Digital Elevation Maps (DEMs), and other relevant information utilizing GIS tools.
   a) Create representative surface cover type classes, defined by their spectral signature, which are usable in assessing trafficability.
   b) Generate slope maps from DEMs which determine slopes beyond vehicle abilities

2) Check created map for validity.
   a) Surface cover classes and slopes through field sampling and GPS point analysis

3) Determine the validity of the hypothesis that any area deemed NoGo by any determination method should be ruled as a NoGo area, regardless of the results of other assessment methods.
**Background Concepts**

Earlier in this thesis, I have reviewed the following:

1. The characteristics of the vehicle and cultural restrictions define non-trafficable areas.
2. It is advantageous to determine where not to drive before initiating any off-road vehicle expedition in unimproved semiarid terrain.
3. To identify where not to drive, it is essential to know the attributes and characteristics of the chosen vehicle and the terrain being considered.
4. There are many drivability obstacles and restrictions in unimproved semiarid terrain. Identifying and locating them requires insight into analysis of what is an obstacle for the vehicle, information about the area, access to sources of data collected over the chosen site and GIS tools to successfully identify and map them.
5. Acquiring, processing and analyzing terrain data from airborne remote sensing and other sources is not a fully automated process and it requires human subjective decision-making and intervention.
6. Multiple factors will likely cause the map not to reflect true field conditions.
   a. Seasonal variation
   b. Weather effects
   c. Time-delay in processing from collection
   d. Limitations of present technology in GIS integration
   e. Remote sensing resolution
f. Terrain representation inaccuracies

g. Other…

7. Enough information about where not to drive in the terrain must be determined to allow a user to:

   a. Determine if their vehicle can drive through the terrain

   b. Avoid most obstacles when route planning and when driving.

**Summary of process**

The main components of the process for making a where-not-to-drive terrain map are:

1) Identifying vehicle characteristics because they determine what is an obstacle.

2) Collect data that will help to identify terrain and obstacles in terrain.

3) Use GIS with relevant data to find obstacles, mark hazardous areas, and graphically depict the terrain with hazards visually marked.

4) Check mapping against other sources, including field data, to validate accuracy.

**Procedure**

1. For this case study, vehicle limitations/restrictions used were: 15+ degrees of slope and vegetation over 2 feet tall and having a stem-diameter of more than 4 inches being beyond vehicle driving capabilities.

2. Location of Case Study: Virginia City, Nevada

3. Identify required relevant data

   a. Airborne remote sensing data
i. SpecTIR airborne hyperspectral reflectance and radiance data sets of Virginia City, NV - flown August 17th, 2007.

ii. Two USGS stereo-paired images of Virginia City, NV flown on June 27, 1948 – for pattern analysis.

b. Digital Elevation Maps
   i. 10-meter W.M. KECK online archive [http://keck.library.unr.edu/]
   ii. 30-meter W.M. KECK online archive [http://keck.library.unr.edu/]

c. Local soil data
   i. Preliminary Geologic Map of the Virginia City Quadrangle, Nevada (Chaney et al., 2002)

d. Local flora information – Whitebread (1976)

e. Local historical weather data
   i. Desert Research Institute (DRI): Western Regional Climate Center (DRI, 2008)
   ii. Western Nevada Climate Survey - Virginia City, NV Climate Summary (WRCC, 2008)

f. Known obstacles & restrictions
   i. Bodies of water
   ii. Natural obstacles (canyons, thick forests, quicksand, etc..)
   iii. Manmade buildings, fences, and other obstructions
   iv. Restricted/off-limits areas

4. Process for processing
   a. Hyperspectral data – SpecTIR airborne Hyperspectral data
i. Process Radiance data set in RSI ENVI to spectrally identify

1. Free-standing water – manual Regions of Interest (ROIs) selection on obvious H2O

2. Vegetation – N-d Visualizer or manual ROI selection on obvious vegetation

3. Manmade
   a. Obstacle (structures, fences, etc..)
   b. Roads – paved, unpaved, and tracks

4. Soils – specifically clays

ii. Visually verify correct spectral associations

iii. Cross-check with information about the local area to further vet findings

iv. Spectral Angle Mapper (SAM) identified spectra

v. Georectify from input geometry using SpecTIR Geographic Lookup Table (GLT)

vi. Create Regions of Interest (ROIs) of each spectral class

vii. Convert ROIs to shape files

viii. Import shapefiles to ArcMap

b. Slope analysis of 10-meter and 30-meter DEM data in ArcMap using max slope of vehicle as criteria for selecting terrain that is too steep to off-road drive – creation of slope too-steep layer files from 10m and 30m DEM data.

5. GIS & Fusion
a. Create two NoGo shapefile overlay files - one using 10-meter and the other 30-meter DEM data analyzed for slope. Displayed in 2D in Plates # 4 and Plate #5.

b. Display class shapefiles in ArcScene overlaid onto 3-dimensional (3D) rendering of terrain using hillshade derived from a DEM.
   i. Determine a minimum of 3 points in each class to field verify.

c. Display 10-meter NoGo overlay on 3D rendering of terrain using hillshade derived from a DEM.

d. Display 30-meter NoGo overlay on 3D rendering of terrain using hillshade derived from a DEM.

e. Display 10-meter and 30-meter NoGo overlays transparently on 3D rendering of terrain using hillshade derived from a DEM.

6. Field validation
   a. Check selected points by collecting samples from each of the material classes and GPS points, using a handheld GPS, to document sample locations and for use in evaluating slope analysis.
b. Take digital photos to document view from the ground and visually validate classes and slope analysis.

c. Document and log findings.

d. Bring field samples back to the spectral laboratory for spectroscopic mapping.

7. Laboratory analysis of field samples

   a. Use GPS point information to determine slope in degrees between select points. Using the change in elevation between points divided by the distance between points to determine percent of slope, then converting the percentage in slope to degrees by taking the Arc Tangent of the percentage.

   b. Compare slope in degrees between points with slope in degrees using the 10-m and 30m DEM data.

   c. Spectrally analyze field samples.

   d. Compare field sample spectra with class spectra determined from analysis of hyperspectral data prior to going into the field.

   e. Document and log findings.

   f. Make conclusions from field and lab analysis.
Fig 2.2 Study Site: Virginia City, Nevada

See Plate #1 for Larger Version

Legend
- Outline of SpecTIR Image Swath

State Boundary Data - Bureau of Land Management (BLM)
Cities Data - Nevada Bureau of Mines and Geology (NBMG)
Terrain photo - National Agriculture Imagery Program (NAIP)
Imaged Area Swath - SpecTIR LLC
**Study Site: Virginia City, NV**

The Virginia City area, is located in Story County, Nevada, ~21 miles from Reno, NV (NNDA, 2008) on the eastern side of the Virginia Range (Vaughan, 2004; Vaughan et al., 2001). Historically, Virginia City experienced ~100 years of mining for gold (Ag) and silver (Au) during the period of 1859 through the 1960s which have left the area with numerous mines, open pits, and surface mine tailings (Vaughan, 2004; Vaughan et al., 2001). Since the mid-1800s vegetation in the Virginia City Range area was stripped over time of pinyon and juniper by local inhabitants for firewood (Young and Svejcar, 1999), leaving the areas surrounding populated areas, such as Virginia City, with significantly reduced amounts of old growth vegetation.

Geology of the area consists largely of both Mesozoic metamorphic and Cretaceous granodiorite rocks overlaid by Oligocene to Miocene volcanic rock (Whitebread, 1976). Minerals such as Ag, As, Au, Cd, Co, Cu, Mo, Ni, Pb, Zn, Se, and Sb are found in this area.

The approximately centered of Virginia City is 39°18’35N 119°39’00W (Google Earth, 2007). The area is accessible using State Route 341, intersecting U.S. 395 near Reno, NV via Geiger Grade and by U.S. 50, southwest in Carson City, NV (NNDA, 2008).

Western Nevada, where the Virginia City area is located, has an arid to semi-arid climate due to the rain shadowing effect of the high Sierra Nevada mountains located to the west.
The majority of the precipitation occurs during the winter season (~13-26 inches annually (WRCC, 2008)) within the higher elevations in the form of snow. There are short wet periods with long periods of drought, during these dry periods the majority of the moisture evaporates, leaving lakebeds and stream areas dry, often with precipitated salt minerals (Vaughan, 2004).

Vegetation is typically sparse [less than 30%] except of slopes that are north-facing which can have dense vegetation [45% or greater]. The species of flora native to the Virginia City area are pinion, juniper, sagebrush, and rabbit brush. Other common, but non-native, species of flora are grass and cheat grass (Vaughan, 2004). Flora for the county of Storey, where Virginia City is located, is largely restricted to three main plant communities: the Low Sagebrush-Grass, the Big Sagebrush-Grass, and the Pinion-Juniper. The upper elevations are occupied frequently by the Pinion-Juniper, typically with an understory of antelope bitterbush and big sage. Above the Pinion Juniper Low Sagebush-Grass communities are typically found. Both big sagebrush and low sage are associated with grasses and forbs (Storey County Commissioners, 1994). Vegetation for the Storey County, Nevada region is listed in Appendix G.

Temperatures range from lows of -10°F, during the winter, to highs of 100°F in the summer, with monthly average temperatures (from 1951-2006) of 67°F in the summer and 34°F in the winter and precipitation ranges from ~13-26 inches annually (WRCC,
The precipitation amount classifies the area as semi-arid according to the Köppen-Geiger classification method (Köppen, 1936). The three collection sites in the Virginia City area were selected for field validation of the surface cover types classes determined through analysis of the SpecTIR hyperspectral data, slope assessment analysis done in ArcMap using the 10 and 30 meter DEM files, and the NoGo map generated in ArcMap using information from the previously stated analysis.

General surface cover types (Taranik, 2009):

1. Rock outcrops (including altered rock)
2. Unconsolidated rock weathering products
   a. Talus
   b. Boulders
   c. Cobbles
   d. Pebbles
   e. Sand
   f. Silt
   g. Clay
3. Soils (have a profile produced by mechanical, chemical, and/or organic processes)
4. Vegetation
5. Water
6. Culture

---

1 See Appendix F for a global climate map based on the Köppen-Geiger classification method.
7. Mixture of surface cover types

Classes identified through analysis of SpecTIR airborne hyperspectral data:

1) Vegetation - Material spectrally having a signature consistent with vegetation
2) POL\(^2\) Tank – one large POL tank
3) Twin POL tanks – two medium-sized POL tanks situated together
4) Water – free-standing water
5) Paved & Aggregate – roads, some unpaved mining roads, and located where manmade base material for construction is located.
6) Road Associated – found along edges of roads
7) Clay – Material spectrally having a signature consistent with clay materials
8) Semiarid mixture– a mixture of surface cover types consisting of a combination of unconsolidated rocks and soil ranging from silt sized to large cobble sized, and sparse vegetation (Pinus, juniper, sagebrush, and grasses).

Collection Sites

Locations for sample collection were taken from improved and unimproved areas. Three to Seven samples of each class were taken with the exceptions of the Water, POL Tank, Twin POL Tanks classes which were secured by fencing and inaccessible. GPS points were taken at collection sites and in places good for testing slope analysis generated from the 10 and 30 meter DEM. These study areas within the SpecTIR imaged area are collection site #1 (CS1), CS2, and CS3.

\(^2\) Petroleum, Oils, and Liquids
CS1 – Area centered at ~39°17′57″N 119°39′21″W. Terrain consists of unimproved and improved terrain with manmade structures, paved and unpaved roads, and mixed vegetation.

CS2 – Centered at ~39°17′32″N 119°39′28″W. It consists of unimproved terrain, improved terrain with manmade structures, paved and unpaved roads, railroad tracks, and mixed vegetation.

CS3 - Centered at ~39°16′39″N 119°39′46″W. Terrain is largely unimproved with no manmade structures, an unpaved mining road, and a mixture of vegetation consisting mostly of pine, juniper, and small shrubs scattered throughout area.
Fig 2.4 Collection Site #2 (CS2) Handheld Garmin GPSMAP 60CSx GPS-collected points taken April 30, 2009 - depicted over National Agriculture Imagery Program (NAIP) (NSMAC, 2006) with (left) and without (right) hyperspectral-derived classes.
Each collection site had slopes that ranged from Go to NoGo by both 10-meter (m) and 30-m DEM slope analysis. Some areas within each collection site were also shown as being NoGo by only one of the DEM slope studies. All three collection sites had examples of the classes: vegetation, paved & aggregate, road associated, clay, and semi-arid. Only CS1 had examples available for materials classes: water, POL tank, and twin POL tanks.

**Sampling**

Each site was sampled using a rock hammer and collection sample bags. GPS points were taken at each sample site and additional GPS points were collected to be used for assessing slope analysis. Digital photos of sample sites and of the collection site area were also taken. Samples were taken based on their classification from the analyzed hyperspectral SpecTIR data. Spectroscopy was done after field collection within the UNR Spectroscopy Laboratory using the ASD FieldSpec Pro spectrometer.

Sites for evaluating slope were chosen to test NoGo by both 10 and 30-meter, NoGo by only one of two, and test areas considered Go by both – having slopes within defined limits.

**Collection Site #1 (CS1)**

Material classes: POL tank, Water, and Twin POL Tanks were inaccessible and collection samples could not be acquired due to fencing, which was not visible in the hyperspectral data. Visual validation was made instead (Plate 7).

Samples of the material spectrally showed as class Paved & Aggregate, visually consistent with prepared aggregate, was samples in two locations around the single POL
Tank and along the road leading up to it. Samples of vegetation were taken from the hillside area, from near the Comstock Lodge, and along the west edge of C street. A sample taken from along the edge of the road, classified as Road Associated, was taken along Ophir Grade. Samples of the semiarid mixture class [a mixture of surface cover types consisting of a combination of unconsolidated rocks and soil ranging from silt sized to large cobble sized, and sparse vegetation (Pinus, juniper, sagebrush, and grasses – see Appendix G)] were taken from a slope just north of the S-curve in C-street. Areas which spectrally had shown up as the Clay class were sampled from two unpaved road areas.

What spectrally appeared to be a large concentration of Road Related class material turned out to be a rooftop of one of the two Nevada Department Of Transportation (NDOT) buildings within NDOT’s paved and fence-secured yard. Permission was granted to take samples of the two large piles of materials within NDOT’s yard by Denis Stark, the NDOT yard supervisor, who described the two piles as salt and sand. The SpecTIR image was taken in August, in the summer of 2007 and only one pile is imaged, there is no salt pile imaged, likely due to seasonal road requirements. Spectrally, the whole DOT yard, minus one roof, fell into the paved and aggregate class.

Slope GPS points were taken at sample sites, on the steep slope north of the S-curves of C Street, and in NDOT’s paved yard.
Collection Site #2 (CS2)

Samples of the material spectrally showed as class Paved & Aggregate were taken from the graded unpaved parking area of the Comstock Railyard and along C street. A sample of material depicted as class Road Associated was taken from the southern edge of a mining road. Vegetation specimens were gathered from the hill slope northwest of the railyard and along the west shoulder of C Street. Samples of mixed surface cover class called “semiarid” class (see Fig 14.8) were taken from a slope northeast of the mining road.

GPS points were taken at sample sites, on graded unpaved Comstock Railyard parking area and on the slope northwest of the railyard.
Collection Site #3 (CS3)

This area consisted of a Y-intersection of a graded unpaved mining road and unimproved semiarid with a very rocky steep slopes. Samples of the mining road were taken representing the Paved & Aggregate class and along the mining road’s southern edge that appeared as Road Associated class on spectral analysis. Vegetation was collected from the steep slope north of the mining road as were rock and soil samples that appear spectrally as Semiarid class.

GPS points were taken at sample sites, on slope north of the road, and on the road.

Fig 2.7 Collection site 3 (CS3) National Agriculture Imagery Program (NAIP) photo (NSMAC, 2006) with plotted GPS points.
SLOPE ANALYSIS

Slope analysis was done in ArcMap using 10-meter (pink) and 30-meter (purple) DEM data. Slopes that were 15 degrees and greater were considered beyond vehicle limits and colored in to indicate the hazard. Handheld GPS measurements were taken in the field with the Garmin GPSMAP 60CSx. These points were plotted into ArcMap, measured using ArcMaps measure tool to calculate distance between points using its snap to feature to lock onto GPS points and calculate the length. This distance and the difference in elevation of the GPS points, derived from the Garmin GPS, was entered into Microsoft Excel and using the formula Arc Tangent of (difference in elevation divided by the
distance), slope in decimal degrees was computed. The results are displayed in Tables T 14.8-14.11 and their associated figures, Fig 14.11 – 14.14. Points and their locations are in table T 14.6. The slopes of $15^\circ$ are also depicted in Fig 14.11-14.14 with GPS point locations.

**Analysis – Slopes from 30m, 10m, and handheld GPS**

There is significant variations between the mapped 30m DEM derived excessive slope, the 10m DEM derived excessive slope, and the handheld GPS results. A drivable road is also observed in Fig 14.11, which both the 30m and 10m derived slope analysis depicted as having a slope beyond limits. Only the handheld GPS was able to distinguish to the level of detail required to determine that the slope of the road was within tolerances.

The presence of the road, which is known to be trafficable, falling within the out of limits for both the 30m and 10m data suggests that the resolution of both of these is too coarse for ideal trafficability assessments and may incorrectly classify terrain. It also implies that known roads and thoroughfares should be digitized and should overrule slope analysis derived from 30m and 10m DEMs. This also disproves one initial hypothesis, that any area ruled an obstacle by any method is an obstacle and should be collectively added together to rule out terrain as non-drivable.
T 2.1 GPS Points 1-36

Notes: Fig 2.9-2.13 GPS plotted points (large picture), slope beyond 15° from 10m DEM data (upper corner - pink), slope beyond 15° from 30m DEM data (lower corner - purple) are displayed over National Agriculture Imagery Program (NAIP) data Tables T2.2-2.6 GPS points with distance, elevation, and slope information from Garmin handheld GPS.  

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Fig 2.9 & T 2.2 GPS Points 0-6
Fig 2.10 & T 2.3 GPS Points 7-9

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Fig 2.11 & T 2.4 GPS Points 10-12

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Fig 2.12 & T 2.5 GPS Points 26-29

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Fig 2.13 & T 2.6 GPS Points 30-35

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3.0 Case Study - Image Processing – Virginia City, NV

This chapter describes the processing of:

1) SpecTIR airborne hyperspectral data

2) Slope analysis - Generating the “NoGo” 15°+ raster files for the 10-meter and 30-meter Digital Elevation Map (DEM)

3) GIS integration and collective analysis to generate a where not to drive (NoGo) map using Research Systems Inc. (RSI) the Environment for Visualizing Images (ENVI) software version 4.2, Environmental Systems Research Institute (ESRI) ArcMap version 9.2 with the Spatial Analyst and 3D Analyst extensions.

4) Lab Spectral Processing of field samples – Spectroscopy using a FieldSpec PRO Analytical Spectral Devices (ASD) Sensor with RS³ and ASD ViewSpectra software.

The area selected for study is Virginia City, NV. Description and field validation of the results of the image processing which follows is described and discussed in section 14.0 Case Study Area Virginia City, NV.

SpecTIR airborne hyperspectral data

The Hyperspectral data was first worked with in RSI ENVI to generate georectified spectrally representative materials class files usable in a GIS assessment of trafficability conducted in ArcMap GIS.

The following procedures were implemented in RSI ENVI:
The SpecTIR radiance data was dimensionally analyzed and noise whitened using the Minimum Noise Fraction (MNF) transformation method to:

1) Assess the inherent dimensionality of the image data set
2) Isolate noise within the data
3) Reduce the computations needed for subsequent processing (Green et al., 1988)

The MNF process translates the data, through a series of affine transformations, so that the resulting images are adjusted to a zero mean, then rotated and scaled to where the noise of each band has a unit variance and is uncorrelated (Boardman et al., 1995). The MNF transformation puts the majority of the essential components into a few spectral bands, ordered from most interest, where noise is perfectly segregated, to least interesting (Altinbas et al., 2005).
Each spectral region of the processed MNF data was visually inspected to determine if any region was too noisy and should be excluded from further processing and analysis. Of the 178 spectral regions, 158 were excluded due to noise. Bad “noisy” images were observed in bands 21-178, Fig 3.1 shows band #53, a “noisy” band. The remaining 20 spectral regions (regions #1-20) were analyzed to identify the most spectrally pure “extreme” pixels using the Pure Pixel Index (PPI) functional procedure (Altinbas et al., 2005) and N-dimensional visualizer manual selection. During a PPI, the data is projected onto random unit vectors repeatedly, with a log kept of the number of times each pixel is extreme (Boardman et al., 1995). The PPI was applied to the selected 20 processed MNF regions with 10,000 iterations, using a threshold factor of 2.5, to determine pixels with relatively high uniqueness scores.
“Extreme” pixels generated from a PPI correspond to spectra of materials, which when combined linearly, produce all of the spectra within the image. The PPI output image contains digital numbers (DN) for each pixel which correspond to the number of times that pixel registered as extreme. The greater the number, the brighter the pixel. PPI images spatially show the location of spectral endmembers visually by their occurrence and intensity (Altinbas et al., 2005).
An output file like the one in fig 3.3 was generated, showing a black background with a series of white dots with various levels of brightness intensity.

As an intermediary step, images generated from the PPI process, for each useable region, was reviewed and the threshold numbers for reducing the amount of pixels to be further examined was determined. This was done by using ENVI’s interactive stretch enhancement tool, manually adjusting and auto-applying the limits within the Input Histogram window (fig 3.1) to determine good threshold criteria. These thresholds were utilized as the discriminating factor within ENVI Region Of Interest (ROI) tool (fig 3.2): Band threshold to ROI (fig 3.3 & 3.4), to generate separate ROIs of the pixels which had the strongest returns within that spectral region.

![RSI ENVI Histogram window used to determine appropriate thresholds it narrowing down the range of pixels to one with the strongest returns.](image-url)
ENVI’s n-Dimensional (n-D) visualization tool (Fig 3.5 & 3.6) was used with these ROIs in conjunction with the 1220 radiance data to generated new n-D derived ROIs which locate, identify and group purest pixels and extreme spectral responses occurring within the dataset (Altinbas et al., 2005). Clustering of some of the pixels was visually apparent when view through the different n-D views, these were selected into ROI groups using the ROI tool.

Fig 3.5 RSI ENVI Region Of Interest (ROI) tool, used for grouping pixels of interest together and for assessing their spectral statistics across the EM spectrum.

Fig 3.6 & 3.7 RSI ENVI Band Threshold to ROI tool (left), used with the user defined parameters (right) for creating ROIs which meet the user defined criteria.

ENVI’s n-Dimensional (n-D) visualization tool (Fig 3.5 & 3.6) was used with these ROIs in conjunction with the 1220 radiance data to generated new n-D derived ROIs which locate, identify and group purest pixels and extreme spectral responses occurring within the dataset (Altinbas et al., 2005). Clustering of some of the pixels was visually apparent when view through the different n-D views, these were selected into ROI groups using the ROI tool.

N-D visualizer is a manual and subjective process involving the selection of pixels which show as unique/outlying/extreme in the n-D generated data-cloud often groups of pixels are selected which largely maintain as a group while view in n-Dimensions. The number of ROIs and the number of point within each ROI selected is dependant on the user.
The spectral statistical mean of each of these n-D generated ROIs was calculated and compared with one another for uniqueness. ROIs were merged together if their average spectral signatures were found to have negligible variations or variations that could be attributed to atmospheric interference. After evaluating, adjusting, and merging – a new set of spectrally unique ROIs emerged. After the n-D visualized ROIs were initially consolidated 21 distinct spectral ROI groups were found (Fig 3.7). The mean of each of these ROIs was mapped using Spectral Angle Mapper (SAM). Those ROIs that mapped significantly similar were merged while those when plotted. Those which when plotted and found to be “too unique”, to be considered reliable or not occurring in sufficient quantity to be considered relevant and representative of enough terrain. The end result was 8 ROIs showing the spectrally unique elements present in the imaged area having multiple occurrences.

16 ROIs that had too few pixels (10 or less) after the evaluation and merging process were eliminated.
17 Classes were reduced to 8 spectral groups, with water and vegetation being manually ROI defined from the reflectance image. Specific minerals and small quantities were deemed limited in value for trafficability assessment based on resolution and inability of remote sensors to determine mechanical behavior.
Fig 3.10 Original spectral plots of the 21 classes assessed to be in the image based on spectral properties.

Fig 3.11 Merged reduce number of unique spectral plots after review and analysis.
To determine the make-up of the 8 identified ROIs, the mean of each was evaluated by using ENVI’s Spectral Analyst (SA). Spectral Analyst generated a weighed probability table, displayed descending order from best match, for each of these substances based on comparing the mean of the ROI against spectral libraries of know spectral signatures. Choice of spectral library used for each of these ROIs was based on visual evaluations both the ROI’s average spectral signature and the physical location of the pixels of the ROI within the image data. Further filtering of spectra was done manually by comparing the SA probability tables against regional information about the minerals and materials known to be in the area. Good example spectra of the known water and vegetation were not found using the described automated methods and manual ROIs for both had to be created in ENVI using visual identification within the SpecTIR reflectance data.

The Spectral Angel Mapper (SAM) weighing mapping method was used to locate similar pixels to the unique ROI spectra, which generated an output and a rulefile image with pixel score value between 0 and 1, 1 being equivalent to a 100% match. The output file generated an image with binary values showing the computers best matches selected, while the rulefile image pixels contained a range of values allowing the user to use the interactive stretch to visually determine tolerances for pixel selection when conducting band threshold to ROI. Radiance data was used for all classes except for vegetation and water which reflectance data was used. SAM of vegetation was restricted to the reflectance bands from 0.4-1.0 µm to utilize the distinct and well documented spectral “red edge” typical of all plants.
Each output file was visually reviewed for quality. If acceptable, the binary image was saved as an image file, georectified using SpecTIR Ground Lookup Table (GLT), and band threshold to ROI with a minimum and maximum threshold tolerance of 1 to create a spatially rectified ROI. Each of these ROIs was then separately exported as a georectified vector file with all points as one record.

If the output file did not generate good results, the rulefile was reviewed. The interactive stretch tool was used to determine a new tolerance level (threshold) for generating a representative pixel group, then this tolerance was used to band threshold to ROI. A 24-bit color TIFF image was saved using the ROI, changed to Red or Blue color, overlaid on the rulefile. This image was georectified using the associated SpecTIR GLT. The spatially rectified image was reviewed and a pixel with the representative data was selected. The properties of the selected pixel were reviewed using ENVI “Cursor Location / Value” tool (Fig 3.12) to determine if it is Red, Green, or Blue (RGB) values. A strong value, indicated by a large number, usually the maximum of 255, was identified within one of RGB colors. Then the georectified TIFF image was loaded in the selected red, green, or blue band corresponding with the identified value. A band threshold to ROI was done using the threshold minimum of 1 and maximum equal to the identified value. This newly generated ROI is spatially rectified and reflects the desired pixels similar to the n-D visualizer generated average spectra. ROI were then separately exported as a georectified vector file with all points as one record. The georectification was done prior to creating the ROI to have the new ROI spatially rectified.
These procedures were repeated for each mean ROI spectral class. These ROIs were exported from ENVI as vector files. The vector files of each class generated in RSI ENVI were imported into ArcMap. A georectified TIFF image of the reflectance data was saved in ENVI and used in ArcMap to define the area of interest that was remotely sensed.

Within ArcMap:

In ArcMap using ArcCatalog, all ROI classes and all other files used in this analysis were defined with a projection of Universal Transverse Mercator (UTM) zone 11 North American Datum 1983 (NAD 83).

The TIFF image of the imaged area 1220 was used to create a polygon file representing the image swath. All files were then clipped to only include the data that fell within the image swath polygon file. This was done by using the ArcToolbox tool “extract by mask” function.

To generate the image swath area polygon used in the analysis, the flight-line TIFF image was converted to raster in ArcToolbox, and within ArcMap, the attributes table was

Fig 3.12 Cursor Location / Value tool display of selected pixel’s Red, Green, and Blue (RGB) values.
opened and all values that equaled 1 were selected. All of the selected pixels were then converted to a shapefile. The shapefile was converted to a line file in ArcToolbox. The line file was then opened in ArcMap and, using the editing function, holes were manually deleted or corrected to have one complete border line file without any holes or gaps (Fig. 3.13). This poly-line file was checked by ArcMap’s editor using topology rules set to “must not have dangles” and “show errors” selected with trim set to 2 meters to ensure that the outline was complete. This outline file then had all its separate line features dissolved into one feature using the edit “dissolve” feature, creating one good outline file of the imaged area of SpecTIR flight-path 1220. Then a new polygon file was created based on the outline line-file in ArcToolbox using its conversion from “Feature to Polygon” to make a solid shape usable for clipping other date to just the imaged area of flight-path 1220.

Imported vector class files from RSI ENVI were spatially evaluated on the quality of spatial rectification with the two Digital Orthoquad (DOQ) files of the imaged area.

**Slope analysis - Generating the “NoGo” 15°+ raster files**

In ArcMap, the sized 30-meter DEM file was analyzed to evaluate slope areas of 15 degrees and greater by using ArcMap’s Spatial Analyst: slope tool. Within the properties of the created slope file, the symbology: Classified properties were set to 3 classes with ranges of 0-10, 10.00000001-15, and 15.00000001-54.31667328 (the maximum slope within this DEM). This was done to visually assess slopes that were good, marginal, and bad respectively.
Spatial Analyst: Raster Calculator was then used on the slope file to find all slopes greater than 15°. A new calculation-file with two classes was generated. Attributes of
this file have the areas that met the defined requirement, of greater than 15 degrees of slope, value of 1 and all others a value = 0. The attributes table of this file was opened and all with value = 1 were selected. The file was then converted from raster to polygon using the value field, with generalize polygons deselected. This creates a new polygon file which includes only the previously selected pixels which represent the slopes that are greater than 15 degrees. The feature class was then converted to raster using the ArcToolbox conversion tool Feature to Raster. Properties of the created Raster file were modified so that only one class was used under the classified section.

This process was repeated on the 10-meter DEM to create a raster of slopes greater than 15 degrees.

**GIS integration and collective analysis**

**Converting the ENVI created class vector-files to polygons**

Each vector class files, previously created in ENVI, was individually added into ArcMap as separate layer files. Then new raster files based on them were created using the Spatial Analyst: Convert: Feature to Raster tool with setting of field: ID and Output cell size: 10. These Raster files will be clipped to size by the polygon file to ensure that they are the sized the same as all other data files.

**Digitizing Manmade, man-altered, or man-restricted cultural features**

In ArcMap known cultural boundaries and structures can be manually drawn in and used for terrain analysis. For this case study I created a NoGo area of private land to be used as a restriction. This area has sections that fall within a normal vehicles abilities to drive,
but due to this restriction these areas are off-limits and included in the NoGo mapping of trafficability.

To do this a new feature was digitized by creating a new shapefile in ArcCatalog and adjusted the features XY coordinate System to match the projection system used. Then in ArcMap, imported the new polygon. Then, using the editing tool, draw a polygon and saved edits.

In this study an artificial restricted area, of privately owned land which partially spans the imaged swath, was used. The area’s polygon file was converted to a raster file, then extracted by mask using the study area polygon to clip-off the non relevant areas.

**Combining NoGo polygons into a No-Go map overlay**

The 30-meter NoGo slope raster file, the standing water, the manmade structure, and the vegetation raster files were unionized into one NoGo raster file and then the aggregate & paved class (related to known roadways) was erased from it in ArcToolbox. The new NoGo rater file was then overlaid onto the NAIP image data for the area.

This process was repeated with the 10-meter NoGo slope raster file.

For validation purposes, each layer was displayed and multiple sites were selected for “ground-truth” field verification.
4.0 Summary & Conclusions

In researching and conducting this trafficability assessment, an understanding of certain key aspects of off-road driving was required to identify what makes an area non-drivable and to use tools and references to locate them. The abilities and parameters of the vehicle used is the key element which defines non-trafficable areas and what is considered an obstacle to driving. The different kinds of obstacles to off-road driving were reviewed from other’s research. Methods of assessing and locating these obstacles was explored and applied to a case study conducted in the semi-arid Virginia City, Nevada area.

This thesis presented what makes an area non-drivable. Remote sensing, specifically airborne, was defined, discussed, and utilized in the context of assessing terrain for the purpose of finding these non-drivable areas. Geographic Information Systems (GIS) was defined, explored, and utilized to also find non-drivable areas. GIS combined multiple data sets with vehicle parameters to conduct analysis using organized procedures; generating an illustrated map of where not to drive in semiarid terrain. This trafficability map was then compared against other studies previously done and compared to ground-truthing of some of its elements in the field.

Many sources of data are available which can be used to conduct an off-road trafficability study. Digital Elevation Mapping (DEM) and aerial photos are some of the better sources for trafficability analysis data. Those with hyperspectral image data provided the most relevant information when conducting the Virginia City, NV case study.
Factors such as slope, terrain pattern, standing water, vegetation, weather, and other obstacles also needed to be considered. Systematic methodologies of excluding non-trafficable terrain were used to eliminate the terrain to avoid. Then, known trafficable terrain was used to override areas which may have been shown to be non-trafficable through other analysis. Each analysis conducted can only be as good as the input data and its resolution. Inherent flaws in each data-set, analysis, and in the fusing of them together provided an imperfect but usable picture of the terrain for off-road driving.

In determining the trafficability of Virginia City, NV, a general understanding of off-road driving, of obstacles, of terrain analysis, and GIS was required. The key observations of this study are:

1. Obstacles must be defined and determined based on the characteristics and abilities of the vehicle to be used. The subject vehicle’s characteristics and abilities define what is an obstacle.

2. Data of the area to be driven needed to be acquired:
   a. Digital Elevation Mappings (DEMs), multiple electromagnetic spectral band imagery (multispectral and hyperspectral) data, and aerial photography provide the best information for remote trafficability assessments
   b. Temporal data sets – acquired at different times of the year may provide additional insight into vegetation, by growth cycle, areas susceptible to
water runoff, pooling, and flash flooding, and areas subject to freezing or turning to mud.

c. Other historical data such as weather data provides seasonal and regional weather patterns, botanical studies provide insight into the type of vegetation, its spatial occurrence patterns and an idea of potential hazard to driving (based on known size and density limits), and other historical and current sources will contribute additional relevant information.

Note: the resolution of each data set affected what could be detected and the quality of the overall results.

i. In the case study, the 10-meter and 30-meter resolution of the DEMs cause fences not to be detected and misclassification of verified trafficable roads as beyond slope limits, using $15^\circ$ or greater as the threshold of too steep for slope analysis in ArcMap. In at least 11 locations for the slope analysis using the 10-meter DEM and at least 12 locations using the 30-meter DEM-derived slope analysis. The two analyses had some overlapping areas and areas which were only ruled as NoGo using one analysis.

3. Functioning roadways and other known trafficable areas should overrule slope analysis from 10-meter and 30-meter DEMs.

4. Each analysis used to assess trafficability is subject to the quality of the data used. Poor resolution (mentioned in 2.c.i.) was the cause of some terrain and cultural features to be miscatagorized and/or not detected. This type of problem and
others occurring in each data set, coupled with the errors attributed to fusion analysis when analyzing the data collectively caused areas to not be rendered in their appropriate trafficability classification. This was discovered on visual inspection of the results in ArcMap and from field validation.

5. Decisions on grouping and excluding of materials using RSI ENVI and ArcMap based on their spectral properties were made by both human and computer was performed during the analysis process. These decisions affected the overall analysis, the number and what classes were defined and the terrain pixels selected into each of the classes.

a. Concerning methodology when analyzing and processing the airborne hyperspectral data and DEM information using GIS software, the following order was used to identify and locate terrain features and non-drivable areas.

**Assessment Order**

1. Slope
2. Water
3. Vegetation
4. Soil for clays
5. Known trafficable areas – which will override areas deemed non-trafficable by other assessments
6. Other – (human-restricted areas, known hazards, etc..)
In collection of samples the following occurred:

1) Some planned sampling areas were inaccessible due to being fenced off or located on private land.

2) Fences were not visible within the hyperspectral data or on the 10-meter or 30-meter DEM data.

3) The POL tank, twin POL tanks, and the Water materials classes could not be validated through sampling due to being inaccessible behind fencing. These had to be validated through field photography (see Plate 8).

4) Surface roughness, in this case numerous rocks and boulders of ~12 inches or smaller, were not visible from SpecTIR airborne data but was obvious from the ground.

5) Not all unpaved mining roads were found based on spectral classification, but were visually apparent on the airborne hyperspectral imagery. This is attributed to “spectral grouping” occurring during spectral classification, where materials that are similar are grouped and assessed collectively as one material with an averaged spectral signature of the class. Since the mining roads were mostly compacted earth and crushed aggregate native to the area their spectrally unique features were likely “spectrally grouped”-in with other materials.

   a) When the SpecTIR hyperspectral-derived classes were spectrally mapped, mining roads showed up as an absence of plotted classified material allowing for their detection.
6) Not all manmade structures were found based on spectral classification; some buildings were not classified into spectral classes and were locatable visually by an absence of plotted classified material. This is also likely due to spectral grouping of spectral signatures into a limited number of groups and the average signature of those material groups deviating too much from the spectral signature of the structures’ imaged pixels.

7) Some areas that were field sampled, based on adaptive field sampling due to some planned areas being inaccessible, fell outside of the imaged area, discovered afterwards when GPS points were incorporated into ArcMap. These areas were excluded from the case study due to a lack of corresponding hyperspectral data.

Important points:

Slope, a key factor when off-roading (Manduchi et al., 2005; Spenko et al., 2006) in semiarid areas, is a function of the vehicle’s tire-terrain adhesion, the driving vector, and the vehicles abilities (Wong, 2001). Slopes greater than 15-20° climbing and 25-30° descending are limiting with most vehicles (Suvinen, 2006).

In semiarid areas, weather in the form of precipitation (Barton et al., 2000; Moore, 1989; Rula et al., 1963) and in dust influence the drivability, visibility, and safety of a vehicle in off-road terrain. Vegetation also can significantly change the drivability of semiarid terrain (U.S. Dept. of The Army, 1990; US Army, 1994). The first 12 inches in
depth of topsoil are also contributors to a terrain’s trafficability (Bassett and Meyer, 1968; Collins, 1971; Rula et al., 1963). The driver, how well they can determine obstacles and off-road drive my affect which area are effectively trafficable (Sheppard, 1988; Wong, 2001).

Some terrain characteristics may be evident by studying and recognizing the overall terrain pattern (TPR) of the area, since similar has similar subsurface and behavioral characteristics (Way, 1978), and by observing the success and failures of other vehicles that have driven in the terrain previously by observing their tracks for successes and failures.

Remote sensing can provide a good view of the terrain for TPR and track assessments in addition to data for terrain feature analysis and identification. By using different segments of the Electromagnetic Spectrum, remote sensors are able to see things that are not visible to the naked eye. All things that are above absolute zero temperature (-273.15°C / -459.67°F / 0° K) emit EM energy (Jensen, 2006) (see Appendix C). Natural materials often exhibit attributes which are spectrally dependant and visible in the VNIR/SWIR and TIR regions of the spectrum. Within the VNIR/SWIR the reflectance values are usable for assessing composition while emissivity is the diagnostic spectral region for the TIR (Salisbury and D’Aria, 1992; Vaughan, 2004). Some of these spectral bands can separate and help distinguish different materials through analysis.
In remote sensing of the Earth’s surface the wavelengths available for analysis are limited due to atmospheric interference (Schott, 1997). Atmospheric gasses absorb much of the sun’s radiation, leaving only several windows in the electromagnetic spectrum usable for surface analysis using remote sensing at 0.4-2.5 µm, 3.0-5.0 µm, and 8.0-12.0 µm (Vaughan, 2004). For example: clays has a spectral absorption feature distinctly in the SWIR spectral channels at 2.2 µm (Preissler and Loercher, 1995) and vegetation can be spectrally detected due to its consistent spectral features in the 0.4-1.0 µm EM wavelength known as “the red edge”. Through the capabilities of GIS analysis, these spectral attributes can be used to spatially identify and locate terrain features and material classes usable to collectively assess trafficability in semiarid terrain.

Using multiple sources of data and analyzing data types using GIS software requires integration and spatial rectification which uses subjective human decisions which have their own issues and errors. The same location can be spatially off significantly from one data source to another causing inaccurate spatial correlation when analyzed and warping and stretching the data to fit the same spatial system. “The benefits of longer term data fusion eventually becomes drawbacks due to the effects of blur (Kelly et al., 2006)”.

Different data types were used to assess Virginia City, NV. Digital Elevation Maps (DEMs) of 10-meter and 30-meter resolution provided slope and spatial relief information used for slope analysis. Hyperspectral SpecTIR data provided an ability to spatially and spectrally locate and identify surface types: vegetation, water, minerals, soils, and manmade features from their radiometric spectral signature.
Resolution of the sensor was significant, as is typical for trafficability assessments. Tracks and wheels are not large or wide enough to compensate for large variations and inaccuracies typical of coarse resolution. Slope and soil are typically not homogenous. Objects spatially located closely to one another (under the minimum spatial separation parameter of the data – resolution) are combined and collectively assessed yielding information that does not accurately represent the terrain. The poorer the spatial resolution, the less representative the data is, causing the resulting trafficability map to also have inaccuracies and be less representative of a true representation of the terrain.

Each analysis method provides information relevant for eliminating terrain from being considered drivable. Non-drivable “NoGo” areas were identified and imported into a GIS system and combined into one non-drivable class, which then had known drivable areas spatially subtracted from it. This removal was found to be necessary because a known trafficable road was assessed as non-trafficable in slope analysis of a 10m or 30m DEM. DEMs of these resolutions depict terrain that falls within the 10 or 30 meters area between their points as averaged together. This provided an inaccurate model for analysis, due to course spatial resolution. The case study showed that some features are collectable by airborne remote sensors and that poor resolution may inhibit detection of surface roughness and some obstacles. The trafficability map created should assist a driver in determining if their vehicle can drive in the terrain and identify which areas remain for path consideration.
Through airborne remote sensing and GIS analysis a trafficability map was created and field validated. The trafficability assessment added a higher level of terrain knowledge compared to visually assessing an air photo by identifying areas which were out of limits by slope. Further, the remote sensing trafficability assessment showed difficulty detecting smaller or spatially thin features, like fence-lines. Spectral materials class mapping derived from analysis of the SpecTIR Hyperspectral data showed some features by omission (ex. mining dirt roads) from spectral classification and missed detecting some small or thin features (ex. fences, smaller boulders, and rocks) entirely. This was due to the way terrain features and attributes are averaged together in areas which fall closer together or smaller than the level of spatial and spectral resolution of the data collected by a sensor. Slope analysis of the 10-meter and 30-meter DEMs also failed to detect some small or thin features and wrongly assessed the slopes of man-altered features (roads) on a significant number of occasions. Most errors were attributed to limited spatial resolution and “spectral grouping”.

What the trafficability assessment did provide was a demonstration of methodologies which successfully classified many of the materials present and identified major areas where someone should not drive. These methodologies should yield better results with higher resolution than the 10-meter and 30-meter DEM data used in this study.
5.0 Appendix A - Data Used

GIS and Spectral data

SpecTIR airborne Hyperspectral radiance and reflectance data
- SpecTIR LLC (SpecTIR, 2007a)

10-meter resolution Digital Elevation Maps from the UNR Keck library (UNR, 2007)
30-meter resolution Digital Elevation Maps from the UNR Keck library (UNR, 2007)

Aerial hyperspectral data from
7.5 Minute National Agriculture Imagery Program (NAIP) imaged November 29, 2006
- W.M. Keck Library (UNR, 2007)

Additional Information Utilized

Historical weather data from Desert Research Institute (DRI) (WRCC, 2008)

Local flora – Axelrod (1956) and Storey County Commissioners (1994)

Geologic information about the Virginia City, NV area - Whitebread (1976)

Mineralogical information - 2002 preliminary mineralogical map Nevada Bureau of Mines and Geology.


SpecTIR Airborne hyperspectral data – Hyperspectral data was shot with the ProSpecTIR VS system which consists of two sensors, the ProSpecTIR V (VNIR) and the ProSpecTIR (SWIR) sensors aligned to allow both sensors to image the same swath simultaneously with forelenses adjustable to have matching ground pixel size for both sensors (SpecTIR, 2008). The chosen flight-swath was scene number 1220 flown at 12:20 PM (SpecTIR, 2007a) on August 17, 2007 at over the Virginia City, NV area.
It was a 3.7 nautical mile flight length, flown South to North at an elevation of 8,859 feet above Mean Sea Level (MSL) [~2639 Above Ground Level (AGL)\textsuperscript{18}] at a ground speed of 120 knots (SpecTIR, 2007b). It took 6 minutes to complete and has a frame rate of 61 Hz (SpecTIR, 2007c). The sensors focal length was 23.1 mm with a pixel size of 30 microns (SpecTIR, 2007b).

SpecTIR provided the dataset which was processed to provide calibrated radiance and reflectance data.

Radiance data was taken using a calibration sphere, which itself was calibrated against a NIST standard at regular intervals. Converting the radiance to reflectance in the 2000-2450 nm was done by SpecTIR using MODTRAN-based atmospheric modeling, empirical-line calibration (ELC), and virtual empirical-line calibration (VELC) procedures (SpecTIR, 2007a).

Radiance data was calibrated by removing the measured dark current signal of the imagery which was measured for each flight line. A bad detector element map was applied to the SWIR utilizing a SpecTIR proprietary compensation algorithm to remove the spectral and spatial contributions of these picture elements in the array. Then a calibration gain file is applied to convert the raw data values into radiance units (SpecTIR, 2007a).

\textsuperscript{18}Based on the elevation of Virginia City, NV being 6,220 feet above sea level (Electric Foundry, 1998).
Data once analyzed, was converted to WGS-84, NUTM11, using SpecTIR generated GLT files. Data considered consistent with USGS digital orthoquad imagery to 2 meters or less (SpecTIR, 2007a).

Reflectance data, decimated to 10-nm from 5nm to utilize the software to its capabilities, was calibrated using a 3rd party industry standard MODTRAN radiative transfer code used within the ATCOR4 software package to correct for atmospheric interference and scattering components. The data that results was evaluated for any artifacts generated by the sensor or model and was compensated for by using library-based spectra modifications and polishing. A secondary ECL correction is part of the SpecTIR reflectance polishing which is based on Savitsky-Golay algorithm (SpecTIR, 2007a).

The 10-meter and 30-Meter DEM data sets came from the UNR KECK online repository. SpecTIR airborne Hyperspectral data was collected on a General Services Administration (GSA) flight on August 17, 2007 using the ProSpecTIR imaging system\textsuperscript{19}. Radiance data is at 5-nm. Radiance data was decimated from 5-nm to 10-nm and converted to reflectance using ATOR version 4.1\textsuperscript{20}, then polished using a light Savitsky-Golay filtration. This purposeful degrading was done because there is no commercial processor available capable of satisfactorily converting 5-nm radiance to reflectance, but

\textsuperscript{19} ProSpecTIR is a dual sensor for the simultaneous collection of SWIR and VNIR made by SpecTIR. Specification available at www.spectir.com (SpecTIR, 2008).

\textsuperscript{20} Airborne ATCOR (ATCOR-4) is software which utilized algorithms to correct small and wide field of view sensor data for atmospheric and topographic anomalies and noise adjustments. This software was originally designed by Rudolf Richter and tested by the (DLR) German Aerospace Center, Wessling, Germany (Richter, 2008).
at 10-nm acceptable results can be generated using the ATOR software (SpecTIR, 2007a).

**Findings & Assessments**

In collection of samples the following occurred:

1) Some planned areas were inaccessible due to being fenced off or private land.

2) Fences were not visible within the hyperspectral data.

3) Several classes could not be validated through sampling due to being inaccessible. These had to be validated through field photography (see fig 14.4).

4) Surface roughness, in this case numerous rocks and boulders, were not visible from SpecTIR airborne data but was obvious from the ground.

5) Areas that had been ruled as un-trafficable “NoGo” areas by 10-meter and/or 30-meter DEM slope analysis were found trafficable – in one case a road ran through the area (see fig 2.9).

6) Not all unpaved mining roads were found based on spectral classification, but were visually apparent on the airborne hyperspectral imagery.

7) Not all manmade structures were found based on spectral classification, but were visually apparent on the airborne hyperspectral imagery.

8) Some areas that were field sampled, based on adaptive field sampling due to some planned areas being inaccessible, fell outside of the imaged area, discovered afterwards when GPS points were incorporated into ArcMap. These areas were excluded from the case study.
9) There was evidence of change from the August 2007 imaging to the May 2009 field assessment. Example: NV DOT’s yard had one large pile of material in 2007 and now had two large piles of material on field inspection in 2009.
5.0 Appendix B  Fig B  Spectral Class Average Spectra from SpecTIR Airborne Hyperspectral Data
5.0 Appendix C - Remote Sensing and the Electromagnetic (EM) Spectrum

Human eyes can sense electromagnetic (EM) radiation in the 0.4 to 0.7µm wavelengths, commonly referred to as the visible (VIS) part of the EM spectrum (Vaughan, 2004). The remainder of the EM spectrum is beyond our abilities to see unassisted, but can be detected, visualized, and analyzed using computers and devices such as remote sensors.

In remote sensing of the Earth’s surface the wavelengths available for analysis are limited due to atmospheric interference (Schott, 1997). Atmospheric gasses absorb much of the sun’s radiation, leaving only several windows in the electromagnetic spectrum usable for surface analysis using remote sensing at 0.4-2.5µm, 3.0-5.0µm, and 8.0-12.0µm (Vaughan, 2004). EM Band/frequency spectral ranges where a substance absorbs radiant energy are known as *absorption bands*. The EM spectral bands which allow radiant energy to efficiently be transmitted through the atmosphere are referred to as *atmospheric windows* (Jensen, 2006).

A non-visible portion of the EM spectrum useful for studying the surface of the Earth [in studies such as trafficability] is the infrared segment of the EM, ranging from 0.7 to 100µm. This segment is commonly further broken down into the near infrared (NIR) from 0.7 to 1.0µm, thermal infrared (TIR) or mid-wave infrared (MWIR) in the region of 2.5-5.0µm, long wave infrared (LWIR) 8-18µm, and far infrared (FIR) is located...
beyond 50µm. It is also common for the VIS and NIR to be used together as VISIR in 0.4-1.0µm. The short-wave infrared (SWIR) is 1.0 to 2.5µm.

All things that are above absolute zero temperature (-273.15°C / -459.67°F / 0° K) emit EM energy (Jensen, 2006) that is detectable by remote sensors. How the material behaves in signal strength and absorption, across the different wavelengths of the EM can be used to determine its makeup. All materials selectively reflect specific EM wavelengths while absorbing others (Jensen, 2006). Changes in radiometric energy across the EM spectrum, collectively give rise to spectral signator. Some well-defined, continuous wavelength ranges in the spectrum of reflected or radiated EM energy, known as spectral regions or spectral bands, can separate and help distinguish different materials while others do not.

Radiance is a function of an object’s kinetic temperature and its spectral emissivity (Salisbury and D'Aria, 1992) for thermal data. Spectral emissivity is most often predicted from a material’s reflectance using Kirchoff’s law, \( \tau(\lambda) + \alpha(\lambda) + \rho(\lambda) = 1 \), with \( \tau(\lambda) \) being spectral transmittance at wavelength \( \lambda \), and \( \rho(\lambda) \) as spectral reflectivity at wavelength \( \lambda \) (Zhang et al., 2005). Stated in its simplest form as the emissivity (E) of a material equals one minus the reflectance (R):

\[ E = 1 - R \] (Nicodemus, 1965; Salisbury and D'Aria, 1992).
5.0 Appendix D - Lab Spectral Processing of field samples

Field samples were collected from areas considered representative of the hyperspectral-derived materials classes. They were sampled and brought back to the university spectroscopy lab for analysis.

Spectral analysis of samples was done using the FieldSpec Pro by Analytical Spectral Devices (ASD) Inc. (fig F.1), RS³ and ASD ViewSpectra software. The according tray was set a few inches from the sensor and the white background template was used to calibrate a white reference in the software. Sampling controls were set to save one file to a designated location. The white template was removed and a spectral signature of the blue background paper on the tray was observed. Samples were placed within the sensor’s field of view, with according tray height adjusted to have the sample surface height at the same level as the white template. The sample was adjusted to ensure that the maximum light form the artificial light source and that the spectra taken were not that of the underlying blue paper.

Fig D1 University of Nevada’s FieldSpec PRO ASD Sensor
The spectral software readout was allowed to go through its 30 sampling iterations and the resulting spectral signature from the sample was observed for quality, and adjustments and resampling was conducted as necessary. Good spectral signatures were observed and saved. Every 15-20 minutes the sensor was recalibrated to the white background template to maintain good readings.

Spectral signatures were exported into ASCII using ASD ViewSpectra software. Spectral signatures were then processed through a white noise calibration to removed anomalies and known sensor-related non-relevant variations. These ASCII files were the imported into RSI ENVI, and a new spectral library was created from them.

Spectral signatures from field samples were scaled to match the same scale as hyperspectral-derived materials class spectra and reviewed against the spectra matching the classes which they were field sampled from (Fig 2.10-2.14). Visual validated classes are discussed in section 2.0 Case Study Area Virginia City, NV.

Spectral signatures from field samples correlated well with the spectral material class average spectra derived from hyperspectral analysis. Supporting the ability to use airborne hyperspectral data to identify and determine different materials in the field useful in assessing the terrains trafficking for off-road driving in semiarid locations.
Fig D2 Average class spectra derived from SpecTIR Hyperspectral data in wavelengths 0.5-2.5 μm
Fig D3 Virginia City, NV: Vegetation - field sample average spectra (solid line) with hyperspectral-derived spectra (dashed line) in wavelengths 0.5-2.5 µm

Fig D4 Virginia City, NV: Semiarid mixture class - field sample average spectra (solid line) with hyperspectral-derived spectra (dashed line) in wavelengths 0.5-2.5 µm
Fig D5 Virginia City, NV: Paved Roads & Aggregate class - field sample average spectra (solid line) with hyperspectral-derived spectra (dashed line) in wavelengths 0.5-2.5 µm

Fig D6 Virginia City, NV: Associated with Roads class - field sample average spectra (solid line) with hyperspectral-derived spectra (dashed line) in wavelengths 0.5-2.5 µm
Fig D7 Virginia City, NV: Associated with Roads class - field sample average spectra (solid line) with hyperspectral-derived spectra (dashed line) in wavelengths 0.5-2.5 µm.

Fig D8 Virginia City, NV: Clay class - field sample average spectra (solid line) with hyperspectral-derived spectra (dashed line) in the 2.0-2.5 µm range considered the diagnostic of clay material.
5.0 Appendix E  Virginia City, Nevada Terrain Pattern Recognition (TPR)
drainage pattern trace

Fig E1 Trace (right) of the Virginia City, NV drainage pattern from two USGS 1948 aerial stereo paired images (Fig E2 one of the pair on the left).

Fig E3 Typical Drainage Patterns (U.S.Dept.of The Army, 1990)
5.0 Appendix F

**World Map of Köppen–Geiger Climate Classification**

updated with CRU TS 2.1 temperature and VASClino v1.1 precipitation data 1951 to 2000

Main climates
- A: equatorial
- B: arid
- C: warm temperate
- D: snow
- E: polar

Precipitation
- W: desert
- S: steppe
- F: fully humid
- W: winter dry
- M: monsoonal

Temperature
- H: hot arid
- K: cold arid
- A: hot summer
- B: warm summer
- C: cool summer
- D: extremely continental

Resolution: 0.5 deg lat/lon

Fig F World climate map based on climate data from 1951-2000 using the Köppen-Geiger climate classification method (Kottek et al., 2006)
5.0 Appendix G – Flora of the Storey County, NV Region  
Derived from the 1994 Storey County Master Plan  
(Storey County Commissioners, 1994)

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abies concolor</td>
<td>White fir</td>
</tr>
<tr>
<td>Agropyron spicatum</td>
<td>Bluebunch wheatgrass</td>
</tr>
<tr>
<td>Agropyron spp.</td>
<td>Wheatgrass</td>
</tr>
<tr>
<td>Amelanchier alnifolia</td>
<td>Serviceberry</td>
</tr>
<tr>
<td>Artemisia arbuscula</td>
<td>Low sagebrush</td>
</tr>
<tr>
<td>Artemisia spinescens</td>
<td>Bud sage</td>
</tr>
<tr>
<td>Artemisia tridentata</td>
<td>Big Sagebrush</td>
</tr>
<tr>
<td>Astragula spp.</td>
<td>Locowhead</td>
</tr>
<tr>
<td>Atriplex canescens</td>
<td>Forwing saltbrush</td>
</tr>
<tr>
<td>Atriplex confertifolia</td>
<td>Shandscale</td>
</tr>
<tr>
<td>Atriplex lentiformis</td>
<td>Quail brush or Big salt bush</td>
</tr>
<tr>
<td>Balsamorrhiza sagittata</td>
<td>Balsamroot</td>
</tr>
<tr>
<td>Bromus inermis</td>
<td>Smooth brome</td>
</tr>
<tr>
<td>Bromus marginatus</td>
<td>Mountain brome</td>
</tr>
<tr>
<td>Bromus tectorum</td>
<td>Cheatgrass</td>
</tr>
<tr>
<td>Carex spp.</td>
<td>Sedge</td>
</tr>
<tr>
<td>Castilleja spp.</td>
<td>Indian paint bush</td>
</tr>
<tr>
<td>Ceanothus velutinus</td>
<td>Snowbrush</td>
</tr>
<tr>
<td>Ceratoides lanata</td>
<td>Winterfat</td>
</tr>
<tr>
<td>Cercocarpus ledifolius</td>
<td>Curlleaf mountain mahogany, Mountain mahogany</td>
</tr>
<tr>
<td>Chrysothamnus nauseosus</td>
<td>Rubber rabbitbrush</td>
</tr>
<tr>
<td>Chrysothamnus viscidiflorus</td>
<td>Sticky-leaf rabbitbrush, yellow rabbitbrush, green rabbitbrush</td>
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<td>Distichlis stricta</td>
<td>Saltgrass</td>
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<tr>
<td>Elymus cinereus</td>
<td>Great basin wildrye</td>
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<tr>
<td>Elymus glaucus</td>
<td>Blue wild rye</td>
</tr>
<tr>
<td>Elymus triricoides</td>
<td>Creeping or beardless wild rye</td>
</tr>
<tr>
<td>Ephedra nevadensis</td>
<td>Mormon tea</td>
</tr>
<tr>
<td>Ephedra viridis</td>
<td>Squaw tea</td>
</tr>
<tr>
<td>Eriogonum spp.</td>
<td>Buckwheat, Shrubby Buckwheat</td>
</tr>
<tr>
<td>Festuca idahoensis</td>
<td>Idaho fescur</td>
</tr>
<tr>
<td>Halogenton glomeratus</td>
<td>Halogeton</td>
</tr>
<tr>
<td>Haploppus spp.</td>
<td>Goldenbush</td>
</tr>
<tr>
<td>Helenium hoopesii</td>
<td>Sneezeweed</td>
</tr>
<tr>
<td>Helinthus spp.</td>
<td>Sunflower</td>
</tr>
<tr>
<td>Hesperochloa kingii</td>
<td>Hesperchloa</td>
</tr>
<tr>
<td>Holodiscus discolor</td>
<td>Ocean Spray</td>
</tr>
<tr>
<td>Juniperus osteosperma</td>
<td>Utah juniper</td>
</tr>
<tr>
<td>Kochia americana</td>
<td>Kochia</td>
</tr>
<tr>
<td>Kochia vestita</td>
<td>Red sage</td>
</tr>
<tr>
<td>Koeleria nitida</td>
<td>June grass</td>
</tr>
<tr>
<td>Scientific Name</td>
<td>Common Name</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Leptodactylon pungens</td>
<td>Prickly phlox</td>
</tr>
<tr>
<td>Lomatium spp.</td>
<td>Desert parsley</td>
</tr>
<tr>
<td>Lupine spp.</td>
<td>Lupine</td>
</tr>
<tr>
<td>Oryzopsis hymenoides</td>
<td>Indian ricegrass</td>
</tr>
<tr>
<td>Penstemon spp.</td>
<td>Beardtongue</td>
</tr>
<tr>
<td>Phlox spp.</td>
<td>Phlox</td>
</tr>
<tr>
<td>Pinus flexilis</td>
<td>Limber pine</td>
</tr>
<tr>
<td>Pinus jeffreyi</td>
<td>Jeffrey pine</td>
</tr>
<tr>
<td>Pinus monophylla</td>
<td>Pinyon pine</td>
</tr>
<tr>
<td>Pinus monticola</td>
<td>Western white pine</td>
</tr>
<tr>
<td>Pinus ponderosa</td>
<td>Ponderosa pine</td>
</tr>
<tr>
<td>Pla secunda</td>
<td>Sandberg bluegrass</td>
</tr>
<tr>
<td>Poa fendleriana</td>
<td>Mutton grass</td>
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<tr>
<td>Poa nevadensis</td>
<td>Nevada bluegrass</td>
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<tr>
<td>Populus fremontii</td>
<td>Freemont cottonwood</td>
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<tr>
<td>Populus tremuloides</td>
<td>Quaking aspen</td>
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<tr>
<td>Prunus virginiana</td>
<td>Chokecherry</td>
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<tr>
<td>Psorothamnus polydenius</td>
<td>Dalea</td>
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<tr>
<td>Purshia tridentate</td>
<td>Bitterbrush</td>
</tr>
<tr>
<td>Ribes spp.</td>
<td>Currant, gooseberry</td>
</tr>
<tr>
<td>Rosa spp.</td>
<td>Rose</td>
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<tr>
<td>Rumex spp.</td>
<td>Dock</td>
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<tr>
<td>Salicornia aSigua</td>
<td>Pickelweed</td>
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<tr>
<td>Salix spp.</td>
<td>Willow</td>
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<td>Salsola tragus</td>
<td>Russian thistle</td>
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<tr>
<td>Sarcobatus vermiculatus</td>
<td>Big greasewood</td>
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<tr>
<td>Sarcobatus vermiculatus var. bailey</td>
<td>Dryland greasewood</td>
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<tr>
<td>SaSucus caerulea</td>
<td>Elderberry</td>
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<tr>
<td>Shepherdia argentea</td>
<td>Silver buffalo berry</td>
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<tr>
<td>Sitanion hystix</td>
<td>Squirrel tail</td>
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<tr>
<td>Sporobolus airoides</td>
<td>Alkalai sacaton</td>
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<tr>
<td>Stephanomeria</td>
<td>Skeleton plant</td>
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<tr>
<td>Stipa coluSiana</td>
<td>ColuSia needlegrass</td>
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<tr>
<td>Stipa comata</td>
<td>Needlegrass and threadgrass</td>
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<td>Stipa occidentalis</td>
<td>Western needlegrass</td>
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<td>Stipa thunberiana</td>
<td>Thunderneedgrass</td>
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<tr>
<td>Suaeda mogninii</td>
<td>Alkalai seepweed or Bush seepweed</td>
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<td>Suaeda torreyana ranisissima</td>
<td>Inkwood</td>
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<td>Symphoricarpous albus</td>
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<td>Tamarix gallica</td>
<td>French tamarisk</td>
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<td>Tetradyinia spinosa</td>
<td>Short-spine horsebrush</td>
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<tr>
<td>Wyethia amplexicaulis</td>
<td>Mule ears</td>
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