



WPI



Improving Winter Road Maintenance in New Mexico

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Abstract

The New Mexico Department of Transportation's (NMDOT) Intelligent Transportation Systems Bureau seeks to implement technological solutions to make the roads safer for drivers. The goal of this project was to improve NMDOT winter maintenance operations. We developed a tool to rank locations for Environmental Sensor Stations and compiled a list of several recommended locations within District 5. We also produced a list of recommendations for how the NMDOT can improve its resource management practices through implementing process and technological solutions.

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4.1.2 Suitability Ranking Formula	Richard Cole	Jeffrey Robinson
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4.2.2 Resource Management	Jeffrey Robinson	Connor Smith, Richard Cole
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Appendix L	Richard Cole	Jeffrey Robinson, Connor Smith
Appendix M	Richard Cole	Jeffrey Robinson, Connor Smith
Appendix N	Matthew Jackman	Richard Cole
Appendix O	Jeffrey Robinson	All
Appendix P	All	All
Appendix Q	Matthew Jackman	All
Appendix R	Richard Cole	All

Table of Contents

- Title Page..... i
- Abstract ii
- Acknowledgementsiii
- Authorship Table v
- Table of Contents.....vi
- Table of Figuresviii
- Table of Tables.....viii
- Executive Summaryix
- 1. Introduction 1
- 2. Background 3
 - 2.1 Road Weather Information System (RWIS) 3
 - 2.1.1 Sensors..... 3
 - 2.1.2 ESS Types 5
 - 2.1.3 Determining an ESS Site 6
 - 2.1.4 Communication and Data Applications 8
 - 2.1.5 Current DOT Best Practices10
 - 2.2 Road Types and Conditions13
 - 2.2.1 Road Classifications14
 - 2.2.2 Weather.....17
 - 2.3 Resource Management and Tracking19
 - 2.3.1 Common Inventory Problems20
 - 2.3.2 Inventory Management Best Practices21
 - 2.3.3 Industry Examples of Inventory Management Practices26
 - 2.4 Summary31
- 3. Methodology.....32
 - 3.1 Objectives 1 & 2.....33
 - 3.1.1 NMDOT Employee Interviews.....33
 - 3.1.2 ArcGIS Mapping34
 - 3.2 Objectives 3 & 4.....34
 - 3.2.1 Suitability Ranking Formula35
 - 3.2.2 GIS Analysis35
 - 3.2.3 Location Determination and Analysis36
 - 3.3 Objectives 5, 6, & 736
 - 3.3.1 ESS Data Application.....36
 - 3.3.2 Recommendations and Future Work37
 - 3.4 Summary37

4. Results and Analysis	38
4.1 Determine ESS Siting Locations	38
4.1.1 Determining ESS Siting Criteria	38
4.1.2 Suitability Ranking Formula	40
4.1.3 Siting Methodology	49
4.1.4 Results of Ranking Analysis within District 5	51
4.2 ESS Data Applications and Alternative Data Sources	55
4.2.1 Communication and Notifications	56
4.2.2 Alternative Sources of Data	56
4.3 Current Winter Maintenance Operations	59
4.3.1 Information Gathering Techniques	59
4.3.2 Resource Management	61
4.3.3 Operation Management	65
4.4 Summary	68
5. Conclusions and Recommendations.....	69
5.1 ESS Siting	69
5.2 Resource Management Recommendations	71
5.3 Future Work	71
References and Bibliography.....	74
Appendix A: Sponsor Description	79
Appendix B: Gantt Chart for On-Site Work	81
Appendix C: General Interview Protocol	82
Appendix D: Patrol Yard Administrator Interview Questions	84
Appendix E: NMDOT Administrator Interview Questions	85
Appendix F: NMDOT Patrol Yard Administrator Interview Minutes.....	86
Appendix G: Test Location Comparison	92
Appendix H: Initial Site Ranking Criteria	93
Appendix I: Snow Removal Priorities	94
Appendix J: Winter Maintenance Operations Recommendations.....	101
Appendix K: Ranking System Needs Chart.....	105
Appendix L: Pros and Cons of Two Evaluation Protocols	106
Appendix N: Description of ArcGIS Maps	108
Appendix O: Final SPOT Report	111
Appendix P: SPOT User Guide.....	113
Appendix Q: Download SPOT	132
Appendix R: Data Collected	133

Table of Figures

Figure E-1: ArcGIS map of top five location in our analysis	x
Figure 2.1 NJIT’s Weather Severity Map.....	12
Figure 2.2: Federal Functional Classification Decision Tree	16
Figure 2.3: Graphical representation of EOQ based on cost calculations.....	25
Figure 2.4: Example of Kanban used by Texas Instruments	30
Figure 3.1: Block Diagram of Project Methodology.....	33
Figure 4.1: Representation of Criteria Ranking Exercise	41
Figure 4.2: Score Demonstration Using Relative Scoring.....	43
Figure 4.3: Scoring Using Thresholds.....	44
Figure 4.4: Score Demonstration Using Goldilocks Principle	45
Figure 4.5: Interpolated Annual Snowfall Layer from ESS Siting Data map	46
Figure 4.6: SPOT Location Data Entry Form displaying drop-down menu	47
Figure 4.7: SPOT Front Page Display	48
Figure 4.8: Weather to Clear Crash Ratio Map Layer	50
Figure 4.9: SPOT Ranking Report Results Mapped in ArcGIS.....	52
Figure 4.10: SPOT Overall Location Ranking Score Graph	53
Figure 4.11: Absolute Location Ranking Breakdown Graph.....	54
Figure 4.12: UDOT Citizen Condition Reporting Application.....	59
Figure 4.13: Sources of Road Treatment Materials	63
Figure 5.1: ArcGIS map of top five location in our analysis	70
Figure A-1: Chart of NMDOT Organizational Structure	80

Table of Tables

Table 2.1: Types of ESS Sensors.....	4
Table 4.1: Test Location Criterion Data	39
Table 4.2: Location Criteria Importance Factors	42

Executive Summary

Inclement weather is a significant problem for motorists throughout the United States, particularly during the winter, causing detrimental effects such as increased likelihood of car accidents and traffic delays that impact quality of life and commercial activities. To keep the millions of miles of roads across the United States safe for drivers, each state has a Department of Transportation (DOT) charged with maintaining the public roads and transportation routes within its borders. This duty requires efficient management of daily operations in order to react to rapidly changing driving conditions. It is especially important to monitor the driving conditions of roads across a state as varied as New Mexico, as the drastic changes in environment, altitude, and topography that define the state produce many distinct climate zones and unique weather patterns. To operate effectively, the New Mexico Department of Transportation (NMDOT) must intelligently manage the deployment of their resources and diligently prepare for incoming weather patterns. This requires thorough tracking of road maintenance materials, consistent plowing and road treatment during storms, and efficient communications in response to changing weather patterns.

The goal of this project was to determine how the Intelligent Transportation System (ITS) Bureau, responsible for incorporating modern technology into NMDOT operations, can assist in the improvement of the NMDOT's winter maintenance operations and therefore the overall safety of New Mexico's roads. This was accomplished by creating a system for determining ideal locations for the placement of Environmental Sensor Stations (ESS) and by analyzing the NMDOT's current winter maintenance practices to identify how the ITS Bureau can assist.

The purpose of an ESS is to collect information about road conditions and weather patterns along a road segment that can be used to make informed decisions when managing winter maintenance operations. Finding the proper locations for ESS is crucial to the NMDOT as their proper installation provides the department with valuable real-time weather and road condition data, helping the patrol yards prepare carefully and respond quickly to changing conditions across their region of responsibility. In order to determine these suitable locations for the placement of ESS, we interviewed patrol yard administrators and area maintenance supervisors to identify location criteria that they deemed important, as well as certain locations within their area of operations at which they believe ESS should be installed. Based on this information, we used Geographic Information System (GIS) mapping to analyze the traffic patterns, crash data, and severity of inclement weather around

the state. We then used this information to create an ESS site ranking tool to determine the most suitable locations for the placement of these stations based on the aforementioned siting criteria.

It is essential for the NMDOT to properly track the assets and materials used by their road maintenance operations to ensure the roads under their care are properly treated. Having even one truck out of commission due to maintenance or a material shortage can significantly increase the difficulty of patrol yards' work in keeping the roads within their area of operations safe for travel. Therefore, ensuring that the NMDOT can efficiently maintain their equipment and acquire road maintenance materials is key to the agency's proper functioning. By interviewing NMDOT administrators, we gained an understanding of how their patrol yards currently manage road maintenance operations and equipment maintenance and material sourcing. Using this information and understanding, we analyzed how the patrol yards can improve the efficiency of their operations through the implementation of inventory management best practices and technological solutions facilitated by the ITS Bureau.

We provided the NMDOT with a ranking tool and protocol to follow when determining where to install new ESS in the future as well as a report on the NMDOT's current winter road maintenance operations with recommendations on how the ITS Bureau could improve the efficiency and effectiveness of those operations. By implementing our recommendations, the NMDOT will be able to make more effective use of their ITS resources in assisting patrol yard operations, thereby making patrol yard workers' jobs easier and allowing them to clear the roads more effectively. We also utilized our ranking tool to identify several potential ESS locations throughout New Mexico, listed here:

- NM-150 Mile Marker 10 - Taos Ski Valley
- I-40 Mile Marker 180 - West of Edgewood
- I-40 Mile Marker 173 - Tijeras Canyon
- US-64 Mile Marker 390 - South of Des Moines
- NM-38 Mile Marker 18 - Red River/Bobcat Pass

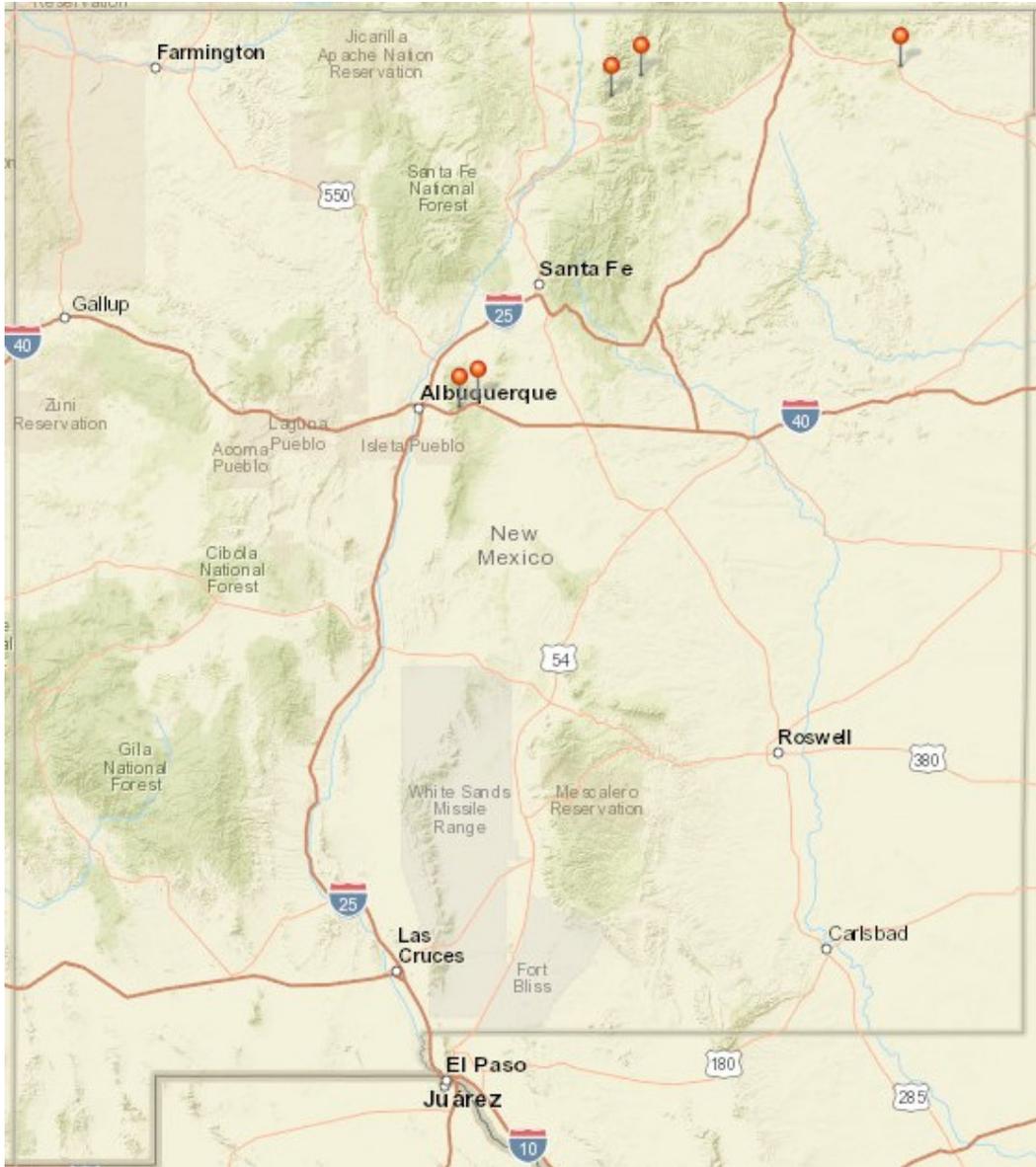


Figure E-1: ArcGIS map of top five location in our analysis

The results of this project will help the NMDOT improve the efficiency and effectiveness of its winter maintenance operations by providing its maintenance managers with access to more information to base their decisions on. This will help the NMDOT to potentially decrease the number of crashes due to weather across the state and improve the overall safety of New Mexico's roads.

1. Introduction

In today's world, people have become connected through the ease of transportation between distant parts of the globe via planes, trains, ships, and highways. This is especially true in the United States, where the over 8.6 million lane-miles of roads throughout the country allow people to travel almost anywhere in their own cars (Bureau of Transportation Statistics, 2013). While the number of lane-miles of road in the U.S. has increased by over 800,000 since 1980, the number of vehicle miles traveled on these roads per year has doubled from 1.527 to 3.040 trillion, an upward trend that continues (Federal Highway Administration, 2016). To keep these roads safe, each state in the U.S. has a Department of Transportation (DOT) charged with maintaining the public roads and transportation routes within its borders, especially during adverse weather conditions. This duty requires efficient management of daily operations in order to react to rapidly changing driving conditions.

In order to maintain the nearly 30,000 lane-miles of highway in the state, the New Mexico Department of Transportation (NMDOT) operates 82 patrol yards and employs 2,205 personnel, a pool of resources that equates to approximately 366 lane-miles of road per patrol yard, or 13.6 lane-miles per employee (Federal Highway Administration, 2014; New Mexico State Government, 2016). To operate effectively, the NMDOT must intelligently manage the deployment of their resources and diligently prepare for incoming weather patterns. These tasks require not only information about what resources are available, but also about the current weather and driving conditions on roads throughout the state. The NMDOT's Intelligent Transportation Systems (ITS) Bureau, which is responsible for incorporating modern technology into NMDOT operations, would like to increase the amount of real-time information on road conditions throughout the state that they and the winter maintenance operation managers have access to. ITS also wants to gain a better understanding of how winter maintenance operations currently work so they can understand how real-time road condition information can be effectively used.

Throughout the nation, state DOTs have implemented Road Weather Information System (RWIS) technology into their information systems and management structures, allowing for careful preparation for weather related changes in road conditions (Abdi et al., 2012; Manfredi et al., 2008). To install new Environmental Sensor Stations (ESS), the physical stations that gather the data in an RWIS, where they will most effectively contribute, the Federal Highway Administration (FHWA)

and the United States Department of Transportation (USDOT) have provided guidelines based on extensive research and field testing of equipment often used in the stations (Boselly et al., 1993; Garrett et al., 2008). In addition to improvements to information technology such as an RWIS, refining DOT's resource management systems shows promise as another potential method for improving road maintenance effectiveness and efficiency, given that current resource management practices are largely based on paper records and employees' intuition and experience.

While the NMDOT has laid the foundation for a functioning RWIS in New Mexico, it currently consists of only three operational ESS, with two along I-10 in the far southwestern corner of the state, and one at the junction of I-40 and US-285 in Clines Corners (NWhA, 2015; T. Brown, personal communication, Aug. 31, 2016). The ITS Bureau would like to expand its RWIS to assist with their data gathering initiatives, but they are currently unsure of the best way to do so and would therefore like to develop an objectively based station siting methodology designed specifically for New Mexico. In addition to the expansion of the New Mexico RWIS, ITS would like to know how NMDOT patrol yards currently organize road maintenance so that they can identify potential areas for improvement through the application of information gathering technology.

The purpose of this project was to determine how the NMDOT ITS Bureau could leverage technological solutions for the benefit of NMDOT winter road maintenance operations. To accomplish this overall goal, we focused primarily on developing a process for identifying and prioritizing suitable locations for ESS throughout New Mexico, with the deliverable also including specific location recommendations for District 5 as a test case. To improve resource management and road condition information dissemination, we made recommendations for future development of technological strategies based on interviews with NMDOT employees. We also identified potential methods for collecting road condition and weather information as alternatives to extending the RWIS in New Mexico, with the intent of providing the foundation for a future NMDOT sponsored project to expand the reach and effect of the ITS Bureau's road condition information network. With our finished project, we gave the ITS Bureau a thorough and consistent process for determining how to expand their RWIS through the placement of new ESS, recommendations for how to apply their technological assets to NMDOT road maintenance operations, and suggestions for ways to supplement their current information network with external resources, ultimately allowing the ITS to better serve the NMDOT in its mission of keeping New Mexico's roads safe.

2. Background

The purpose of the ITS Bureau is to inform and advance NMDOT maintenance practices through the implementation of technological solutions, ensuring safe, efficient and reliable transportation within New Mexico. For the purposes of our project we have focused on the Bureau's obligations relating to the state's road network, specifically with regards to road clearance in winter storm events. In this chapter, we provide a thorough overview of three of the main categories of information needed for efficient, well informed road maintenance operations:

- Road Weather Information System (RWIS)
- Road Types and Conditions
- Resource Management and Tracking

2.1 Road Weather Information System (RWIS)

The intelligent use of technology for the monitoring of road surfaces, traffic, and weather conditions provides essential information for the management of DOT operations. One of the most effective tools for monitoring conditions is through the use of Environmental Sensor Stations (ESS), which allow for automated monitoring of conditions such as precipitation, wind speed and direction, air and road temperature, and visibility (FHWA, 2016). ESS are very similar to the Automated Weather Stations (AWS) employed by many weather agencies, with the important exception that they gather information relevant to road conditions, such as road temperature or snow accumulation, in addition to atmospheric data. Whether used in conjunction with AWS systems installed by other agencies or as stand-alone data collection tools, ESS are valuable instruments for DOT maintenance operation managers.

2.1.1 Sensors

The information that a DOT wants to gather from an ESS often determines the set of sensors that will be deployed on the station (Vaisala, 2009). Sensor technology is constantly being developed and refined to improve the quality and variety of data able to be collected by ESS where only manual means were previously available; however, there is still only a limited number of sensors available to DOTs.

As shown in Table 2.1, which lists common sensors installed on ESS and the data they collect, there are often multiple choices of instrumentation available to gather information on a given condition (Manfredi et al., 2008).

Table 2.1: Types of ESS Sensors (Source: Manfredi et al., 2008, p. 23)

Roadway Element	Sensor
Air Temperature	Thermometer
Water Vapor (Dewpoint or Relative Humidity)	Hygrometer
Wind Speed and Direction	Conventional and Sonic Anemometer and Wind Vane or combined sensor (Aerovane)
Pavement Temperature, Pavement Freeze Point Temperature, Pavement Condition, Pavement Chemical Concentration	Pavement Sensor
Subsurface Temperature	Subsurface Temperature Probe
Subsurface Moisture	Subsurface Moisture Probe
Precipitation Occurrence	Rain Gauge, Optical Present Weather Detector
Precipitation Type	Rain Gauge, Optical Present Weather Detector
Precipitation Intensity	Rain Gauge, Optical Present Weather Detector
Precipitation Accumulation	Rain Gauge, Optical Present Weather Detector, Hot-plate Type Precipitation Sensor
Snow Depth	Ultrasonic or Infrared Snow Depth Sensor
Visibility	Optical Visibility Sensor, Closed Circuit Television Camera
Atmospheric Pressure	Barometer
Solar Radiation	Solar Radiation Sensor
Terrestrial Radiation	Total Radiation Sensor
Water Level	Pressure Transducer, Ultrasonic Sensor, Float Gauge, or Conductance Sensor

While each ESS installation is different, most stations will be equipped to record wind speed and direction, precipitation quantity and type, pavement temperature and grip factor, air temperature, humidity, and dew point. The choice of instruments to install on an ESS is determined by several factors, including the desired level of detail of the data, possible location or power restrictions at the site, and the typical weather conditions the station is intended to track. As different sensors require different amounts of power, at locations with access only to off-grid power solutions such as solar, the ability to provide a consistent supply of power to the sensing and data transmission equipment

of an ESS may become a problem, requiring careful selection of sensing instruments based on power limitations. This issue is discussed further in Section 2.1.4.

Additionally, the technology in this field is changing so rapidly that even Table 1 above is out of date in certain respects, leading to some stations installed only months apart employing different technologies, which may mean that the quality of data from each station in an RWIS cannot be necessarily considered consistent (T. Brown, personal communication, August 31, 2016). For example, an older ESS usually includes sensors embedded in the pavement of a road to sense grip factor and pavement condition, while a newer station might employ laser or microwave technology to measure the same conditions from a distance, allowing the newer station to gather more accurate and relevant data while leaving sensing equipment less vulnerable to damage due to traffic or accidents. While ideally the best and widest variety of sensing equipment available at an installation would be used for each ESS, in practice including only a limited number of sensors is cost effective. As a result, most ESS must be customized to track the particular conditions that the DOT wants to know about, making the proper placement and configuration of each and every station a critical factor in the utility of the RWIS overall.

2.1.2 ESS Types

There are two general types of ESS used in a RWIS, local and regional, each with its own requirements and uses (Manfredi et al., 2008; FHWA, 2016, Zhao et al., 2015). While the general structure of the stations is identical, the two types differ in sensor selection and placement. Each station usually carries the general sensor suite described in Section 2.1.1. While the regional ESS stops there, the local stations will tend to have additional sensors to cover site-specific observational needs.

According to the FHWA (2008) guidelines, a regional ESS is very similar to an AWS in that it collects data relevant to an entire region rather than a small stretch of highway in order to be used to run road weather prediction models (Abdi et al., 2012; Manfredi et al., 2008; Zhao et al., 2015). While studies disagree on the best distance between stations to accurately record data over a region, having each regional ESS 20 to 30 miles apart is the accepted standard, with closer spacing permitting more accurate condition monitoring. A network of regional stations is often harder for a DOT to implement due to the cost of the stations, usually making the installation of more than a handful impractical (T. Brown, personal communication, August 31, 2016). Additionally, not all

DOTs have a meteorologist on staff to analyze the data produced by the RWIS, requiring outsourcing of weather forecasting to a commercial meteorological company, adding significant operating costs on top of the already expensive station installations (Boselly et al., 1993; T. Brown, personal communication, September 8, 2016). Despite these significant drawbacks, the benefits of a regional system should not be overlooked as they provide important information for detailed tracking of weather patterns, allowing for more informed preparation, and therefore improved response times for weather events (Boselly et al., 1993; Manfredi et al., 2008).

A local ESS is intended to record data about a specific location - usually a bridge, river, or mountain pass - by using a location-specific suite of instruments to measure conditions such as pavement grip factor, snow accumulation, or water level to supply data that is overlooked by the regional ESS or AWS network (Abdi et al., 2012; Manfredi et al., 2008; Zhao et al., 2015). There are very few guidelines for placement of this type of station due to its need for adaptation to a specific site, and while a local ESS focuses more thoroughly on one location, it still adds to the regional weather data network. When laying out an ideal RWIS network, a web of regional stations should be laid out and then augmented with the required local stations, which in some cases can simply mean modifying an existing regional ESS to gather more specific information.

2.1.3 Determining an ESS Site

In order to make the most effective use of an ESS, the station must be configured to the exact location and relevant data, requiring consideration of a variety of details (Manfredi et al., 2008). In order to accomplish this, data on the local climate, traffic levels, and accident history must be combined with information from local maintenance workers to determine locations where increased information gathering could benefit the DOT. However, there is currently no standard procedure to determine the best site. In most cases, a site will only be ideal for gathering one particular type of environmental data while lacking the ability to monitor other conditions, making it necessary to consider the typical conditions found at each potential location when ranking sites (Manfredi et al., 2008; Liuhui, et al. 2015).

Once a general area in need of an ESS is determined, the exact location for the station must be decided (Manfredi et al., 2008; Liuhui et al. 2015; Abdi et al., 2012). Many factors go into choosing a site, including environmental factors such as foliage and terrain, the feasibility of collecting the necessary data, the difficulty and cost of placing a physical station, and the ability of

the DOT to easily access the station for any necessary maintenance. To assist state DOTs in this task, the FHWA and USDOT have published general ESS siting guidelines, recommendations on what factors should be taken into account when determining ESS locations and how these factors should be considered in relation to one another (Boselly et al., 1993; Garrett et al., 2008). These guidelines provide a basic system for analyzing and comparing different potential ESS locations primarily based on what information a DOT would receive from each. The guidelines that each report details vary on some minor points, such as ideal distance between regional ESS, but they are in agreement on most, such as the specification that an ESS should be placed on a concrete slab between 30 to 50 feet from the highway with low foliage surrounding it, on a flat or minimally sloping area, and away from any locations showing potential pooling of water due to heavy rain or flooding. Both sets of guidelines agree that stations should be placed with foremost regard for “hot spots,” locations that receive particularly severe traffic, weather, or some combination of both, but they also suggest that ESS should be placed at locations that are representative of the broader weather and traffic patterns over an area to ensure broad and thorough RWIS coverage.

In determining ideal ESS sites, it is important to consider not only what data a particular location will generate, but how this data will be used (Boselly, 1993; Manfredi, 2008). Boselly and Manfredi propose that this data application can be divided into three categories: prediction, detection, and monitoring. As described by Boselly (1993), prediction is the forecasting of approximate weather and road conditions at a location based on current data trends, detection is the identification of potentially dangerous conditions as they occur, and monitoring is the real-time inspection of the conditions at a location. When siting stations, these categories of data usage can be correlated to the two main ESS types discussed in Section 2.1.2, with both monitoring and detecting usage corresponding to local ESS, and the task of prediction being placed mostly on the regional network. What this means is that when choosing locations for monitoring or detecting, each site must allow for the gathering of data specific to its main purpose, ideally while maintaining its relevance across a region. For example, if an ESS is to be placed to monitor snow drifts, it should be placed at a location that suffers both high winds and snow. In the case of an ESS intended for prediction, on the other hand, the location chosen must allow the station to gather information that is indicative of the conditions across an entire region, while maintaining a reasonable distance between the stations. While each use case is helpful to winter maintenance operations in its own way, Boselly (1993), Garrett (2008), and Manfredi (2008) agree that the most useful implementation

of RWIS is in the category of prediction because it allows a DOT to allocate resources ahead of an incoming weather event, which helps the patrol yards respond as quickly as possible when weather conditions do finally change. This does not mean that detection and monitoring are not useful and all three studies agree that any use of RWIS data is better than no use if it is implemented correctly.

While the guidelines provided by the FHWA and USDOT do provide a solid starting point for ESS siting, they are ultimately only guidelines, and it is nearly impossible to find ESS locations that adequately fit all given criteria, with most requiring some degree of compromise due to state-specific environmental conditions or oddly designed roads (Manfredi et al., 2008). Because of this, it is very important for a state DOT to produce their own extensions to the FHWA and USDOT guidelines specific to their state, as they will be the ones deciding on ESS locations and making use of the resulting data (Manfredi et al., 2008; Liuhui, et al. 2015).

Thermal Mapping

Boselly (1993) and Manfredi (2008) also discuss the potential value of thermal mapping of roadways in determining new ESS sites. Thermal mapping is usually done by attaching a thermal sensor to a vehicle and driving along a section of road where an ESS location has been proposed. The thermal data produced by this investigation allows the DOT to identify locations along the road segment that show signs of temperature anomaly, in terms of being significantly hotter or colder than average, due to any number of environmental factors along the road. Both Boselly and Manfredi claim that by using this thermal map to place ESS at the locations of the minimum, maximum, and mean road temperatures measured along a road segment, a DOT can utilize the data produced by these three ESS to extrapolate the approximate road conditions along the entire mapped road segment. As useful as this may be, however, this mapping service must be outsourced to the ESS manufacturer, so the cost of the thermal mapping, location analysis, and weather modeling will be an important consideration in determining whether this process will be useful for a DOT. Additionally, the cost of placing three ESS in relatively close proximity will be a significant issue, as the funds may be better used to place ESS in three separate locations of interest.

2.1.4 Communication and Data Applications

To be made useful, information gathered from an RWIS must be accessible by both DOT employees and the general public in a timely manner (Manfredi et al., 2008; Vaisala, 2009). Many

systems already in place, such as telephone cables, cellular networks, Ethernet and fiber optic cables, radio, and satellites, can facilitate this data transmission. As each system has its own unique benefits and drawbacks, the deciding factors for which network will be used to transmit data from an ESS are usually the quantity of data that must be transmitted, the cost of installation, the availability of power, and the expected operational costs of a connection, with the latter two being of particular concern when using wireless data connections. The communication options available at a site can limit the number and type of sensors that can be installed and can also significantly impact the cost of the station. This means that potential sites can often be ruled out because of limited access to communication lines or an inability to power wireless communication devices, leading this to be one of the most important factors when planning ESS sites.

Once the information from an ESS is collected and communicated to a central storage database, either owned by the manufacturer or the DOT, real-time analysis of the data can begin so that the correct information can be given to the correct people (Manfredi et al., 2008). As discussed in Section 2.1.3, DOTs can use RWIS data for multiple purposes, but most prominently for prediction of incoming weather events and the detection of road condition emergencies at particular locations. This allows the DOT to prepare and respond more effectively for those weather events and road conditions than they would be able to otherwise. One data analysis technology that is growing in popularity is the integration of RWIS data with Geographic Information System (GIS) software to enable a DOT Maintenance Division to monitor weather and road conditions in real time. By doing so, a DOT can increase their operational efficiency by better tracking where resources are needed at any given moment through a visual format (FHWA, 2016; Manfredi et al., 2008). GIS also allows for incorporation of RWIS data with other possible technologies such as Automatic Vehicle Location (AVL) on DOT equipment for easier tracking and management of resources (J. Di Ruggiero, personal communication, September 16, 2016). Additionally, the number of technologies that can be integrated with GIS mapping will only increase as time goes on, so as the DOT makes use of additional technology, they can make increasingly sophisticated and centralized use of GIS in their planning and management efforts.

The information gathered by a RWIS is not only useful to the DOT, but it can be incredibly beneficial to the general public as well if distributed effectively (Goodwin, 2003). State DOTs throughout the nation are developing systems using mobile phone applications or website widgets to disseminate road condition information to the public (NMDOT, 2016). These include systems like

the NMDOT's NMRoads website that displays weather conditions, traffic patterns, and other useful information such as work zones to facilitate road trip planning, allowing the public to be informed in cases of severe weather or unusual traffic routing (Manfredi et al., 2008). Additionally, many state and European DOTs are testing the implementation of connections between a local ESS and dynamic message signs (DMS) to warn drivers about road conditions such as icing or dust storms ahead and prevent dangerous and potentially fatal situations for drivers (T. Brown, personal communication, August 30th; J. Buddemeyer et al., 2010; Goodwin et al., 2003). By effectively distributing the road condition information gathered by RWIS to the public, DOTs can work towards their overall goal of improving the safety of all motorists.

2.1.5 Current DOT Best Practices

DOTs across the nation are modernizing their operations through the implementation of RWIS and integration of the information received from them into their operations (Goodwin et al., 2003). Some DOTs are ahead of the curve and are experimenting with new technology and uses of RWIS data, while others are just beginning to install ESS to make the best use of the current technology.

Maintenance Decision Support System (MDSS)

In 2001, the FHWA created a functional prototype of an MDSS to assist DOTs in the management of winter road maintenance operations (FHWA, 2015; UCAR 2016). The goal of this project was to create a management support application to assist in the planning and management of DOT winter maintenance operations. In order to do so, the FHWA enlisted the help of the University Corporation for Atmospheric Research (UCAR) to create an application that utilized data available to DOTs to create predictions for road conditions within their states over the next 48 hours. This application would allow the maintenance supervisors to make more informed decisions about when and where to allocate resources during a winter weather event based on this weather prediction. The functional prototype MDSS that was produced is still operational today, the 16th version of the application was released in 2011. The current system incorporates RWIS, NOAA, NWS, and state DOT AVL data to produce weather and road condition predictions and display them in a visual format. This allows for the intuitive understanding of current and predicted conditions and easy decision making.

In 2002, a Pooled Fund Study (PFS) version of the FHWA's functional prototype MDSS was created to improve the prototype's integration into DOT operations with regards to winter maintenance operations, personnel scheduling, and managing material constraints (Chien et al., 2014; FHWA, 2015; Meridian, 2016). In order to do so, the PFS enlisted Meridian Environmental Technology Inc. to develop a multi-level application that consumed RWIS data, weather reports and predictions, and manually entered reports on current road conditions and maintenance operations to generate predictions of future road conditions and material usage during DOT operations. The PFS also created an application that tracks the current material usage and operational information such as plow location and road conditions at the sites of ongoing maintenance operations. The PFS version of the MDSS then combines the prediction and operation tracking applications to monitor road conditions and usage of materials in practice, and makes comparisons to the expected results to determine if current operations are generating the expected results and being efficient. This allows the DOT maintenance operation supervisors to monitor current operations' resource usage and road conditions, while comparing them to a predicted data set to make decisions on how to modify current operations to keep the roads clear and safe for drivers during a storm.

New York State Department of Transportation (NYSDOT)

In 2013, the NYSDOT decided to investigate improvements to its current RWIS, and brought the New Jersey Institute of Technology (NJIT) in to complete a report on their current system and ways that it could be improved (Chien et al., 2014). Prior to the start of the project, the NYSDOT RWIS consisted of 32 ESS in varying states of disrepair. Most of the stations had problems with incomplete data collection or transmission due to miscalibration of the equipment and a lack of maintenance. Further study also indicated that ESS sites were not evenly distributed across the NYSDOT's 11 regions, leading to patrol yards in some regions having access to more information than others, with some regions lacking even a single operational ESS within their area of operations. It was also discovered that most of the ESS had different sets of sensors installed, so the data collected varied widely in value and relevance between stations. After a comparison between the New York RWIS and the systems in the neighboring states of Massachusetts, Connecticut, Pennsylvania, and New Jersey, the NYSDOT also determined that they lacked a proper system for determining the placement of new ESS, the sensors that would be installed on each ESS, and the implementation of the data that the RWIS collected.

Given this deficiency, NJIT created a system for determining the placement of new ESS within New York (Chien et al., 2014). Their site ranking method was split into two sections: an analysis of the importance of the site, and a cost benefit analysis of placing an ESS at that location. In order to create a method for ranking the importance of the site, NJIT developed a new ranking map of the state of New York's climate based on the severity of the winter weather that a location typically received. This was determined by creating a weighted sum formula that took in how much snow and freezing rain each location received in a year, as well as the average ground temperature and the number of days that the ground temperature was below freezing. They then produced a map of these severity levels across the state, as shown by Figure 2.1.

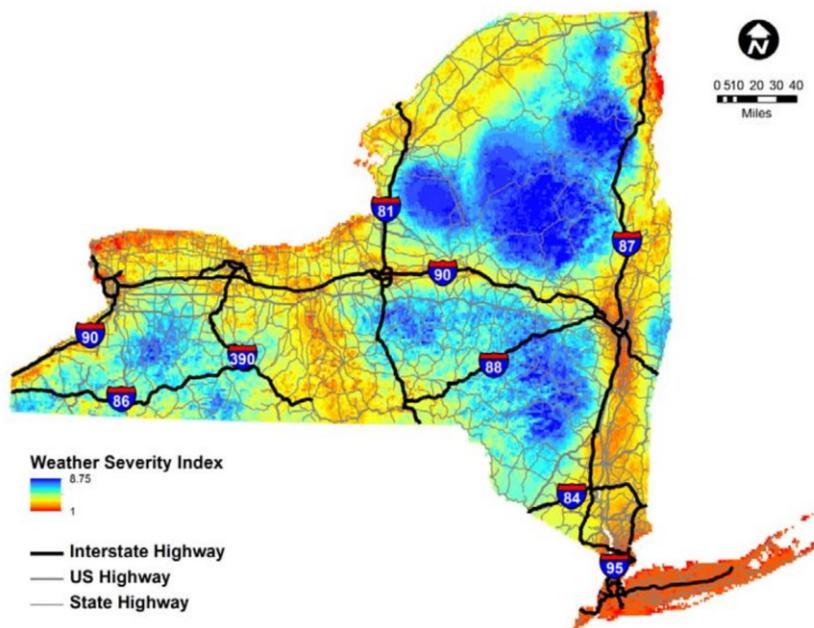


Figure 2.1 NJIT's Weather Severity Map (Source: Goodwin et al., 2014)

This map was then combined with an analysis of the area coverage that the station would provide at that site, taking into account the coverage of other proposed sites or existing stations, to determine ideal locations for new ESS. By the conclusion of this analysis, NJIT determined 38 optimal locations for new ESS around New York State.

After ranking the potential sites by their potential value to NYSDOT operations, NJIT then created a cost-benefit analysis that took into account the Average Annual Daily Traffic (AADT) received by each one mile segment of highway in New York (Chien et al., 2014). This cost benefit analysis compared the traffic that each location received and the general cost of installing and

maintaining an ESS at each location and would remove any location where the costs outweighed the benefits. After running the cost-benefit analysis on each of the aforementioned 38 proposed locations, all were determined valuable enough to keep. The NJIT report then went on to recommend creating a specific process for maintaining ESS across the state of New York, as well as a guide for the order in which the 38 locations should be installed based on their importance to improving the RWIS. The report also provided recommendations for improving integration of the RWIS into maintenance operations through the application of the PFS MDSS in order to increase the efficiency of winter road maintenance operations, as well as the overall safety of the New York road network.

Other States

Other states have expanded the usefulness of RWIS data by applying it to other developing technologies related to road safety and maintenance (Goodwin et al., 2003). The Idaho Department of Transportation deployed ESS to monitor the road conditions during winter storms as a way to analyze the effectiveness of its winter maintenance operations and find areas of the state that need to improve their winter road maintenance practices. States such as Montana and Wyoming have implemented ESS to supplement and automate Variable Speed Limit systems (VSL). In these cases, ESS collect data from locations known to have the worst traction along a strip of road, and use this information to select the best speed for travel along that segment of road in the given conditions. This speed limit is then displayed on a Dynamic Message Sign (DMS) as the new speed limit for that stretch of road. Additionally, some states, such as Idaho and Minnesota, are utilizing data gathered by ESS to determine when automated road deicing systems should disperse chemicals to treat the road. Systems such as these are still in development, so the benefits they provide are not fully understood, but the integration of RWIS in DOT operations is nevertheless expected to increase in the coming years, theoretically leading to improvements in the overall efficiency of the DOTs as well as the safety of the roadways within their jurisdiction.

2.2 Road Types and Conditions

While monitoring and predicting road and weather conditions is exceptionally important, knowledge of the roads and their physical properties allows a DOT to make informed decisions about how to properly manage maintenance of these roads. In this section we will discuss specific

road types, including scenic byways and interstate highways, the effects that inclement weather has on roads, and examples of how different states are combatting weather-related issues such as snow and ice.

2.2.1 Road Classifications

The classification of a road is often associated with various attributes, such as traffic patterns and road surface type, as well as specific rules about maintenance that must be properly adhered to by the DOTs. These classifications often get factored into the order of importance for maintenance operations, leading them to be very important factors to a DOT. Two specific types of roads that the NMDOT (2015) focuses its attention on are scenic byways and the interstate highways; however, the NMDOT has its own classification system for the roads under its jurisdiction.

Scenic Byways

In 1995, a proposal was approved for the designation of scenic byways throughout the nation as a means to promote domestic tourism and to showcase the natural beauty of the varied landscapes in the United States (Federal Highway Administration, 1995). To support the expected increase in traffic on these roads and to support the scenic byway system as a whole, the proposal called for safety improvements that would allow safe navigation along them by commercial and personal vehicles, including motorcycles. Due to these heightened maintenance standards for scenic byways, they require more vigilant care in the winter months than normal routes.

The state of New Mexico has twenty-five scenic byways that comprise over 2,900 miles of road throughout the state (New Mexico Tourism Department, 2016). The federal government mandates that these roads receive a certain quality of care, requiring the NMDOT to give these routes additional attention throughout the year. These byways are specifically intended for tourism, adding additional reasons for the NMDOT to keep them well maintained.

Interstate Highways

According to the NMDOT, the interstate highways, U.S. highways, and state roads that fall under the NMDOT's jurisdiction receive more attention in terms of their overall upkeep than the local and county roads (Uyttebrouck, 2016). Whereas some of the roads in New Mexico are concrete or even rock or dirt, the interstate highways are made with an asphalt surface with clean fractured

rock lying underneath (Keller and Sherar, 2003). This is because these high traffic volume roads require a sturdier surface like asphalt because water and other weather conditions do not deteriorate the road surface as quickly. This also allows the NMDOT to not damage the road as much during winter maintenance operations such as plowing or salting, reducing the need for repairs and the amount of road material that the patrol yards need to stock.

Functional Classification System

In order to maintain construction and maintenance standards for roads around New Mexico, the NMDOT uses a functional classification system derived from nationwide guidelines published by the FHWA (NMDOT, 2013; FHWA, 2013). According to the FHWA functional classification system, each road in the country fits into a distinct category along a numbered scale, with levels 1 and 2 covering exclusively interstate highways and other expressways, levels 3 and 4 including major and minor arterial routes, levels 5 and 6 including major and minor collector roads, and level 7 including only local roads. Figure 2.1 describes the general breakdown of this classification system, with regards to how each road classification level relates to the others.

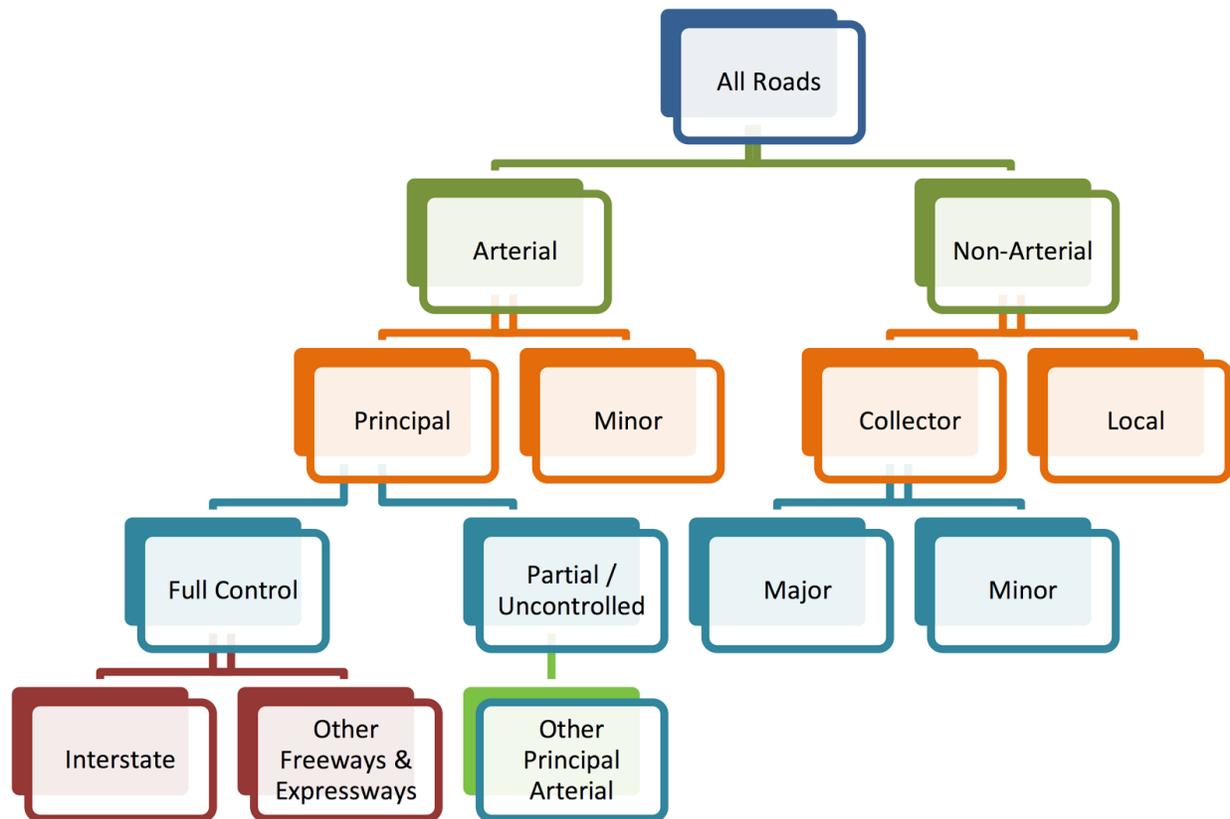


Figure 2.2: Federal Functional Classification Decision Tree (FHWA, 2013)

These classifications help distinguish roads by setting consistent standards for each level regarding maintenance priority level, Average Annual Daily Traffic (AADT), and physical characteristics such as lane width, shoulder width, and controlled access (NMDOT, 2013; FHWA, 2013). For example, interstate highways, level 1 roads, are required to have twelve foot wide lanes, at least four foot wide inner shoulders and ten foot wide outer shoulders, must be divided, and must have fully controlled access via ramps. On the opposite end of the scale, local roads, level 7 roads, must have lane widths of eight to ten feet, have no minimum shoulder width requirements, and must be undivided with open access to neighboring land. These clearly-defined distinctions help DOTs around the country prioritize maintenance, snow clearance, and traffic monitoring to ensure that more heavily trafficked roads, particularly levels 3 and above, receive appropriate attention to maintain the bulk of traffic flow in a given area.

2.2.2 Weather

Weather patterns such as heavy snowfall, can create numerous problems for drivers, including damage to the roads themselves and the creation of dangerous driving conditions. If the temperature of the pavement is too low, it can lead to infrastructure damage in the road (Goodwin, 2006). Additionally, precipitation like snow and rain can cause low pavement friction, which can lead to accidents. To combat these issues, DOTs must constantly conduct maintenance operations, especially during extreme weather events.

Weather Problems

Weather brings along with it many negative effects that can significantly impact travel and the overall maintenance of roads. Factors such as visibility impairments, precipitation, high winds, and temperature extremes can create issues with roadway conditions and overall safety of driving (Federal Highway Administration, 2016). The improper care of roads during heavy precipitation, specifically snow, can greatly affect the safety and efficiency of road travel. Additional factors like air temperature, humidity, and water level in nearby rivers or streams can also affect a road's condition and how the DOT might treat the roads. While roughly 22 percent of crashes in the United States are weather-related, 17 percent of these occur during snow or sleet, 13 percent occur on icy pavement, and 14 percent occur on snowy or slushy pavement. Additionally, lanes can be flooded by heavy rains and melted snow or obstructed by wind-blown debris or snow, causing travel on these roads to be nearly impossible.

In the state of New Mexico, the climate can vary greatly between the northern and southern parts of the states. The north is a mountainous region, it contains the Sangre de Cristo Mountains and the highest mountain in the state, with a peak elevation of 13,161 feet, so it is usually colder than the southern part of the state and can get a large amount of snow during the wintertime. (T. Brown, personal communication, August 31, 2016). On the other hand, the south is much flatter and warmer. The main weather concerns in the southern part of the state involve the issue of dust storms due to the deserts and a lack of vegetation. As a whole, New Mexico can also experience high winds speeds in most parts of the state, which can create severe dust storms and snow drifts.

Weather Related Maintenance

Adverse weather causes operating and maintenance costs to increase significantly for numerous entities including DOTs, commercial vehicle operators, and law enforcement agencies causing most state DOTs to budget roughly 20 percent of their maintenance budget for winter road maintenance (Federal Highway Administration, 2016). State DOTs around the nation have implemented different techniques to deal with inclement weather (Goodwin, 2003). States like South Dakota and Alabama have low visibility warning systems in place to help alert drivers to be vigilant when in transit. Through the utilization of environmental sensor stations (ESS), the California Department of Transportation utilizes a motorist warning system to help prevent accidents. Most important to winter maintenance, however, is the presence of anti-icing operations in states such as Montana, Idaho, and Minnesota. These states all use similar chemicals and methods to keep the roads from getting too slick during snow and freezing rain situations. In the particular case of Idaho, the Idaho Transportation Department (ITD) uses the internet and weather forecasts to identify impending snow and frost threats. In response, the ITD then sprays the anti-icing chemical on the roads before the weather event. Additionally, there are four “indicator areas” along each highway that the ITD checks to see if frost has migrated from the shoulder into travel lanes. If this begins to happen, then the road must be retreated.

The current techniques the NMDOT (2015) uses to clear roads of snow and ice include plowing and spreading salt, cinder, and sand. In addition to sand and salt, the NMDOT also uses chemical deicers for faster melting of ice if the conditions require it. The NMDOT used to pretreat roads, but a legal case halted that practice, causing them to not currently have a pretreatment procedure for their roads, but they are looking to re-implement one at some point in the near future. To prepare for winter maintenance, the NMDOT does specific pre-winter preparation, which includes ensuring that there are enough of these materials in place at least one month prior to the first expected weather event. They also manage their inventory of these items throughout the winter to prevent the possibility of a stockout, described in Section 2.3.2. In addition to their stockpiles of salt, sand, cinder, and deicer, the NMDOT also manages their trucks, plows, spreaders, and smaller items such as plow blades, headlights, and brake pads. To assist in this, the NMDOT has a standard plan for equipment maintenance to help prevent frequent replacement of such assets. To help protect their snow removal equipment and prevent long-term damage from corrosion, all of the equipment is washed and has Lubra-seal applied after every storm.

The NMDOT (2015) has also created a Winter Maintenance Guide that details the directions for properly clearing the roads. This guide provides the theoretical flow of operations during the winter, specifically during a winter storm event. It includes an outline of proper snow plowing procedures in addition to laying out thresholds for the start of certain types of operations such as salting and plowing. It also includes the NMDOT's classification system for the severity of a storm, which runs on a scale from one to five, with five being the most severe. To assist in the planning of winter maintenance operations, the guide also lays out the winter maintenance priorities that roads can be grouped into on a scale of 1 to 5, with priority 1 routes being the most important. These priorities are based upon the average traffic the road receives, the road classification, and the input of the district manager. While the specific maintenance techniques among the priorities is similar, during a severe winter event, higher priority roads are dealt with first, often leaving roads on the priority 3 and lower levels to be cleared after the storm.

2.3 Resource Management and Tracking

While keeping the roads clear during winter maintenance operations is important, this cannot be done without the proper maintenance and tracking of equipment and resources. Awareness of the location, quantity, and condition of resources is crucial for the proper management of road maintenance operations (Bailey & Helms, 2007). Regardless of the type of resource in question, be it road salt, spare snow plow parts, or road maintenance machinery as a whole, keeping track of inventory is a primary concern in planning the road maintenance operations that keep New Mexico's roads in a safe, drivable condition. Running out of spares on a critical part for a snow plow or salt truck during a snowstorm, for example, could greatly reduce the ability of the DOT to keep roads clear and ensure safe travel. On the contrary, having an excess of spare parts for any vehicle or hardware will likely result in deterioration, loss, or obsolescence of spare parts over time, wasting valuable government funding. For these reasons, it is essential for inventory to be closely monitored by the NMDOT to ensure that it has the right parts in the right places, in the right quantities, and at the right time (M. Aghajanian, personal communication, April 15, 2016). In this section we will discuss several tactics for optimizing inventory management, the two major issues faced by inventory management systems, and several real-world examples of the implementation of these concepts.

2.3.1 Common Inventory Problems

In attempting to properly manage inventory, it is quite easy to stray from an optimal method of management by being too frugal or too cautious with resource allocation, both quite understandable strategies that can have serious impacts on the financial effectiveness of a business or utility provider (Bailey & Helms, 2007). By attempting to keep inventory quantities minimal, and thereby minimize inventory carrying costs, it is possible for a company to face frequent and/or severe stockouts, halting service or production until the missing item can be restocked. This can cost the company dearly, both with its lost profits and inconvenience to the public, as well as internal costs incurred by accelerating shipping and handling of new parts needed to remedy the situation. On the contrary, an overly cautious attitude to inventory management, intended to minimize stockouts, can result in similar degrees of cost, for different reasons. By carrying inventory, a company invests in products with finite useful lifetimes and loses money on storage, obsolescence, and shrinkage. To effectively manage inventory for a company, then, it is necessary to understand the risks of both extremes.

Costs of a Stockout

In inventory management, one of the worst possible scenarios to encounter is that of a stockout, when inventory for a specific tool, part, or commodity runs out, leaving the company in trouble (M. Aghajanian, personal communication, April 15, 2016). Beyond their immediate inconvenience, stockouts are carefully avoided for their associated costs, resulting from lost commerce during downtime and extra costs added to expedited processing for necessary replacement equipment. In production industries, the primary cost of a stockout is the reduced or stopped commerce that would normally occur during the same time frame. By preventing assembly lines or transport vehicles from running, products cannot be completed or delivered on time, potentially eliminating this income. As a result of this high cost from lost income, additional costs are usually added in the form of expedited shipping for new inventory, in an attempt to reduce losses from the stockout. In the case of the DOT, such stockouts are of particular concern, as the organization is responsible for maintaining roads throughout an entire state, rather than maintaining production lines or other specialized machinery. Being a government-funded organization, the DOT may not have any personal lost income to worry about in the case of a stockout, but it must concern itself with safety and commerce throughout its jurisdiction, ensuring individuals can travel safely,

and businesses can rely on truck-borne shipments. The DOT must therefore measure the cost of a stockout to be the lost income of the state economy overall as a result of slowed shipments, stranded commuters, or the costs of road accidents, such as loss of life, emergency service deployment, and time consuming paperwork. The DOT must therefore act in accordance with the criticality of its role to the public in working to get its inventory replenished quickly in case of a stockout, as there can be no wasted time in keeping roads well maintained.

Costs of Carrying Inventory

Given the unfavorable outcomes of a stockout situation, the alternative extreme may seem preferable; carrying excess inventory at all times may be seen as the only safe option for companies providing utilities or public services, especially for those working directly on maintenance operations as opposed to administration (Bailey & Helms, 2007). However safe this tactic might seem as a method of avoiding stockouts, it too may cause undesirable and unproductive costs as a result of several factors. Chief among these is the cost of capital. In the case of government agencies the cost of capital is highly visible as it is the rate of interest that the agency pays on state issued bonds. Capital used to purchase and store excess and potentially obsolete inventory could be used more productively for other purposes or to reduce or eliminate debt from the state balance sheet (M. Aghajanian, personal communication, April 15, 2016). Similarly, when holding inventory for an extended time without exhausting supplies, obsolescence becomes an issue. For example, excessive inventory replacement parts may last longer than the machine they were intended for, making the remaining inventory valueless to the operation unless they take steps to sell off or modify the stock to fit the current application, potentially incurring further expense. In addition to this is the issue of shrinkage, or the loss of some excess inventory due to extended storage through theft, deterioration, or accidental damage, leading to losses on the operation's investment in this stock beyond the issues of purely holding onto the inventory for an extended time.

2.3.2 Inventory Management Best Practices

Beyond the bare necessity of avoiding resource depletion or surplus, proper inventory management allows for the reduction of waste in terms of both time and funding (Bailey & Helms, 2007). In an inventory driven system, goods can be grouped into three categories; maintenance, repair, and operations, the three divisions that define MRO inventory. The practices of proper MRO inventory management are based around this central idea of categorization, placing parts with

different degrees of criticality and commonality in separate categories and assigning each group or individual part a set practice for keeping inventory at an acceptable level. In practice, there are many valuable techniques for maintaining consistent MRO inventory, several of which are explained below.

ABC Inventory Classification

In setting appropriate standards for inventory tracking and upkeep, it is often necessary to classify spare parts, tools, and components by their defining features as they relate to everyday operation (M. Aghajanian, personal communication, April 15, 2016). Such classification often falls along the lines of an ABC classification system, which breaks down the parts within the inventory system into ‘A’, ‘B’, and ‘C’ categories based on several criteria related to their stockout costs. Within an ABC classification system, stock within the ‘A’ category is always the most critical, and therefore most closely watched within the system, often having long procurement lead times, high unit prices, low accessibility, or particularly high criticality to normal operations. Items in the ‘C’ category, by contrast, are relatively inexpensive and easy to procure, while still being essential to operations. These parts, such as nuts, bolts, or drill bits, are generally kept in excess at all times, as the benefits associated with managing inventory are outweighed by the benefits of ensuring that stock of these parts is always available. In between the two groups is the ‘B’ category, made up of items with relatively high unit prices and fairly long procurement lead times, or a similar combination of characteristics making both carrying costs and stockout costs equally severe for these parts. Items in the ‘B’ category thus are at an intermediate step in the inventory system and must be monitored closely, but not as tightly as those in the ‘A’ category, as these may be more commonly available or less expensive items to procure.

Kanban Systems

In a production or maintenance environment where a supply of spare parts is consistently being consumed by regular maintenance or parts failures, a kanban system provides a simple and quick method for keeping track of parts usage (Congdon & Hitt, 1992; Anderson, 2010). The term kanban roughly translates to “card you can see” or “sign card,” and a kanban system is based on just that. In a kanban system each spare part, or a fixed quantity of spare parts of the same type, e.g. nuts and bolts, is associated with an individual kanban card carrying identifying information about the quantity, type, and location of parts it represents. When the part or container of parts is removed

from inventory to be used, the worker making use of this resource deposits the kanban into a dropbox and/or scans the card into an electronic system, to notify the system or manager that this portion of inventory has been taken out of stock. Based on the return of cards, inventory management personnel are able to monitor which parts are being used in what quantities and when, allowing for calculation of acceptable reorder points and reorder quantities.

In addition to a planning advantage, a well implemented kanban system offers other benefits to the efficiency of production, or in the case of the DOT, maintenance, primarily as a result of the increased availability of information about inventory use when compared to a manually entered or less regimented inventory system (Congdon & Hitt, 1992). In a hypothetical situation in which a particular spare part was the subject of a disproportionately large demand, the tracking of particular instances of its use, or the sheer volume of kanban cards received by the system would bring attention to this issue, and highlight the need for improvement in the system necessitating the use of this part. Even in the case that this excessive use did not result in a material shortage, bringing attention to such large demands provides a basis for investigating any possible refinements to the relevant inventory management or production procedures.

In practice, this system may be implemented in many ways, one of which being the use of vending machines to regulate the distribution of spare parts and tools on the shop floor, a practice equally relevant to production and maintenance environments (M. Aghajanian, personal communication, April 15, 2016). By implementing a vending machine for regulating inventory, it becomes possible to directly and remotely track particular usage patterns and resource allocation, down to the individual supplies withdrawn for each work order. This is possible by restricting material access to supplies in the vending machine to workers with proper permits and legitimate work order information to enter as validation for item withdrawal. In this respect, vending machines are a particularly sophisticated method of implementing a kanban system, allowing total control over inventory in this system and allowing immediate, detailed, and reliable reporting of usage to both the company and its suppliers, when used in combination with a Vendor Managed Inventory system as discussed below.

Setting Reorder Points

When setting reorder points for different parts or consumables in an inventory system, several factors must be considered. At its most basic, setting a reorder point is a decision based on

how much supply is left at the point that another order is placed for a specific item, and ensuring that this quantity is sufficient to last through the lead time of the new order (Bailey & Helms, 2007). In pursuit of this goal, it is first necessary to assess the criticality of parts in inventory and arrange all supplies using this criterion. While a slight gap between the exhaustion of inventory and the arrival of a new order may be perfectly acceptable for some supplies, others, such as crucial machine components or frequently used tools, may cause extreme inconvenience, danger, or additional costs if unavailable for any extended time. By assessing the necessity of a part to normal production or maintenance function, it is possible to determine an acceptable buffer quantity for a part, so that when considering other qualities of the part such as usage and order lead time, it may be restocked at a more conservative rate. In addition, it is important to consider whether an item has a suitable substitute. Knowledge of the patterns of demand for a part whose criticality may vary over time are essential to determining necessary inventory practices. For a snow plow blade, for example, the criticality of having replacements on hand will vary significantly between the summer and winter. Compounding the problem further is the issue of lead times, the amount of time it takes for an order to arrive once placed, which may fluctuate based on demand, and must be analyzed and predicted to successfully set a standard reorder point, or a calculation for one.

Economic Order Quantities (EOQ)

In addition to setting proper reorder points, the practice of assigning economic reorder quantities to the resulting orders is also important. This is important to efficiently manage the storage of inventory, as well as to prevent stockouts and overstocking (Bailey & Helms, 2007). While the issues are different, the result of either over or understocking is the same: increased costs. The issues and costs related to stockouts and overstocking as related to the determination of EOQs are covered in further detail in Section 2.3.2.

Based on data about costs it is possible to approximate an optimal order quantity for a given inventory item, using an EOQ model as seen in Figure 2 (Bozarth, 2011).

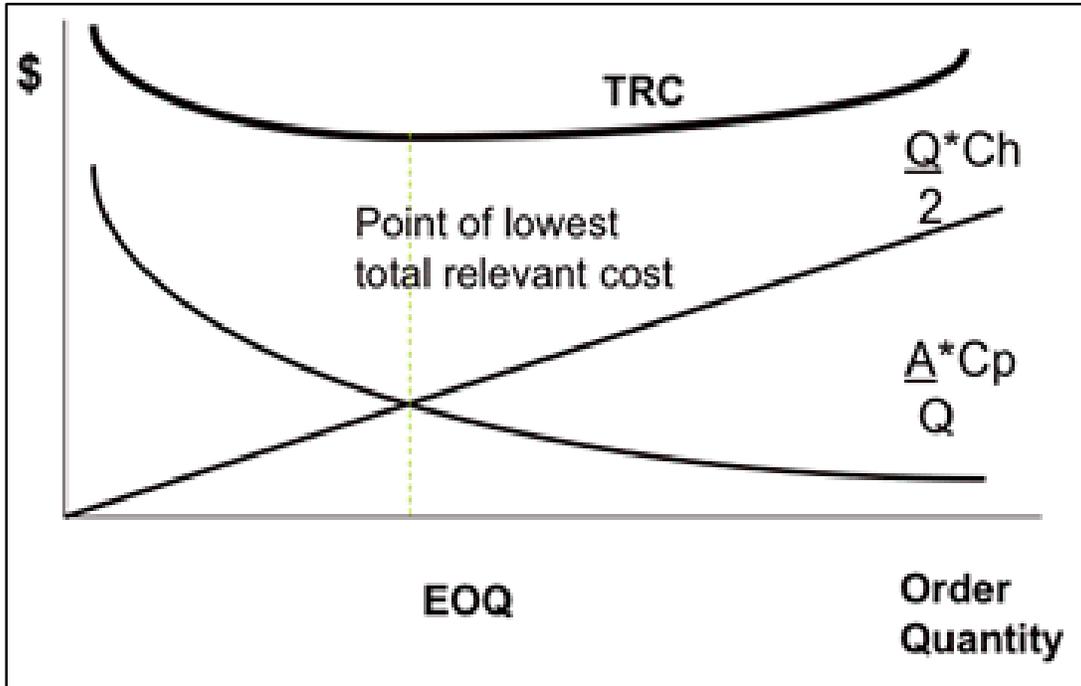


Figure 2.3: Graphical representation of EOQ based on cost calculations (Bozarth, 2011)

In one model, several defining characteristics of a particular inventory item are defined as fixed variables, namely: A - yearly demand, C_h - yearly holding cost per unit of the item, C_p - cost to place an order of items, and Q - order quantity. With the exception of Q , each of these variables changes per item although for the purposes of the EOQ calculation they are held constant at an approximate or average value to give a reasonably reliable, though not perfectly accurate, estimate of the order quantity that will generate the lowest costs. In determining the EOQ of an item, the key value to consider is the Total Relevant Cost (TRC), denoting the total yearly cost of an order of items as a function of order quantity.

The TRC of a particular order quantity is the value that the EOQ seeks to minimize and is calculated as the sum of the yearly ordering cost (AC_p/Q) and the yearly holding cost ($QC_h/2$) (Bozarth, 2011). It is determined this way to demonstrate, within an acceptable margin, the total cost that an order will create for a company based on the costs associated with shipping, handling, and restocking of an item, as well as the costs of holding stock of a particular item for an extended time. Where the TRC reaches its minimum is therefore the Economic Order Quantity, which means that the calculation for an item's EOQ can be derived as:

$$EOQ = \sqrt{\frac{2AC_p}{C_h}}$$

Supplier Partnerships

According to Bechtel and Patterson (1997), in keeping pace with inventory demands and supply requirements, an important cost and time saving measure may be to form partnerships with parts or bulk commodity wholesalers. If possible, allying with particular vendors for a wide range of inventory needs will consolidate the entire inventory system for an organization, removing the complication of placing various orders for parts with different suppliers while promoting the creation of a mutually beneficial relationship between the merchant and the consumer. By purchasing large quantities or wide varieties of parts from the same provider, it is more likely for the consumer organization to receive reduced pricing and improved service, as this relationship makes it in the best interest of the distributor to attend thoroughly to the needs of an important consumer.

Vendor Managed Inventory (VMI)

In much the same vein as partnering with suppliers, a potentially beneficial tactic for managing inventory is the initiation of a vendor-managed inventory system, wherein the vendor for a set of supplies takes responsibility for restocking a consumer's inventory (Waller, Johnson, & Davis, 1999). This removes the burden of continually ordering parts or consumables from the supplier, allowing the consumer to simply update their supplier on current inventory status, and continue with business until restocking shipments arrive. This arrangement may produce cost savings for the consumer company by simplifying the process of managing inventory, reducing product costs in the same way as that of a partnership, and improving the consistency of stock levels by consolidating the management and resupplying processes for a company, or even simply a subset of its overall inventory.

2.3.3 Industry Examples of Inventory Management Practices

To provide a clearer representation of the benefits that the above inventory management considerations can produce, this section will discuss several real-world examples of the implementation of industry best practices in combating both overstocking and stockout issues.

Among the cases discussed are: the Tennessee Valley Authority and its multi-million dollar inventory investment reductions through ABC inventory classification, the improvement of Texas Instruments production efficiency with the introduction of a kanban system, and the streamlining of inventory management through supplier partnerships and VMI at the Burns Harbor plant of the Bethlehem Steel company.

Tennessee Valley Authority

During the 1990s and early 2000s, the Tennessee Valley Authority (TVA), the largest public power company in the U.S., underwent significant changes to its inventory management system in response to massive inefficiencies in its previous system (Bailey & Helms, 2007). In the past, the TVA had managed its inventory in a rather simple way, consisting of only a Reorder Point (ROP) and Reorder Quantity (ROQ) for each part in stock, with the ROP set at one part remaining, and the ROQ set at approximately a year's supply, ensuring that maintenance crews always had consistent and regulated stock. However, in practice this system was widely disregarded, with maintenance managers instead working in the interest of keeping power running, and keeping upper management from punishing them for stockouts, ordering nearly all inventoried parts in quantities well beyond their defined ROQ. This led to significant overstocking of everything, both critical spares and commodities such as cleaning supplies, with most departments of the firm carrying multiple years' worth of inventory as a result of panicked ROQ increases during unusual hikes in inventory usage that were never corrected. Though the TVA was not required to pay significantly for carrying their vast inventory as a result of their governmental tax-exempt status, they were paying for their 'safety' inventory by way of their monetary investment in this inventory, as well as the usual issues associated with carrying excess inventory over time, namely obsolescence, damage, and shrinkage. In addition to this, the TVA did not have any centralized, set goals for their inventory investment or quantities throughout its various power plants, allowing for the continued unchecked growth of inventory to absurd levels. Starting from a minimum of \$182 million in 1980, the TVA's investment in inventory grew to a massive \$323 million in 1991, before reducing to \$282 million at the start of the inventory system reforms at the end of 1995.

To combat this blatant waste of money, the TVA began its extensive program of reform from the top down, centralizing and standardizing its inventory practices across all power stations and creating a 'virtual' inventory shared among them, to make clear to the new inventory

management division of the company what investments were being made, and what parts were kept in stock (Bailey & Helms, 2007). This allowed the company to better control its inventory system, and more closely monitor its operations as the firm proceeded to reform its more immediate issues with excess inventory, beginning by refining its approach to restocking. In response to the blunt ‘one-size-fits-all’ ROP and ROQ system of the past, the TVA decided to implement a new system based on the template of ABC inventory, stratifying different supplies into several categories based on criticality and availability. As this system was implemented, inventory was broken down into spare parts, bulk commodities, and consumables, with each monitored independently and given its own set of ROP and EOQ standards, also allowing current inventory investments to be categorized and catalogued along the lines of these divisions. Based on this analysis, the TVA determined that more than 80 percent of its current inventory investments were in the category of spare parts, a disproportionate amount resulting from its previous overly cautious and under regulated system. In addition, the TVA determined that over \$75 million of inventory was beyond its maximum set stock level under the old system, and \$89 million of its inventory had not been used on over three years. In response to this vast waste, the TVA further enhanced its already aggressive inventory reform plan to include a target reduction of \$100 million dollars invested in inventory at the end of five years, to be achieved by the combined reduction of existing excess, creation of supplier partnerships, and sharing of inventory among power stations within their system. The TVA successfully followed through on these practices, trimming \$100 million from their existing inventory within four of the allotted five years of reform, and within this saving almost \$70 million on their surplus inventory reductions alone, while maintaining their power generation levels and streamlining maintenance operations. Though only \$47 million of savings was actually observed, the remainder being attributable to expansions in the TVA power distribution network during the same period, their massive improvement in inventory investment is a compelling example of the ways in which a government-funded utility can benefit from the inventory management practices discussed above.

Texas Instruments Precision Controls Department

At the Texas Instruments (TI) Precision Controls Department in Attleboro, Massachusetts, the company’s production performance and efficiency was being seriously hampered by poor inventory management practices stemming from overcompensation in emergencies, similar to the issues faced by the TVA discussed earlier (Congdon & Hitt, 1992). In the case of Texas Instruments, however, the poor choices made in the interest of stabilizing inventory and production processes led

to an oscillation between overstocking and frequent stockouts rather than consistent and growing excess inventory. TI inventory managers began the cycle by keeping inventory at the minimum possible levels to avoid the high costs of investing in surplus inventory, resulting in periodic stockouts on spare parts for machines used in production, and therefore a scramble to fix the existing parts, find replacements supposedly hidden in back stock, and get a rush shipment of new parts to prevent continued inefficiency. This resulting overstocking would soon be seen as a burden and a source of possible refinement for business costs by managers, and would be actively reduced, or allowed to run down to previous levels in pursuit of short term increases in cost effectiveness. This would place stock levels back near where they began, leading to further stockouts and continuation of the vicious cycle. To remedy this problem, TI began by moving all stock of spare parts relevant to each machine on the production line to a cabinet nearby that machine, thereby eliminating the confusion and wasted time in finding spare parts hidden in back stock, and ensuring that the existing inventory levels could be easily checked by the workers. With the aid of the workers, TI managers determined appropriate spare parts quantities to stock in these cabinets, as well as the optimal locations of these parts within the cabinets. The managers then took this information and used it to create a kanban system for their spare parts inventory, where each part was associated with a kanban providing information about the part, the quantity of parts represented, and its location of origin in the facility.

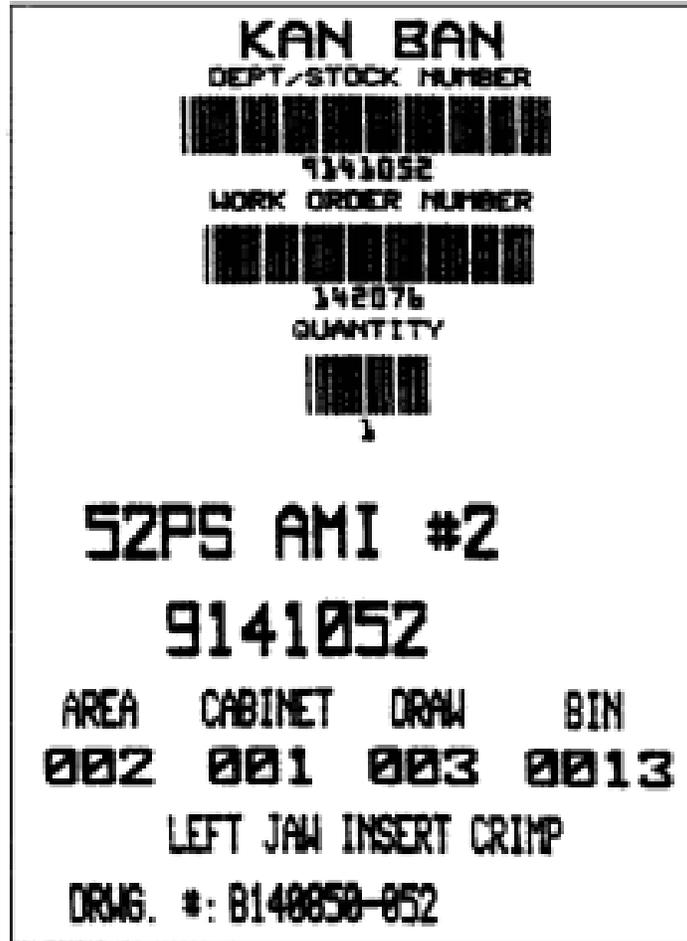


Figure 2.4: Example of Kanban used by Texas Instruments (Source: Congdon & Hitt, 1992)

In practice, when a worker took any spare part out of stock to be used, the kanban attached would be placed into a card holder atop the parts cabinet, to be picked up by a manager later on (Congdon & Hitt, 1992). These kanban would be retrieved by managers daily and entered into an electronic tracking system to determine remaining stock, and when necessary, initiate a reorder request. This kanban system provided a simple and rapid method of keeping track of spare parts consumption on the production line, and gave workers and managers alike a tangible reminder of their available inventory, allowing usage patterns to be tracked and faults detected by the sheer number of kanban being returned. After implementing the kanban system, one of the managers noticed a particular spare part was being used disproportionately frequently as a result of the more granular tracking, and initiated an investigation into the use of that machine with the help of the manufacturer and a company manufacturing engineer. This investigation resulted in the determination of a more efficient method of running the machine, and therefore a substantial

reduction in the quantity of spares required by the machine, saving the company further costs by making inventory a tool in addition to a resource. Further, the kanban system allowed for streamlining of inventory of parts common to multiple machines, by using the cards as placeholders rather than identifying tags, directing workers to a central supply of the common part. By implementing a kanban system for their production lines, the TI Precision Controls Department saw substantial improvements to the complexity and convenience of their inventory management system, in addition to reduced costs, major benefits for a seemingly simple change to their inventory system.

2.4 Summary

There are numerous factors to keep in mind when determining ESS locations, such as weather patterns, terrain, and the availability of power lines. The FHWA and USDOT have created guidelines on the best process for determining ESS locations, and many states have expanded upon these guidelines to create their own techniques for placing ESS. Additionally, there are several known inventory management best practices that the NMDOT could potentially implement to improve on their current system, each with its own pros and cons. This information will be referred to throughout the rest of our report to provide background information on our methods. In the next chapter, we will explain the methods by which we gained information concerning how the NMDOT has been handling winter maintenance and what they considered important about ESS placement.

3. Methodology

The goal for this project was to identify potential methods the New Mexico Department of Transportation's ITS Bureau can use to better assist the NMDOT in their winter road maintenance operations. This would allow the NMDOT to accomplish its overall goal of improving internal efficiency and the overall maintenance of the roads under its jurisdiction, making the New Mexico roadways safer for the public to travel on. To accomplish this we developed a process for identifying and comparing suitable locations for Environmental Sensor Stations (ESS) throughout New Mexico, and provided recommendations for how the ITS may be able to directly implement technology to assist in road maintenance management. To accomplish our goal, our group completed the following objectives:

1. Identified the criteria needed to assess the feasibility and merit of an ESS location within New Mexico.
2. Identified the best visual representation of the criteria to enable general location identification and assist data comprehension.
3. Developed a computerized process to evaluate and prioritize ESS locations under consideration using the aforementioned criteria.
4. Identified the most useful places to locate ESS locations in District 5 using our model.
5. Identified current winter maintenance and resource management practices as a guide for the ITS Bureau to assist the NMDOT's operations.
6. Identified how the patrol yards and winter maintenance managers could implement ITS technologies to improve road maintenance practices.
7. Identified additional methods that could be considered to provide real-time road condition and resource monitoring information.

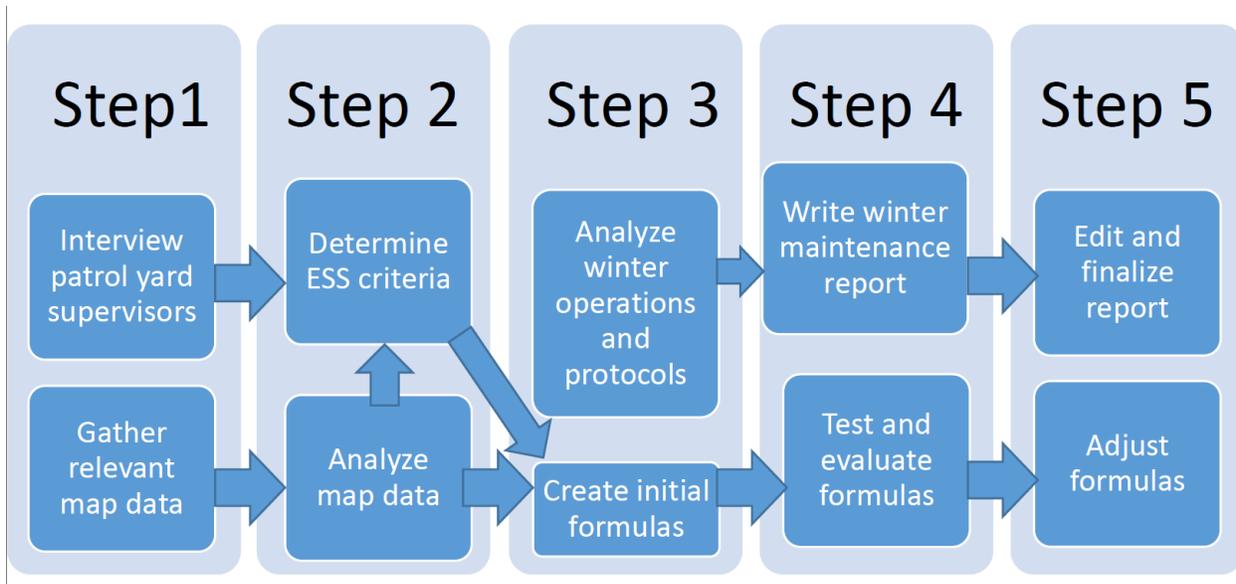


Figure 3.1: Block Diagram of Project Methodology

To achieve these objectives, we conducted interviews and produced a system for identifying suitable locations for the placement of ESSs based on the research detailed in section 2.1. In this chapter, we provide an explanation of these methods and the rationale behind their selection.

3.1 Objectives 1 & 2

To accomplish objectives 1 and 2 from the list above, we first collected relevant information from NMDOT employees about their experiences with managing winter weather on the roads within their areas of operation. We then used this information to identify distinct ESS siting criteria, and from this analysis compiled data concerning these criteria using ArcGIS Online. By doing so, we confirmed that we had identified what the NMDOT wanted from their RWIS and gave the NMDOT a centralized location for all of the information needed for siting ESS in the most appropriate and cost-effective locations.

3.1.1 NMDOT Employee Interviews

In order to develop our understanding of the NMDOT’s needs, our group visited the Albuquerque Traffic Management Center (TMC) and the NMDOT District 3 Office to interview NMDOT employees. At the District 3 Office, we interviewed five administrators to gain a sense of the managers’ perspective on winter road maintenance, following the general interview protocol in

Appendix D and the interview questions in Appendix F. We chose the particular administrators to interview based on their experience in their positions, as well as their knowledge of the operations at the patrol yards. In addition to these administrators, we also interviewed two upper level administrators at the Albuquerque TMC using the process outlined in Appendix D combined with the questions in Appendix G. To supplement these interviews, we attended the Federal Highway Administration (FHWA) Capability Maturity Model (CMM) Transportation Systems Maintenance and Operation (TSM&O) meeting. At this meeting we took notes on the presentations and recorded any information that pertained to our project.

Following these interviews, we analyzed the minutes taken at each to determine what factors NMDOT employees considered important when determining the placement of an ESS. Based on these factors, we identified several types of data about the road network, climate, and terrain, such as average daily traffic density, annual precipitation, and elevation, throughout New Mexico that we could objectively analyze to compare prospective ESS locations.

3.1.2 ArcGIS Mapping

Once we had identified what types of data we needed to collect, we concluded that we would need to create a map-based visual representation of these data, rather than a spreadsheet, to allow easy analysis and understanding. The software we used to create our maps also had to allow us to export relevant data for use in a model. After comparing the GIS tools available, we determined that ArcGIS Online was the best choice for our project due to the NMDOT's familiarity with the software and its ease of use. With this software we were able to gather data from maps created by other users and upload our own data in various formats (.csv, .zip, etc.) to create our own maps using information we obtained from the National Weather Service (NWS), the National Oceanic and Atmospheric Association (NOAA), and the NMDOT's databases. Once these data had been compiled into a common map set, we arranged and formatted the maps to enable easy interpretation by basic users, as well as extraction by a computer program for more thorough analysis.

3.2 Objectives 3 & 4

To accomplish objectives 3 and 4, we analyzed the data we collected through the methods described in section 3.1 to create a process by which the NMDOT can determine the best locations for new ESS. By ranking and weighting the different data available, we created a formula that could

be used to objectively compare the suitability of any two locations within New Mexico, and could then be applied to our GIS maps to determine ideal ESS locations for the NMDOT.

3.2.1 Suitability Ranking Formula

Having obtained the criteria to consider when placing an ESS from our interviews with NMDOT administrators, we developed a process for determining suitable locations for new ESS from these data, weighing the benefits and drawbacks of these sites. Our team then determined importance factors for the criteria on a scale of one to five, five being the most important, based on both the analysis described in section 3.1.1 and a comparison of the availability of information for each criterion at potential locations identified by the NMDOT. We then had our sponsor rank the same criteria in order of importance to allow us to compare our perspectives and discuss the reasoning behind both sets of rankings. The rankings resulting from this discussion were then compared to our original importance factors and a final importance factor was determined for each criterion. We then utilized these importance factors and our sponsor's feedback to create an additional criteria ranking system based on a 100 point, or percentage point, based system.

Within each of these criterion ranking systems, we then created two different individual formula sets; one completely relative, and the other absolute. In the relative formula set, each criterion was scored relative to the maximum and minimum criterion data provided in a particular data set, whereas the absolute formula set scored each criterion based on fixed maximum and minimum thresholds determined by a statistical analysis of each data set and discussion with our sponsor. Once we had developed prototypes of these two formula sets, we presented them to our sponsor to hear their feedback and choose which of the formula sets we would use in our finalized location ranking system.

3.2.2 GIS Analysis

Using the maps created by the process described in section 3.1.2, we created a site ranking tool in Excel using the formulas described in Section 3.2.1 to calculate the total ranking that each criterion should receive, as well as the overall suitability rating for each location, outputting this result as another CSV file and an Excel report.

3.2.3 Location Determination and Analysis

With this site ranking set calculated, we then uploaded the CSV containing our site rankings to ArcGIS as a new map layer. We overlaid this map on top of the map set created by the methods in section 3.1.2 as a new layer to allow us to visually verify the validity of the results. We then compared this ranking map to several desired ESS locations identified by NMDOT employees, to ensure that our ranking system produced reasonable results for these well understood locations. Based on visual inspection and comparison with the predetermined list to ensure that desired locations received an appropriate ranking, we changed the weighting factors of our formulas to see if we could generate results that we believed were valid as well as to experiment with what the changes did to ensure that our rankings were balanced and logical. Once we believed that we had a valid ranking system, we presented the results to our sponsors and got their feedback. We then made the changes that our sponsors suggested and repeated the process until both the group and sponsor were satisfied with the results of the ranking system.

3.3 Objectives 5, 6, & 7

In order to accomplish objectives 5 through 7 our group analyzed the current winter road maintenance processes used by the NMDOT, and the potential benefits of the application of the data obtained by an RWIS to these processes. To do so, we identified what resources the NMDOT currently has access to, ascertained how these resources are managed, and determined how current management practices could be improved through the use of ITS technological solutions, RWIS data, and alternative road condition and weather information collection methods.

3.3.1 ESS Data Application

To better understand the current system of winter road maintenance operations, we analyzed the information collected during the interviews described in section 3.1.1. This information, combined with the NMDOT's Winter Maintenance Guide, allowed us to distinguish differences between the winter road maintenance guidelines and the actual practices of the patrol yards. By comparing this information to our background research on resource management, we identified potential areas for improvement the NMDOT could work on to streamline its winter road maintenance practices. We then took the data that would be gathered from ESS and, in combination with our understanding of potential improvement opportunities, analyzed how this information

could be used to advance the aforementioned methods. We drafted recommendations for potentially effective ways to apply RWIS data for the improvement of winter maintenance operations.

3.3.2 Recommendations and Future Work

Using the analysis and recommendations gained from the process laid out in section 3.3.1 as well as information gathered from the interviews described in section 3.1.1, we created a list of recommendations for work that the NMDOT's ITS Bureau could undertake in the future to improve winter maintenance efficiency and effectiveness through the application of technological solutions. Extending from recommendations gathered from our interview minutes and discussions with our sponsors, we also used online searches and discussions with our sponsor to research possible sources of real-time road condition and weather information from outside of the NMDOT that the ITS Bureau could try to access. We compiled these findings into a list of potential projects that either the ITS Bureau or future research groups could undertake and included them in this report.

3.4 Summary

Through the use of the methods described in this chapter, we were able to develop a methodology for identifying and ranking high priority ESS sites and to recommend how the information collected by these stations can be used by the NMDOT. We also were able to collect information on the current winter maintenance management system with respect to resource management practices. This allowed us to analyze this information with the goal of improving road conditions in New Mexico and therefore improving the safety of the people who travel on them. In the next chapter we will present the results of our research along with our analysis of these results.

4. Results and Analysis

The overall goal of our project was to make roads safer for drivers by providing the ITS Bureau with a system to place ESS around the state, and an analysis of the current NMDOT winter road maintenance operations and recommendations for how to improve them. In this chapter, we will present the results and analysis of our project and explain how this goal has been met. This information can be broken down into two sections by the general topic covered: Determining ESS Siting Locations and Current Winter Maintenance Operations.

4.1 Determine ESS Siting Locations

We used information received from interviews and GIS analysis in addition to our research described in Chapter 2 to create an ESS siting procedure relevant throughout New Mexico. This was refined and applied to create a ranked list of potential ESS locations within NMDOT District 5.

4.1.1 Determining ESS Siting Criteria

From interviews with NMDOT employees we were able to determine what the employees considered important information to take into account when finding suitable ESS locations. The information from these interviews is based on many years of experience responding to winter weather conditions in New Mexico and was analyzed to produce the following important criteria for the siting of ESS:

- Wind speed affects the severity of a storm and snow drifts and is thus important to monitor.
- Priority 1 and 2 roads are the main focus of the patrol yards. Roads of priority 3 to priority 5 are usually left to melt on their own without extra care.
- The temperature of the air and the road affects what type of material is applied to the roads during winter maintenance operations.
- Monitoring visibility and snow depth is critical to the work of plow drivers.
- Knowing what type of precipitation is currently occurring and how fast it is falling is critical to Area Maintenance Supervisors (AMS) when determining when to send out units.

- Knowing the surface traction of roads allows the AMS to allocate resources where they are needed most.

The supervisors who were interviewed also provided our group with several suggestions for potential ESS locations and reasons behind why these locations are important:

- NM-528 to Rio Rancho was recommended due to very unpredictable weather, so having an ESS on this road would allow the patrol yard to be aware of rapid weather changes.
- I-25 near the San Felipe and Santo Domingo pueblos tends to be dangerous during the winter due to snow drifting and high winds, which combine with the area’s rolling hills to create hazardous driving conditions
- The “Big I” in Albuquerque, which is the intersection of I-25 and I-40, is used by thousands of cars every day. Numerous accidents occur in this location.
- I-40 near Tijeras Canyon was also specified as a good location for an ESS because of extremely unpredictable weather that can result from the local topography. The canyon can have several different types of weather occurring at the same time making storm preparation difficult. In addition, if there is especially inclement weather, the NMDOT can recommend the closure of I-40 to state police, protecting people from driving through dangerous weather or being stranded on the highway in desolate areas.

We gathered information about these locations as well as Clines Corners, which would serve as a control location in our work as an ESS has already been placed at that intersection. These data were combined into a spreadsheet shown in Appendix G, an excerpt of which can be seen in Table 4.1. These data were analyzed to create an initial list of important criteria to take into account when ranking possible ESS locations, as found in Appendix H.

Table 4.1: Test Location Criterion Data (Excerpt from Appendix G)

Criteria	Clines Corners (I-40/US-285)	Tijeras (I-40/NM-14)	"The Big I" (I-25/I-40)	San Felipe (I-25 MM248)
Average Wind (mph)	8	UNKNOWN	8.3	UNKNOWN
Average Annual Snow (in)	42	9.6	10	8.7
Average Annual Rain (in)	19.69	9.45	9.39	11.3
Functional Class within ½ mi	1, 3	1, 4, 5	1, 1	1, 5, 6
Snow Removal Priority within ½ mi	1, 3, 5	1, 2, 3	1, 1, 3	1, 3

From our discussion with our sponsors, we determined that areas with a high ratio of weather-related accidents to clear-weather accidents are preferable locations for ESS, so that these accidents can potentially be prevented. Because our initial goal was to find locations in District 5 to help with winter maintenance, Tim Brown said that less focus should be on areas with dust or sand.

While cities generally have high volumes of traffic, we determined that in most cases it is more important to have an ESS outside of the cities due to the greater difficulty of acquiring weather data in these locations. After looking at the maps of where all the patrol yards in the state are, we decided that having an ESS too far from a patrol yard would not be helpful, because after a certain distance the information gathered by the ESS cannot be used to respond in a timely manner. Having an ESS too close to a patrol yard is also not productive as the patrol yard employees can gather that information themselves.

We took the feedback from our sponsor and created a final list of criteria for siting ESS:

- Average wind speed
- Average wind gust speed and time length
- Average annual snowfall
- Average annual rainfall
- Snow removal priority of roads within ½ mile
- 2013 Average Annual Daily Traffic (AADT)
- Ratio of clear weather to weather-related crashes
- Distance to nearest patrol yard
- Distance to nearest ITS installation
- Fire risk
- Altitude
- Distance to power
- Distance to communications
- Local environment
- Local topography
- Average road grade within 2 miles
- On tribal land

4.1.2 Suitability Ranking Formula

We utilized this list of relevant criteria to create a ranking system that the NMDOT can apply to determine where to place new ESS. This system took the form of a ranking formula based

Table 4.2: Location Criteria Importance Factors (Excerpt from Appendix M)

Criterion	Team's Importance Factor (5 to 1)	Sponsor's Importance Factor (1 to 13)	Final Score (%)	Deal Killer?
Wind data	1	2	12	NO
Average annual snow (in)	4	2	15	NO
Average annual rain (in)	2	11	4	NO
Functional Class within ½ mile	3	-	-	NO
Snow Removal Priority within ½ mile	4	4	6	NO

Developing the Formula

Utilizing these criteria and importance percentages, we developed our location ranking formula by comparing data values between sites for each criterion and by using the importance percentages to directly set how heavily-weighted each of these criteria would be in the formula. This formula was essentially a direct implementation of our point rankings, where a location's data value for a given criterion was ranked relative to an upper and lower threshold for that criterion. This relative ranking was then converted into a value out of the total number of points allotted to that criterion. Once the data for each criterion at a location was allotted its appropriate number of points, the total points given to all criteria for that location were summed up to produce a final ranking value on a scale from one to one hundred. We then broke down this general formula into two distinct arrangements based on how the points allotted to each location were determined.

Determining Points Awarded

As mentioned in the preceding section, our formulas took two distinct forms based on the same general structure, an "absolute" version and a "relative" version as mentioned in Section 3.2.1. In the case of the relative formula, each data point about a location is ranked purely in the context of the other locations being ranked. For the absolute formula, each data point about a location is ranked in the context of the entire area of investigation. One major effect of this distinction is that in the absolute ranking, most cases will not receive either full points or zero points for any given criterion, while the relative formula automatically assigns full points to the highest data point of the set and zero to the lowest data point. While the absolute ranking will consistently produce the same ranking value for a given site, the relative formula will produce different rankings based on the

specific set of sites in the comparison. In essence, the absolute formula is objective and broad, while the relative formula is intended to highlight distinctions among a few similar sites.

Within these two formula types, each of the criteria needed to be given points based upon the 100 point criteria ranking scale discussed above, and how the associated data for each criterion relates to certain thresholds. This requires each criterion to have its own calculation to calculate these points properly. One of these calculations for allocating points would be completely relative, a graph of which can be seen in Figure 4.2.

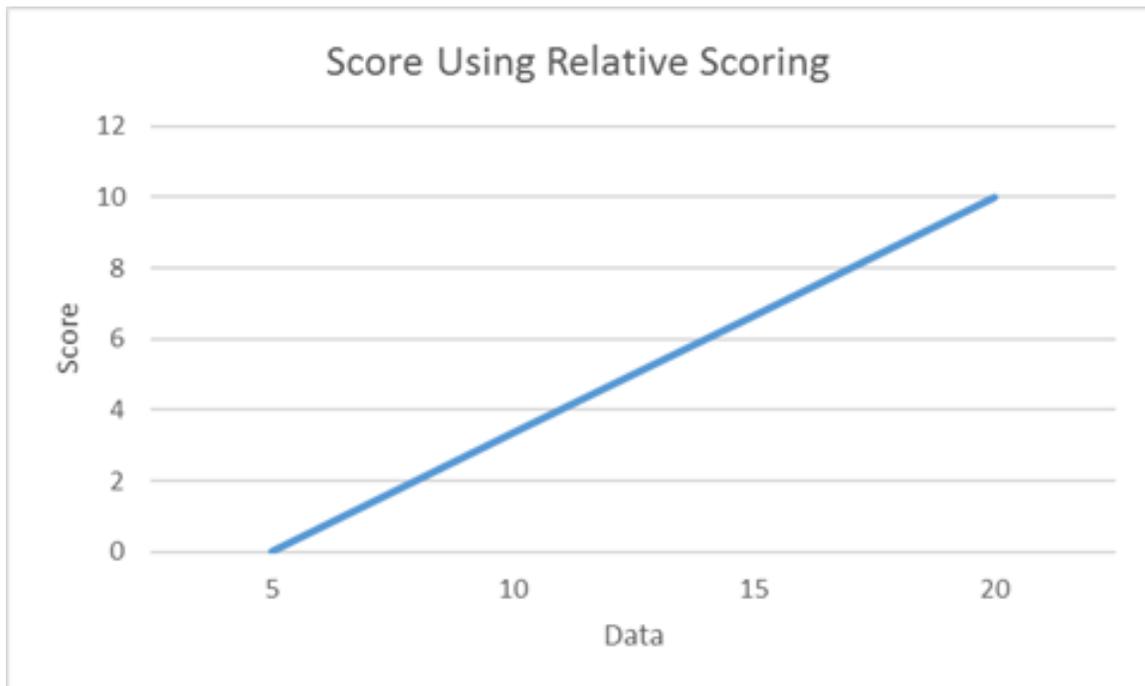


Figure 4.2: Score Demonstration Using Relative Scoring

In this type of scoring calculation, the point allocation lies along a linear scale with hard stops at the ends. This was used throughout the relative version of our formula, where we set the endpoints of the linear scale for each criterion at the maximum and minimum data values input for that individual criterion, so the ranking for each site would be completely relative to the other sites entered.

The absolute formula, on the other hand, does not rely on a solely linear scale, but rather a threshold based calculation as seen in Figure 4.3.

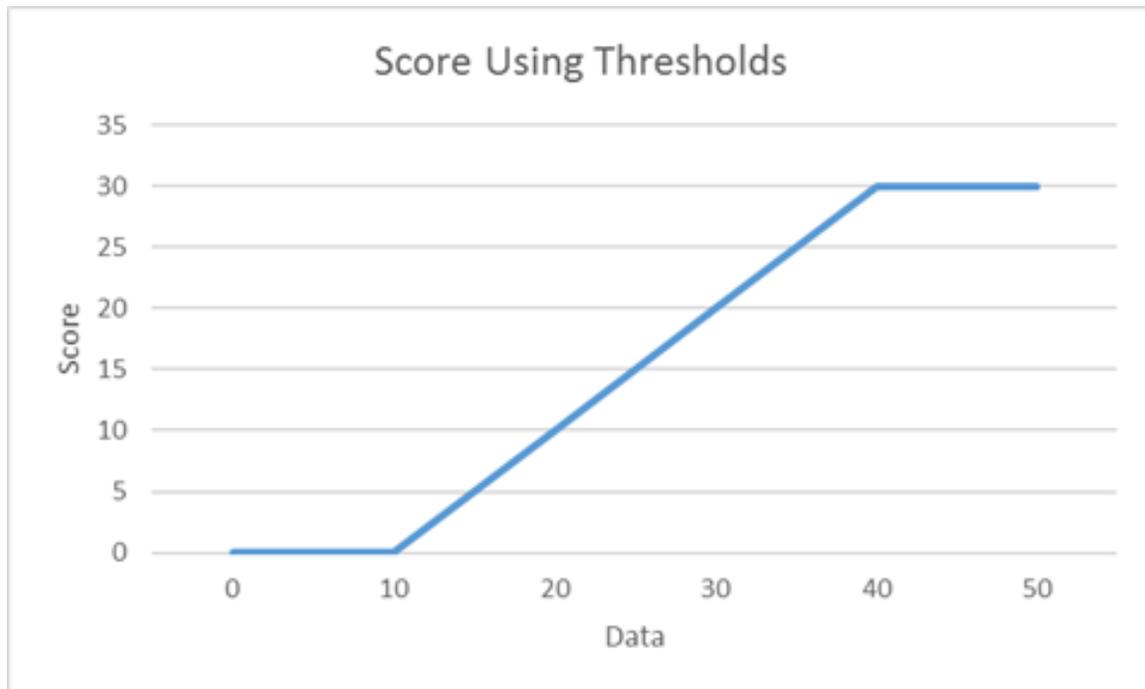


Figure 4.3: Scoring Using Thresholds

In the application of this type of formula, any data point at or above the set maximum threshold for that data type will receive the highest possible score, while any point at or below the minimum threshold will receive the lowest possible score. Any point between the minimum and maximum will be scored along a linear scale, similarly to the relative calculation. Rather than being defined by the data itself, however, this threshold calculation is wholly defined by the judgment of the user based upon the placement of the thresholds, which can result either in a more objective ranking or a heavily biased one. We believe that the ideal thresholds should be based on a statistical analysis of data values observed for that criterion around the whole of New Mexico, with the ideal upper threshold set at the 75th percentile and the ideal lower threshold set at the 25th percentile. This system creates objective and unbiased rankings, but allows change based upon the user’s input.

In our ranking tool, we make use of both types due to the different purposes they serve, ideally allowing the NMDOT to make nuanced distinctions between potential ESS sites that a single formula would not allow. However, in certain cases, particularly within the absolute ranking formula, we found that neither of these scoring systems would work. For example, distance-related criteria, such as the distance to patrol yard or ITS unit, would not fall neatly along a linear scale, with locations that are too close or too far both being of little use. To handle these particular cases, we

thus needed to use a comparison that would assign a low value to data points that were too high or too low, and only award maximum points to those that were “just right”. In order to do this, we utilized the Goldilocks Principle as the basis of our third scoring system, the function of which is demonstrated in Figure 4.4.

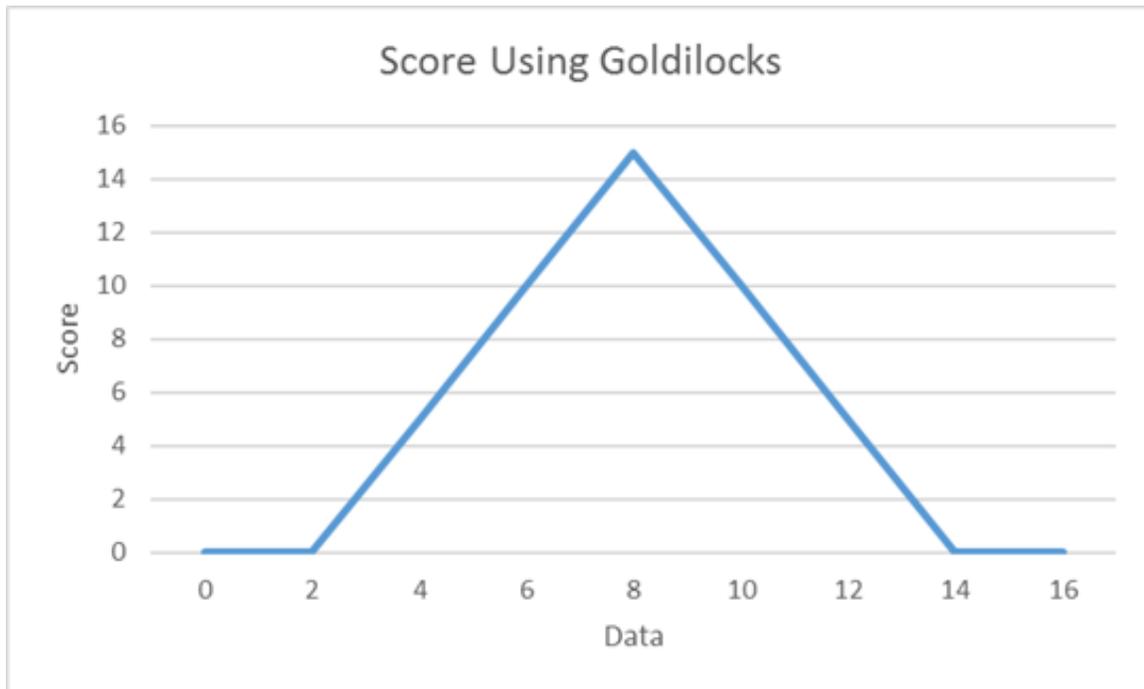


Figure 4.4: Score Demonstration Using Goldilocks Principle

GIS Maps

Once we had assigned the relevant comparison method to each criterion in our formulas, we then set about gathering the relevant data using ArcGIS and the automation and analysis tools that the software can provide. We first gathered useful maps on ArcGIS Online and compiled them into one map set to centralize all of the information we would need. We then used the analysis tools provided by ArcGIS to refine some of the data, such as New Mexico statewide crash data from 2010 through 2014, which was analyzed to calculate the ratio of crashes that occurred during clear weather to crashes that occurred during weather events along different road segments. We created two different map sets on ArcGIS, with one focused on crash data, seen in Figure 4.8, and the other covering all other necessary data for the ranking calculations such as precipitation, as shown by Figure 4.5. A description and link for each of these map sets can be found in Appendix N.

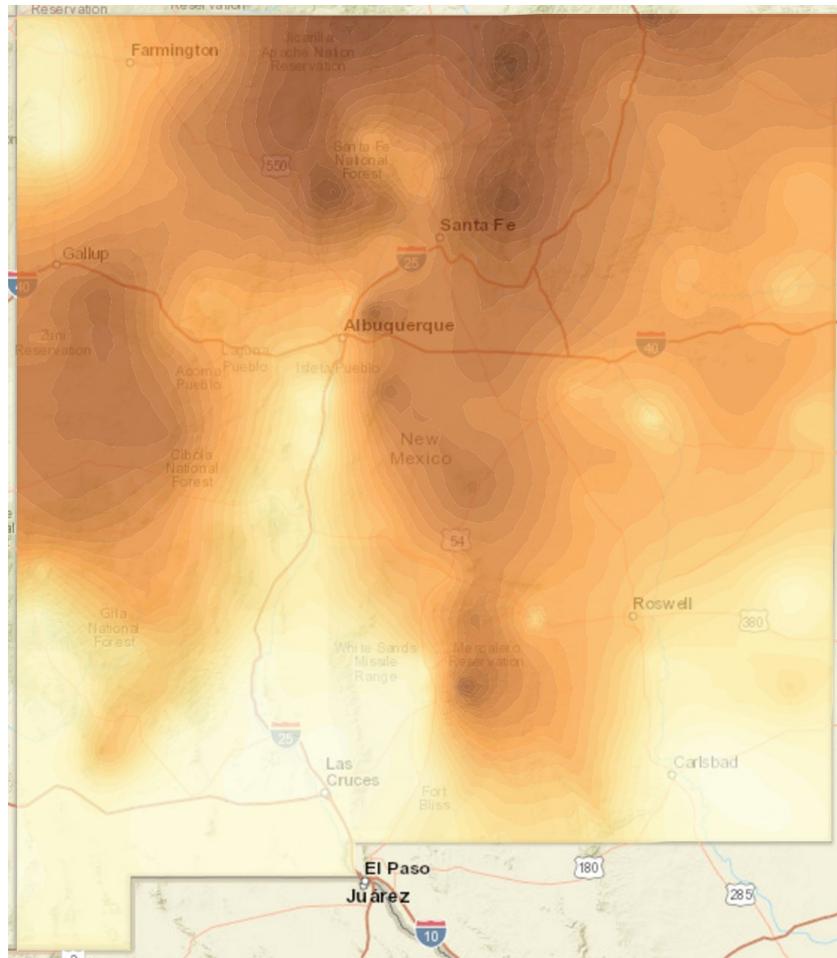


Figure 4.5: Interpolated Annual Snowfall Layer from ESS Siting Data map (Appendix N)

Once we had successfully accomplished this analysis, we then attempted to use the analysis tools to consolidate all relevant data for the ranking formula into one layer, which would allow us to import only one data file into our formulas rather than individual Excel files for each criterion. Had this worked, we could have created a largely autonomous siting analysis tool that would import all GIS data at once, parse it, and output site rankings with minimal human involvement. However, we found that we could not do so for several reasons, such as multiple map layers being unavailable in a usable format for the analysis tools and certain data sets, such as information on wind speeds, being unavailable on ArcGIS or in any format we could use to create a map layer. The data that we could and could not collect is described in Appendix R.

Although we could not find data on some criteria, we still considered them significant enough to include in the hope that the NMDOT would be able to access these data in the future.

The effect of these missing data sets is that our formulas will produce lower rankings for all sites for which these data are unavailable, but due to our inability to access these data for all sites ranked, our site rankings remain relevant and comparable.

Excel Ranking Program

Having determined how each criterion should be ranked relative to the others, and how points for each criterion should be calculated, we then used Microsoft Excel to create an automated program to apply our ranking formulas. We decided to name this ranking program the Station Placement Optimization Tool, or SPOT. We began by using the Visual Basic Editor built into Excel to create a data entry form that would intake information about each location criterion and store the data in an organized tabular format on one worksheet. A user could enter, modify, or delete data for a location by using the drop-down menu at the top of the form and the “Save...” or “Clear...” buttons, as shown in Figure 4.6.

The screenshot shows the 'SPOT Location Data Entry Form' with a drop-down menu open for 'Location'. The menu lists several location options: NM-150 MM10 (Taos Ski Valley), I-40 MM180 (West of Edgewood), I-40 MM173 (Tijeras Canyon), US-64 MM390 (Des Moines), NM-38 MM18 (Red River), I-40/US-285 (Clines Corners), US-64 MM273 (Palo Flechado Pass), and I-25 MM331 (Serafina). The form includes various input fields for data such as Average Road Grade, Annual Rain, Distance to Power, and AADT, along with 'Save This Data' and 'Clear This Entry' buttons at the bottom.

Field	Value
Data Set Currently Editing:	NM-150 MM10 (Taos Ski Valley)
Location	NM-150 MM10 (Taos Ski Valley)
Average Road Grade 2 Miles	0
Average Annual Rain (in)	21
Latitude	
Dist ITS Unit (mi)	12
Longitude	
Fire Risk (0 Very High, 5 No Risk)	4
Ratio of Weather to Clear Crashes	12
Distance to Power (mi)	15
Average annual snow (in)	62.5
Distance to Communication (mi)	15
2013 AADT	800
Local Environment	
Average Wind Gust	0
Functional Class	
Local Altitude Range (meters)	900
In Tribal Land?	NO
Dist Patrol Yard (mi)	8
Length of AADT Road Segment (mi)	7.59
Altitude (Meters)	2650
Comment 1	District 5
Snow Removal Priority	4
Comment 2	

Figure 4.6: SPOT Location Data Entry Form displaying drop-down menu

Once we had successfully enabled the data entry form to store, retrieve, and clear data, we designed a front page, as shown in Figure 4.7, that would display two short paragraphs, one briefly describing the function of the SPOT program and the other providing an overview of how to

operate the program. This front page also displayed two buttons, one to launch the data entry form, and the other to calculate the site rankings and display the ranking report.

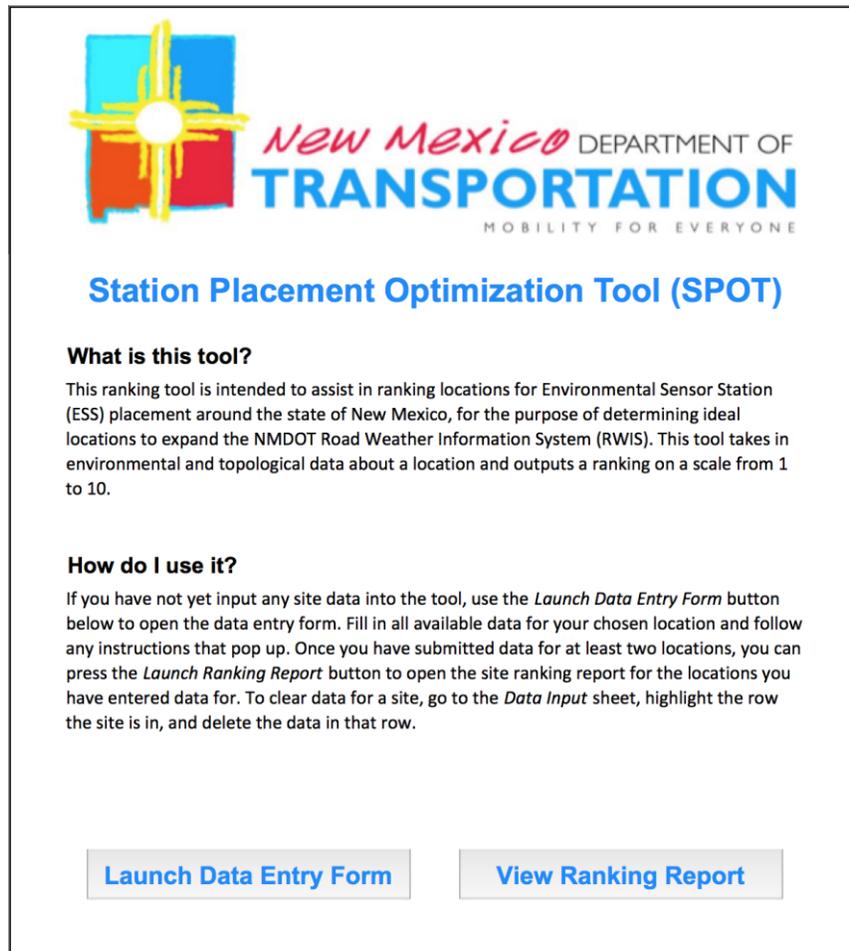


Figure 4.7: SPOT Front Page Display

Once a user clicked the second button, having already input data for at least two locations, SPOT runs the data through both our absolute and relative ranking formulas and outputs the resulting site rankings as a condensed ranking report.

The SPOT ranking report displays the location names and rankings according to both formulas, the latitude and longitude of each location, certain warning codes, and three graphs to represent the rankings. By displaying the latitude and longitude of each location, the report would allow the rankings to be easily exported and uploaded to ArcGIS for a visualization of the results, allowing the user to easily display and understand the location of each site and its associated ranking. The warning codes displayed by SPOT in our final version consisted of warnings about power and

communication line availability, as well as whether or not the site was located near tribal land. This was implemented by calculating if a station was more than 1.5 miles from power or communication lines, or within one mile of tribal land, a flag is generated to indicate the need for further review.

The ranking report also includes three bar graphs to assist in comprehension of the results, with the first graph showing the total absolute and relative rankings for each site, and the second and third showing a stacked bar graph of the absolute and relative rankings, respectively. By displaying the total rankings next to each other visually, the report allows the user to understand the value of each location more intuitively than just by the raw ranking values. By displaying a stacked bar graph of each location's ranking, the report would provide the user with an extra explanation for why each site received the ranking it did, with each segment of the graph showing how significantly each criterion contributed to the overall ranking. A sample ranking report, produced by our own site analysis, is included in Appendix O.

Checking the Formula

Once we had completed the design of our formulas and the collection of our data on ArcGIS, we tested SPOT by ranking different locations within Districts 3 and 5 to determine whether or not reasonable ranking values would be output. Among other locations, we used the test locations described in Section 4.1.1 to determine whether our rankings were in agreement with the sentiments shared by the administrators that identified the test locations to begin with. Based on the ranking results SPOT produced, we found that we did not need to make any significant revisions to the formulas, criteria weightings, or thresholds. Despite needing to change little of the original SPOT system, we added two extra spaces for new criteria, to provide our sponsors with a more substantial foundation to work from in modifying the tool. We also created a User Guide that provides useful information about how to use and modify the tool, which the NMDOT can use to get the best use out of SPOT. This User Guide can be found in Appendix P.

4.1.3 Siting Methodology

To make use of these formulas and maps, we also needed to develop a methodology for implementing these tools, so that any ITS employee could read through our guide and quickly begin using our system to determine ideal ESS sites. This section will briefly describe how we used our SPOT to locate ESS sites within District 5, and how our methodology will likely differ from that

used by the NMDOT for the same overall purpose. For a full guide on the use of our formula, see Appendix P.

To determine potential sites we began by using our ArcGIS Crash Map, described in Appendix N, to find road segments that had high ratios of weather related crashes to clear weather crashes. Figure 4.8 shows this crash ratio map layer, where red-orange roads represent the segments of roads with high crash ratios and the dark blue represent segments with low crash ratios. The colors in between these points scale linearly with the crash ratio of that segment, with white segments being the mean. In addition to identifying locations with high crash ratios for ranking, we also selected locations with a combination of a moderate crash ratio and a high AADT, as both types of locations were deemed to be significant as potential ESS sites.



Figure 4.8: Weather to Clear Crash Ratio Map Layer

After compiling a list of such hot-spot locations within District 5, we used our ArcGIS ESS Siting Map, also described in Appendix N, to gather data on each criterion at these locations. We then input these data into SPOT to determine our final location rankings for District 5, the results of which are listed in Section 4.1.4 below. When the ITS Bureau seeks to determine ideal ESS

locations, however, their methodology will likely take on a significantly different process. This process will determine locations to analyze based upon where the NMDOT plans to do roadwork in the next four years. This is because the ITS Bureau does not have the funds to implement more than one or two ESS every year, so if they can include their ESS installations in the planning for current roadwork projects, the funding will come from the District level DOT budget rather than the ITS itself, allowing for more ESS to be placed across the state.

When siting ESS, we started with a blank map, and used our ArcGIS map sets to highlight ideal locations that we could then rank using SPOT. On the other hand, the NMDOT will most likely start with a map of upcoming road work sites around the state, so a user within the NMDOT can skip the first hot-spot finding stage of our methodology and move directly to the data gathering and analysis stage. By bypassing the site-finding stage and moving directly to the site ranking stage, the ITS Bureau will be able to use SPOT in exactly the way it was intended; to streamline siting comparisons and make objective judgments on which sites will be better suited for ESS installation.

4.1.4 Results of Ranking Analysis within District 5

Once we had refined our ranking formulas to a satisfactory degree, we used SPOT to conduct an analysis of twenty locations from around New Mexico to determine which locations we should recommend to the NMDOT for the placement of new ESS. Appendix O includes the full ranking report produced by SPOT for these locations, while the top five sites according to the absolute ranking formula are listed below.

1. NM-150 Mile Marker 10 - Taos Ski Valley
2. I-40 Mile Marker 180 - West of Edgewood
3. I-40 Mile Marker 173 - Tijeras Canyon
4. US-64 Mile Marker 390 - South of Des Moines
5. NM-38 Mile Marker 18 - Red River/Bobcat Pass

Figure 4.9 shows an ArcGIS map layer produced by uploading the table included in the SPOT ranking report as a CSV file, to provide a visual representation of all ranked locations and their scores.

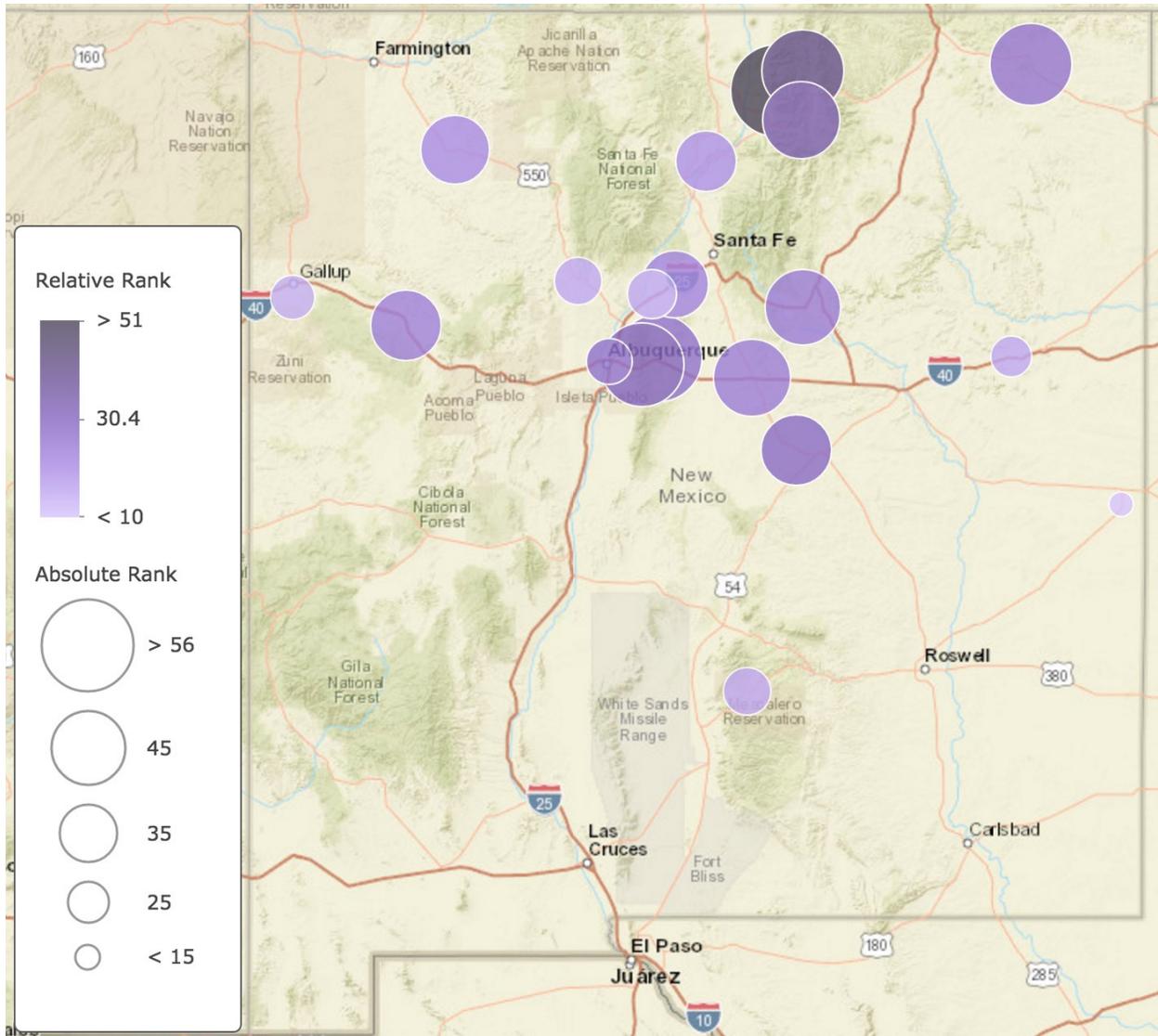


Figure 4.9: SPOT Ranking Report Results Mapped in ArcGIS

In the full ranking report, it is apparent that the absolute and relative formulas produce vastly different ranking values for the same set of locations, as illustrated by the Overall Location Ranking Score graph shown in Figure 4.10.

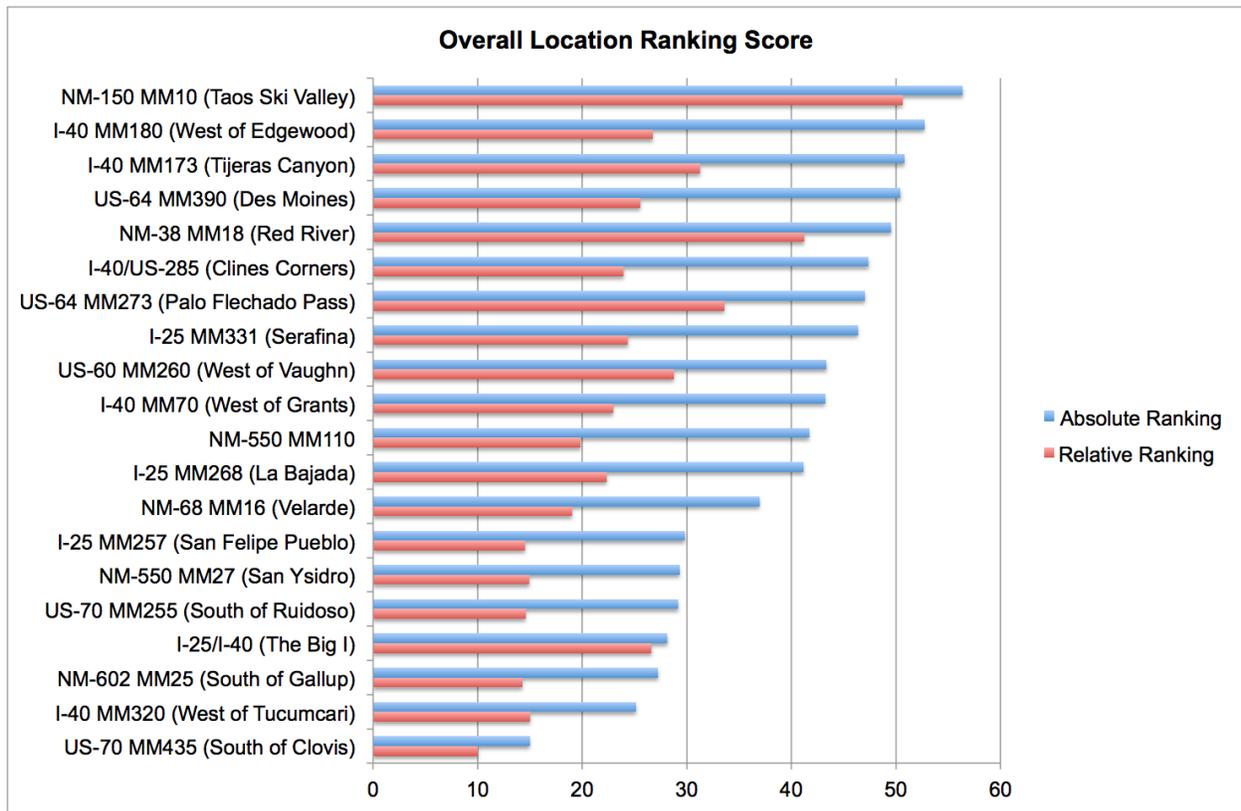


Figure 4.10: SPOT Overall Location Ranking Score Graph (Excerpt from Appendix O)

This graph displays not only the distinctions between the two formulas, but also the value each provides to the report overall. As shown in Figure 4.10, the locations have been ranked by their absolute rankings, as the absolute formula provides a better measure of the value of each location when compared against a large group of locations. The relative formula is best used to analyze distinctions between closely ranked locations, as seen in the rankings for US-60 MM 260 and I-40 MM 70, where the relative formula provided a six point difference in favor of US-60 MM 260 while their absolute rankings were nearly identical.

Due to the different criteria weightings and calculations used to achieve its ranking values, the results produced by SPOT may be difficult to rationalize without an understanding of how each criterion factored into a location’s overall score. Thus, we have included two stacked bar graphs into the SPOT ranking reports to display a breakdown of the points awarded for each criterion at each location. Figure 4.11 shows the first of the two stacked bar graphs included in the ranking report, describing visually the criterion-by-criterion breakdown of the absolute rankings.

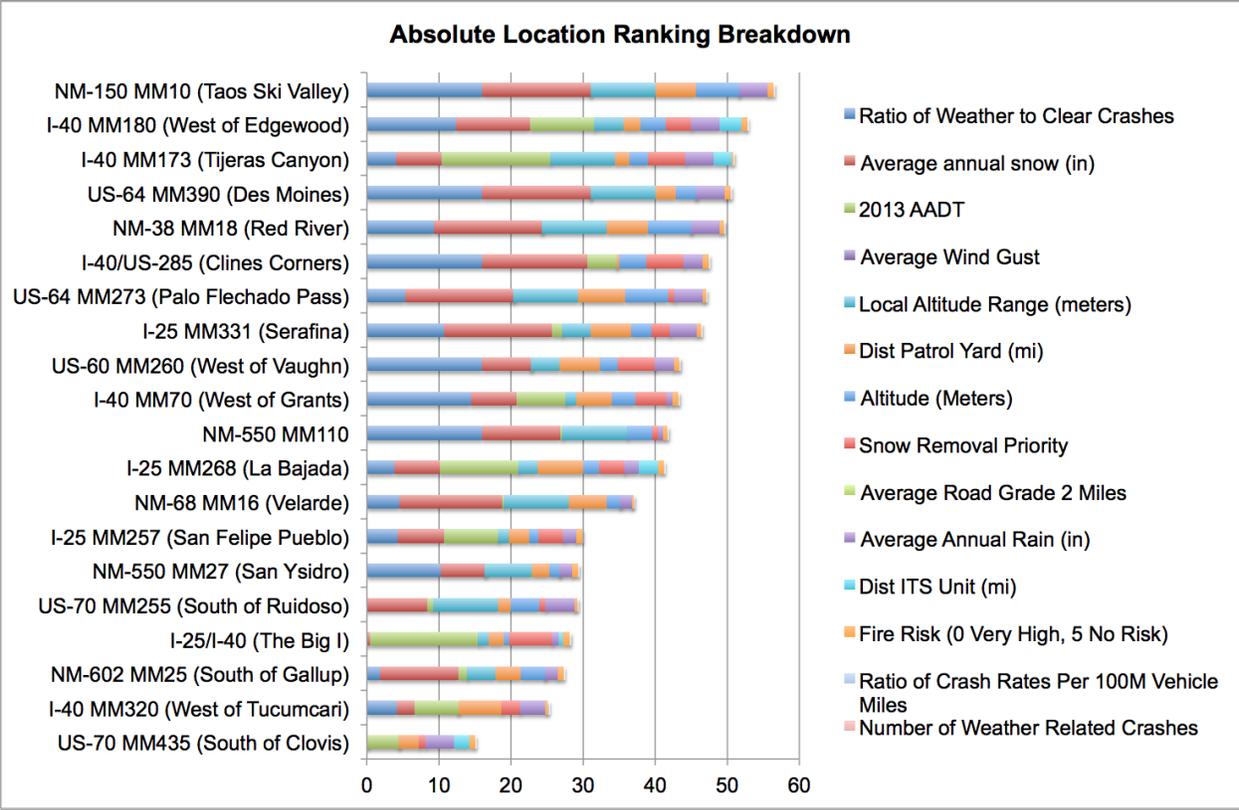


Figure 4.11: Absolute Location Ranking Breakdown Graph (Excerpt from Appendix O)

The stacked bar graphs in the report provide a more in depth explanation of why certain locations received the rankings they did. This also can be used to determine outliers by finding locations that received the least or most points possible in the absolute and looking at what they received in the relative formula. If the results for that location or every other ranking appear to be skewed, this indicates that the location in question is an outlier.

The rankings generated by the SPOT are created for many different reasons, often these reasons can be deduced by comparison of the absolute and relative rankings a location received. If you start by analyzing the stacked bar graph of the rankings that NM-150 MM10 received, it becomes quite apparent that it received top marks in both crash ratio, snowfall, altitude, and altitude range. Each of these criterion are relatively high scoring sections, making it no surprise that this location received the top ranking from both formulas. However, if one looks closer, one will also notice that the score NM-150 MM10 received for AADT is almost non-existent. This indicates why this location has such a high ratio score because while it does not receive a large amount of traffic, most of this traffic appears to happen during weather events, producing a high ratio. This analysis

makes sense when taking a step back from the data and seeing that this road leads to a winter ski resort, a road that will generate more traffic in winter weather than in clear weather because people want to ski.

One of the other interesting sites in the ranking is the ranking received by the intersection of I-25 and I-40. This location ranked fairly low in the absolute ranking but around the middle of the relative ranking. Looking at the stacked bar graphs, it becomes relatively clear why this happened. This location generates the majority of its points in the AADT, so much so that almost every other location generates almost no points in the relative rankings for AADT. This implies that this location is an extreme outlier in terms of AADT, and indeed it receives the most traffic out of any other location in New Mexico. However because it has such a high AADT and in New Mexico it is much more likely to have a clear day than a weather event, the ratio of weather related crashes to clear weather crashes is very low, meaning that the location receives almost no points for that major category. This means that its absolute ranking will be very low but the relative ranking will indicate that it is a location that should be looked into just for the fact of one outlying criterion.

Both of these examples indicate strengths and weaknesses of the SPOT. As seen in the intersection of I-25 and I-40, SPOT very easily points out places that might be overlooked just based upon the absolute formula, showing the importance of both formulas. However, both of these examples also point out potential shortcomings of the system. While NM-150 MM10 receives the highest score, because of its drastically low AADT, it might not be the most useful location. And while the intersection of I-25 and I-40 might score relatively low, the sheer number of crashes that occur at that location might warrant extra monitoring due to the increased chance of litigation. This indicates that the rankings must be taken with a grain of salt as they do not account for the social or legal reasons for implementing an ESS, they just look at the hard data.

4.2 ESS Data Applications and Alternative Data Sources

Once a system for gathering road condition data has been implemented, such as the RWIS network, the NMDOT should apply this information as efficiently and effectively as possible to ensure that road maintenance practices are positively impacted by the changes. Additionally, as the new ESS are implemented, other sources of information can be used as a stopgap solution and to supplement the final RWIS.

4.2.1 Communication and Notifications

We have identified several potential methods the ITS Bureau could utilize to involve real-time road condition data in everyday maintenance management practices. These methods center around the incorporation of data into the existing NMRoads framework to allow administrators and managers to be notified immediately of road condition changes in their area, and to provide some additional information to the public nearby.

Currently, the NMDOT uses its online road monitoring system, NMRoads, to provide valuable information about road conditions, work zones, crashes, and traffic patterns to the public. While the system is mainly used to manually check on road conditions while planning trips, the website has the ability to provide users with notifications via email or text about sections of road of particular interest to them. By applying ESS data to this notification system, the NMRoads mobile application could be used to provide administrators with notifications about road condition data within their area of operations. By setting certain thresholds for notification triggers, such as snow depth, temperature, or grip factor, the administrators can be notified of particular conditions that would require DOT intervention, thereby reducing the patrol yards' reliance on manual patrols to monitor road conditions.

During our interviews, we determined that most NMDOT administrators were only supplied with older model phones for work which are incapable of checking and receiving emails or using the internet. Without these features, the administrators would currently be required to use either a computer or their personal phone using their own data plan to get road condition notifications from NMRoads. This limitation would significantly hinder the implementation of such notification systems, thereby reducing the effectiveness of RWIS data. This problem could be easily avoided by providing every supervisor with a smartphone for work.

4.2.2 Alternative Sources of Data

While placing ESS throughout the state is a major priority for the NMDOT's modernization efforts, they would also like to leverage other technologies to enhance their road condition information system. To do this they would like to look into other sources of weather information that they might be able to incorporate into their system in the future. Some of these sources of information could include using social media to detect trends of weather related posts in a particular

area, getting weather data from Automated Weather Stations (AWS) around the state, and even potentially using the data gathered and transmitted by modern cars and trucks to determine road conditions.

The National Weather Service (NWS) and National Oceanic and Atmospheric Administration (NOAA) both already have AWS placed around the state of New Mexico as part of their national weather monitoring network, but the NMDOT does not have direct access to the data produced by these stations. While AWS do not produce road-specific data such as grip factor or pavement temperature, they are effective tools for reporting typical weather data such as air temperature, precipitation quantity, and wind speed and direction. We believe that the NMDOT could benefit from this AWS data both by enhancing the information available to road maintenance managers, as well as gaining more accurate site information for the placement of ESS in the future.

Due to the prominence of social media in contemporary society, our group believes that if the NMDOT could access weather-related posts to sites like Twitter, their information gathering network could benefit significantly. If they could access such posts via some type of geo-analysis program, the NMDOT could improve their understanding of the public perspective on road and weather conditions that would assist in understanding driving conditions at a given time and place. The NMDOT could also create its own app allowing users to report weather conditions on a given road, or could build such reporting functionality into NMRoads to aggregate the same public knowledge. Social media could also be analyzed to gather public opinions of what the NMDOT could do better or is currently doing well.

We also recommend that the NMDOT strengthen its communications with state and local police to more efficiently share weather data in both directions and make sure that there is a degree of communication transparency between the two. During our visit to the Capability Maturity Model Transportation Systems, Management & Operations (CMM/TSM&O) meeting in Albuquerque, there was a discussion on the same subject wherein it was mentioned that in many cases information is unintentionally withheld from either organization due to disorganized communications. By creating a written memorandum of understanding, the NMDOT and state and local police could ensure that information is passed to the correct organization.

The New Mexico Trucking Association (NMTA) also keeps track of weather in the state to help keep trucks and their drivers safe. The NMDOT could get in contact with the NMTA as

another means of tracking weather information, which would provide a particularly valuable resource as most of the NMTA's data is gathered from truckers currently out experiencing the weather firsthand. This could be implemented by creating ties with the New Mexico Ports of Entry and the trucking dispatchers or monitoring the trucking radio channels to catch and flag weather-related chatter in real-time.

A data source similar to gathering information from truckers could be connected vehicles, or the installation of sensors on snow plows or salt spreader trucks owned by the NMDOT. By installing sensors on certain NMDOT vehicles, the ITS would be able to expand their road condition monitoring system to the immediate environment of their own trucks, allowing for enhancements to the information generated by winter storm patrols. This would also allow the NMDOT to monitor the effectiveness of its maintenance operations, allowing the supervisors to modify current operations if necessary. By preparing to connect to a future connected vehicle network, the NMDOT could ready itself to tap into the vast pool of road condition data that most DOT administrators believe is going to appear in the next five to ten years.

The NMDOT could also take a different approach to gathering information from its plows during winter maintenance operations by utilizing one of the resources already available to them the plow operators themselves. The NMDOT could install a laptop, PDA, or tablet in the cab of each of their plows and create an app by which the plow operators could easily submit a form describing current weather conditions, much like the citizen condition reporting app created by the Utah Department of Transportation (UDOT) seen in Figure 4.12. This would make it easier for operators to report conditions, meaning that they will likely do so, providing their supervisors with more information on the conditions in the field. Such a reporting app will also be discussed in Section 4.3.3.

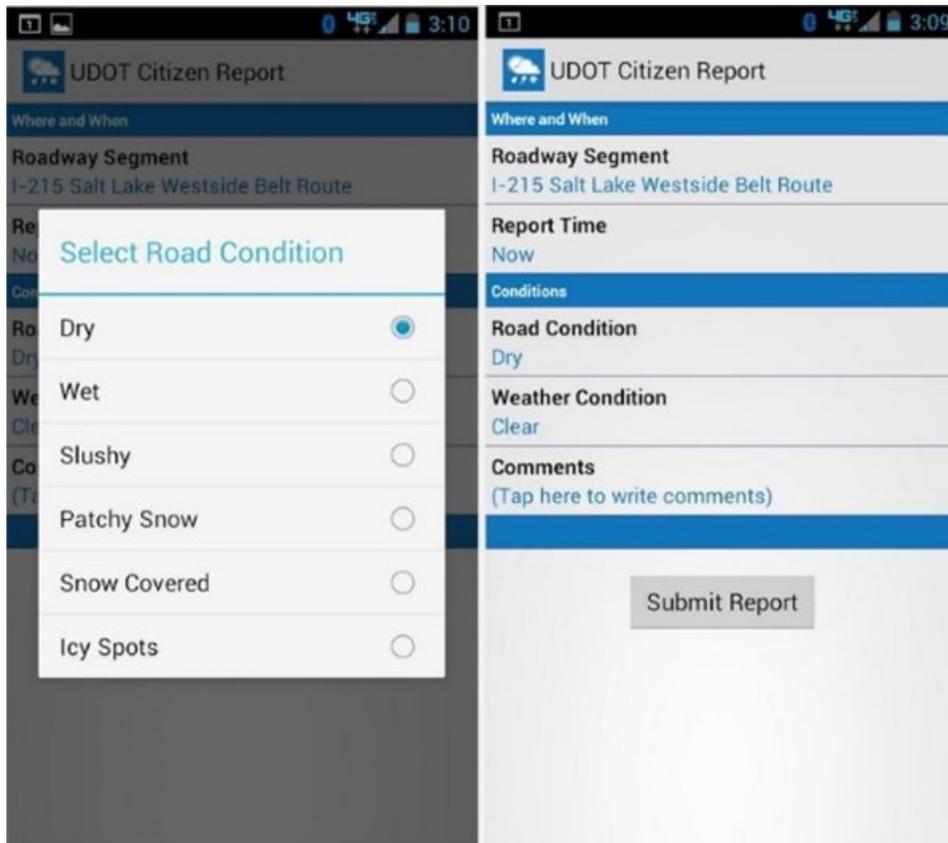


Figure 4.12: UDOT Citizen Condition Reporting Application (Source: FHWA, 2015)

4.3 Current Winter Maintenance Operations

From interviews with NMDOT employees and by studying NMDOT documentation such as the Winter Maintenance Guide, we were able to determine the winter maintenance practices currently used by patrol yards. This information allowed us to evaluate these practices and analyze where the ITS Bureau could better assist the patrol yards with maintenance operations.

4.3.1 Information Gathering Techniques

Through our interviews with the patrol yard administrators, our group identified the current methods that the winter maintenance operations managers use to determine when to begin operations such as plowing, salting, or sanding. The two main ways that the patrol yards obtain useful information for the beginning of these operations is by using the local and national weather services and observing specific, predetermined locations through the use of patrols.

One of the most useful sources of information that the NMDOT patrol yards currently rely on is the National Weather Service (NWS), which provides patrol yards with a weekly forecast briefing covering the types of weather conditions to be expected in the region for the next week. This briefing is attended by administrators of different levels, from the ITS Bureau to the area maintenance supervisors (AMS) and patrol yard managers. These briefings are very helpful in determining what the general weather pattern might be over a week but often lack specific details on when a storm is expected to hit an area. Additionally, because the briefings are weekly, the weather patterns near the end of the period covered can change significantly, making it hard to make specific plans. To fill in the more specific information that the patrol yards managers and AMS need, they rely on the forecasts of local meteorologists from news channels and radio stations. Because these sources often disagree, the supervisors must either choose one that they believe or create an educated guess on specific details of a storm such as precipitation amounts and time of arrival. The supervisors and managers then utilize this information to decide how they will properly prepare the patrol yards for the storm by making sure enough equipment, materials, and personnel are available when they are needed.

When the anticipated time of the arrival of a storm approaches, the patrol yard managers and AMS will start to change the usual work schedules to allow the yard to always have the proper number of employees during the course of the storm. Sometimes it is necessary to send people home early from their shift so they can come back later or have people work longer shifts to prepare the trucks and patrol yard for operations. The AMS will also send patrols to specific, predetermined locations to monitor the severity of conditions so the supervisor can determine whether or not it is the right time to send out trucks. These locations are considered to be places where poor weather conditions will start the earliest, so monitoring the conditions there will provide the patrol yards with the information on when to begin operations to maintain the roads across a region. When those patrols report that the conditions have reached a certain threshold, the AMS will start the winter maintenance operations throughout the area. While this is an effective way to decide when to begin operations, it relies heavily on historical data of a location to interpolate weather across an entire region. This is not always accurate and the unmonitored locations have a chance to become unsafe due to lack of knowledge about them. Additionally, the AMS can only gather as much information as they have patrols. If they had access to constant data about certain locations through an ESS, they could make more use of those patrols to cover a greater area and not rely on historical

weather data so heavily. These ESS stations could also provide data to analyze rather than having an employee eyeballing the conditions and deciding based upon their observations on what to report. These data can be used to implement thresholds that can always be used and relied on while each employee on patrol might have different opinions on what constitutes severe enough weather conditions to send out maintenance units.

4.3.2 Resource Management

NMDOT administrators provided us with information on current inventory management processes used by NMDOT patrol yards during winter maintenance operations. This information covered resource management concerns related to equipment maintenance, road treatment materials inventory, and manpower.

Equipment Maintenance

The most significant resource management concern identified by the NMDOT administrators was that of equipment maintenance, as their equipment is one of the most important parts of their ability to keep the roads under their jurisdiction clear and safe. During the winter months, patrol yards face significant difficulties with equipment reliability, due to the harsh weather and extensive road clearing operations, which cause frequent breakdowns. During an extended series of winter storms, the administrators noted that the availability of snow plows can drop as low as ten percent, due to these aforementioned breakdowns. Another difficulty patrol yards have in keeping their fleets running is that, at least in District 3, the NMDOT only has one field mechanic, and he is not always available during storms. During the winter, this mechanic can sometimes call for one or two assistants, but this assistance is not reliable and the sheer amount of maintenance work that must be done during a storm can spread them thin. Additionally, some of the newer equipment that is still under warranty must be returned to the dealership for maintenance, requiring extended wait times for service.

Further complicating service is the issue of spare parts. While the patrol yards keep some small parts on-site, in many cases the field mechanic must order parts or return to the main maintenance facility to pick up the proper part after beginning a job. This requires additional equipment downtime and increased stress on the remaining functional equipment. Having the possible replacement equipment at each patrol yard so that the maintenance engineer can have

access to any resources they need can decrease this downtime, especially during storms when the possibility of needing to replace a major part is higher due to the increased wear and use of the equipment. Such a system would require a well implemented inventory management system based upon the theories outlined in Section 2.3, such as a Kanban system to maintain the required materials at each patrol yard. This would allow the limited number of field mechanics to make the best use of their time by not having to go back to the main maintenance yard for most materials, returning equipment to operational status faster.

Road Treatment Materials

During winter storms, NMDOT patrol yards make use of several different road treatment substances, most notably salt, cinder, and Ice Slicer. In different conditions, varying mixtures of these materials are used to clear snow and ice from the roads, with salt and cinder intended for most storms and Ice Slicer mixes reserved for particularly low temperatures; when salt and cinder would either be unable to melt the snow, or would cause the melted snow to refreeze into sheet ice. Each of these materials comes from a different location in the region, with salt shipped in from Carlsbad, cinder coming from the Santa Fe area, and Ice Slicer distributed from the Farmington area.



Figure 4.13: Sources of Road Treatment Materials

Figure 4.13 shows where these cities lie in relation to the rest of the state. These locations are quite distant from the majority of the state when poor weather conditions are taken into account, and each distributor serves multiple states aside from New Mexico. When patrol yards must restock their stores of road treatment chemicals in the middle of the winter, poor road conditions and high demand in the southwestern US overall often hinders the suppliers' ability to deliver on time. This

means that while NMDOT patrol yards often order additional materials with several days' worth of material left, they have significant difficulty estimating correct lead times for resupplying. To combat this problem, patrol yards often share resources during storms, and attempt to keep each other functional during times of such high demand. Despite this sharing requiring extensive paperwork and tedious tracking processes, the patrol yards often rely on each other when the distributors cannot deliver the necessary supplies. If the NMDOT could implement a system such as Vendor Managed Inventory (VMI), as described in Section 2.3, major problems such as stockouts during a storm could be avoided. This can dramatically increase the safety of the roads by having the proper maintenance materials available when they are needed. The implementation of a VMI would also eliminate the need to ship materials between patrol yards to help supplement supplies that are low before or during a storm, allowing the NMDOT to allocate those resources to other jobs, thus increasing their overall efficiency. A VMI would also put the responsibility of managing the inventory into the hands of the suppliers, allowing the NMDOT to allocate its manpower to other tasks.

Manpower

In addition to the physical resource management issues faced by NMDOT patrol yards in obtaining the proper quantities of road clearing materials and in keeping their equipment functional, the patrol yards must also carefully manage their employees to ensure they are working as much as possible without exceeding the maximum number of hours a particular employee can work in any given day. During the winter, patrol yards often have difficulty managing their employees due to the long shifts they must endure leading up to and following severe winter storms. In many cases, patrol yards also have to handle varying degrees of employee dedication and skill, with a few employees tending to avoid working on holidays or during particularly bad storms, while others are simply not trained thoroughly enough to handle some of the equipment. Thus, patrol supervisors and AMS must carefully monitor the employees they assign to each shift during the winter to ensure that all employees can be useful, while not slacking off or being overworked. While other state DOT's utilize private contractors to assist with the clearing of the roads in their jurisdiction, the NMDOT does not. This is due to the quick clearing of the roads after the conclusion of a storm because of environmental factors such as sun intensity and comparatively high average air temperatures. This allows the NMDOT to allocate that money to other projects, a significant benefit due to the

NMDOT's limited budget. However, the use of contractors to clear the non-major roads in an area would allow the back roads to be considerably safer during and after a winter weather event.

4.3.3 Operation Management

Based on information gathered through our interviews with NMDOT administrators, we determined how the patrol yard Area Maintenance Supervisors (AMS) organize their drivers and other employees to efficiently and effectively clear roads during winter storms, and how employees record the sections of road they clear and resources they use in doing so. Operations during a storm are very different than the preparation for a storm and require a constant flow of information from the units in the field to the dispatchers and supervisors to keep the roads clear and safe for the public. The NMDOT must also minimize its liability during operations by keeping precise track of its operations and making timely and correct decisions related to operation and resource management.

One of the major flows of information is between the dispatchers and the units in the field, whether that be a supervisor or a truck operator. The NMDOT dispatchers track where the trucks are, what they are currently doing, such as plowing, salting, or getting refitted in the patrol yards to return to work, and what personnel are on duty. All supervisors are required to call in at the beginning and end of their shifts, and all workers are required to sign in at their patrol yards. This allows the supervisors and dispatchers to be aware of not only who is on duty but also how long that person has been on duty, allowing them to make informed decisions on scheduling and route changes. This is very important because the labor unions state that a worker cannot work more than ten hours in a day, and therefore the patrol yards usually operate on three eight-hour shifts a day during a severe weather event.

Communication between employees and dispatchers also allows supervisors to get real-time information on the current conditions of the roads from the units in the field. The AMSs then use this information to decide where to best allocate their resources. This is supplemented by information that is relayed from the local police department patrols about general road conditions across an area. According to a police lieutenant and captain as well as several NMDOT administrators at the TSM&O meeting that we attended, the NMDOT will often deploy resources to assist in the operation of clearing accidents during a storm if the police ask for it. However, the flow of information appears to only be utilized in critical or dangerous conditions, such as the report

from a police patrol that there is ice build-up on a road. There does not appear to be a continuous flow of information on conditions that the police patrols are facing, but only when the situation is already critical. This means that the NMDOT supervisors can only use the information from the police patrols in a reactionary manner rather than proactively. While this system is effective in gathering information about critical road conditions, other state DOT's have tried to improve this by implementing easier ways for plow operators to report road conditions while they are in the field rather than having to call into dispatch. In Idaho, this was implemented through the creation of a mobile application for use on PDAs installed in the cab of their snow plows, allowing the driver to report a road condition by choosing predetermined options on the form (Goodwin, 2003). The Idaho Transportation Department found that this greatly increased the number of reports that the operators in the field sent in to dispatchers on the road conditions they were experiencing. Implementing a system like this across the NMDOT's fleet of plows, and possibly extending it to the State Police, could increase the amount of information available to the NMDOT's AMS during winter maintenance operations, providing them with potentially valuable information on current conditions and effectiveness of the current operations.

Once the information is obtained from units in the field, the AMSs must choose how they want to continue operations. This is very heavily based upon the snow removal priorities found in Appendix I, where the operations always start with maintaining all priority one routes in their region. During really bad storms, the maintenance operations will often have most units on the priority one routes and very few on the priority two routes. As the operations progress, if the reports that the AMSs receive from the field indicate that the operation is keeping the priority one routes clear, they will allocate more resources to the priority two routes to begin to clear them better. This process of allocating resources is governed very strongly by the amount of equipment and personnel available and often results in priority three and below roads not having designated maintenance crews on them until after a storm has passed, sometimes to the point where these roads will be cleared by the sun melting the snow and ice and not by the NMDOT's winter maintenance operations. Implementing a system like one of the MDSS described in Section 2.1.5 could improve the decision making systems of the AMS and allow them to have access to more data in a central location rather than having to use multiple resources and databases.

Road Treatment Recording

In order to track road maintenance for legal and managerial reasons, plow and truck drivers must follow certain guidelines during a storm. They are required to go through a checklist to ensure the proper functioning of the truck and its equipment when they start their shift, when they switch to a new truck during their shift, or when they return from maintenance operations. This checklist is extensive and ensures that the equipment is in functioning and safe condition before it is used in maintenance operations, minimizing the risk of damage to the truck and other property as well as ensuring the safety of the operator. In addition to this, they are required to maintain a record of their route and operations while they are in the field. This is a written form that the drivers must fill out every time they change directions and includes information such as time, miles driven, salt dispensed, and plowing done. This form also means the driver sometimes has to leave the cab of the truck to check on the status of their salt, sand, or cinder load. This form could be replaced by an electronic form with data entry fields or even a completely automated system using an Automatic Vehicle Location system (AVL) and sensors monitoring the spreading system. This would significantly decrease the amount of time that the operator must stop operations and increase their efficiency and the amount of time that they can spend treating the roads during their shift. Additionally, this would also save the NMDOT money on labor and paper due to each form not requiring manually entry into the database at the end of the storm, also ensuring that no data is lost in the paperwork shuffle at the conclusion of the operations.

However, even this requirement of semi-frequent checking on the status of the truck's load often is not sufficient for the driver to know the state of their load due to snow build-up in the truck bed causing the load to not only compact due to moisture but to appear to have more material than is actually there because of the layers of snow. This can lead to a condition known as tunneling within the bed of the truck where the bed is full, but the load is so compact that as the conveyor of the spreader tries to grab material, no further material falls to replace it, causing the conveyor to no longer grab new material to spread. Often, this happens in the middle of an operation, when a driver might not notice this problem due to the weather conditions. This results in the drivers believing that they are properly treating the road when they are not, causing the documentation to be incorrect and potentially dangerous conditions to go untreated. To resolve this problem, the driver must notice that this is happening and stop operations to knock the load loose manually. Tunneling can also lead to the driver not knowing the correct amount of load that they have in the truck's bed as

there is no automated measuring system in the truck. Instead, based on their prior experience and guesswork the drivers must estimate how much material is remaining and how much longer they can operate before they run out. The implementation of an AVL, as mentioned above, in addition to implementing sensors to monitor the current load in the truck and the operation of the spreading system could assist the operator in detecting when a problem like tunneling occurs as well as knowing when the amount of material left in the truck is running low and needs to be refilled.

4.4 Summary

By analyzing the information gathered from our interviews with NMDOT administrators and ArcGIS map sets, we were able to come up with an effective methodology for placing ESS throughout the state of New Mexico and several strategies for improving this system in the future. We also identified current NMDOT road maintenance and resource management practices, and created recommendations for how these practices can be improved. In the next chapter, we will summarize the conclusions and recommendations reached in this chapter, and will discuss potential areas for future improvement on our work.

5. Conclusions and Recommendations

The purpose of this project was to identify methods the NMDOT ITS Bureau could use to improve road maintenance effectiveness, particularly during the winter, to ameliorate road conditions and driver safety around New Mexico. To accomplish this overarching goal, we worked on achieving three sub-goals: developing an ESS siting methodology, producing recommendations for alternative information gathering methods to assist in identifying problematic road conditions around the state, and suggesting improvements to current NMDOT resource management practices. In this chapter we will summarize the deliverable results of our project, which were discussed in detail in Chapter 4, as well as our recommendations for future extensions and improvements of our work by either the ITS Bureau or other research teams.

5.1 ESS Siting

The primary goal of our project was to develop a siting methodology for ESS in New Mexico to provide the NMDOT with a better understanding of road conditions at key locations around the state and thereby allow patrol yards to resolve these dangerous conditions quickly and effectively. To accomplish this goal, we assembled a GIS map set containing relevant data and designed a computerized ranking tool, or Station Placement Optimization Tool (SPOT), to compare sites, along with an analysis procedure describing how these tools should be used.

Through the use of ArcGIS, we were able to compile several maps containing data corresponding to the siting criteria discussed in section 4.1.1. Using these maps and additional information collected from our sponsors, we were able to devise a weighting system for the criteria, and go on to create the SPOT based on comparing site data to set thresholds to determine points earned for each criterion. Through the use of the SPOT to analyze locations across New Mexico with high AADTs or crash ratios as a test case, we recommend these sites for new ESS:

1. NM-150 Mile Marker 10 - Taos Ski Valley
2. I-40 Mile Marker 180 - West of Edgewood
3. I-40 Mile Marker 173 - Tijeras Canyon
4. US-64 Mile Marker 390 - South of Des Moines
5. NM-38 Mile Marker 18 - Red River/Bobcat Pass

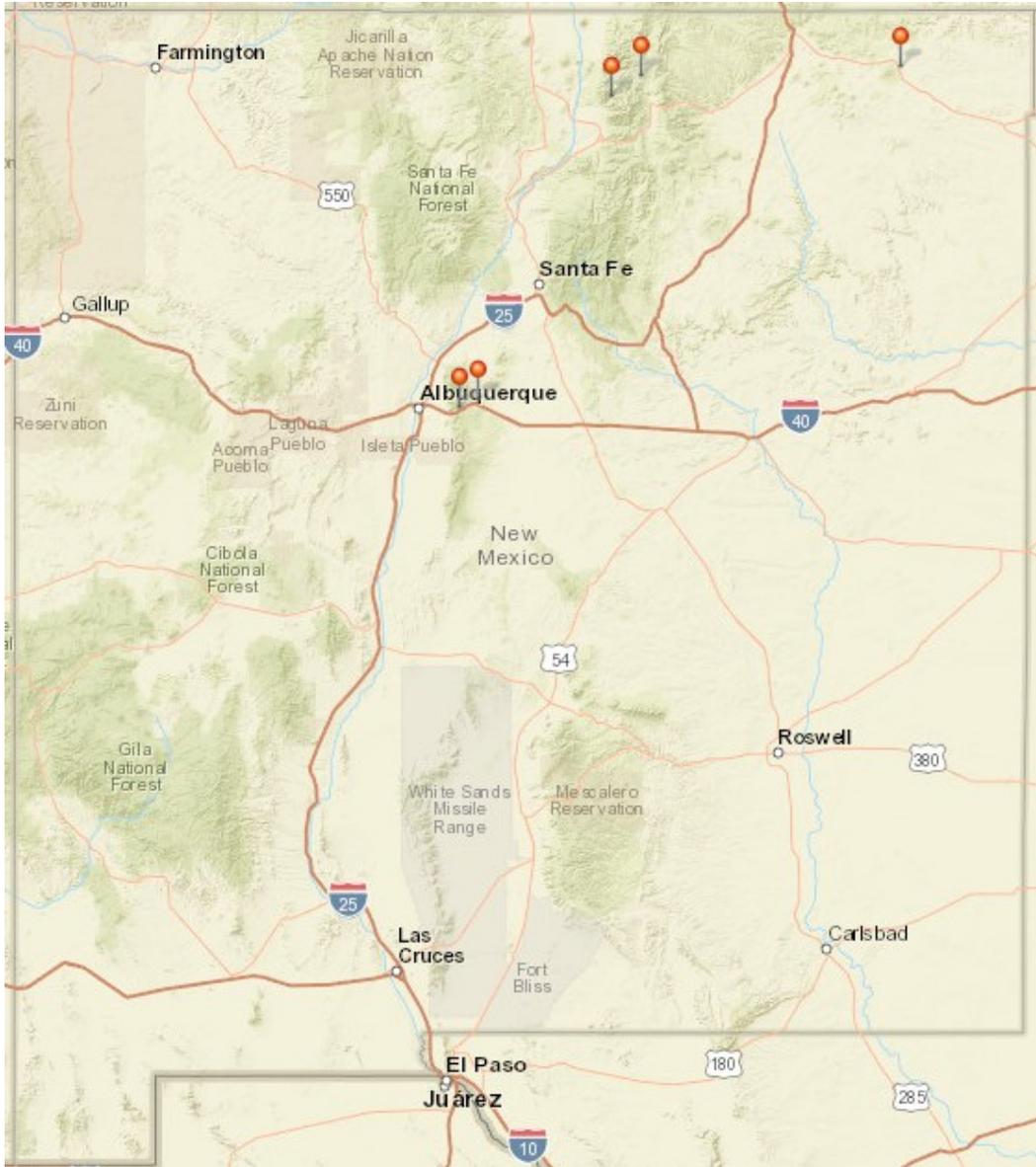


Figure 5.1: ArcGIS map of top five location in our analysis

These locations were chosen because they are the top 5 highest ranked in the absolute formula. Further information about the rationale behind these locations and the specifics of the SPOT results can be found in Appendices O and Q. An in-depth explanation of the SPOT can be found in Section 4.1. We recommend that the NMDOT's ITS Bureau use the SPOT created by our group through the methodology detailed in Appendix P to determine other locations for new ESS throughout New Mexico.

Following the implementation of ESS, we recommend that the information gathered from each station is displayed to the public through the NMRoads application, as is currently done with the two existing ESS in New Mexico. An effective way to make roads safer is to inform drivers of particularly dangerous road conditions, so the efficient dissemination of weather station data is key to road safety. This can also be expanded to increase the amount of data available to the AMS by setting up accounts in NMRoads and creating thresholds for them to receive alerts about the roads in their region. Their accounts should also have more permissions when it comes to viewing data such as being able to access real-time camera and RWIS information.

5.2 Resource Management Recommendations

Another objective of our project was to suggest ways that winter maintenance management practices currently employed by the NMDOT could potentially be improved. In Appendix J, we discuss in detail our recommendations for how NMDOT patrol yards can improve their resource management efficiency, which center around the application of inventory management best practices and ITS to resource management methods currently in use. By applying process and technological solutions to inventory tracking and detecting, patrol yards would be able to more accurately keep track of their inventory, and would be able to more easily communicate their inventory needs to their suppliers.

5.3 Future Work

Throughout our work and recommendations, we have identified areas where future NMDOT internal projects or other research projects can be focused to extend from and further develop the work we have accomplished. Some of the recommendations we have created for such extensions include refining SPOT to add more detail and analysis, automation, or extend it to other applications. We recommend that an analysis of the condition data available at different locations, outside of the bounds of SPOT, be done to determine optimal levels for the alert thresholds mentioned in Section 5.1, and that these thresholds be implemented for AMS. We additionally recommend that the NMDOT collaborate with external organizations like the State Police, the NWS, or NOAA to expand the breadth and depth of the NMDOT's RWIS.

Improving SPOT

While we are confident in the site ranking formula that we have designed, we believe that further work can be done to improve its effectiveness and ease of use. Looking into additional ways to retrieve information about weather and the condition of roads would be beneficial, either to make the formula more accurate, or as supplemental information for the ITS to provide to patrol yards. For example, our team was unable to find specific information regarding average wind velocity or gusts, which would be valuable information for ESS siting or determining expected road conditions at a location. Finding a way to acquire this information would be beneficial for improving the accuracy of our system.

There are also possible criteria that our team did not utilize that could be useful in improving the accuracy of SPOT. This includes such criteria as implementing a cost-benefit analysis based on the AADT, similar to the criterion that used by the NYSDOT as described in Section 2.1.5, or a rate of weather related crashes per million vehicle miles traveled. Our group did not utilize these, despite already having included all of the criteria needed to create these calculations, because we did not want to complicate the formula by adding the potential for double counting of data. However, considering criteria such as these might provide a new and valuable perspective on the rankings, provided that the new point allotments for each criterion are adjusted to prevent double counting.

Another area for improvement on SPOT is the data input method as it currently relies on manual input of all necessary data. Investigating potential ways to implement automated data entry could be a valuable way to decrease the amount of time and work needed to use this tool. One possible way to achieve automation would be creating ArcGIS layers for every criterion to allow for easy data extraction and automatic input into SPOT. Additionally, further exploration of the features of Microsoft Excel might produce more efficient methods of inputting data into the tool.

To expand upon our work, SPOT could also be adapted to fit a variety of decision making processes, not just for ESS placement. This could entail adapting the ranking criteria to identify dangerous road geometry, stretches of road that might require guardrails or other safety measures, or additional locations for dynamic message signs or cameras. If these uses are successfully implemented, the results could be combined to create an overall ITS safety plan to describe how the NMDOT should go about implementing various technologies to improve their existing ITS

infrastructure. SPOT can also be integrated into the NMDOT's systems engineering architecture to demonstrate how the NMDOT is using its federal funding in a logical and systematic way.

Other Recommendations

Implementing the thresholds mentioned in Section 5.1 requires a study of winter operations and when AMS decide to start winter operations during a storm. This is not something that our group looked at and is an integral part of the usefulness of the data collected from the RWIS, therefore making it a high priority. This could be done as an analysis of operation before or after the implementation of the new ESS, however, the data collected by the RWIS might be useful in determining the effectiveness of the maintenance operations, something that is an important part of that analysis and the way that our group suggests is the best use of time and resources.

We encourage the NMDOT to share road condition information and RWIS data with the NWS, NOAA, and New Mexico Trucking Association in addition to gaining access to the real-time data from their weather stations. Although these weather stations would not record any road specific information such as grip factor, they can provide the NMDOT with data on atmospheric conditions. Additionally, the ITS Bureau could implement a version of application mentioned in Section 4.2.2 for reporting road conditions not only in the cabs of the NMDOT plows but also look to expand it to include the state and local police as well as the general public to gather more information across the state. The ITS Bureau can also look into the possible use of analyzing social media to determine what the public is saying about the weather conditions. Any one of these systems can help the NMDOT keep the roads safer by providing patrol yards with more real-time weather information to make more informed decisions about how to allocate their resources.

By implementing our ESS siting methodology, resource management recommendations, and reaching out to the organizations mentioned for additional information, we believe that the NMDOT can improve the efficiency and effectiveness of its road maintenance practices, ultimately improving the safety of all motorists in New Mexico.

References and Bibliography

- Abdi, A., Lind, H., & Birgisson, B. (2012). Use of road weather information system (RWIS) as assistive tool for effective winter road maintenance: Technical and Contractual interactions. *International Journal of Engineering and Technology*, 2(12), 2002-2012.
- Anderson, D. J. (2010). *Kanban*. Sequim, Washington: Blue Hole Press. Retrieved from: <http://books.google.com/books?id=RJ0VUkfUWZkC>
- Bailey, G. J., & Helms, M. M. (2007). MRO inventory reduction—challenges and management: a case study of the Tennessee Valley Authority. *Production Planning and Control*, 18(3), 261-270. <http://dx.doi.org/10.1080/09537280601127351>
- Bechtel, C., & Patterson, J. L. (1997). MRO partnerships: a case study. *International Journal of Purchasing and Materials Management*, 33(2), 18-23. <http://dx.doi.org/10.1111/j.1745-493X.1997.tb00027.x>
- Berrocal, V. J., Raftery, A. E., Gneiting, T., & Steed, R. C. (2010). Probabilistic weather forecasting for winter road maintenance. *Journal of the American Statistical Association*, 105(490), 522-537. <http://dx.doi.org/10.1198/jasa.2009.ap07184>
- Boselly, E. S., Thornes, E. J., & Ulburg, C. (1993). Road Weather Information Systems Volume 1: Research report. *Strategic Highway Research Program Publication-SHRP-H-351*, National Research Council, Washington, DC, 90-93.
- Boselly, E. S., Thornes, E. J., & Ulburg, C. (1993). Road Weather Information Systems Volume 2: Implementation Guide. *Strategic Highway Research Program Publication-SHRP-H-350*, National Research Council, Washington, DC, 90-93.
- Bozarth C., (2011, January 28). Economic Order Quantity (EOQ) Model: Inventory Management Models: A Tutorial. Retrieved April 24, 2016 from: <https://scm.ncsu.edu/scm-articles/article/economic-order-quantity-eoq-model-inventory-management-models-a-tutorial>
- Buddemeyer, J., Young, R., Sabawat, V., & Layton, E. (2010). *Variable speed limits system for Elk Mountain corridor*. Laramie, WO: Wyoming Department of Transportation. Retrieved from: http://ntl.bts.gov/lib/44000/44300/44325/WYDOT_ElkMtnVSL_FinalReport.pdf
- Chatterjee, K., & McDonald, M. (2004). Effectiveness of using variable message signs to disseminate dynamic traffic information: Evidence from field trials in European cities. *Transport Reviews*, 24(5), 559-585.
- Chien, S., Meegoda, J., Luo, J., Corrigan, P., & Zhao, L. (2014). Road weather information system statewide implementation plan. University Transportation Research Center. 49997-19-24 & 55505-02-05. Retrieved September 10, 2016 from: <http://www.utrc2.org/sites/default/files/pubs/Final-Road-Weather-Information-Systems.pdf>

- Congdon, W. S., & Hitt, R. A. (1992, March). Applying JIT to spare parts control. *Quality*, 31(3), 45. Retrieved from: <http://search.proquest.com/docview/235201977>
- Cooksey, S. R., Jeong, H. S., & Chae, M. J. (2011). Asset management assessment model for state departments of transportation. *Journal of Management in Engineering*, 27(3), 159-169. doi:10.1061/(ASCE)ME.1943-5479.0000055
- Federal Highway Administration. (2013). Highway Functional Classification Concepts, Criteria and Procedures. Retrieved 9/19/16 from: https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/fcauab.pdf
- Federal Highway Administration. (2015). Citizen Reporting of Current Road Conditions. Retrieved from: http://www.ops.fhwa.dot.gov/weather/best_practices/citizenreportingcrc/index.htm
- Federal Highway Administration. (2015, October). Road Weather Management Program Projects and Programs. Retrieved 4/10/16 from: http://www.ops.fhwa.dot.gov/weather/mitigating_impacts/programs.htm
- Federal Highway Administration. (2016, April 12). How Do Weather Events Impact Roads? Retrieved April 19, 2016, from http://www.ops.fhwa.dot.gov/weather/q1_roadimpact.htm
- Federal Highway Administration, Office of Interstate and Border Planning. (2016). Business Models for Implementing Geospatial Technologies in Transportation Decision-Making, Appendix C: State DOT Case Studies. Retrieved April 26, 2016 from: https://www.gis.fhwa.dot.gov/bus_model_rpt_3-08/bus_model_appc.htm#nm
- Fries, R., Chowdhury, M., & Ma, Y. (2007). Accelerated incident detection and verification: A benefit to cost analysis of traffic cameras. *Journal of Intelligent Transportation Systems*, 11(4), 191-203.
- Garrett, J. K., Boyce, B., Krechmer, D., & Perez, W. (2008). *Implementation and evaluation of RWIS ESS siting guide*. Washington DC: Federal Highway Administration. Retrieved from: <http://ntl.bts.gov/lib/30000/30700/30706/14448.pdf>
- Goodwin, L. C., & Pisano, P. (2003, May). Best Practices for Road Weather Management. Road Weather Retrieved April 3, 2016 from: <http://www.velocidade.prp.pt/Sites/velocidade/CentroDocumentacao/InvestigacaoEstudos/75 - Best Practices - CaseStudiesFINALv2-RPT.pdf>
- This report discusses the case studies on the best practices for managing roads in different types of weather.
- Hanbali, R. M. (1994). Economic impact of winter road maintenance on road users. *Transportation Research Record*, 1442, 151-161. Retrieved from <http://onlinepubs.trb.org/Onlinepubs/trr/1994/1442/1442-018.pdf>
- Holik, W. A., Schneider, I. V., William, H., & Miller, C. M. (2016). Quantitative Assessment of Snow Plow Sensor Failure Impacts on Winter Maintenance Operations [Abstract]. In *Transportation Research Board 95th Annual Meeting Compendium of Papers*. Retrieved from: <http://trid.trb.org/view.aspx?id=1392699>

- Janiga, D. (2005). Five keys to effective inventory management. *Plant Engineering*, 59(6), 36-37.
- Keller, G., PE, & Sherar, J., PE. (2003). *Low-Volume Roads Engineering*. Washington DC: USAID.
- Larson, C. D., & Skrypczuk, O. (2004). Comprehensive data collection to support asset management at Virginia Department of Transportation. *Transportation Research Record*, 1885, 96-103. doi:10.3141/1885-14
- Lebo, J., & Schelling, D. (2001). Low Volume Rural Roads. *Transport Economics*. Retrieved April 11, 2016, from <https://openknowledge.worldbank.org/bitstream/handle/10986/11805/339410trn121120EENote2.pdf?sequence=1&isAllowed=y>.
- Li, Y., Fang, Y., Seeley, N., Jungwirth, S., Jackson, E., & Shi, X. (2013). Corrosion by chloride deicers on highway maintenance equipment: Renewed perspective and laboratory investigation. *Transportation Research Record: Journal of the Transportation Research Board*, 2361, 106-113.
- Manfredi, J., Walters, T., Wilke, G., Osborne, L., Hart, R., Incrocci, T., & Schmitt, T. (2005). *Road weather information system environmental sensor station siting guidelines*. Washington DC: Federal Highway Administration. Retrieved from: <http://www.ops.fhwa.dot.gov/publications/ess05/ess05.pdf>
- Manfredi, J., Walters, T., Wilke, G., Osborne, L., Hart, R., Incrocci, T., ... & Krechmer, D. (2008). *Road weather information system environmental sensor station siting guidelines, version 2.0*. Washington DC: Federal Highway Administration. Retrieved from: <http://ntl.bts.gov/lib/30000/30700/30705/14447.pdf>
- Meridian Environmental Technology Inc. (2016). Maintenance Decision Support System Multi-State Pooled Fund Study. Retrieved September 2, 2016 from: <http://mdss.iteris.com/mdss/pfs/>
- National Weather Service, Office of Climate, Water, and Weather Services. (2013). Snow Measurement Guidelines for National Weather Service Surface Observing Programs. Retrieved April 10, 2016, from: http://www.nws.noaa.gov/om/coop/reference/Snow_Measurement_Guidelines.pdf
- New Mexico Department of Transportation. (2010). NMDOT Patrol Yards. Retrieved April 26, 2016, from http://dot.state.nm.us/content/dam/nmdot/Travel_conditions/maps/patrol_yd_D.pdf
- New Mexico Department of Transportation. (2012). Intelligent Transportation Programs. Retrieved March 27, 2016, from <http://dot.state.nm.us/en/ITS.html>
- New Mexico Department of Transportation. (2013). NMDOT Functional Classification Guidance Manual. Retrieved September 16, 2016, from http://dot.state.nm.us/content/dam/nmdot/planning/NMDOT_FC_Guide.pdf
- New Mexico Department of Transportation. (2015). Winter Maintenance Guide. Retrieved April 25, 2016, from http://dot.state.nm.us/content/dam/intrans/hwyops/go/2014_2015WinterMaintGuide.pdf

- New Mexico State Government. (2016). Sunshine Portal. Retrieved March 27, 2016, from <http://sunshineportalnm.com/sample/#section=BudgetsExpenditures>
- New Mexico Tourism Department. (2016). New Mexico True. Retrieved April 04, 2016, from <https://www.newmexico.org/scenic-byways/>
- Norrman, J., Eriksson, M., & Lindqvist, S. (2000). Relationships between road slipperiness, traffic accident risk and winter road maintenance activity. *Climate Research*, 15(3), 185-193.
- Osborn, L. (2016). Average Annual Snowfall in New Mexico. Retrieved March 27, 2016, from <https://www.currentresults.com/Weather/New-Mexico/annual-snowfall.php>
- Perrier, N., Langevin, A., & Campbell, J. F. (2007). A survey of models and algorithms for winter road maintenance. Part IV: Vehicle routing and fleet sizing for plowing and snow disposal. *Computers & Operations Research*, 34(1), 258-294.
- Summer, S. D. (2006). *U.S. Patent Application No. 11/446,873*. Washington, DC: U.S. Patent and Trademark Office.
- The Road Information Program. (2016a, January). Key facts about America's surface transportation system and federal funding. Retrieved from: http://www.tripnet.org/docs/Fact_Sheet_National.pdf
- The Road Information Program. (2016b, February). New Mexico Transportation by the Numbers: Meeting the State's Need for Safe, Smooth and Efficient Mobility. Retrieved from: http://www.tripnet.org/docs/NM_Transportation_By_The_Numbers_TRIP_Report_February_2016.pdf
- United States Department of Transportation. (2016). Resources for Government. Retrieved March 27, 2016 from <https://www.transportation.gov/resources/government>
- United States Department of Transportation, Federal Highway Administration. (2014a). *Public Road Mileage, Lane-Miles, and VMT 1980 - 2014* [Data file]. Retrieved from: <http://www.fhwa.dot.gov/policyinformation/statistics/2014/vmt422c.cfm>
- United States Department of Transportation, Federal Highway Administration. (2014b). *State Highway Agency-Owned Public Roads - 2014; Rural and Urban Miles; Estimated Lane-Miles and Daily Travel* [Data file]. Retrieved from: <https://www.fhwa.dot.gov/policyinformation/statistics/2014/hm81.cfm>
- United States Department of Transportation, Federal Highway Administration. (2015). Best Practices for Road Weather Management. Retrieved April 30, 2016 from: http://www.ops.fhwa.dot.gov/publications/fhwahop12046/rwm20_newmexico1.htm
- United States Department of Transportation, Federal Highway Administration, Office of Highway Policy Information. (2015). United States Total Vehicle Miles Traveled, 1900 to 2015 [Data File]. Retrieved from: http://www.google.com/publicdata/explore?ds=gb66jodhlsaab_#!ctype=l&strail=false&bc=s&d&nselm=h&met_y=VMT&scale_y=lin&ind_y=false&rdim=state&ifdim=state&tdim=truel&hl=en_US&dl=en_US&ind=false

- United States Department of Transportation, Office of the Assistant Secretary for Research and Technology, Bureau of Transportation Statistics. (2013). *Table 1-6: Estimated U.S. Roadway Lane-Miles by Functional System(a)* [Data file]. Retrieved from: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_06.html
- United States Department of Transportation, Office of the Assistant Secretary for Research and Technology, Intelligent Transportation Systems Joint Program Office. (2015). *Connected Vehicle Pilot Deployment Program*. Retrieved from: <http://www.its.dot.gov/pilots/>
- United States Department of Transportation, Office of the Assistant Secretary for Research and Technology, Intelligent Transportation Systems Joint Program Office. (2015). *ITS Research 2015-2019, Connected Vehicles*. Retrieved from: http://www.its.dot.gov/research_areas/connected_vehicle.htm
- University Corporation for Atmospheric Research. (2016). Maintenance Decision Support System. Retrieved September 2, 2016 from: http://www.rap.ucar.edu/projects/rdwx_mdss/
- Uyttebrouck, Olivier. (2016, February 5). Negative Report on NM roads disputed. *Albuquerque Journal*. Retrieved from: <http://www.abqjournal.com/718734/news/negative-report-on-nm-roads-disputed.html>
- Vaisala. (2009). Vaisala Guardian Road Weather Information System. Retrieved April 18, 2016 from: http://www.coralsales.com/attachments/90/Vaisala_-_Guardian.pdf
- Waller, M., Johnson, M. E., & Davis, T. (1999). Vendor-managed inventory in the retail supply chain. *Journal of Business Logistics*, 20(1), 183-203. Retrieved from: <http://ezproxy.wpi.edu/login?url=http://search.proquest.com/docview/212661919?accountid=29120>
- Zhao, L., Chien, S. I., Liu, X., & Liu, W. (2015). Planning a road weather information system with GIS. *现代交通学报：英文版*, 23(3), 176-188. doi:10.1007/s40534-015-0076-0

Appendix A: Sponsor Description

The New Mexico Department of Transportation (NMDOT) (2012) is a department of the New Mexico state government run by Thomas J. Church, the Cabinet Secretary for the NMDOT. It is dedicated to ensuring safe and efficient travel throughout New Mexico while facilitating economic development and preserving the environment. In order to fulfill its duty of maintaining the nearly 13,000 centerline miles of interstates, U.S. highways, state highways, and other non-county or town roads in the state, in addition to railway and aviation activity, the NMDOT receives a budget of \$1.2 billion, the second highest budget under the Executive branch of New Mexico's government (New Mexico State Government, 2016). The majority of this funding comes from state level taxation and tolls as well as federal grants by any of the 11 agencies of the United States Department of Transportation (2016). This budget provides the NMDOT with the backbone for its operations, including its over 2,200 employees, 82 road maintenance patrol yards, and 34 construction crews. To coordinate this network of resources, the NMDOT (2012) is split up into six bureaus: Operations/Training Academy, Intelligent Transportation Systems (ITS), State Construction Bureau, State Maintenance Bureau, Fleet Management, and State Materials Bureau. Similarly, the state is administratively divided into six Districts, allowing the NMDOT to effectively distribute the resources of the Statewide Bureaus.

One of the main goals of the ITS Bureau (2012) headed by Charles Remkes is the improvement of road safety and efficiency during adverse conditions via the implementation of modern technological solutions. These include but are not limited to equipment such as their 64 digital road signs, 84 traffic cameras, and numerous weather and traffic sensors deployed around the state (NMDOT, 2012). These technologies make possible remote monitoring of road conditions and the real-time provision of relevant information to those on the roads. This wealth of information gives bus drivers, truckers, and ordinary drivers the necessary knowledge to plan their routes or otherwise prepare accordingly for poor weather, accidents, or simply heavy traffic. The ITS Bureau (2012) also makes use of its network to facilitate the operations of the NMDOT and study how to improve traffic and resource management throughout the numerous maintenance and construction operations undertaken daily. In Figure 3 below, the ITS Bureau is highlighted in red.

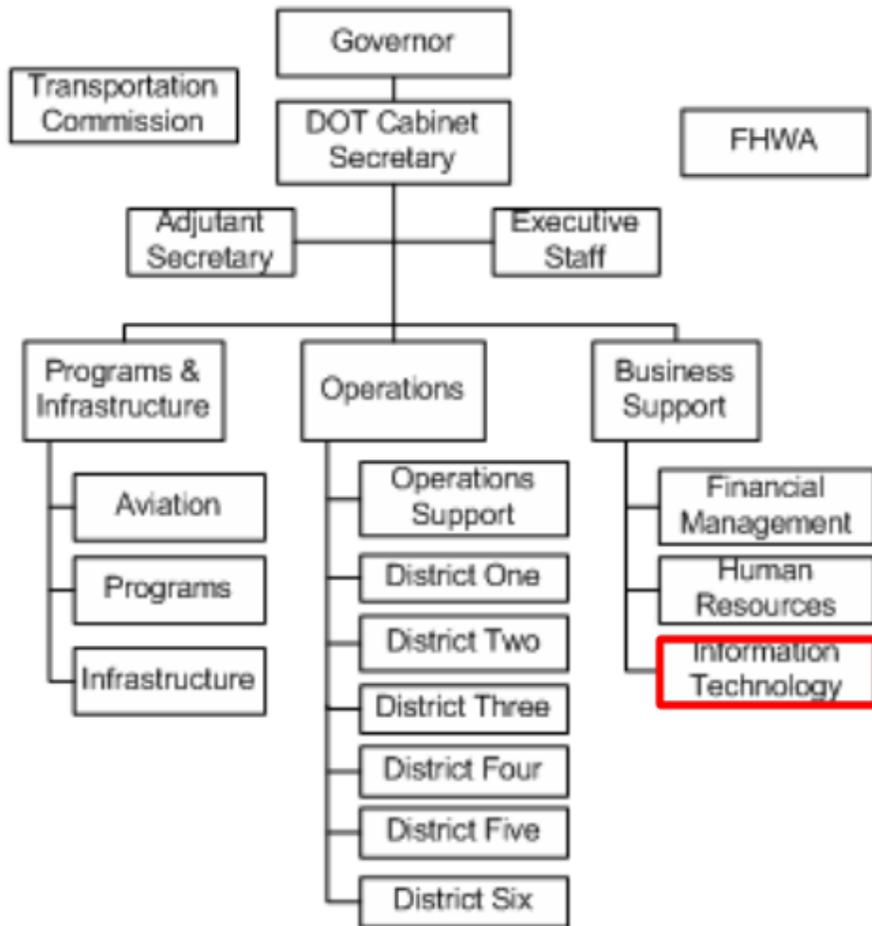
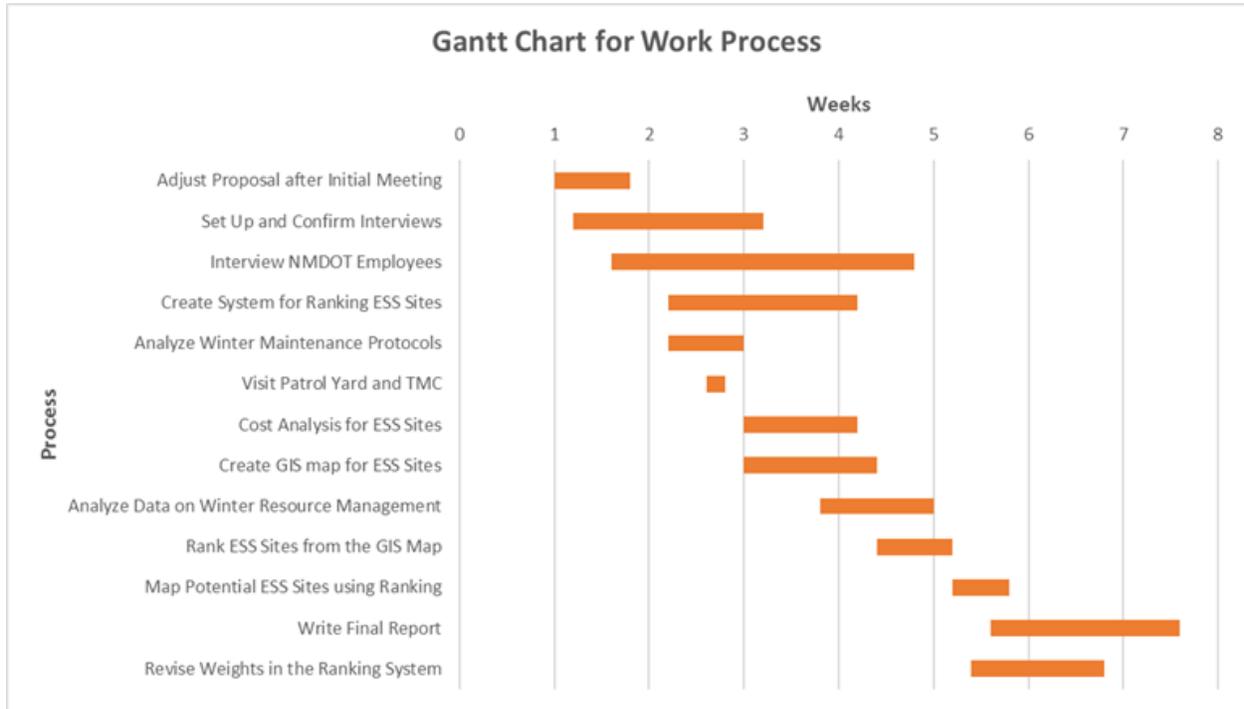


Figure A-1: Chart of NMDOT Organizational Structure (Federal Highway Administration, 2016)

Appendix B: Gantt Chart for On-Site Work



Appendix C: General Interview Protocol

At least one week before interview:

- Find out the background of the person being interviewed
 - Job title
 - Job description
 - Their position in the chain of command
 - Other helpful information relevant to the information intended to be gained from the interview
- Contact the person you are going to interview to set up a time and type of interview (phone/video call or in person)
 - If the interview will occur in person, determine a place.
 - If the interview will be a phone or video call, determine who is calling whom.
 - If they call us, make sure they have one of our numbers to call
 - Ask if the person will allow audio recording and if they would like to remain anonymous.

Two days before the interview:

- Finalize a list of questions for interview
 - Some or all from Appendices D - G
- Finalize and send out the agenda for the meeting to everyone involved
 - Include in email the relevant information about the location and mode of the meeting

Day of the interview:

- Dress appropriately for the situation, or if in doubt, professionally
- Review the agenda and ensure everyone on the team that will be conducting the interview is aware of what information is sought as a result of the interview
 - Ensure all present team members know:
 - Information looking to be obtained
 - General topic of conversation
 - Relevant background of the person being interviewed

The Interview:

- 1) Basic Agenda:
 - a) Greet the person being interviewed formally and introduce our group members who are present as well as giving an overview of what the goal of our project is.
 - b) Confirm if the person will allow audio recording and if they would like to remain anonymous.
 - c) Conduct the interview
 - i) Ask the prepared questions, and any relevant follow up ones that come up during the interview
 - ii) Respond to any questions the interviewee has
 - iii) Thank them for their responses and time
 - d) Ask if we can have a follow up interview if appropriate or needed

No more than one day after the interview:

- Send personal thank you email or letter to interviewee thanking for their time
- Review minutes from the meeting and determine the relevant information gathered
 - Record relevant data
 - Determine if other interviews are required to gain more information or answer remaining questions
 - Type up a transcript or summary of the interview and send it to the interviewee(s) to verify what they said was correct and that their views are correctly represented

Appendix D: Patrol Yard Administrator Interview

Questions

Winter Maintenance:

- How do you allocate resources during an extreme winter weather event?
 - How does the inventory management get taken into account?
- How do you determine when to send out plows and other winter maintenance equipment?
- How do you monitor the current road conditions?
- Where do you get your weather information during a storm?
- What resources are most commonly used in your patrol yard?
 - Do these resources get special monitoring? How and why?
- What resources would cause the most problems if you ran out of them and how would you react to a lack of those items?
- How do you determine the allocation of resources to specific trucks during winter maintenance operations?
- What problems did you encounter this past winter with the inventory system and how might these problems be mitigated in the future?

RWIS:

- What do you know about or have you ever worked with an RWIS?
- What road conditions would be most useful to monitor in real-time using an RWIS system?
- What factors do you consider important in determining where to place an ESS?
- What difficulties do you face when trying to place an ESS or when interacting with the RWIS?
- Within your area of operations, what locations would you like to have more real-time road condition information about? Do any of these locations experience extreme weather conditions or problems related with heavy traffic?
- Can any factors or data sets produced by an ESS be considered important enough to outweigh the system's cost? Why or why not?
- Would you prefer a network of stations to monitor conditions over a large area or data about specific sites at the expense of a larger picture? Please explain.
- Do you think that an ESS would be useful if placed in the jurisdiction of your patrol yard? Please explain.

Appendix E: NMDOT Administrator Interview

Questions

Winter Maintenance:

- How do you allocate resources during an extreme winter weather event?
 - How does the inventory management get taken into account?
- How are resources distributed to the patrol yards during the winter?
 - How is this determined, ie. does each yard get the same resources or does it depend on the conditions the yard faces in its area of operations?
- If a yard runs out of a resource, how is that problem fixed?
 - Do the resources get allocated from a nearby patrol yard or do they get reordered?
 - Does this happen before a patrol yard runs out (such as when a patrol yard is running low before storm?
- How do you get your weather information during a storm?
- Are any resources managed on a higher level than the patrol yards, ie. truck deployment to yards?
 - If so, how is this distribution determined?
- What resources would cause the most problems if you didn't have them?

RWIS:

- What road conditions would be most useful to monitor in real-time using an RWIS system?
- What factors do you consider important in determining where to place an ESS?
- What difficulties do you face when trying to place an ESS or when interacting with the RWIS?
- Within your area of operations, what locations would you like to have more real-time road condition information about? Do any of these locations experience extreme weather conditions or issues with heavy traffic?
- Can any factors or data sets produced by an ESS be considered important enough to outweigh the system's cost? Please explain.
- Do you currently have a system for determining optimal ESS locations? Why or why not?
- Would you prefer a network of stations to monitor conditions over a large area or data about specific sites at the expense of a larger picture? Please explain.

Appendix F: NMDOT Patrol Yard Administrator Interview Minutes

District 5 Road Maintenance Team

NMDOT District 3 Meeting Minutes

Thursday, September 8th, 2016 - 10:00-11:30AM

Attendance

Team Members:

- Richard Cole Present
- Matt Jackman Present
- Jeff Robinson Present
- Connor Smith Present

Sponsors:

- Timothy Brown Present
- John Di Ruggiero Present

NMDOT Administrators:

- Todd Dunlap Present
- Tom Kratochvil Present
- Jonathan Lujan Present
- Johnny Perea Present
- Marc Romero Present

Meeting Chair:

- Richard Cole

Secretary:

- Jeff Robinson

Minutes

- **D3 Administrators Present:**
 - Tom Kratochvil - Assistant District Engineer
 - Jonathan Lujan - Area Maintenance Supervisor
 - Marc Romero - Patrol Supervisor
 - Johnny Perea - Deputy Area Maintenance Supervisor
 - Todd Dunlap - Deputy Area Maintenance Supervisor
- **How do you allocate and track resources during an extreme winter weather event?**
 - They track how much salt/sand/cinder is used by which truck, and where
 - Not with AVL, just paperwork to document where/when
 - Truck driver estimates yardage per mile based on how open dump gate is
 - Need to record salt/cinder yardage use because of frequent litigation
 - Very specific records, every change of direction and minute and quantity
 - Managers and supervisors review and enter records electronically after storms
 - Usage of salt/cinder is checked against inventory after storm
 - Inventory is checked at each patrol yard and they share info
 - salt/cinder/ice slicer mixed in different ratios for different conditions
 - In colder weather, salt/cinder turns snow into ice by melting and refreezing, ice slicer used instead
 - Very important to know temperatures when treating roads
 - They keep close watch on inventory and order constantly for Tijeras area
 - Salt comes from Carlsbad, cinder from Santa Fe
 - When ordering more supplies, they estimate 2-4 days lead and if not possible to get delivery in that time, yards and districts share supplies
 - Lots of paperwork to track supply transfers
 - “More cumbersome than it should be” - Tom
 - They tried to get sensors for trucks to monitor salt/cinder usage but couldn’t - they still need to rely on estimation and manual paperwork
 - Sensors (automation) would be great, but not there yet
 - Hard for drivers to know when they have run out of supplies in truck, experienced drivers are good at this
 - Moisture in load can make salt stick together, conveyor tunneling into bottom of load (truck empty or load tunneling/compacting?)
 - Sensors at dump gate would be covered in ice during heavy storms, so sensors would have to be very advanced or cleverly implemented/protected
 - Yards arrange and communicate to make sure patrols are keeping up with storm info and aware of storm going between patrol areas
 - Try to figure out how to keep resources moving in direction of storm, so all patrols are ready

- Manpower is a big issue - sickness and long patrol shifts, drivers not always available
 - When not driving, guys on shift are always working on some kind of prep work or maintenance at yard
 - Starting a snowstorm, first shift is 16 hours then every shift after is 12 (if necessary)
 - Even if snow stops quickly, need to continue long shifts to clean up trucks and maintain equipment to be ready for next storm
 - They stay ready all times so they can move fast if a storm rolls in quickly
 - Takes lots of coordination to handle consecutive storms
- **How do you determine when to send out plows and other winter maintenance equipment?**
 - Send patrols (sometimes the AMS themself) to known historical “hotspots” and they report when the conditions at those locations reach a certain point
- **How do you monitor the current road conditions?**
 - When weather service (NOAA/NWS) says storm is on the way, they assemble trucks & people, but don’t do anything until the snow starts falling
 - Other NMDOTs pre-treat roads with MgCl to give them time to start clearing roads after snow starts
 - MgCl very corrosive to trucks and mechanisms
 - Pre-treating is difficult, need to use metal pipes because of cold, but PVC can resist corrosion better
 - Too thick layer of pre-treatment will make road slick
 - This caused deadly crash, litigation stopped all pre-treatment but now looking to bring it back
 - When storms move into Edgewood area, guys look at different weather stations on TV/radio and some go out on patrols to watch and wait for the weather while others prepare trucks and get crews together
 - When storm incoming, 8 hour shifts for patrols - someone is always on patrol from a few days before a storm, so they know immediately when weather arrives
 - Special purpose crews will also get pulled for 8 hour patrols
 - On patrols, supervisors frequently go out to historical worst weather locations and check conditions constantly
 - Weather station info would be more helpful, would give managers more notice and accurate info to add to patrols
- **Where do you get your weather information during a storm?**
 - AMS interact with police often, to discuss road conditions and closures
 - NWS gives weekly presentations
 - Use the local weather and news channels
 - Patrols in the field
- **If you see vastly different conditions on patrol compared to predictions/expectations, what do you do?**
 - If secondary road is bad, might send trucks over while keeping some on interstate to maintain it
 - Level 1 roads re highest priority at all times, but plows can respond to lower priority roads if very bad, just not always

- Priority 3, 4, 5 roads are usually allowed to just melt off, 1/2 are very important and closely watched
- React immediately to information on conditions rather than wait until the end of a shift, will even take trucks from other patrol yards to deal with it if necessary - trucks go where needed in storms
- **What resources would cause the most problems if you ran out of them and how would you react to a lack of those items?**
 - Equipment first, then manpower
 - Supplies also very difficult, supplier has many customers to account for and materials are not supplied consistently
 - In D3, they share salt etc. between patrols easily due to distance, but over larger districts is harder
 - Interstates are sometimes closed, to keep people in ABQ for safety when interstate east is dangerous
 - Road closures are worse for road conditions, traffic helps keep ice melted
 - Stopped trucks on interstate big issue in winter
- **How do you determine the allocation of resources to specific trucks during winter maintenance operations?**
 - Every truck get filled before it leaves, no such thing as a half load
- **How often during the year do you run into resource management problems?**
 - Tom - all the time, especially around holidays or superbowl, everyone is “sick”
 - Johnny - some guys are dedicated, others are more interested in taking off for family/holidays, etc.
 - If the same guys avoids multiple storms, will be reprimanded
 - When hiring, guys are asked if they can show up on short notice at any hour for heavy snows/surprise storms
 - Sometimes guys need to be added on for extra hours on top of 8 hr shifts, but only rarely
 - Mark - in middle of storms, ice etc. will break trucks, so they need to bring in mechanic in middle of storm sometimes
 - Supervisors are aware of equipment conditions, frequently getting equipment checked and mechanics called
 - Every shift PM (prev. maint) sheet must be filled out for leave and return to ensure trucks are in good shape, or at least equip condition is monitored
 - If something is wrong with truck, fill out work orders to get trucks fixed
 - They only keep small parts on hand, serious repairs mechanics source parts
 - Only 1 field mechanic for all of D3, he gets 1 or 2 helpers in winter sometimes
- **What do you know about or have you ever worked with an RWIS?**
 - Currently 5 weather stations in NM depending on your count
 - 1 on I-40 at top of hill near Edgewood wiped out by trucker
 - Do we want to put it back, or use potential insurance \$\$\$ to install a new one elsewhere?
 - All agree that it is a useful spot to have one, so it might get put back there

- Currently ESS are going in wherever road work is being done and the funds are available
 - We want to come up with a real plan which is why our team is here
 - Weather sensor stations supplied by Vaisala, cameras are NMDOT spec
- **What factors do you consider important in determining where to place an ESS?**
 - Ambient temp for road and air
 - Wind speed (very important)
 - Causes snow drifts, blowing snow/storms
 - Visibility (not much), only for plow safety
 - Precipitation amount
 - Type of precipitation (dense/light snow, freezing rain, etc.)
 - Weather condition in general
 - Tim wants to send “grip factor” notifications to Patrol Supervisors and AMS
 - They also say that wind speed and precipitation data would be good to have
 - Goal is to take work off the guys, keep roads in better shape
- **What difficulties do you face when trying to place an ESS or when interacting with the RWIS?**
 - Currently do not have any to work with so do not know
 - Tim - end goal of project is email, text, any kind of notification that would be useful, ideally allow for real-time monitoring from patrol yards
 - Weather stations operating now - 3 send data to NMRoads real time, easier than going to Vaisala web interface for same info
 - ITS can set a road segment on NMRoads for patrol yards to sign up for, so they can get notifications on road condition info available for those areas
 - Even just 1 road segment would be useful, if highway is getting bad weather then secondary nearby will be bad too
- **Within your area of operations, what locations would you like to have more real-time road condition information about? Do any of these locations experience extreme weather conditions or problems related with heavy traffic?**
 - Tijeras
 - San Felipe/Santo Domingo pueblos (dips, wind, hills)
 - Rio Rancho - weather over big hill unpredictable
 - Big I - many lawsuits, very useful to know, high population
 - I-25 has dust storms in D4/5, north of ABQ
 - D6 also has dust problems
 - D3 needs ESS in Tijeras Canyon, also near the town of Tijeras (worst patrol for D3 snow)
 - Most snowstorms start east near Edgewood and climb hill
- **Would you prefer a network of stations to monitor conditions over a large area or data about specific sites at the expense of a larger picture? Please explain.**
 - As a district, 3 watches weather and tries to prepare a few days ahead
 - Specific location info would be very helpful, but still hard to use because Tijeras Canyon has different weather in different parts of canyon

- If I-40 east of canyon is bad, can have State Police shut down I-40 in Tijeras to keep people safe in ABQ

Other Information

- 5 patrol yards in D3
- NM state has recently upgraded to narrow-band radio system to reduce costs and dead spots - not perfect, but better
- They have ~10 trucks total, 7-8 on each patrol
 - If they need more trucks on patrol, reaction is as quick as possible - trucks are kept ready
 - Trucks on patrol are always fully loaded with salt/sand/cinder
- Tim - Do you know reliability % for trucks?
 - Drops massively in winter, sometimes down to 10%
 - Working with warranties is difficult, time wasted at dealer but warranty void if field mechanic works on them
 - Often means that a truck under warranty will not come back for weeks once it breaks down
 - They only have one mechanic so he is often busy during storms
 - They hire one or two more secondary mechanics during the winter but it is still not enough
- Biggest problem is really people driving too fast, bad drivers cause more problems than weather for traffic
- Supervisors need smartphones for intelligent monitoring to help

Appendix G: Test Location Comparison

Criteria	Clines Corners (I-40/US-285)	Tijeras (I-40/NM-14)	"The Big I" (I-25/I-40)	San Felipe (I-25 MM248)
Average Wind (mph)	8	UNKNOWN	8.3	UNKNOWN
Average Annual Snow (in)	42	9.6	10	8.7
Average Annual Rain (in)	19.69	9.45	9.39	11.3
Functional Class within ½ mi	1, 3	1, 4, 5	1, 1	1, 5, 6
Snow Removal Priority within ½ mi	1, 3, 5	1, 2, 3	1, 1, 3	1, 3
Highest 2013 AADT Nearby	16000	68000	187000	35000
Weather Related Crashes (2010)	5	15	56	2
Dist. Patrol Yard (mi)	1	1.5	4.5	7
Dist. ITS Unit (mi.)	0	4	0	4.3
Fire Risk (0 high, 5 non)	3	0.5	5	4
Clear Weather Crashes (2010)	10	23	~250	17
Environment	desert/arid	arid/forest	City	desert/arid
Local Topography	flatlands	mountains	flatlands	rolling hills
In Tribal Land?	NO	Nat'l Forest	NO	YES

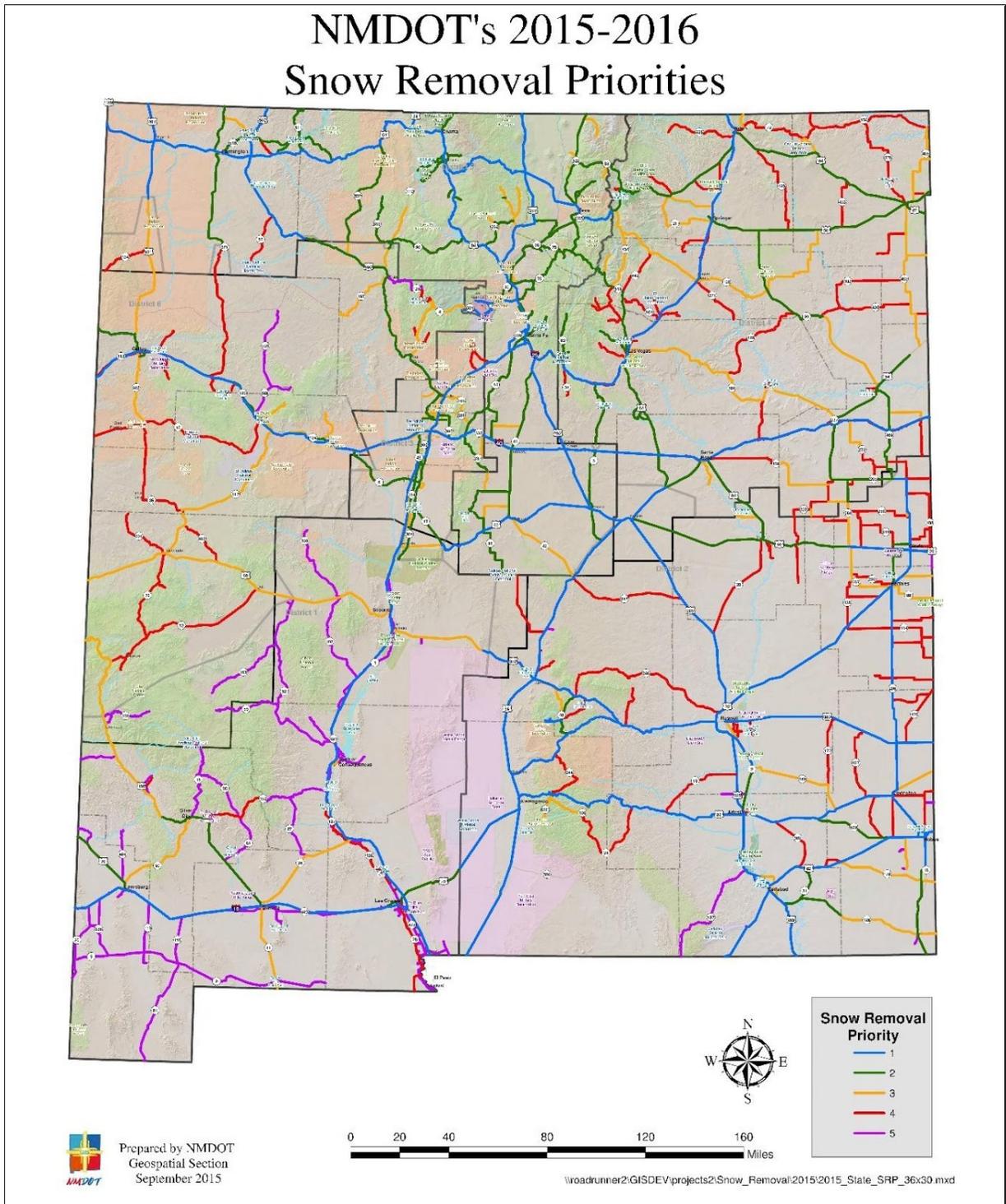
Appendix H: Initial Site Ranking Criteria

These Importance Factors, mentioned in Section 4.1.1, are the original importance factors and ESS siting criteria our group determined in order to begin developing our formulas.

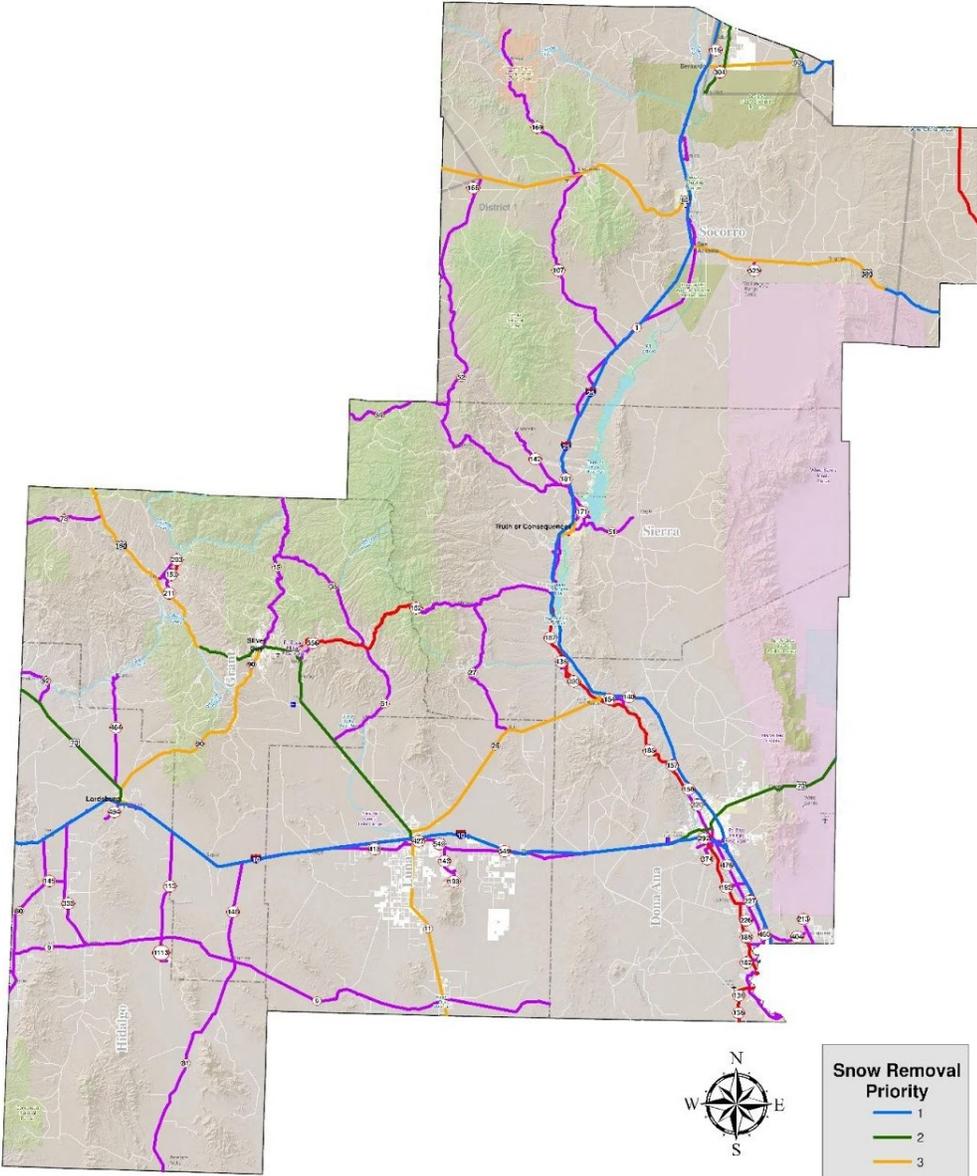
Criteria	Importance Factor
Average Wind Speed (mph)	1
Average Annual Snowfall (in)	4
Average Annual Rainfall (in)	2
Nearby Roads' Functional Classification	3
Nearby Roads' Snow Removal Priority	4
Average Annual Daily Traffic (2013)	5
Weather-related Accidents within 2 miles	5
Distance to Nearest Patrol Yard (mi)	4
Distance to Nearest ITS Unit (mi)	2
Fire Risk	1

Appendix I: Snow Removal Priorities

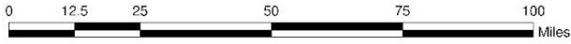
NMDOT's 2015-2016 Snow Removal Priorities



NMDOT Maintenance District 1
Snow Removal Priorities
2015-2016



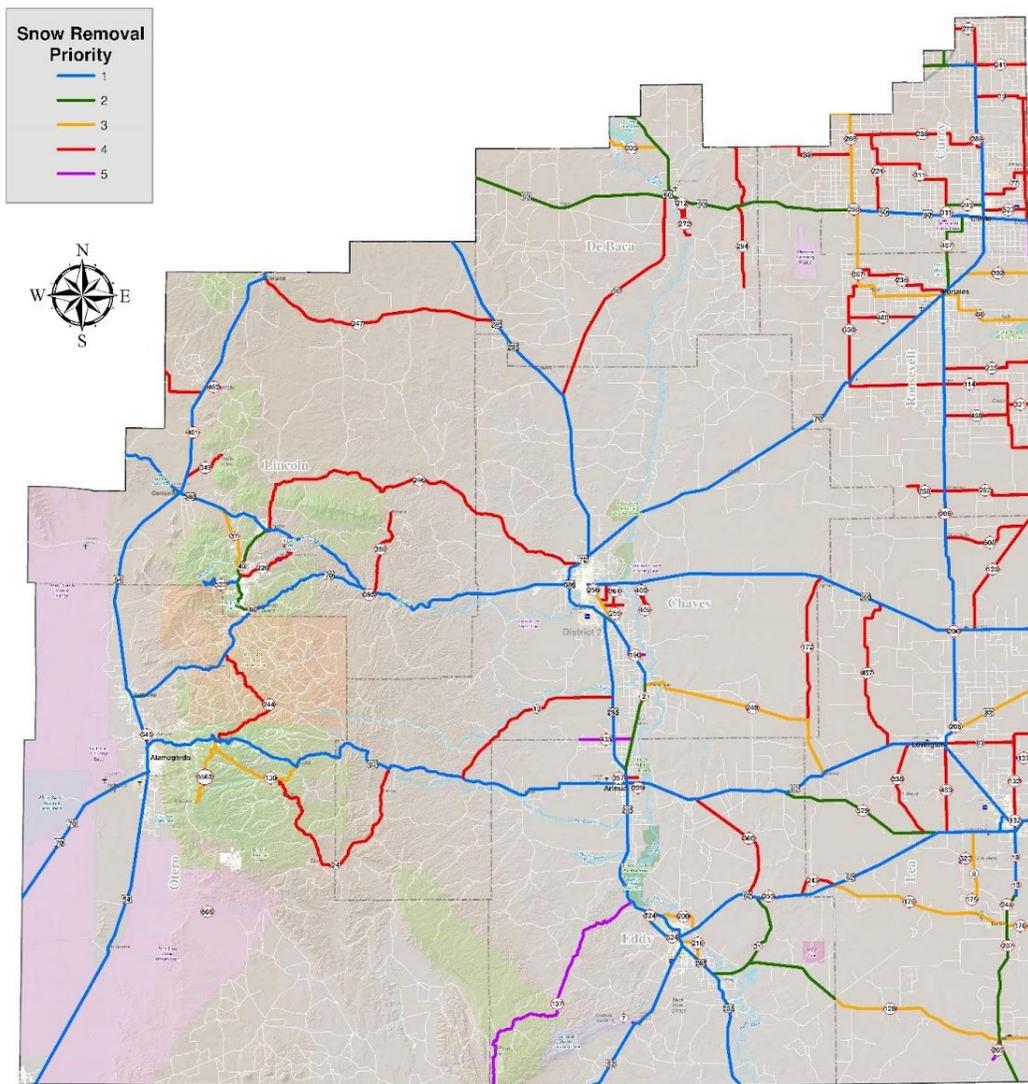
Prepared by NMDOT
Geospatial Section
September 2015



Snow Removal Priority	
Blue line	1
Green line	2
Orange line	3
Red line	4
Purple line	5

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NMDOT Maintenance District 2 Snow Removal Priorities 2015-2016

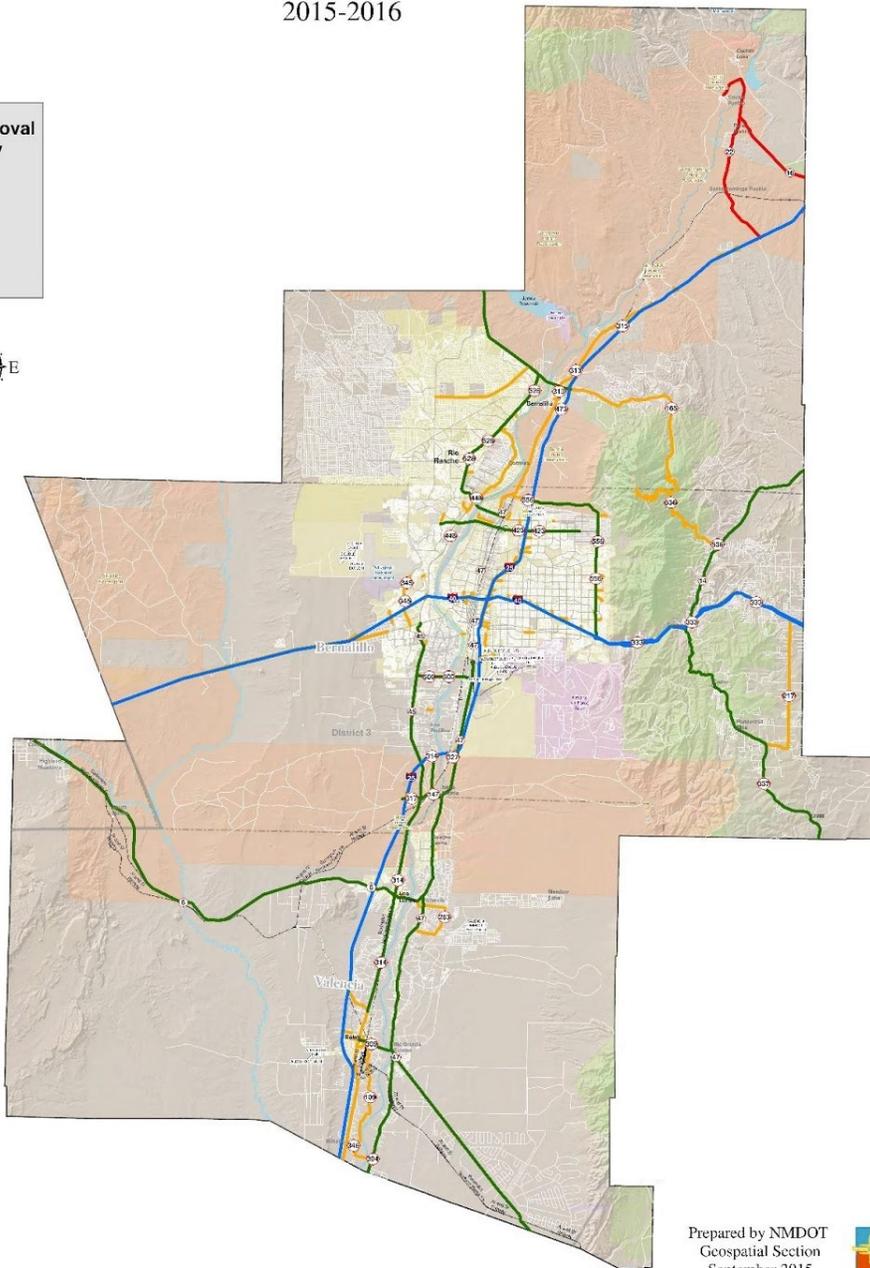


Prepared by NMDOT
Geospatial Section
September 2015



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NMDOT Maintenance District 3 Snow Removal Priorities 2015-2016

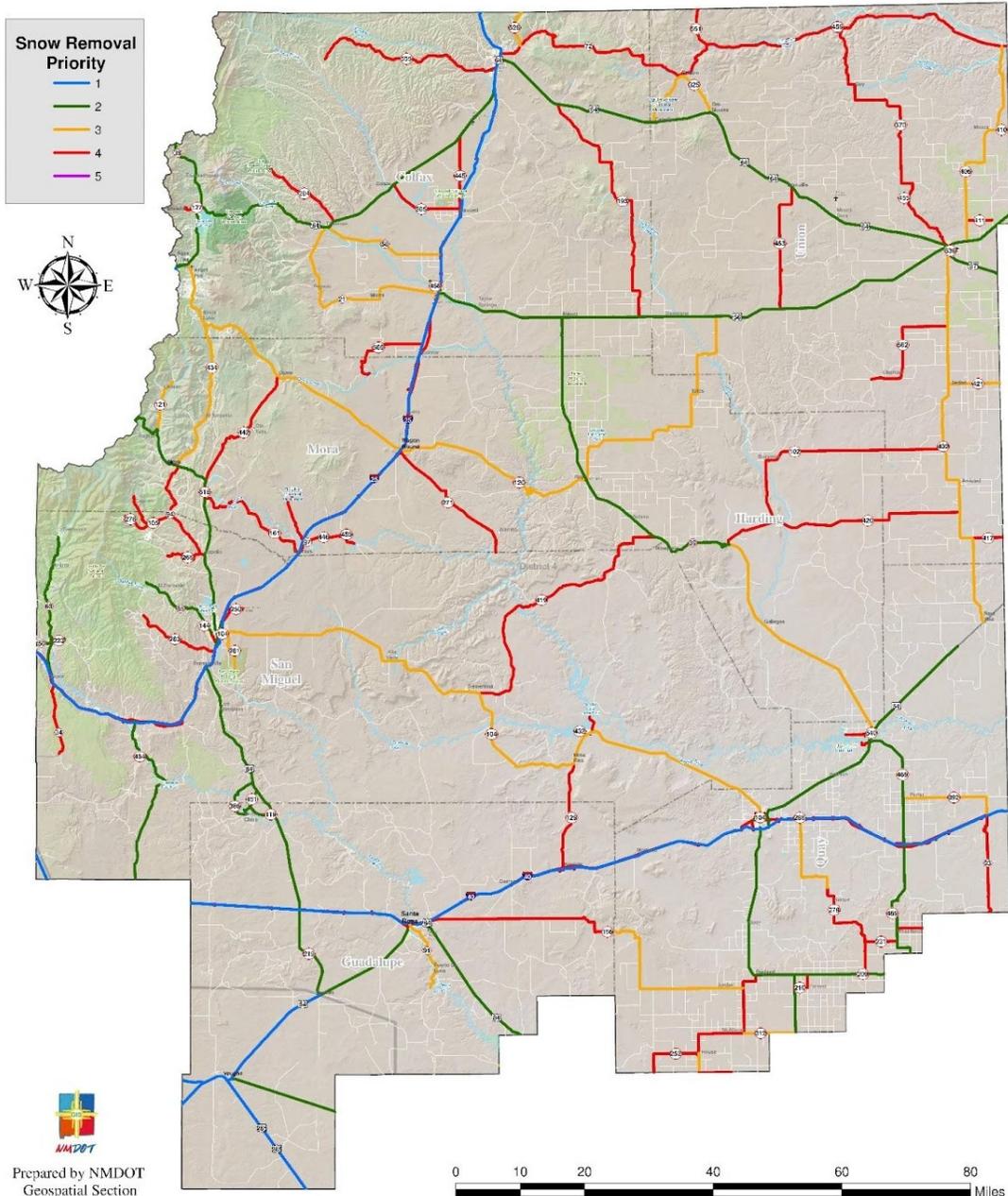


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Prepared by NMDOT
Geospatial Section
September 2015



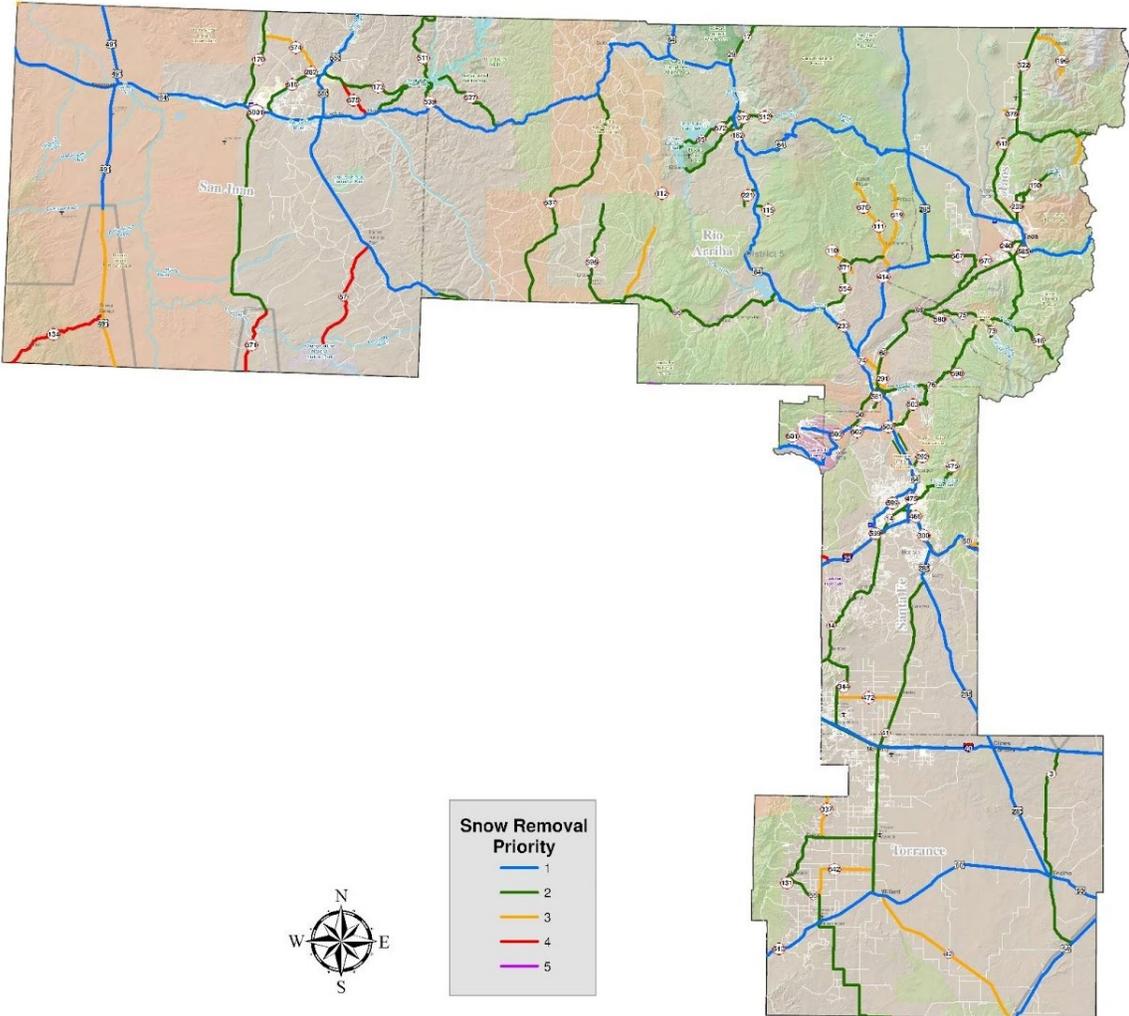
NMDOT Maintenance District 4 Snow Removal Priorities 2015-2016




Prepared by NMDOT
Geospatial Section
September 2015

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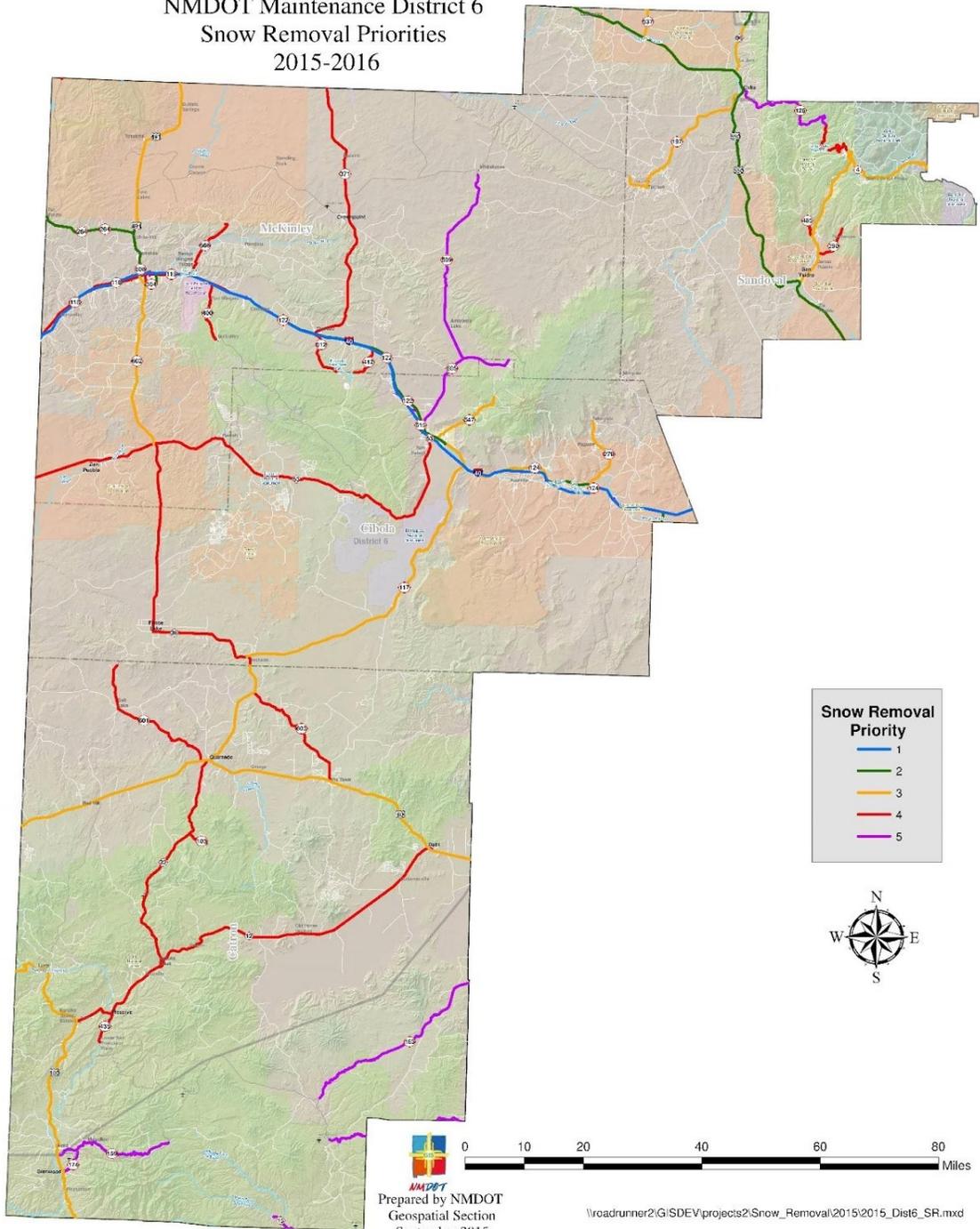
NMDOT Maintenance District 5
Snow Removal Priorities
2015-2016



Prepared by NMDOT
Geospatial Section
September 2015

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NMDOT Maintenance District 6
Snow Removal Priorities
2015-2016



Appendix J: Winter Maintenance Operations

Recommendations

After meeting and interviewing patrol yard supervisors, our group determined areas where the ITS Bureau could help patrol yards improve their productivity based on their feedback and our prior research on industry best practices. We have not studied the implementations of these recommendations and have theorized them in a best case scenario, meaning that while these recommendations might not be possible to implement currently, further investigation should be conducted to determine if these methods can be applied in the future.

One of the biggest problems that snow plow operators face during winter maintenance operations is an inability to measure exactly how much salt, sand, or cinder is in their truck bed at a given time and how much is being deployed over a certain distance as mentioned in Section 4.2.3. To provide drivers this valuable information, we recommend installing sensors both in or under the bed and on the conveyor and spreader system of the dispenser trucks, to measure both the quantity of material in the bed and the rate at which it is being dispensed. By determining how much material is in the bed and how much the spreader is spreading, it is possible to calculate, or at least approximate, the rate of a truck's material usage. Given this information, drivers would be better able to control and monitor the amount of material they dispense on the roads, and would have an easier time recording their work, even using the existing paper-based road treatment recording system, described in Section 4.2.3.

If this load status information given to drivers could be additionally fed into an electronic system, such as an Automated Vehicle Location (AVL) system, that tracked each plow and treatment truck's route and load status remotely, the current paper-based recording system could be effectively replaced. While the electronic systems required to make use of such an arrangement would be create another piece of equipment requiring maintenance and care itself, implementing such an AVL or automatic load monitoring system would provide highly valuable information to area maintenance supervisors and NMDOT dispatchers that would enable them to more carefully manage their operations. In addition, such an electronic system would save valuable time currently spent on manually entering information, both for the drivers during storms and supervisors

monitoring them. This system could provide more precise measurements of material usage than drivers can currently achieve by approximation.

Even if a full AVL or load tracking system cannot be implemented due to complexity or cost, the ITS could still use technological means to improve the efficiency of treatment recording by replacing the current paper recording form with an electronic form to be filled out on a smartphone or laptop located in the cab of the truck. By removing paper from the system, the completed forms could be quickly imported to whatever electronic record keeping system the DOT uses, eliminating the ‘middleman’ of manually importing the information. This would save time and reduce the likelihood of losing data due to damage to the paper or misreading of the paper form. In fact, Idaho has implemented such a system in their plow trucks, where a driver can report material usage and road condition information through a premade electronic form on a PDA installed in the truck’s cab, something that the NMDOT could use as a template for this application.

One of the other improvements that the NMDOT could make is to create an electronic inventory tracking database, accessible to all managers and supervisors, to centralize and back up inventory data from patrol yards around the state. The NMDOT could build off of such an electronic inventory system by implementing a dashboard to display information from other nearby patrol yards, such as the number of trucks available, the amount of salt and other material available, and the number of crews that are currently working. Currently, this dashboard system could also be implemented to display basic information that is useful for managers and dispatchers in real-time, allowing them to go to one location for all of the information that they require like personnel on duty or data received from the NMDOT’s RWIS. This database could make the jobs of the managers and supervisors easier by helping them make more informed decisions about resource sharing, road clearing organization, and maintenance part stocking. In Iowa, a similar system has already been implemented, with the Iowa DOT designing an electronic dashboard system specifically for tracking salt spreading around the state, with the goal of assisting the DOT with meeting usage targets and staying clear of budget limits (Goodwin, 2003).

Additionally, the NMDOT could employ this electronic inventory system combined with a sensor network to implement an automatic vendor-managed inventory (VMI) for their road treatment materials, the theory of which is described in Section 2.3.2. This would function by utilizing the sensors to calculate how much of a material was placed in a truck and subtracting that

amount from the inventory system either automatically or through an electronic input form. If the NMDOT did not wish to outfit their fleet with these sensors, the electronic inventory system could also be employed by having each driver fill out an electronic material requisition form when his or her truck is filled, which would then be recorded by the system. Using this system, a report could be generated for each patrol yard after a storm showing how much of a material was used and a report sent to the supplier for that material showing usage and current stock. By providing this direct view of the patrol yard's supplies through access to the database, the vendors can see when the quantity drops below a specified minimum and send out another shipment of road treatment material that will raise the total inventory of the specific supply back up to the determined maximum. This would allow the materials to be delivered at the correct time without a direct request from the patrol yard.

The patrol yards could also implement other elements of inventory management best practices, such as kanban and setting proper reorder points, to develop their own more sophisticated inventory management protocol. By assigning a kanban to each piece of maintenance equipment, tool, or portion of material, the patrol yard could keep an accurate record of what resources see use when and in what location, and could therefore track usage patterns to get a better picture of the way their inventory works. Additionally, the kanban system will allow the patrol yards to track the usage of equipment to see which parts wear out faster and replace them in a timely fashion without any downtime as well as spot any potential overuse of certain materials and take corrective measures to stop this excessive usage. Through this analysis, the patrol yard managers and area maintenance supervisors could determine average lead times for different material orders, and thus determine ideal reorder points and economic order quantities to make the most cost-effective use of their inventory.

The proper upkeep of trucks and equipment is another issue that patrol yards face, especially during the winter months. The patrol yards clean and prepare equipment for incoming storms, but upkeep becomes more difficult if these storms last for an extended period of time, or multiple storms appear in quick succession. In some cases, plows or road treatment trucks can be put out of commission as a result, and cannot be fixed until the district's field mechanic becomes available. This is a major problem for the NMDOT, as the patrol yards in District 3 in particular, only have access to one field mechanic. This mechanic has trouble keeping up with the breakdown of trucks during events, especially if a truck needs to be transported to the NMDOT's main maintenance yard to get a part that is only stored there. To help solve this issue, the NMDOT could hire more field

mechanics for districts with poor weather conditions, such as 3, 4, and 5. Doing this would allow more plows to be on the road at any given time and the patrol yards to be more efficient with the clearing of highly-trafficked routes. This could also be supplemented by utilizing the kanban system described in the previous paragraph to determine what common parts trucks need during maintenance operations that are not currently at patrol yards. By stocking these items at the patrol yards, the field mechanics can make the most efficient use of their time by not having to transport trucks to the main maintenance yard to get fixed, allowing equipment to return to service faster.

By implementing some of our recommendations here, the NMDOT should be able to improve the efficiency and effectiveness of the patrol yards' operations, thereby improving the overall quality of their maintenance operations and the safety of the roads across the state.

Appendix K: Ranking System Needs Chart

Need
<ul style="list-style-type: none">• Parse the data to create a logical analysis• Ability to process data of different types and units• Must have differentiation between rankings (a 7 must be better than a 6)• Avoids clustering of rating when possible• Create visual representations of rankings• Results should be able to be easily implemented in other programs (like GIS)• Easy to understand how the ranking tool functions both up front and behind the scenes
Want
<ul style="list-style-type: none">• Modifiable based upon what the user wants• Easily adaptable to include new information• Automated data extraction• Automatic report generation
Avoid
<ul style="list-style-type: none">• Over-complication, anyone should be able to use and understand the ranking system

Appendix L: Pros and Cons of Two Evaluation Protocols

Total Points Based on Importance Factor	
Pros	Cons
<ul style="list-style-type: none"> • Modifiable without reorganizing entire criterion ranking • Can add a new criterion by simply determining its importance factor 	<ul style="list-style-type: none"> • Possibly too easily modified, if too many criteria are included, the limited range of importance factors can cause the effect of the rankings to be diluted • Only coarse adjustments possible, five point jumps minimum distinction between rankings (Criteria with the same importance factor are not necessarily the same importance) • System is not clearly defined, formula must account for changing point total when criteria are added, removed, or modified • System is entirely subjective

100 Total Points Allocated by Importance	
Pros	Cons
<ul style="list-style-type: none"> • Forces the user to rethink the importance of the criteria every time they modify the ranking, which helps the ranking remain accurate to its intent • Allows for more finely distinguished ranking levels • Consistent total point count; formula can be designed around 100 total points and remain same even if criteria are modified 	<ul style="list-style-type: none"> • The user must take the time to redo the entire ranking system if they want to modify it or add a criterion • System is entirely subjective

Appendix M: Final Criteria Ranking

Criterion	Team's Importance Factor (5 to 1)	Sponsor's Importance Factor (1 to 13)	Final Score (%)	Deal Killer?
Wind data	1	2	12	NO
Average annual snow (in)	4	2	15	NO
Average annual rain (in)	2	11	4	NO
Functional Class within ½ mile	3	-	-	NO
Snow Removal Priority within ½ mile	4	4	6	NO
2013 AADT	5	4	15	NO
Ratio of Weather to Clear Crashes	5	1	16	NO
Dist Patrol Yard (mi)	4	9	7	NO
Dist ITS Unit (mi)	2	12	3	NO
Fire Risk	1	13	1	NO
Altitude	2	6	6	NO
Distance to Power	4	-	BOOLEAN	YES
Distance to Communication	4	-	BOOLEAN	YES
Local Environment	2	6	FLAG	NO
Local Topography	1	10	9	NO
Average Road Grade	3	8	6	NO
In tribal land	BOOLEAN	-	BOOLEAN	YES
Total Points Allotted			100	

Appendix N: Description of ArcGIS Maps

ESS Siting Data

This map features all of the data necessary to fill in our group's ranking tool. Each data set on the ranking tool can be filled in using a single layer, sometimes a layer holds more than one type of data needed in the ranking tool. This map can be found at:

<http://www.arcgis.com/home/webmap/viewer.html?webmap=3858c7568def4ca29670da3688c7e1fc>

This map has the following layers that can be turned off or on as needed:

- **2010 Crash Ratio with AADT**
Shows the ratio of clear and weather related accidents for 2010 and the 2013 AADT
- **New Mexico AADT 2013**
Shows the AADT for road segments for 2013
- **Snowfall Interpolation**
Shows where there, historically, has been a lot of snowfall
- **Precipitation Data Interpolation**
Shows where there has been a lot of precipitation historically
- **NMDOT Patrol Yards**
Displays the location of every patrol yard
- **ITS Infrastructure**
Shows where NMDOT cameras and dynamic message signs are set up
- **Global Biomes**
Shows the different biomes/environments that exist in New Mexico
- **NMDOT Districts**
Outlines the 6 districts
- **NM Indian Reservations**
Outlines and color codes the different tribal lands
- **GLDAS Precipitation 2000 - Present**
Giant weather map that shows how much rain different areas receive starting in 2000
- **Terrain**
Will give the altitude of any location upon clicking there
- **U.S. Forest Service - Wildfire Hazard Potential**
Displays the wildfire risk for any spot in the United States

NM Crash Data

This map compiles the crash data on New Mexico that the NMDOT has access to. It includes layers that have been formatted to display information about specific types of weather for

ease of use. Our group used this map to determine hotspots for crashes of different types. This map can be found at: <http://lee->

eng.maps.arcgis.com/apps/View/index.html?appid=b61fdb6263374690bdc5b49adf414bd7

This map has the following layers that can be turned off or on as needed:

- **2012 Crash Ratio and AADT**
Ratio of clear and weather related accidents as well as the AADT for 2012.
- **2011 Crash Ratio and AADT**
Ratio of clear and weather related accidents as well as the AADT for 2011.
- **2010 Crash Ratio and AADT**
Ratio of clear and weather related accidents as well as the AADT for 2010.
- **2014 Crashes Along 2013 AADT Segments**
Ratio of clear and weather related accidents as well as the AADT for 2013. Clicking on a stretch of road will bring up a pie chart that summarizes all the different types of accidents that occurred there in 2014.
- **2013 Crashes Along 2013 AADT Segments**
Ratio of clear and weather related accidents as well as the AADT for 2013. Clicking on a stretch of road will bring up a pie chart that summarizes all the different types of accidents that occurred there in 2013.
- **2012 Crashes Along 2013 AADT Segments**
Ratio of clear and weather related accidents as well as the AADT for 2013. Clicking on a stretch of road will bring up a pie chart that summarizes all the different types of accidents that occurred there in 2012.
- **2011 Crashes Along 2013 AADT Segments**
Ratio of clear and weather related accidents as well as the AADT for 2013. Clicking on a stretch of road will bring up a pie chart that summarizes all the different types of accidents that occurred there in 2011.
- **2010 Crashes Along 2013 AADT Segments**
Ratio of clear and weather related accidents as well as the AADT for 2013. Clicking on a stretch of road will bring up a pie chart that summarizes all the different types of accidents that occurred there in 2010.
- **Motor Vehicle Crashes, New Mexico, 2010-2014 - ACRASH1014**
Displays all reported crashes in New Mexico for the years 2010-2014. Each color represents a different weather related event to have caused the accident
- **NM weather crash data 2012**
Shows all accidents that involved some type of weather for 2012
- **NM weather crash data 2011**
Shows all accidents that involved some type of weather for 2011
- **NM weather crash data 2010**
Shows all accidents that involved some type of weather for 2010
- **NM clear weather crash data 2012**
Shows all accidents that didn't involve weather for 2012
- **NM clear weather crash data 2011**
Shows all accidents that didn't involve weather for 2011
- **NM clear weather crash data 2010**

- Shows all accidents that didn't involve weather for 2010
- **NM fog crash data 2012**
Shows all accidents that involved fog for 2012
- **NM fog crash data 2011**
Shows all accidents that involved fog for 2011
- **NM fog crash data 2010**
Shows all accidents that involved fog for 2010
- **NM sleet/hail crash data 2012**
Shows all accidents that involved sleet and or hail for 2012
- **NM sleet/hail crash data 2011**
Shows all accidents that involved sleet and or hail for 2011
- **NM sleet/hail crash data 2010**
Shows all accidents that involved sleet and or hail for 2010
- **NM dust crash data 2012**
Shows all accidents that involved dust for 2012
- **NM dust crash data 2011**
Shows all accidents that involved dust for 2011
- **NM dust crash data 2010**
Shows all accidents that involved dust for 2010
- **NM rain crash data 2012**
Shows all accidents that involved rain for 2012
- **NM rain crash data 2011**
Shows all accidents that involved rain for 2011
- **NM rain crash data 2010**
Shows all accidents that involved rain for 2010
- **NM wind crash data 2012**
Shows all accidents that involved wind for 2012
- **NM wind crash data 2011**
Shows all accidents that involved wind for 2011
- **NM wind crash data 2010**
Shows all accidents that involved wind for 2010
- **NM other crash data 2012**
Shows all the accidents during 2012 that didn't fit into any other category of weather
- **NM other crash data 2011**
Shows all the accidents during 2011 that didn't fit into any other category of weather
- **NM other crash data 2010**
Shows all the accidents during 2010 that didn't fit into any other category of weather
- **NM snow crash data 2012**
Displays all the accidents that occurred during 2012 that involved snow
- **NM snow crash data 2011**
Displays all the accidents that occurred during 2011 that involved snow
- **NM snow crash data 2010**
Displays all the accidents that occurred during 2010 that involved snow
- **New Mexico AADT 2013**
Shows the AADT for all roads during 2013

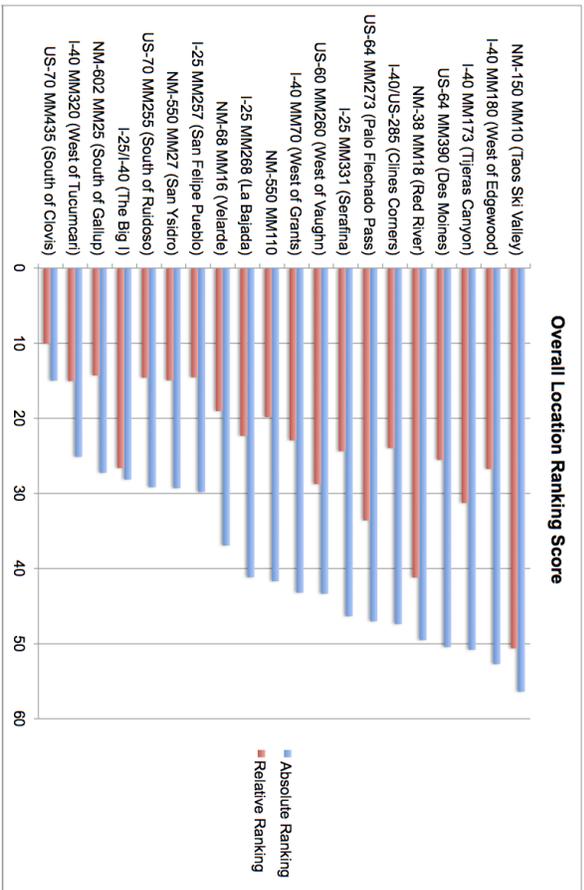
Appendix O: Final SPOT Report

SPOT Site Ranking Report

Location	Latitude	Longitude	Absolute Ranking	Relative Ranking	Flags
NM-150 MM110 (Taos Ski Valley)	36.57	-105.51	56	51	1,2
I-40 MM180 (West of Edgewood)	35.11	-106.30	53	27	
I-40 MM173 (Tijeras Canyon)	35.08	-106.41	51	31	
US-64 MM390 (Des Moines)	36.71	-103.80	50	26	
NM-38 MM18 (Red River)	36.67	-105.33	50	41	1,2
I-40/US-285 (Clines Corners)	35.01	-105.67	47	24	
US-64 MM273 (Palo Flechado Pass)	36.41	-105.34	47	34	
I-25 MM331 (Serrafina)	35.39	-105.33	46	24	1,2
US-60 MM260 (West of Vaughn)	34.61	-105.37	43	29	1,2
I-40 MM70 (West of Grants)	35.29	-107.99	43	23	1,2
NM-550 MM110	36.26	-107.66	42	20	1,2
I-25 MM268 (La Bajada)	35.52	-106.19	41	22	1,2
NM-68 MM16 (Velarde)	36.19	-105.98	37	19	
I-25 MM257 (San Felipe Pueblo)	35.46	-106.34	30	15	3
NM-550 MM27 (San Ysidro)	35.54	-106.83	29	15	1,2
US-70 MM255 (South of Ruidoso)	33.27	-105.70	29	15	1,2,3
I-25/I-40 (The Big I)	35.10	-106.63	28	27	
NM-602 MM25 (South of Gallup)	35.45	-108.75	27	14	1,2,3
I-40 MM320 (West of Tucuman)	35.12	-103.93	25	15	1,2
US-70 MM435 (South of Clovis)	34.31	-103.20	15	10	

Flag Codes:

- 1: Power lines are not available nearby
- 2: Communication lines are not available nearby
- 3: Site is on or near Tribal Lands



Appendix P: SPOT User Guide

Appendix P begins on the next page.

Station Placement Optimization Tool (SPOT) User Guide

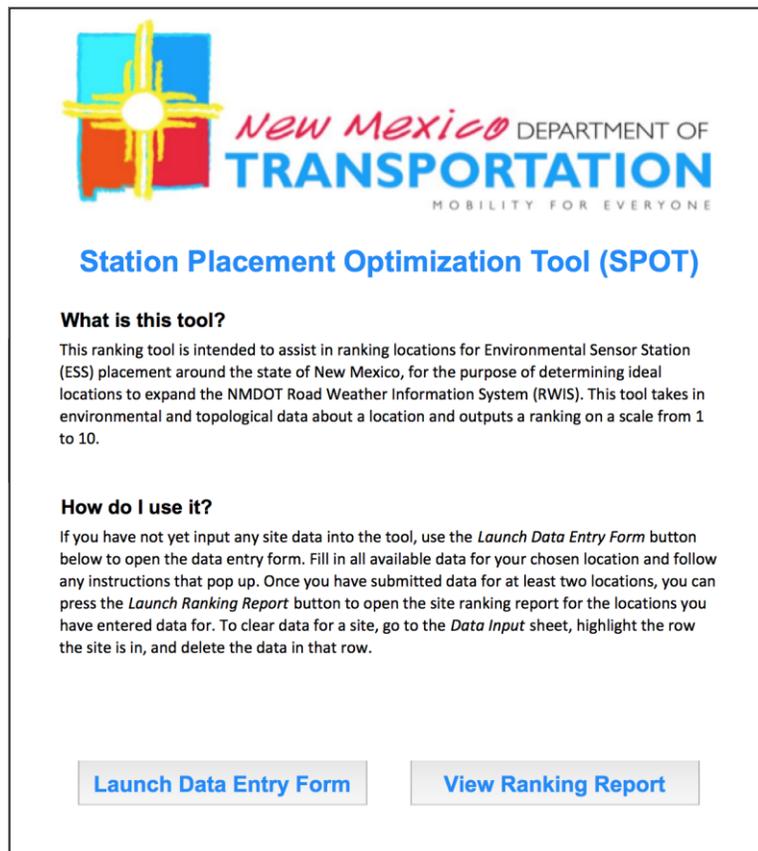


1.0 Setup

1. Open up the file: StationPlacementOptimizationTool.xlsx
2. Ensure that macros are enabled within the Excel workbook, as the main functions of SPOT require macros.
3. Open or Navigate to the ESS Siting Data map on ArcGIS to begin gathering data:
<http://www.arcgis.com/home/webmap/viewer.html?webmap=3858c7568def4ca29670da3688c7e1f>
[c](#)

2.0 Entering New Location Data

1. From the Introduction Page, select Launch Data Entry Form.



 **New Mexico** DEPARTMENT OF
TRANSPORTATION
MOBILITY FOR EVERYONE

Station Placement Optimization Tool (SPOT)

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How do I use it?

If you have not yet input any site data into the tool, use the *Launch Data Entry Form* button below to open the data entry form. Fill in all available data for your chosen location and follow any instructions that pop up. Once you have submitted data for at least two locations, you can press the *Launch Ranking Report* button to open the site ranking report for the locations you have entered data for. To clear data for a site, go to the *Data Input* sheet, highlight the row the site is in, and delete the data in that row.

[Launch Data Entry Form](#) [View Ranking Report](#)

2. Enter a descriptive name into the Location data entry box on the Data Entry Form.

SPOT Location Data Entry Form

Data Set Currently Editing:	<input type="text"/>	Average Road Grade 2 Miles	<input type="text"/>
Location	<input type="text" value="Inc. Intersect/Mile Marker"/>	Average Annual Rain (in)	<input type="text"/>
Latitude	<input type="text"/>	Dist ITS Unit (mi)	<input type="text" value="Linear Distance"/>
Longitude	<input type="text"/>	Fire Risk (0 Very High, 5 No Risk)	<input type="text"/>
Ratio of Weather to Clear Crashes	<input type="text" value="Weather"/> <input type="text" value="Clear"/>	Distance to Power (mi)	<input type="text"/>
Average annual snow (in)	<input type="text"/>	Distance to Communication (mi)	<input type="text"/>
2013 AADT	<input type="text"/>	Local Environment	<input type="text" value="Optional"/>
Average Wind Gust	<input type="text"/>	Functional Class	<input type="text" value="Optional"/>
Local Altitude Range (meters)	<input type="text"/>	In Tribal Land?	<input type="text" value="YES/NO"/>
Dist Patrol Yard (mi)	<input type="text" value="Linear Distance"/>	Length of AADT Road Segment (mi)	<input type="text"/>
Altitude (Meters)	<input type="text"/>	Comment 1	<input type="text"/>
Snow Removal Priority	<input type="text" value="Sum of (6-[Level]) Nearby"/>	Comment 2	<input type="text"/>

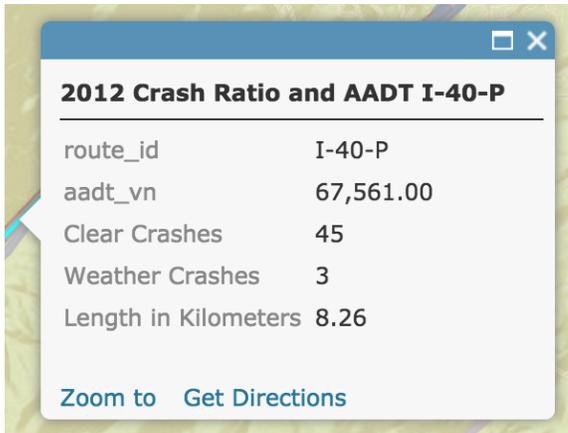
Input This Data
Clear This Entry

3. Turn on the desired layers, using the table below, within the ESS Siting Data map to view the appropriate data.

Criterion	Map Layer
Latitude/Longitude	Use Measure Tool
Number of weather/clear crashes	2012/2011/2010 Crash Ratio with AADT
Average Annual Snowfall	Snowfall Interpolation, GLDAS Precipitation
2013 AADT	New Mexico AADT 2013, 201X Crash Ratio and AADT
Average Wind Gust	N/A
Local Altitude Range	Terrain
Distance to Nearest Patrol Yard	NMDOT Patrol Yards
Altitude	Terrain
Snow Removal Priority	(See Appendix I)
Average Road Grade	N/A
Average Annual Rainfall	Precipitation Data Interpolation, USA Mean Rainfall, GLDAS Precipitation
Distance to Nearest ITS Unit	ITS Infrastructure
Fire Risk	U.S. Forest Service - Wildfire Hazard Potential
Distance to Power	N/A
Distance to Communication	N/A

Local Environment	Global Biomes, Basemap Tab
Functional Class	NMDOT Functional Class
In Tribal Land or Not	NM Indian Reservations
Length of AADT Road Segment	New Mexico AADT 2013, 201X Crash Ratio and AADT

- Click at the desired location and view the pop-up.



- Record the data provided in the pop-up and enter into the appropriate data entry box in the Data Entry Form.

SPOT Location Data Entry Form

Data Set Currently Editing:	<input type="text"/>	Average Road Grade 2 Miles	<input type="text"/>
Location	<input type="text" value="Inc. Intersect/Mile Marker"/>	Average Annual Rain (in)	<input type="text"/>
Latitude	<input type="text"/>	Dist ITS Unit (mi)	<input type="text" value="Linear Distance"/>
Longitude	<input type="text"/>	Fire Risk (0 Very High, 5 No Risk)	<input type="text"/>
Ratio of Weather to Clear Crashes	<input type="text" value="Weather"/> <input type="text" value="Clear"/>	Distance to Power (mi)	<input type="text"/>
Average annual snow (in)	<input type="text"/>	Distance to Communication (mi)	<input type="text"/>
2013 AADT	<input type="text"/>	Local Environment	<input type="text" value="Optional"/>
Average Wind Gust	<input type="text"/>	Functional Class	<input type="text" value="Optional"/>
Local Altitude Range (meters)	<input type="text"/>	In Tribal Land?	<input type="text" value="YES/NO"/>
Dist Patrol Yard (mi)	<input type="text" value="Linear Distance"/>	Length of AADT Road Segment (mi)	<input type="text"/>
Altitude (Meters)	<input type="text"/>	Comment 1	<input type="text"/>
Snow Removal Priority	<input type="text" value="Sum of (6-[Level]) Nearby"/>	Comment 2	<input type="text"/>

- Repeat steps 1 to 5 for each criterion.
- When all data is entered, select “Input This Data”.
- If this is the first data set being entered since opening the document, navigate to the “Data Input” tab and ensure that the data was entered.

3.0 Editing Data For an Existing Location

- From the Introduction Page, select Launch Data Entry Form.

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How do I use it?

If you have not yet input any site data into the tool, use the *Launch Data Entry Form* button below to open the data entry form. Fill in all available data for your chosen location and follow any instructions that pop up. Once you have submitted data for at least two locations, you can press the *Launch Ranking Report* button to open the site ranking report for the locations you have entered data for. To clear data for a site, go to the *Data Input* sheet, highlight the row the site is in, and delete the data in that row.

[Launch Data Entry Form](#) [View Ranking Report](#)

- In the Data Entry Form, click on the drop down menu and select the site in which data needs to be modified.

SPOT Location Data Entry Form

Data Set Currently Editing:	<input type="text" value="NM-150 MM10 (Taos Ski Valley)"/>	Average Road Grade 2 Miles	<input type="text"/>
Location	<input type="text" value="NM-150 MM10 (Taos Ski Valley)"/>	Average Annual Rain (in)	<input type="text"/>
Latitude	<input type="text" value="I-40 MM180 (West of Edgewood)"/>	Dist ITS Unit (mi)	<input type="text" value="Linear Distance"/>
Longitude	<input type="text" value="I-40 MM173 (Tijeras Canyon)"/>	Fire Risk (0 Very High, 5 No Risk)	<input type="text"/>
Ratio of Weather to Clear C	<input type="text" value="US-64 MM390 (Des Moines)"/>	Distance to Power (mi)	<input type="text"/>
Average annual snow (in)	<input type="text"/>	Distance to Communication (mi)	<input type="text"/>
2013 AADT	<input type="text"/>	Local Environment	<input type="text" value="Optional"/>
Average Wind Gust	<input type="text"/>	Functional Class	<input type="text" value="Optional"/>
Local Altitude Range (meters)	<input type="text"/>	In Tribal Land?	<input type="text" value="YES/NO"/>
Dist Patrol Yard (mi)	<input type="text" value="Linear Distance"/>	Length of AADT Road Segment (mi)	<input type="text"/>
Altitude (Meters)	<input type="text"/>	Comment 1	<input type="text"/>
Snow Removal Priority	<input type="text" value="Sum of (6-[Level]) Nearby"/>	Comment 2	<input type="text"/>

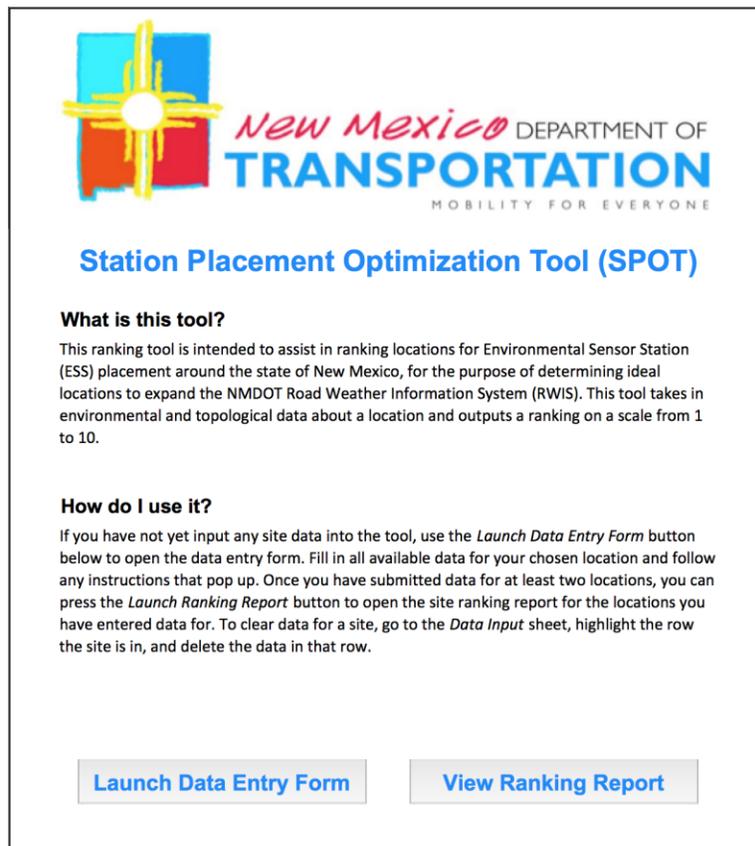
- Modify whichever data needs to be updated or changed.

4. Click the “Save This Data” button to confirm any changes.
5. If this is the first data set being edited since opening the document, navigate to the “Data Input” tab and ensure that the data was edited correctly.

4.0 Deleting an Existing Location

4.1 Using the Clear This Entry Tool

1. From the Introduction Page, select Launch Data Entry Form.



The screenshot shows the introduction page for the Station Placement Optimization Tool (SPOT). At the top is the New Mexico Department of Transportation logo, which includes a stylized sun and the text "New Mexico DEPARTMENT OF TRANSPORTATION MOBILITY FOR EVERYONE". Below the logo is the title "Station Placement Optimization Tool (SPOT)" in blue. The page contains two sections: "What is this tool?" and "How do I use it?". The "What is this tool?" section explains that the tool is used for ranking locations for Environmental Sensor Station (ESS) placement around the state of New Mexico. The "How do I use it?" section provides instructions on how to use the tool, including how to launch the data entry form and how to view the ranking report. At the bottom of the page are two buttons: "Launch Data Entry Form" and "View Ranking Report".

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[Launch Data Entry Form](#) [View Ranking Report](#)

- Click on the drop down menu for Data Set Currently Editing.

SPOT Location Data Entry Form

Data Set Currently Editing:	<input type="text" value="NM-150 MM10 (Taos Ski Valley)"/>	Average Road Grade 2 Miles	<input type="text"/>
Location	<input type="text" value="NM-150 MM10 (Taos Ski Valley)"/>	Average Annual Rain (in)	<input type="text"/>
Latitude	<input type="text"/>	Dist ITS Unit (mi)	<input type="text" value="Linear Distance"/>
Longitude	<input type="text"/>	Fire Risk (0 Very High, 5 No Risk)	<input type="text"/>
Ratio of Weather to Clear Crashes	<input type="text"/>	Distance to Power (mi)	<input type="text"/>
Average annual snow (in)	<input type="text"/>	Distance to Communication (mi)	<input type="text"/>
2013 AADT	<input type="text"/>	Local Environment	<input type="text" value="Optional"/>
Average Wind Gust	<input type="text"/>	Functional Class	<input type="text" value="Optional"/>
Local Altitude Range (meters)	<input type="text"/>	In Tribal Land?	<input type="text" value="YES/NO"/>
Dist Patrol Yard (mi)	<input type="text" value="Linear Distance"/>	Length of AADT Road Segment (mi)	<input type="text"/>
Altitude (Meters)	<input type="text"/>	Comment 1	<input type="text"/>
Snow Removal Priority	<input type="text" value="Sum of (6-[Level]) Nearby"/>	Comment 2	<input type="text"/>

- Select the location name for the location that should be deleted.
- Select “Clear This Entry” and, if you are sure you would like to delete the data set, click “OK” on the pop-up.

SPOT Location Data Entry Form

Data Set Currently Editing:	<input type="text" value="NM-150 MM10 (Taos Ski Valley)"/>	Average Road Grade 2 Miles	<input type="text" value="0"/>
Location	<input type="text" value="NM-150 MM10 (Taos Ski Valle)"/>	Average Annual Rain (in)	<input type="text" value="21"/>
Latitude	<input type="text" value="36.57"/>	Dist ITS Unit (mi)	<input type="text" value="12"/>
Longitude	<input type="text"/>		<input type="text" value="4"/>
Ratio of Weather to Clear Crashes	<input type="text"/>		<input type="text" value="15"/>
Average annual snow (in)	<input type="text"/>		<input type="text" value="15"/>
2013 AADT	<input type="text"/>		<input type="text"/>
Average Wind Gust	<input type="text"/>		<input type="text"/>
Local Altitude Range (meters)	<input type="text" value="900"/>	In Tribal Land?	<input type="text" value="NO"/>
Dist Patrol Yard (mi)	<input type="text" value="8"/>	Length of AADT Road Segment (mi)	<input type="text" value="7.59"/>
Altitude (Meters)	<input type="text" value="2650"/>	Comment 1	<input type="text" value="District 5"/>
Snow Removal Priority	<input type="text" value="4"/>	Comment 2	<input type="text"/>

- If this is the first data set being deleted since opening the document, navigate to the “Data Input” tab and ensure that the data was cleared.

4.2 Manually Deleting the Data

- Navigate to the “Data Input” tab.

- Select the row or rows for the locations that you want to delete.

	A	B	C	D	E
1	Location	Poor Weather Crashes	Clear Weather Crashes	Ratio of Weather to Clear Crashes	Average annual snow (in)
2	NM-150 MM10 (Taos Ski Valley)	12.0	9.0	1.3	62.5
3	I-40 MM180 (West of Edgewood)	44.0	73.0	0.6	25.6
4	I-40 MM173 (Tijeras Canyon)	43.0	164.0	0.3	20.5
5	US-64 MM390 (Des Moines)	14.0	17.0	0.8	35.5
6	NM-38 MM18 (Red River)	10.0	21.0	0.5	85.0
7	I-40/US-285 (Clines Corners)	15.0	17.0	0.9	31.4
8	US-64 MM273 (Palo Flechado Pass)	23.0	73.0	0.3	55.0
9	I-25 MM331 (Serafina)	16.0	30.0	0.5	34.5
10	US-60 MM260 (West of Vaughn)	9.0	8.0	1.1	21.0
11	I-40 MM70 (West of Grants)	52.0	76.0	0.7	20.5
12	NM-550 MM110	44.0	52.0	0.8	26.4
13	I-25 MM268 (La Bajada)	24.0	95.0	0.3	20.5
14	NM-68 MM16 (Velarde)	16.0	57.0	0.3	31.1
15	I-25 MM257 (San Felipe Pueblo)	23.0	84.0	0.3	20.5
16	NM-550 MM27 (San Ysidro)	19.0	37.0	0.5	20.2
17	US-70 MM255 (South of Ruidoso)	23.0	225.0	0.1	23.0
18	I-25/I-40 (The Big I)	260.0	4879.0	0.1	12.5
19	NM-602 MM25 (South of Gallup)	35.0	202.0	0.2	26.5
20	I-40 MM320 (West of Tucumcari)	8.0	30.0	0.3	15.4
21	US-70 MM435 (South of Clovis)	19.0	365.0	0.1	10.0
22					
23					
24					
25					

- Right click to open the Excel right click pop-up menu.
- Select “Delete This Row.”
- Navigate to the “Ranking Calculation” tab and repeat steps 2-4.
- Navigate to the “Relative Ranking Calculation” tab and repeat steps 2-4.

5.0 Generate Ranking Report

- From the Introduction Page, select “View Ranking Report.”



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[Launch Data Entry Form](#) [View Ranking Report](#)

2. The results of the ranking report will be calculated and you will be taken to the “Ranking Report” sheet.
 - a. Note: If there is no location data entered, doing this will generate an error message.

6.0 Modifying Criteria Weighting

1. Navigate to the “Criteria & Importance” tab.
2. Locate the row titled “Final Score (%)”.

	A	B
1	Criteria	Ratio of Weather to Clear Crashes
2	Sponsor's Importance Factor (1 to 13)	1
3	Final Score (%)	16
4	Deal Killer	
5	Have Data	
6	Max Threshold	0.75
7	Min Threshold	0.1
8		
9	Max Relative	1.33
10	Min Relative	0.05

3. Modify the numbers in this row to change the weights for each category.
4. Ensure that after changing these weights, the total number of points for all criteria still equals 100.

7.0 Modifying Absolute Ranking Thresholds

1. Navigate to the “Criteria & Importance tab.
2. Locate the rows titled “Max Threshold” and “Min Threshold”.

	A	B
1	Criteria	Ratio of Weather to Clear Crashes
2	Sponsor’s Importance Factor (1 to 13)	1
3	Final Score (%)	16
4	Deal Killer	
5	Have Data	
6	Max Threshold	0.75
7	Min Threshold	0.1
8		
9	Max Relative	1.33
10	Min Relative	0.05

3. Modify the numbers in either of these two rows to reflect the new preferred thresholds.
 - a. Note: Do not modify the “Max Relative” or “Min Relative” cells for any criterion, as these define the relative nature of the formula.

8.0 Adding a Criterion

8.1 Adding an Entry Field to the Data Entry Form

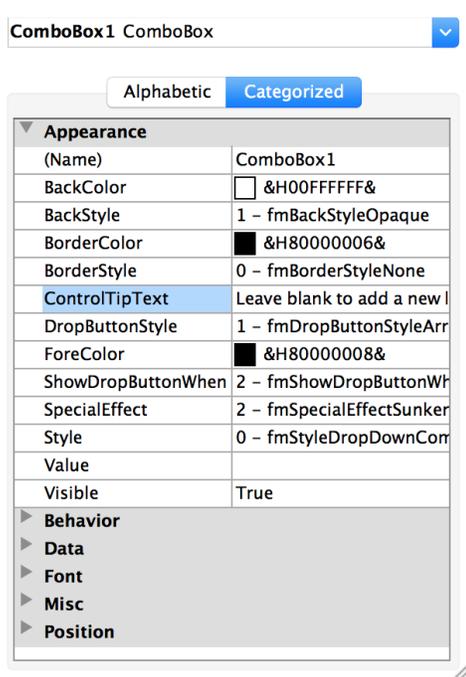
1. Open the Excel Visual Basic Editor
2. Open the “LocationDataInput” Form from the “Project” window on the left.

- Using the “Toolbox,” add a Label and a TextBox to the form by drawing an appropriately sized rectangle for each on the form.

- Arrange the form as you see fit by clicking and dragging the form components around. Form dimensions and locations are determined in pixels.
 - If you need additional space on the form for your new components, use the “Properties” window to adjust the Height and Width of the form as needed.
 - Similarly, you can use the “Properties” window to modify the Height and Width of each form component.
 - To manually position a form element, use the Left and Top fields.

Position	
Height	22
Left	156
Top	48
Width	258

- To modify the font of a Label or TextBox, use the Font field on the “Properties” window.
- To make tooltips pop up when you hover over a form element, use the ControlTipText field on the “Properties” window to enter your desired tooltip.



8.2 Connecting Entry Field to the “Data Input” Sheet

- Make a note of the numbers of the Labels and TextBoxes you have added to the Form. These will be visible in the “Properties” window.
- In the Visual Basic Editor, right click on the LocationDataInput Form and select to “View Code.”
- Once you have opened the code for the Form, locate the section at the top that appears as below. Copy and paste one of the existing lines at the bottom of the section, and modify the Label number to be that of the Label you just added to the Form. Then modify the code following the equals sign to either reference a particular cell (as is shown by the majority of the lines in this screenshot), or to show text of your choice. To show a specific text string, after the equals sign write the text you would like to show within a pair of quotation marks. This line of code will set your new Label to say whatever you would like it to, so you should use the name of the criterion or data point you want

entered into your new TextBox.

```
Label1.Caption = Worksheets("Data Input").Range("A1").Value ' Set criterion names on form from sheet columns
Label2.Caption = Worksheets("Criteria & Importance").Range("B1").Value
Label3.Caption = Worksheets("Criteria & Importance").Range("C1").Value
Label4.Caption = Worksheets("Criteria & Importance").Range("D1").Value
Label5.Caption = Worksheets("Criteria & Importance").Range("E1").Value
Label6.Caption = Worksheets("Criteria & Importance").Range("F1").Value
Label7.Caption = Worksheets("Criteria & Importance").Range("G1").Value
Label8.Caption = Worksheets("Criteria & Importance").Range("H1").Value
Label9.Caption = Worksheets("Criteria & Importance").Range("I1").Value
Label10.Caption = Worksheets("Criteria & Importance").Range("J1").Value
Label11.Caption = Worksheets("Criteria & Importance").Range("K1").Value
Label12.Caption = Worksheets("Criteria & Importance").Range("L1").Value
Label13.Caption = Worksheets("Criteria & Importance").Range("M1").Value
Label14.Caption = Worksheets("Criteria & Importance").Range("N1").Value
Label15.Caption = Worksheets("Criteria & Importance").Range("O1").Value
Label16.Caption = Worksheets("Criteria & Importance").Range("P1").Value
Label17.Caption = Worksheets("Criteria & Importance").Range("Q1").Value
Label18.Caption = Worksheets("Criteria & Importance").Range("R1").Value
Label23.Caption = Worksheets("Data Input").Range("X1").Value

Label24.Caption = "Comment 1" ' blank criteria placeholders
Label25.Caption = "Comment 2"
```

- Next, find the section of code just below this that appears as below. Once again, copy and paste one line of the code, specifically a line that ends with "", and change the number following TextBox to be that of the TextBox you added to the Form. Make sure that there are only two quotation marks following the equals sign, or your TextBox will have text in it once you launch the form, and this text will be saved into the Data Input sheet. This line of code will make sure that your new TextBox is empty when you launch the Form.

```
TextBox1.ForeColor = RGB(150, 150, 150) ' Grey Color
TextBox1.Text = "Inc. Intersect/Mile Marker" ' Preset Text
TextBox2.ForeColor = RGB(150, 150, 150)
TextBox2.Text = "Weather"
TextBox19.ForeColor = RGB(150, 150, 150)
TextBox19.Text = "Clear"
TextBox3.Text = "" ' set text to empty
TextBox4.Text = ""
TextBox5.Text = ""
TextBox6.Text = ""
TextBox7.ForeColor = RGB(150, 150, 150)
TextBox7.Text = "Linear Distance"
TextBox8.Text = ""
TextBox9.ForeColor = RGB(150, 150, 150)
TextBox9.Text = "Sum of (6-[Level]) Nearby"
TextBox10.Text = ""
TextBox11.Text = ""
TextBox12.ForeColor = RGB(150, 150, 150)
TextBox12.Text = "Linear Distance"
TextBox13.Text = ""
TextBox14.Text = ""
TextBox15.Text = ""
TextBox16.ForeColor = RGB(150, 150, 150)
TextBox16.Text = "Optional"
TextBox17.ForeColor = RGB(150, 150, 150)
TextBox17.Text = "Optional"
TextBox18.ForeColor = RGB(150, 150, 150)
TextBox18.Text = "YES/NO"
TextBox20.Text = ""
TextBox21.Text = ""
TextBox22.Text = ""
TextBox23.Text = "" ' blank criteria placeholders
TextBox24.Text = ""
```

- Next, find the section of the code that appears as below. Copy and Paste the last line of this section before the Unload command. Change the letters inside the quotation marks to match the last unused column in the "Data Input" sheet, or if you are unsure of this, simply move to the next letter in alphabetical sequence. Change the number next to TextBox to match that of the TextBox you added to the Form. This line of code will input the data from your new TextBox into the last column of the

“Data Input” sheet.

```
ws.Range("A" & LastRow).Value = TextBox1.Text 'Adds the TextBoxes into Last Blank Row
ws.Range("B" & LastRow).Value = TextBox2.Text
ws.Range("C" & LastRow).Value = TextBox19.Text
ws.Range("D" & LastRow).Value = (TextBox2.Text / TextBox19.Text) ' calculates the Crash Ratio
ws.Range("E" & LastRow).Value = TextBox3.Text
ws.Range("F" & LastRow).Value = TextBox4.Text
ws.Range("G" & LastRow).Value = TextBox5.Text
ws.Range("H" & LastRow).Value = TextBox6.Text
ws.Range("I" & LastRow).Value = TextBox7.Text
ws.Range("J" & LastRow).Value = TextBox8.Text
ws.Range("K" & LastRow).Value = TextBox9.Text
ws.Range("L" & LastRow).Value = TextBox10.Text
ws.Range("M" & LastRow).Value = TextBox11.Text
ws.Range("N" & LastRow).Value = TextBox12.Text
ws.Range("O" & LastRow).Value = TextBox13.Text
ws.Range("P" & LastRow).Value = TextBox14.Text
ws.Range("Q" & LastRow).Value = TextBox15.Text
ws.Range("R" & LastRow).Value = TextBox16.Text
ws.Range("S" & LastRow).Value = TextBox17.Text
ws.Range("T" & LastRow).Value = TextBox18.Text
If TextBox18.Text = "YES" Then
    ws.Range("U" & LastRow).Value = 1
Else
    ws.Range("U" & LastRow).Value = 0
End If
ws.Range("V" & LastRow).Value = TextBox20.Text
ws.Range("W" & LastRow).Value = TextBox21.Text
ws.Range("X" & LastRow).Value = TextBox22.Text
ws.Range("Y" & LastRow).Value = ((TextBox2.Text / TextBox19.Text) * 100000000) / (TextBox4.Text * 365 * 3 * TextBox22.Text) ' calculates t
ws.Range("Z" & LastRow).Value = TextBox23.Text ' blank criteria placeholders
ws.Range("AA" & LastRow).Value = TextBox24.Text
Unload LocationDataInput ' close the data entry form and unload from memory
```

6. Scroll down the form further until you come upon a section of code that looks nearly identical to the last section. In this section, complete the same steps you just did for the earlier section. This section refers to the DataRow variable, and not the LastRow variable as above, so either copy your line of code from the second section or be sure to change this variable to suit. As with the last step, this line of code will input whatever is entered into your new TextBox to the “Data Input” sheet.
7. Scroll down slightly to find the section of code that appears as below. Once again, copy and paste the last line of code at the bottom of this section. Modify the number following TextBox at the beginning of the line to be the number of your new TextBox. At the end of the line of code, change the number after the comma to be the column number your data was entered into by the last piece of code. For example, if in the last section you instructed the program to enter data from your TextBox into column “AA,” the number at the end of this line should be 27, as AA would be the 27th column. This line of code will retrieve data from the “Data Input” sheet and present it in your new

TextBox when you want to edit data for a location.

```
.TextBox1.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 1) ' pull location data into form
.TextBox2.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 2)
.TextBox19.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 3)
.TextBox3.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 5)
.TextBox4.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 6)
.TextBox5.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 7)
.TextBox6.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 8)
.TextBox7.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 9)
.TextBox8.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 10)
.TextBox9.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 11)
.TextBox10.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 12)
.TextBox11.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 13)
.TextBox12.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 14)
.TextBox13.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 15)
.TextBox14.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 16)
.TextBox15.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 17)
.TextBox16.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 18)
.TextBox17.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 19)
.TextBox18.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 20)
.TextBox20.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 22)
.TextBox21.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 23)
.TextBox22.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 24)

.TextBox23.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 26) ' Blank criteria placeholders
.TextBox24.Value = ActiveWorkbook.Sheets("Data Input").Cells(.ComboBox1.ListIndex + 2, 27)
```

8. Just below this section of code, you will see a section that looks exactly like the section referenced in step 2 of this guide. In this section, you will follow the same steps as you did in step 2, to ensure that the TextBox will empty if you have not selected a location from the drop-down menu.
9. To ensure that your TextBox will function properly, launch the LocationDataInput Form and enter some random information into your new TextBox for an existing location. Once you save the data, go to the “Data Input” sheet and check if your data was saved in the proper column and row. If not, look back through these steps and ensure you have used the proper cell references.

8.3 Adding to the “Criteria & Importance” Sheet

1. In the “Criteria & Importance” sheet, go to the first empty column.
2. In the first row, enter your desired name for the new criterion. In the “Data Input,” “Ranking Calculations,” and “Relative Ranking Calculations” sheets, add references in the first row and last column of each to display this name.
3. In the third row of the sheet, enter your desired percentage point value for your new criterion. Be sure to check if the percentage points for all criteria still sum to 100 points.
4. In the sixth row of the sheet, enter your desired maximum absolute threshold for the criterion. If you leave this blank, the point calculation formula will malfunction.
5. In the seventh row of the sheet, enter your desired minimum absolute threshold for the criterion. If you leave this blank, the point calculation formula will malfunction.
6. In the ninth row of the sheet, enter a formula to select the maximum data value from the entered data in the “Data Input” sheet for your new criterion. The idea is to set this cell to always be the maximum of the data set so the relative formula can reference this as a maximum threshold.

7. In the tenth row of the sheet, enter a formula to select the minimum data value from the entered data in the “Data Input” sheet for your new criterion. The idea is to set this cell to always be the minimum of the data set so the relative formula can reference this as a minimum threshold.
8. Using the Named Range Editor, give individual names to the cells containing the point value, absolute thresholds, and relative thresholds for your new criterion. Make a note of these names, as you will need them to add your new criterion to the calculations in the next section.

1	Criteria	Ratio of Weather to Clear Crashes
2	Sponsor's Importance Factor (1 to 13)	1
3	Final Score (%)	16
4	Deal Killer	
5	Have Data	
6	Max Threshold	0.75
7	Min Threshold	0.1
8		
9	Max Relative	1.33
10	Min Relative	0.05

8.4 Inserting New Calculations

1. In the “Project” window of the Visual Basic Editor, click on the ViewRankingReport Module to view the code for the Module that calculates and displays the site rankings.
2. Locate the section of code that appears as below. This section of code pulls data from the “Data Input” sheet, applies a formula to calculate the ranking points for each, and enters this data into the “Ranking Calculations” sheet. To add a calculation for your new criterion, copy and paste the second to last line, which has “Formula” in the middle, and paste it just below that same line. Given the template of the other calculations, modify this line to enter your desired formula into the cell selected at the beginning of the line. Ensure that the cell you will enter the data into is not the same as any of the other formulas, and that the formula references the proper columns in the “Data Input” sheet. Also change any named references like “Ratio_Max” to be the names you have given to the points and thresholds of your new criterion. Once you have altered the formula and references as needed, look at the last line of this section. At the end of the line, change the “U” to be the column of the “Ranking Calculations” sheet that will contain the result of your new calculation. This final line in the section adds up all of the rankings for the individual criteria to produce the overall absolute ranking

2. In the “Ranking Report” sheet, edit the data for the two stacked bar graphs to add data series for your new criterion. Use the name on the “Criteria & Importance” sheet as the reference for the series name, your named ranges as the reference for the series’ Y values, and the same “Abs_Locations” named range as the reference for the series’ X values.

9.0 Troubleshooting

9.1 Introduction Page buttons not doing anything

1. Ensure that Macros are enabled in the workbook.
 - a. If they are, check that the Macros are correct and attached to the buttons.
 - i. If they are correct and attached, close and reopen the workbook.
 - b. If they are not, enable macros and try again.

9.2 Report not Generating Correctly

2. Ensure that Macros are enabled in the workbook.
 - a. If they are, check that the Macro for report generation is correct and attached to the button.
 - i. If it is correct and attached, close and reopen the workbook.
 - b. If they are not, enable macros and try again.
3. Ensure that there are no extra rows that should be deleted in the “Data Input” tab, “Ranking Calculation” tab, and “Relative Ranking Calculation” tab.
 - a. If there is, delete these rows and generate the report again.
 - b. If there is not, check deeper into the VBA macro scripting.

Appendix Q: Download SPOT

Here is a link to download SPOT:

<https://drive.google.com/file/d/0B63kSsoyZPD7RGIySTM4Uk11UGM/view?usp=sharing>

If there are any issues with the macros embedded in the SPOT excel file, we have provided download links for the code driving the macros.

Data Entry Form (“LocationDataInput”):

<https://drive.google.com/open?id=0B63kSsoyZPD7WUpJcXRoTWkzRzA>

“Launch Data Entry Form” Button (“Button1”):

<https://drive.google.com/open?id=0B63kSsoyZPD7OXV1YTF2UEdIYmM>

“View Ranking Report” Button (“Button2”):

<https://drive.google.com/open?id=0B63kSsoyZPD7d0ZfRVQ1cHZJckk>

Appendix R: Data Collected

Criteria	Data Collected
Average Wind Speed	
Average Wind Gust	
Average Annual Snowfall	✓
Average Annual Rainfall	✓
Snow Removal Priority	✓
2013 Average Annual Daily Traffic (AADT)	✓
Ratio of Clear Weather to Weather-Related Crashes	✓
Distance to Nearest Patrol Yard	✓
Distance to Nearest ITS Installation	✓
Fire Risk	✓
Altitude	✓
Distance to Power	
Distance to Communication	
Local Environment	✓
Local Topography	✓
Average Road Grade Within 2 Miles	
On Tribal Land	✓