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Use of Travel Time, Travel Time Reliability, and Winter Condition Index Information for Improved Operation of Rural Interstates

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Use of Travel Time, Travel Time Reliability, and Winter Condition Index Information for Improved Operation of Rural Interstates

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ABSTRACT

Using intelligent transportation systems to help report traveling conditions has been reserved for urban areas. The goal of this research was to help develop a new methodology for incorporating travel times calculated from intelligent transportation system (ITS) technology into Wyoming's road and weather condition reporting system. Bluetooth sensors and speed sensors were used to measure travel times on I-80 between Cheyenne and Laramie, as well as WY-28 between Farson and Lander in Wyoming. From previous research, the distribution of travel times on I-80 show two distinct modes. Travel times from the WY-28 corridor were then calculated to determine if this trend was common with other rural highways. The next step in this research was to determine the best way to measure travel times on a rural corridor. Bluetooth sensor travel time data were compared to speed sensor travel time data. Then a travel time index was created for I-80 from one year of speed sensor data. This travel time index was then modeled with weather variables downloaded from road weather information system (RWIS) stations. Finally, a methodology for implementing and evaluating this new travel time reporting procedure was developed. The results of this research will help to improve the current condition reporting system by incorporating both physical conditions (slick in spots, high wind speed, etc.) with travel times. This will help all types of travelers to more accurately quantify the severity of traveling conditions.

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1. INTRODUCTION

The incorporation of Intelligent Transportation System (ITS) features into transportation facilities is a rapidly growing practice in today's transportation community. Many transportation agencies have started doing this with great success. Some examples of ITS utilization include providing travel time updates on dynamic message signs (DMS) to communicate congestion and reporting road and weather conditions on the Internet. The public uses these road reports to determine how much time should be allotted for a trip, which routes should be taken on the trip, and if the trip should even be made. This is a very important part of the overall transportation system for many commuters in big cities where obtaining information about travel times at the start and end of their work day is essential. For the Wyoming Department of Transportation (WYDOT), however, the focus of its ITS efforts is on highway safety, particularly during extreme weather conditions.

During the winter months, travel conditions on Wyoming roads are often the worst in the United States. Wyoming roads are used by the most diverse groups of travelers imaginable. On any given day, Wyoming roads can be used by commercial traffic, cross-country travelers, recreational travelers, and even commuters, depending on the corridor. Some of these users know what to expect from Wyoming weather, while others have little or no experience operating their vehicles in bad weather conditions. For this reason, it is important that the information provided to the users be as accurate as possible and be available in a timely manner from a wide variety of sources.

One way this can be done is by reporting travel times. Obtaining information about expected travel times is a major consideration for drivers in high population density areas, where congestion can happen every day. However, the effects of road conditions on travel times have yet to be utilized in a rural transportation system. If reporting of travel times is added to the Wyoming transportation system, this would help drivers to more accurately assess real-time travel conditions.

The variety of users on rural roads presents a challenge for reporting real-time travel conditions on rural corridors. Semi-truck drivers, recreation travelers, and commuters will all obtain weather and road information differently. For the state of Wyoming, there is a large difference in traffic composition between Interstate highways and rural two-lane highways. According to the WYDOT Vehicle Miles Traveled report, traffic flow on I-80 in Wyoming can contain between 50% to 75% semi-trucks, and I-25 in Wyoming can have around 25% semi-trucks (Wyoming Department of Transportation, 2009). Rural two-lane roads, on the other hand, provide more access to recreational areas and towns, and therefore might have a more even distribution of recreation seekers, commuters, and semi-trucks. Since no two roads are alike, it is important to report accurate, up-to-date information so all travelers feel comfortable with their decisions on all road types.

Wyoming's current system for reporting road and weather conditions uses the Internet, radio, phone, and television to relay the exact state of the roads. However, people have noted in surveys that the current system only affects their traveling behavior when “No Unnecessary Travel” or “Road Closed” is being reported on their route (Edwards, 2008). If travel times are determined and displayed in a reasonable, consistent manner, this additional information can positively influence driver behavior and driver decision-making for the whole traveling community throughout the state of Wyoming.

1.1 Problem Statement

The research presented in this report is part of an overall plan to improve the credibility, reliability, and quality of traveler information provided by WYDOT. From previous research, it has been discovered that travelers in Wyoming would like to see a "rating system" for reporting traveling conditions (Ringenberg, 2011). This "rating system" could be used in conjunction with travel times and general travel conditions in order to reach out to a variety of travelers on Wyoming highways.

The basis for this new rating system will come from travel time calculations. In order to do this, speed sensor equipment from WYDOT and vehicle monitoring devices such as Bluetooth readers will be utilized. Bluetooth reading technology is relatively new to the ITS community. This technology senses vehicles by identifying a Media Access Controller (MAC) address from a Bluetooth enabled device inside of the vehicle. These MAC addresses can be tracked along a route to produce very accurate travel times. Besides being more accurate, Bluetooth readers could also be more cost effective for measuring travel time compared with speed sensors currently being used. The individual units for each sensor might be less expensive, and fewer Bluetooth readers are needed to completely measure travel times. Effectively, only two Bluetooth readers are needed to measure a vehicle's travel time along a route. Speed sensors and Bluetooth technologies will be tested in the field, and the results from this field test will help create an estimation algorithm for both Interstate highways and two-lane rural highways.

The last step of this research will be to develop a procedure to display the travel time index, as well as a procedure to survey travelers. There might be a basis for larger scale deployment across the state of Wyoming if there is a positive response from all types of travelers. It is the goal of this research to improve the pre-trip and during-trip decision-making ability of travelers in the state of Wyoming.

1.2 Research Objectives

The research presented in this report is part of a larger research effort with the following objectives:

- Determine the applicability of using traditional urban travel time and travel time reliability measures in a rural setting for the purpose of giving drivers assistance in making traveling decisions
- Investigate methods of estimating travel time and travel time reliability
- Investigate the applicability of using rankings system driven by travel times to convey the severity of road and weather conditions on rural roads

1.3 Thesis Objectives

The following is a list of research objectives:

- Determine the applicability of using Bluetooth technology in conjunction with or in place of speed sensor technology to calculate travel times in a rural setting
- Develop travel time and travel time reliability calculation methodologies for Bluetooth and/or speed sensor technology on rural roads
- Develop a rating system that will help convey severe travel conditions to travelers on rural highways by using travel time and travel time reliabilities

1.4 Research Tasks

The following tasks will be done in order to fulfill the research objectives:

- Research, purchase, and install Bluetooth sensor technology on the I-80 corridor. After the Bluetooth sensors collect data for a predetermined amount of time, the data will be downloaded, and then travel times will be calculated.
- Compare travel times calculated from the Bluetooth sensor to travel times calculated from speed sensors over the same period of time. A recommendation will be made as to the technology required to calculate travel times on rural corridors.
- Use speed sensor data from the past two winters to determine a methodology for calculating and reporting travel time and travel time reliability.
- Develop a road and weather condition index based on the calculated travel time reliabilities and verify this threshold-based condition reporting system by modeling it against weather conditions.
- Propose a methodology for surveying focus groups and random travelers about the travel time index

1.5 Report Outline

This report is divided into the following sections:

1. Introduction
2. Literature Review
3. Location Description
4. Data Sources
5. Methodology and Results
6. Proposed Road Condition Index Traveler Information Method and Survey Procedure
7. Summary and Conclusions
8. Bibliography
9. Appendices

The Literature Review will discuss current practices and methodologies related to calculating and reporting travel times to the public. The Location Description section will define the project location on I-80 between Cheyenne and Laramie, Wyoming, and state highway WY28 between Farson and Lander, Wyoming. Section 4, Data Sources, will describe the data that were used and the problems encountered with data collection. Section 5, Methodology and Results, will focus on the methods used to collect and organize data and the results that were discovered. Section 6 will discuss the proposed implementation and evaluation of the new traveling condition reporting system. The Summary and Conclusions in Section 7 will present a summary of the research, which conclusions should be drawn from the results, and future research tasks that should be considered.

2. LITERATURE REVIEW

The first step in fulfilling the research objectives is to determine the state of the practice through review of existing journal articles and technical reports on the topic. This section will first summarize existing research on traveler information in Wyoming that indicated a need for the additional research. Next, existing literature on the methodologies for calculating travel times and travel reliability will be summarized. The final section of the section will review literature on methods for providing pre-trip and during-trip information for travelers.

2.1 Traveler Information in Wyoming

There are many ways travelers can obtain road and weather information. The Internet is easily accessible from anywhere in the world if the person is using the right device. Dynamic Message Signs installed along the highway give information without the driver having to look too far away from the road. It is important to always keep these sources functional and their messages clear and concise. Not all travelers will want to receive information in the same way, however. For example, a semi-truck driver will most likely receive information from Dynamic Message Signs since they are always on the road, whereas a commuter will most likely check a website before starting a short trip. Multiple studies have been conducted for the state of Wyoming in order to determine which of these methods is most effective when communicating with travelers.

Since 2008, there have been many research initiatives to help develop a decision-support system that utilizes real-time weather, speeds, and travel times to help improve WYDOT's travel information reporting. The first part of this research was to determine the effectiveness of the current road and weather condition reporting system. In order to do this, frequent travelers and random travelers were given a survey. The survey asked numerous questions about the quality of information WYDOT broadcasts, which type of information was most important to them, and what they would like to see changed about WYDOT's road and weather condition reporting system.

Overall, frequent travelers around the state of Wyoming expressed a need for an improved road and weather condition reporting system. Focus groups were asked when they took serious note of the conditions, and the most common response was when the "No Unnecessary Travel" advisory was in effect (Edwards, 2008). This means all the other types of conditions that can be reported (wet, slick in spots, slick, blowing snow, black ice, wind gusts, and drifted snow) are not considered as serious, and they do not affect traveling behavior. If WYDOT wants more than one condition to be taken seriously, WYDOT needs to change the way it approaches road and weather condition reporting. The goal of this research will be to help travelers make better decisions by creating a more decision friendly system that will incorporate travel times and a ranking system in place of a condition reporting system.

In order to accomplish this goal, travel time calculations need to be efficient and accurate. This can be done many different ways. The current method for calculating travel times for WYDOT is to record speeds from remote speed sensors placed on the highway, but there are other methods that could prove to be more accurate and cost effective. Floating car methodologies are emerging in urban transportation networks as the key method for calculating travel times. Utilizing these same methodologies for rural highway use could prove to be a more cost efficient and effective way of measuring travel times.

2.2 Calculating Travel Times

Travel times have emerged as a key component for transportation systems. They can be used to determine how well a corridor is performing, as well as point out hot spots that may need to be addressed for improvement. In more urban areas of the world, travel times are an essential source of information regarding congestion. It is important for travelers to be well informed so they can make route decisions. There are several different methods for calculating travel times, and there are advantages and disadvantages to each. The following section outlines numerous studies in which several different travel time collection techniques were used.

The most popular use of travel times has been in congested city traffic, where complex algorithms need to be employed because of signalized intersections and the unpredictability of stop-and-go traffic. Since the routes we are interested in do not have signalized intersections and are not prone to stop-and-go traffic, the travel time calculation will be relatively straightforward. Both corridors of interest for this research are heavily equipped with instruments that will help determine travel times. WYDOT owns many speed sensors and road weather information systems, and these are set up all around the state of Wyoming.

Wyoming is one of the most rural states in the United States. For any particular highway in the state, there might be several minutes between two cars. This is why it is so difficult to measure travel times in rural areas. There have not been many studies concerning travel times and rural areas. Most studies about collecting and reporting travel times have been done for urban networks, where moving large volumes of traffic efficiently is the main goal. Nonetheless, the main purpose of this research is to determine the applicability of using travel times to inform drivers of the severity of weather conditions for the state of Wyoming.

2.2.1 Speed Sensors

Although speed sensors have only been used for research purposes in the past, the utilization of speed sensors could help dramatically improve WYDOT’s road and weather information system. The speed sensors can be used to adjust Variable Speed Limit (VSL) signs or to inform the public of current speeds and travel times being experienced by people on the route. This research will specifically look at travel time calculations using speed sensors. It is not an easy task to use speed sensors to calculate travel times. Unlike Bluetooth readers, where calculations only involve subtracting time stamp hits between two locations, speed sensors require more calculation and precision to determine the travel time between an origin and a destination.

A technical report from the University of Wyoming sought to fine tune a method for calculating travel times and travel time reliabilities using speed sensors (Ringenberg, 2011). A methodology was created based on speed sensor readings that were aggregated every 15 minutes for one year. In this technical paper, speed sensors were proven to be a reliable way to calculate travel times in rural situations. However, in order for these calculations to be accurate, the available sensors need to be within a reasonable range (around 10 miles per sensor), and they need to stay active for long periods of time. One of the goals of this research is to improve on the travel time calculation methodologies developed in past research and to create new methods of calculating travel times through the use of Bluetooth sensors.

2.2.2 Bluetooth Sensors

Two more commonly used methods of calculating travel time are the “Pilot Car Method” and the “Floating Car Method,” The “Pilot Car Method” is a simple calculation technique where a driver is paid to complete the route in question. Once the driver finishes driving the route, the driver reports the travel time. The advantage to calculating travel times by this method is simplicity. The only equipment needed is a stopwatch, a vehicle, and a competent driver. However, the downside to this method is the lack of real-time data. The traffic conditions on the route could be very different by the time the driver is done traveling and reporting the travel time.

The “Floating Car Method” involves monitoring individual vehicles as they travel along a route. There are many ways this can be done, either by matching license plates or by matching unique electronic signatures originating from inside the vehicle. The latter is a growing field made possible through toll tag tracking and Bluetooth device tracking technology. Tracking Bluetooth enabled devices is an attested way to monitor individual vehicles while keeping personal information safe.

There have been many successes using Bluetooth type sensors, and most are more cost effective compared with speed sensors. However, it is not known how well they will work in a rural environment. In most situations, Bluetooth sensors have been used to calculate travel times on high volume roads near populous cities, but it is unknown how well they will work with a lower volume roadway and with fewer people using a Bluetooth enabled device.

When a Bluetooth device starts to look for another device to match itself to, it enters “Discoverable Mode.” This is when the Bluetooth device can be read from a Bluetooth sensor on the side of the road. When the Bluetooth sensor discovers the Bluetooth device, it records a unique electronic signature attached to that device. This unique electronic signature is called a Media Access Control (MAC) address. A simple example of the process for using Bluetooth sensors to match MAC addresses and calculated travel times can be seen in Figure 2.1.

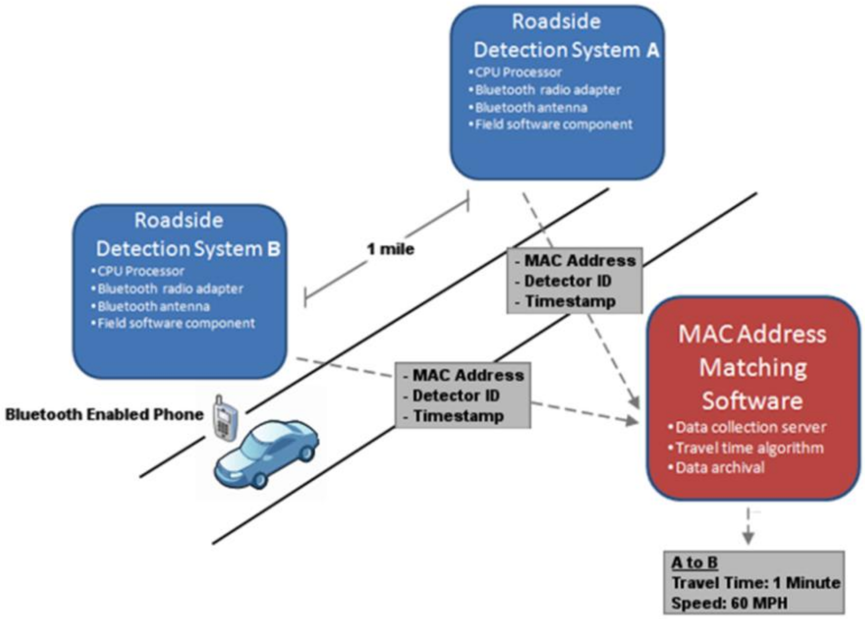


Figure 2.1 MAC Address Matching Method (Hardigree, 2011)

The three variables needed to calculate travel time from Bluetooth sensors are the detector ID (to identify the sensor), MAC address (to identify individual cars), and a time stamp. If the same MAC address is read on two different detectors, then all that needs to be done is to subtract the two timestamps to calculate the travel time. Matching individual MAC addresses between Bluetooth sensors can be a tedious job. For this reason, companies that sell Bluetooth sensors usually offer complimentary MAC address matching software. This emerging technology of Bluetooth readers is becoming the topic of many research projects across the world.

A study from the Georgia Institute of Technology titled “An Investigation of Bluetooth Technology for Measuring Travel Times on Arterial Roads: A Case Study on Spring Street” is a good example of a study using Bluetooth readers to measure travel time. Bluetooth readers were set up along a corridor, and a probe vehicle was equipped with GPS devices and Bluetooth devices with known MAC addresses (Vo, 2011). This was done to establish ground truth travel times on the corridor. In order to determine the detection rates of the Bluetooth readers, vehicle detection cameras were placed at each site. Bluetooth readers were placed at two different sites, about one mile apart from each other.

At each site, multiple Bluetooth readers were placed at different heights (7 feet, 10 feet, and 14.5 feet) at each location. Site 1 and site 2 produced very different results for detection rates. At site 1, the Bluetooth reader at 10 feet produced the most MAC addresses. Whereas, at site 2, the reader at 10 feet produced the least amount of MAC addresses. This suggests that more than one Bluetooth reader is required at different heights in order to achieve a high detection rate. Out of a total of 589 MAC addresses detected by both sites, only 71 of these MAC addresses matched for both sites. Since the estimated number of vehicles that went through both sites was a total of 3,964, the detection rate was calculated at 1.8%. There were also multiple outliers since the test site has multiple attractions (gas stations, fast food restaurants, and parking areas) along with multiple intersections. This created a multitude of outlying data points, which were identified and removed by performing a Z-Test on the data set.

After the outliers were removed it was determined that the Bluetooth readers were successful in collecting accurate travel time. Even though a detection rate of 1.8% was achieved, it was determined that Bluetooth readers were successful in reporting the actual travel times being experienced by travelers. However, they recommend that multiple units should be used at different heights in order to obtain the highest possible detection rate.

There have been many different techniques used to filter and compare Bluetooth travel times to actual travel times experienced by travelers. A study from the University of Maryland called "Data Collection of Freeway Travel Time Ground Truth with Bluetooth Sensors" investigates the use of Bluetooth sensors for reporting ground truth travel times in place of the probe vehicle technique (Haghani, Hamedi, Sadabadi, Young, & Tarnoff, 2010). To do this, they converted travel times from the Bluetooth sensors to an average speed for each vehicle. These speeds were then compared with pilot car data. A four-step method was used to filter the data: in the first and second step, outlying observations were filtered; in the third and fourth step, observations were filtered out under sampled and erratic time intervals.

The first step performed was filtering the data by calculating a moving average of speeds. The study tried moving averages with radii of 1, 2, 3, and 4 mph, and they determined that a moving average of 4 mph was the best option. The second step identified speeds beyond ±1.5 times the standard deviation, then these speeds were thrown out of the data set since they are outliers. The third and fourth steps involved filtering under sampled and erratic time intervals. For each time interval, a minimum number of observations must be met. The equation for the minimum number of observations can be seen in Equation 1.

$$n_{min} = \frac{V_{thresh} * T * PSR}{60}$$

Equation 1. Minimum Number of Observations for Travel Time Calculation

Where

n_{min} = minimum number of observations required per time interval

V_{thresh} = threshold hourly volume of traffic below which ground truth estimation with low sampling rate may not be reliable

T = length of time interval (min)

PSR = percentage of sampling rate that can be reasonably sustained throughout the analysis period

A statistical hypothesis test was performed for each speed bin to determine whether or not there was a significant difference between the Bluetooth mean speeds (μ_{BT}) and the pilot car mean speeds (μ_{FC}). The null and alternative hypotheses from this study can be seen in Equation 2.

$$\begin{cases} H_0 : \mu_{\text{BT}} = \mu_{\text{FC}} \\ H_1 : \mu_{\text{BT}} \neq \mu_{\text{FC}} \end{cases}$$

Equation 2. T-Test Hypothesis

The study failed to reject the null hypothesis for all speed bins 45 mph and below. This means there was not a significant difference between the speeds calculated by the Bluetooth mean speeds and the floating car mean speeds for the lower speeds on the freeway. The study concluded there was no significant difference between the Bluetooth sensors and ground truth. The quality of the data from the Bluetooth sensors are adequate for use in travel time calculations.

Many studies here have showcased the use of Bluetooth technology for local street and intersection applications, but none have addressed the use of Bluetooth sensors for high speed arterial situations. A study from KMJ Consulting Inc. in Ardmore, PA, investigated the use of Bluetooth readers on an arterial corridor (KMJ Consulting Inc., 2011). Bluetooth sensors were placed on US Route 1 in northeast Pennsylvania, which is 3.9 miles long and has 13 signalized intersections. Two methods of travel time measurement that were employed in this study included Bluetooth technology and car runs using GPS equipment and laptops with PC Travel software. This PC Travel software measures travel time, speed, delay, and number of stops. This second method was called the "Test Car Run Method."

The test car run method was done during the peak hours of the day (7:00 am to 9:00 am and 4:00 pm to 6:00 pm). The speeds of the test car run method were compared to the average speed from the Bluetooth sensors. The study used the Federal Highway Administration (FHWA) Travel Time Data Collection Handbook to verify that the number of samples obtained is greater than the minimum sample size specified in the handbook. In a segment with three to six signalized intersections and 95% confidence with ±5% error, the minimum sample size was 25. Bluetooth sensors were able to match 5.32% to 6.17% of the total volume seen on the roadway. The matching of these two data sets can be seen in Figure 2.2, where the squares represent the test car run method and the solid red line represents the average speed per hour calculated by the Bluetooth sensors.

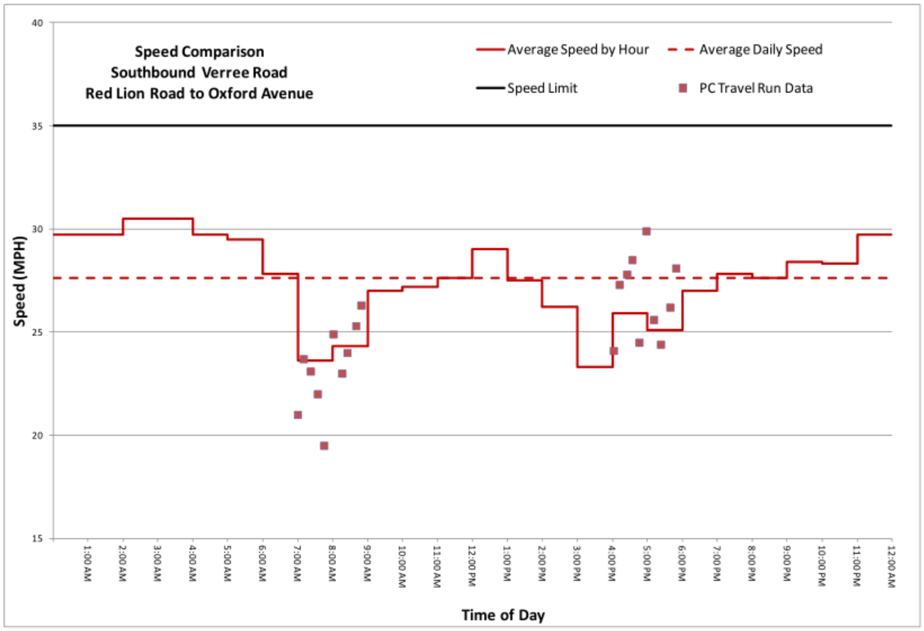


Figure 2.2 Bluetooth Sensors vs. Test Car Run Method (Haghani, Hamedi, Sadabadi, Young, & Tarnoff, 2010)

The paper also prepared a cost comparison between the test car run method and the Bluetooth devices. The initial cost of the Bluetooth devices range from $11,640 to $14,665, and the cost for the test car run method, as performed by the study, was $3,146 for three days, $4,066 for five days, and $4,986 for seven days. At first, it looks like the test car run method looks like the cheaper method. But when the "cost per data point" is calculated for each method, the Bluetooth devices really are the better option. Also, as the amount of segments goes up so does the cost for the test car run method. If more than 12 three-mile segments need analysis, the Bluetooth is by far the most feasible option. If these two methods were applied on the I-80 corridor between Cheyenne and Laramie, the cost of installing Bluetooth readers would be significantly less expensive. Since corridors in Wyoming are so much longer than those in more urbanized areas, it makes more sense to invest in car sensing equipment rather than paying people to travel these long 50-mile corridors to report travel times.

Sometimes it is important to build a personalized product from the ground up in order to insure accurate testing. The Texas Transportation Institute designed and constructed its own Bluetooth readers from scratch (Texas Transportation Institute, 1998). The project was separated into three different phases. The first phase involved developing and testing the Bluetooth readers. This means testing the impacts of different antennas on the detection rate, optimizing the detection rate with different processors, and finding the most efficient way to process the data from the Bluetooth reader. The second phase of the project tested the portable Bluetooth reader device. And finally, the third phase was long-term device testing and software refinement.

For the long-term testing, the portable Bluetooth devices were placed at six arterial intersections in the city of Houston, Texas. The inquiry period for these Bluetooth devices is longer than other readers previously discussed at 10 seconds. This means that any MAC address retrieved from the sensor could be up to 10 seconds off. Overall, the study confirmed that this method of probe-based travel time provides the highest number of data points while also being one of the least expensive methods of measuring travel time.

So far, Bluetooth data have only been compared to actual travel times calculated by cars physically driving the route themselves. However, a study submitted to the "Journal of Modern Transportation" in March of 2012 studied the differences among four travel time calculation methods including: Co-Pilot data, Bluetooth sensors, the TRANSMIT system, and the INRIX database system (Liu, Chien, & Kim, 2012). The Co-Pilot data were collected by probe vehicles with GPS equipped inside the vehicle. The Bluetooth sensors collect and match MAC addresses from Bluetooth enabled electronic devices along a specified route. The TRANSMIT system tracks electronic toll tags known as E-ZPass. The INRIX system tracks a fleet of 5 million trucks, vans, and other vehicles with a hybrid GPS and floating car system. The study was done on Interstate 287 in New Jersey, which was divided into four segments.

In order to evaluate each device accurately, all travel times were converted to average vehicle speed. The speeds were then compared using standard error of the mean (Equation 3), speed error bias (Equation 4), and average absolute speed error (Equation 5).

$$\sigma_{SEM} = \frac{\sigma}{\sqrt{N}}$$

Equation 3. Standard Error of the Mean

$$e_{SEB} = \frac{1}{N}\sum_{t=1}^{N} e_t$$

Equation 4. Speed Error Bias

$$e_{AASE} = \frac{1}{N}\sum_{t=1}^{N} |e_t|$$

Equation 5. Average Absolute Speed Error

Where N is the total number of data points, and e_t is an estimated travel time between $t=1$ and N.

The analysis of these four travel time data collection methods was divided into four different analyses. The first analysis compared the INRIX database system and the Bluetooth with the Co-Pilot probe vehicle data. The values calculated from the SEM, AASE, and SEB were all small for the Bluetooth data compared with INRIX, which means that the average speed calculated by the Bluetooth readers is closer to the speed data from the Co-Pilot data. INREX underestimated the speed from the Co-Pilot data by an average of 2.84 mph. The second analysis compared the TRANSMIT toll collection tags to the Co-Pilot data.

The third analysis conducted compared all three travel time collection methods to the Co-Pilot data. All the data from all four links were combined for the analysis. From this analysis, the following conclusions were made: 1) travel speed estimates from Bluetooth sensors relate closer to the probe vehicle speeds compared with the INRIX data, 2) INRIX's travel speed estimates are biased because of negative speed error bias values, and 3) TRANSMIT data catch speed variation that the probe vehicle misses. The last of the analyses compared TRANSMIT data with Co-Pilot data under incident condition. Four incidents were observed on two different days. Under conditions where an incident occurred, the estimates between the TRANSMIT data and Co-Pilot data were even further apart according to the SEM, AASE, and SEB.

The paper concluded that the Bluetooth data represented ground truth travel times more accurately than the INRIX database system, and the TRANSMIT toll collection reveals variations in travel times that the ground truth did not detect. The study also determined that accuracy of the travel time data from TRANSMIT was not dependent on the length of the link. Overall, the toll tag reader, commercial vehicle tracker, and pilot car methods are still valid ways to calculate travel times, but Bluetooth sensors have less bias when it comes to changing road conditions.

Bluetooth readers are also becoming the subject of performance measure testing in many major cities. Two studies from the state of Oregon have researched this very subject. A study from Portland, Oregon, called "Arterial Performance Measures with Media Access Control Readers" places Bluetooth devices on Interstate 5 between the towns of Tualatin and Sherwood in Oregon (Quayle, Koonce, DePencier, & Bullock, 2010). Manual GPS travel times were also calculated with probe vehicles. The main objective of the study was to validate the effectiveness of measuring travel times with Bluetooth readers.

The corridor used for this study had a peak hour volume of around 1,000 vehicles per hour. During two peak periods of travel, the Bluetooth readers collected between 16 and 39 data points. Many data points were collected, so an outlier test was used to filter out some unacceptable data. The moving standard deviation test was used for this particular study. If p was more than a set number of standard deviations away from the mean, then it was treated as an outlier and taken out of the data set.

It was determined that the ground truth travel times matched the travel times measured by the Bluetooth readers. Future research from this project will include integrating travel time results from Bluetooth readers into other aspects of the Intelligent Transportation System. It will also be used in the future to optimize signal timing in Oregon.

A second study from Oregon called "Wireless Data Collection System for Travel Time Estimation and Traffic Performance Evaluation" used Bluetooth devices to compute intersection performance measures (ODOT/OTREC, 2012). Since this study was done for intersection performance, a single car's Bluetooth device MAC address could be read multiple times. Therefore, a method was constructed to group these multiple MAC address reads together. Multiple probe vehicles were sent out to the intersections, and each probe vehicle calculated the time it took them to travel through the intersection. The time it took to travel through the intersection was called the "Threshold Time." For this particular study, the threshold time was calculated to be 65.28 seconds. Since the Bluetooth had an inquiry time of one read for every 3.84 seconds, there was a maximum group size of 17 for an individual MAC address. This helped to separate MAC addresses that were recorded multiple times, but may be taking multiple trips.

For travel time calculations, only one MAC address per vehicle needs to be used per data collection unit, so the timestamp of the MAC address with the highest Received Signal Strength Indicator (RSSI) was used. The units used for RSSI measurement is decibels. An RSSI was recorded along with a MAC address when a Bluetooth enabled device passed the data collection unit along a route.

In order to determine whether or not the Bluetooth readers are reporting accurate travel times, 20 probe vehicles were sent out along the route to determine ground truth travel times. Three different travel times were calculated for each probe vehicle: one was calculated manually from inside the vehicle, and two were calculated from MAC addresses from known Bluetooth enabled devices in each probe vehicle. It was determined there was no significant difference between the ground truth travel times and the travel times calculated from the data collection units. Similar to other studies, there were multiple outliers in the data set. Three different methods were used to identify outliers: the moving standard deviation method, the box plot method, and the gap method. The best performing method of removing outliers was the moving standard deviation. After the outliers were removed, the calculated travel times were shown to be as accurate as the travel times calculated by the probe vehicles.

2.3 Travel Time Reliability Measures

This section will introduce information from three different publications about different ways to calculate travel time and travel time reliability. Two of these publications come from the Federal Highway Administration (FHWA), and one study comes from the Florida Department of Transportation (FDOT). A TRB paper from FDOT discusses their travel time reliability model, how it is being applied in real world situations (weather events, incidents on the road, and other unforeseen circumstances), and the results it has given (McLeod, Elefteriadou, & Jin, 2011). FDOT has its own four-step methodology for measuring travel time reliability. Step one is identifying possible scenarios, step two is estimating the travel time for each section, step three is estimating the probability of occurrence for each scenario, and step four is the development of a travel time distribution for each section.

The four scenarios FDOT came up with are recurring congestion, incidents, weather, and work zones. Travel times influenced by congestion were determined using planning applications from the Highway Capacity Manual and from a microscopic simulation program called CORSIM. A ratio of non-blocking incidents and blocking incidents was determined from the 2007 Sunguide FDOT District 4 Report. Then, using data from the FDOT Crash Analysis Reporting System, the probability of a blocking incident per lane-mile per year was determined for each section, and for four different scenarios: no rain and no work zone, rain and no work zone, no rain and work zone, and rain and work zone. These probabilities were used for situations where an incident was causing congestion.

The three scenarios used for weather conditions included clear weather, light rain, and heavy rain. It was considered to be a clear weather scenario when less than 0.01 inches of rain fell per hour. Light rain is rainfall between 0.01 and 0.05 inches per hour, and heavy rain is considered to be any rainfall greater than 0.05 inches per hour. The probability for each of these scenarios was determined for each hour, and then applied to the related freeway. It was determined that speed reductions are 6% for light rain and 12% for heavy rain for freeways in Florida. Since data were not as available for work zone travel times, the default values (3% between 10 pm and 7 am and 1% for all other hours) were set for the probability of having a work zone on a certain segment. Each individual probability was multiplied together to determine a total probability for a certain situation. Travel times are then aggregated every hour for every section of roadway for analysis and reporting.

The current statistic FDOT is using to determine travel time reliability is the "percentage of trips that arrive on time." On time is defined as a vehicle traveling no less than 10 miles per hour below the free flow speed within a time period. The definition of free flow speed for these reliability calculations is five miles per hour above the posted speed limit. Between 2005 and 2009, the percentage of trips on time ranged from 92.8% and 99.9%. The lowest reliable roadways are the most urbanized sections and the most reliable roadways were the roads outside the seven most populous counties in Florida. These travel times are illustrated for Broward County in Figure 2.3.

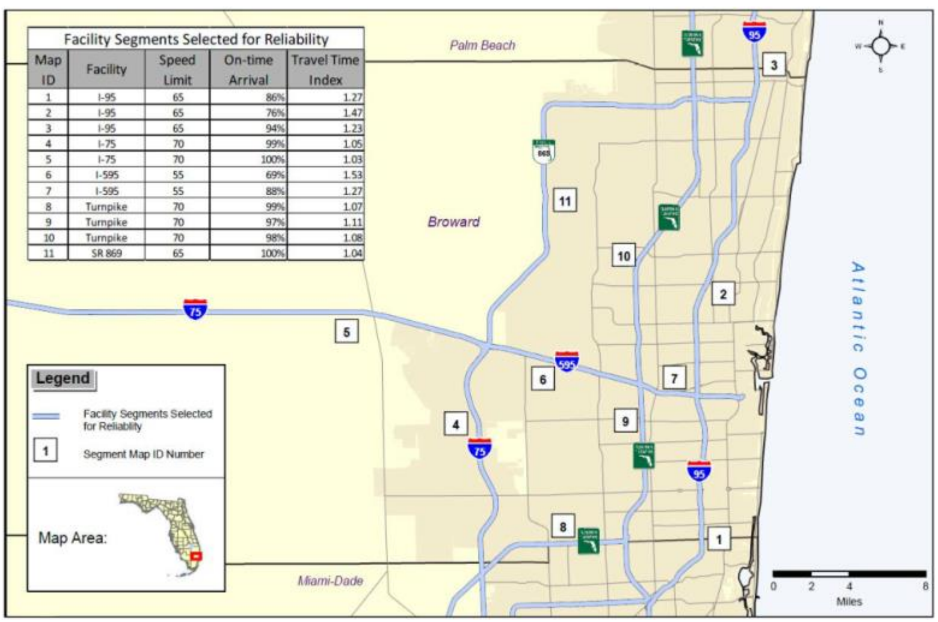


Figure 2.3 Travel Time Reliability for Broward County CITATION McL11 \l 1033 (McLeod, Elefteriadou, & Jin,

This travel time reliability model is currently being used by FDOT to prioritize projects, calculate performance measures, and report reliability to the public. In the end, FDOT has successfully developed, tested, and refined the travel time reliability model at the statewide level.

The FHWA has released numerous studies and papers that help agencies manage their own unique transportation systems. These next two papers are publications from the FHWA that are meant to help agencies organize travel time data and to calculate travel time reliability. The “Travel Time Data Collection Handbook” was published by the FHWA in 1998. The handbook first focuses on how to develop a data collection plan, then covers current and emerging methods of measuring travel time (from 1998), and finally ends with a discussion on data reduction, summary, and presentation. Although the handbook is 14 years old, it still contains pertinent information on how to manage and present travel time information (Texas Transportation Institute, 1998).

The second chapter of the handbook discusses how to develop and implement a data collection plan. The first steps to developing a plan are to establish the study’s purpose and objective, understand the uses and users, define the scope of the project, select a data collection technique, develop a data collection schedule, conduct training, and perform pilot studies. The handbook describes each step of the process in great detail. Only after all these steps are completed can the travel time data be collected.

When it comes to travel time measurements, a very similar method to MAC address matching is license plate matching. Chapter 4 of the “Travel Time Data Collection Handbook” discusses four different methods of license plate matching: manual, portable computer, video with manual transcription, and video with character recognition. Like MAC address matching, an advantage to license plate matching is there will be a larger sample of motorist travel times, which means a better understanding of the variability of travel times. With license plate matching there should be a matching percentage of around 10%, and the minimum sample size for any travel time calculation should be around 30 matched license plates. The handbook elaborates on each license plate matching technique and discusses helpful hints on how to make the experience easy for the researcher. Later in chapter 6, the handbook discusses research efforts in vehicle signature matching and how this may be the future of travel time calculations.

The last chapter before the appendices in the “Travel Time Data Collection Handbook” is chapter 7: data reduction, summary, and presentation. This chapter introduces several different ways to report travel times. A run summary includes travel times for each segment, causes of delay, and time spent at different speed ranges. Another popular type of summary for quality control purposes is an aggregated run summary. If there are multiple segments analyzed, an aggregated summary separates each segment’s travel time into interval times. Then for each segment a cumulative time is calculated, and an average speed is calculated for each segment.

The second publication from the FHWA is titled “Travel Time Reliability: Making It There on Time, All the Time.” In this publication, the FHWA has set fourth five different methods that can be used to calculate travel time reliability (Lyman & Bertini, 2007):

- Percentile Upper Limit (85^{th} and 90^{th} Percentile)
- Travel Time Index
- Buffer Index
- Planning Time Index
- Misery Index

Each travel time reliability calculation method has advantages and disadvantages. The Percentile Upper Limit method gives a travel time with the side note that a traveler will be able to travel this route, within the stated amount of time, 85%-90% of the time during current conditions. Giving the percentile helps the public feel like the travel time number is more reliable. However, more data are required to calculate this type of travel time reliability. The Travel Time Index is a measure of how close travel times are with free flow travel times. The closer this number is to 1, the closer the actual travel times are to the free flow times. This type of travel time reliability is easier to calculate, but it does not give travelers enough useful information to make an informative decision. The Buffer Index is calculated by subtracting the actual travel time and the free flow travel time. This informs the traveler of the extra time required to travel on a certain corridor. The Planning Time Index is a ratio of the 85^{th} or 90^{th} percentile travel time divided by free flow travel time. This may be helpful for agencies when they evaluate corridor performance, but the traveling public will not be able to use a ratio to make traveling decisions. The Misery Index is a measure of how centrally located the travel times are distributed. This is calculated as the average travel time minus the 20^{th} percentile travel time divided by the average travel rate.

Each of these travel time reliability methods can be easily reported to the public, but the way the public interprets them is another issue. These travel time reliability calculation methods were tested on rural roads in Wyoming, and it was determined that the most effective way to relate travel time reliability to the public is through the Percentile Upper Limit method (Ringenberg, 2011). People will be more inclined to trust the travel time reported if there is a footnote that says the travel time is 90% reliable.

2.4 Methods of Reporting Traveling Conditions

Road and weather information needs to be presented in a way that does not confuse the driver. A document recently released by the FHWA called “Guidelines for Disseminating Road Weather Advisory and Control Information” sets ground rules for multiple intelligent transportation systems. All types of information dissemination devices are listed in this document. When the time comes to start reporting data to the public, these guidelines will be followed in order to ensure maximum driver understanding.

2.4.1 FHWA Guide for Reporting Traveling Conditions

All the methodologies and formulas would be pointless to perform unless the results can be reported to the public in a clear and consistent manner. Many state DOTs are starting to incorporate websites and dynamic message signs to relay important information to the public. This information needs to maintain a certain quality and consistency across all these agencies so cross-country travelers have an easier time understanding the information presented to them across the country. To address this issue, the FHWA compiled the “Guidelines for Disseminating Road Weather Advisory and Control Information.” The purpose of this document was to introduce the three different ways of communicating travel information to the public (dynamic message signs, auditory messages, and web-based messages) and how to properly convey travel information for each of these communication devices (FHWA, 2012). For the purposes of this research, this report will only focus on how to report travel times for each form of communication.

When reporting travel times on a dynamic message sign, it is important not to overload the user with information. The traditional way to report travel times is to put a destination on the left and the travel time in minutes on the right. However, studies have shown that this display does not affect users' perceptions of their actual travel time. There are a couple of alternative displaying options that can help increase the credibility of travel times. One way is to report a travel time to a destination with a time-stamp (i.e., Travel Time to Laramie, 30 min at 5:30). Another way to convey credible travel times is with a range (i.e., Travel Time to Laramie, 25-35 minutes). These two methods for displaying travel times increase credibility with the users on the roadway. Travel times to multiple destinations can be displayed, but then the reliability of reporting a range with a time-stamp is lost.

The same methods of reporting travel times are true when reporting through auditory reports. These types of messages are usually received by dialing 511 on any kind of telephone. Similar to the dynamic message signs, it is important to not report a long message. However, there can be more content in these messages since this communication method does not occupy the eyes of the users. Auditory messages can include the distance for the reported travel time as well as direction. This information is very useful for new drivers in a corridor, and it is one of the advantages to reporting road conditions over the phone.

Web-based reporting methods are quickly becoming the most popular way for travelers to receive updates on road conditions. There are many guidelines as to how to set up a web page including font size, types of fonts, web camera displays, color selection, and icon selection. With color selection, it is important to avoid color combinations that might hinder people who are color blind. Severe weather alerts should use a bright color to draw attention, and it should be placed on the main page of the website. Since people can look at a website for longer periods of time, there are more leniencies with respect to layout. Overall, web sites that report travel conditions should have a logical, consistent layout which can be easily comprehended by the public.

2.4.2 Pre-Trip and During-Trip Information

In order to keep drivers informed and up-to-date on current road conditions, pre-trip and during-trip information needs to be accurate and easily available. Currently, WYDOT employs a number of communication devices to inform drivers of hazards and extreme conditions that they face farther ahead on their route. The www.wyoroad.info website is a great resource for travelers to learn of the possible road and weather conditions. Dynamic Message Signs (DMS) installed on the side of the road give the travelers a current report of the conditions ahead. Other communication methods utilized by WYDOT include 511 telephone service, highway advisory radio, and broadcast radio. All these methods are useful for receiving road and weather information, but they are not used equally. In order to determine which communication devices are most effective and how they can be improved, surveys were created and distributed among random travelers and frequent travelers in 2008 (Edwards, 2008).

Before the survey was distributed, an analysis of the current DMS messaging procedure was analyzed. The three major conclusions from the analysis were:

- Operators should be more aware of the changing road and weather conditions and change the message more often.
- Road and weather condition messages should be separate from public service announcements.
- Messaging procedures need to be more consistent.

The traveler information survey revealed important information about the effectiveness of the WYDOT reporting system, including:

- The top three sources of information for travelers were from DMS, 511 phone service, and the WYDOT website.
- During extreme weather events, DMS messages need to be updated more frequently.
- DMS messages need more specific information.

Overall, travelers highly value the messages on dynamic message signs. However, only a few different types of messages were taken seriously: accident ahead, road closed, or no unnecessary travel. Also, the survey concluded that drivers tend to take the actions suggested by the DMS message (e.g., turn off cruise control). The addition of dynamic message signs to Wyoming highways has been great for travelers, but the procedure for displaying messages needs to be improved.

The state of Utah has a similar road and weather condition reporting system. The Utah Department of Transportation conducted a study in the year 2000 to determine which methods were more popular when receiving road condition information. The survey from the Utah RWIS Department of Transportation asked people how important is the weather and road condition information, what kind of information is most helpful, which type of weather and road conditions are the most important, which sources of information are the most important and when do you seek information (Martin, Perrin, Meldrum, & Quintana, 2000). The people surveyed were split into four classes: commuters, travelers, truckers, and recreational travelers.

Each class has a unique method for retrieving roadway information. For example, it can be assumed that travelers (people who travel more than 150 miles for one trip) and truckers are on the road longer than other people, which means weather and road conditions are more likely to change while they are traveling. Since they cannot access the Internet while they are driving, it is important for them to receive reports on changes in conditions via changeable message signs or highway advisory radio. Whereas a commuter or a recreational traveler will most likely check the weather and road conditions on the Internet before leaving, and the conditions are less likely to change while they are traveling.

The results of the survey confirmed some of these assumptions, as well as brought to light new ideas about driver information. When recreational and commuter travelers were asked which information is most important to them (average travel speeds, estimated travel time, alternative routes available, road surface conditions, or weather conditions), their responses were fairly evenly distributed. However, long-distance travelers and truckers were more likely to respond with “road surface conditions” and “weather conditions” as the type of information they find most helpful.

The next question on the survey gave a long list of weather and road conditions and asked people to rank the relative importance of knowing each condition. Overall, truckers and long-distance travelers find all weather and road conditions more important compared with recreation and commuter travelers. This may be true because, more than likely, the long-distance traveler and trucker are driving on unfamiliar roads. The type of weather conditions travelers gave a low importance rating to include light rain, thunderstorm, snow flurries, and heavy rain. The most important weather conditions according to the travelers surveyed are road closures, black ice/ice, drifting snow, snow pack, and fog. This is to be expected since these types of conditions severely affect the way travelers drive to their destination.

One of the most important questions from the survey is which ways are best when communicating information. Once again, commuters and recreational travelers shared similar responses, and long-distance travelers and truckers shared similar responses. The two most popular responses for all travelers were "Changeable Message Signs" and "Commercial Radio." However, commuters and recreational travelers also gave high rankings for Highway Advisory Radio (HAR) and TV. The Internet was given as an option for retrieving information, but all travelers ranked it somewhat low. This is most likely because the survey was taken in 2000, and the Internet was not as readily available as it was in 2013. The lowest ranked methods for all travelers were pagers, kiosks/information desks, and CB radio. Overall, the long-distance travelers and truckers found all methods of receiving information more helpful compared with commuters and recreational travelers.

The survey from Utah enforces the importance of displaying severe roadway and weather information on the Variable Message Signs (VMS). Even with the increased accessibility of the Internet, the safest way for drivers to receive information while driving is through VMS and the radio. For long-distance travelers and truckers, it is important to keep these devices updated, so they are well informed about the changing conditions on their route.

2.5 Summary of Literature Review

The goal of any transportation agency is to provide reliable, accurate information to travelers so they can make informed decisions regarding their trip. Travel time reporting is becoming one of these important pieces of information. For most transportation systems, it has been used to report congestion conditions in large urban areas. Speed sensors have already been utilized on rural Interstate corridors in Wyoming, but the addition of Bluetooth could prove to be an easier, more cost effective means of calculating travel times. Many studies have proven that Bluetooth sensors are more cost effective and efficient compared with the other options of travel time calculation.

From previous studies, the current system of reporting traveling conditions in Wyoming needs improvement. WYDOT will need a method to report travel times, as well as a method to improve its current process of reporting travel conditions. Methodologies from this literature review were used to test the effectiveness of Bluetooth sensors on rural highways as well as create a new system of travel condition reporting. As was previously discussed, the FHWA has released a set of guidelines for this exact situation. These guidelines will be used to create a plan that can be implemented for future use by WYDOT. Improving the road and weather information system in Wyoming can help improve the safety of drivers by keeping them better informed.

3. LOCATION DESCRIPTION

This section will discuss the two research locations and the technology currently installed in each location. The first section will discuss the general layout and statistics from the I-80 corridor between Cheyenne and Laramie, Wyoming, and state highway WY28 between Farson and Lander, Wyoming. The next section will talk about the Intelligent Transportation System (ITS) technology that is installed in each corridor. The following section will discuss pre-trip information sources available to travelers, and the last section will detail the information available to travelers on the road.

Currently, WYDOT employs speed sensors, Road Weather Information Systems (RWIS), and Dynamic Message Signs (DMS) to help collect and report road and weather conditions to the public. The current system for reporting conditions to the public is by posting the exact conditions of the roadway. For example, if the road is slick, the DMS and the website will say “Slick” for that roadway, and if there is blowing snow across the road, the DMS and website will say “Blowing Snow.” The most serious reports that can be shown on the website or on a DMS are “No Unnecessary Travel” and “Road Closed.”

Since this research will utilize speed sensors already installed and owned by WYDOT, the number of rural highway corridors available for this research is limited. The focus for WYDOT is on Wyoming’s most heavily traveled corridor, Interstate 80. Speed sensors are set up on three different sections of I-80 between Evanston to Cheyenne, and WYDOT is starting to expand speed sensor technology into more rural corridors, like state highway WY28 between Lander and Farson. This route is more commonly known as “South Pass” since it traverses the south side of the Wind River mountain range. This will be the second area of focus for this research.

3.1 Interstate 80 between Cheyenne and Laramie

This segment of road goes between mile posts 317.2 in Laramie and 358.2 in Cheyenne. On this 41-mile stretch of highway there are 14 speed sensors, three Road Weather Information Stations (RWIS), nine web cameras, and 12 DMSs. The speed sensors are Wavetronix SmartSensorHD sensors, and they are located at the mileposts listed in Table 3.1, along with the location of the three Bluetooth sensors, marked as BT next to the milepost number.

Table 3.1 I-80 Speed and Bluetooth Sensor Locations

Speed Sensor Mileposts
317.2 (BT)
321.5
324
324.8
325.8
326.9
330
334.5 (BT)
335.5
336.1
336.5
338.11
340.5
343.8 (BT)

(BT) = Bluetooth sensor

I-80 between Cheyenne and Laramie is a four-lane highway, with the exception of the segment between mileposts 317 and 324 where a climbing lane was added to account for the steep uphill grade in the eastbound direction. This corridor averages one interchange every five miles, and the only attractions around this section of I-80 is a recreation area called Vedauwoo. The five lanes on the steep grade are separated by a rigid median barrier. Between mileposts 324 and 343.8, the terrain of the corridor becomes relatively flat, and the highway divides to create a grassy median. There is 1,200 feet of elevation change between Cheyenne (6,000 feet) and Laramie (7,200 feet). The highest point on the corridor is at milepost 324, and its elevation is around 8,000 feet. Figure 3.1 shows the ITSs set up on the I-80 corridor between Cheyenne and Laramie.

The three Bluetooth sensors were installed at mileposts 317.2, 334.5, and 343.8. It was important to place the Bluetooth sensors near speed sensors that provided volume count information in order to conduct analysis on penetration rates and the difference in travel times calculated. It was also important to place the sensors as far away from each other as possible along the route, so the calculated travel times could be as accurate as possible for the Cheyenne-Laramie corridor. Only two sensors are needed for analysis, but a third was installed for quality control and as back-up in case one sensor failed in the field.

The three RWIS stations set up on I-80 are located at mileposts 325.9, 330, and 339.2. Each station measures air temperature, road surface temperature, sub-grade road temperature, relative humidity, dew point, precipitation intensity, precipitation type, and wind speed. A picture of an RWIS station is shown in Figure 3.2

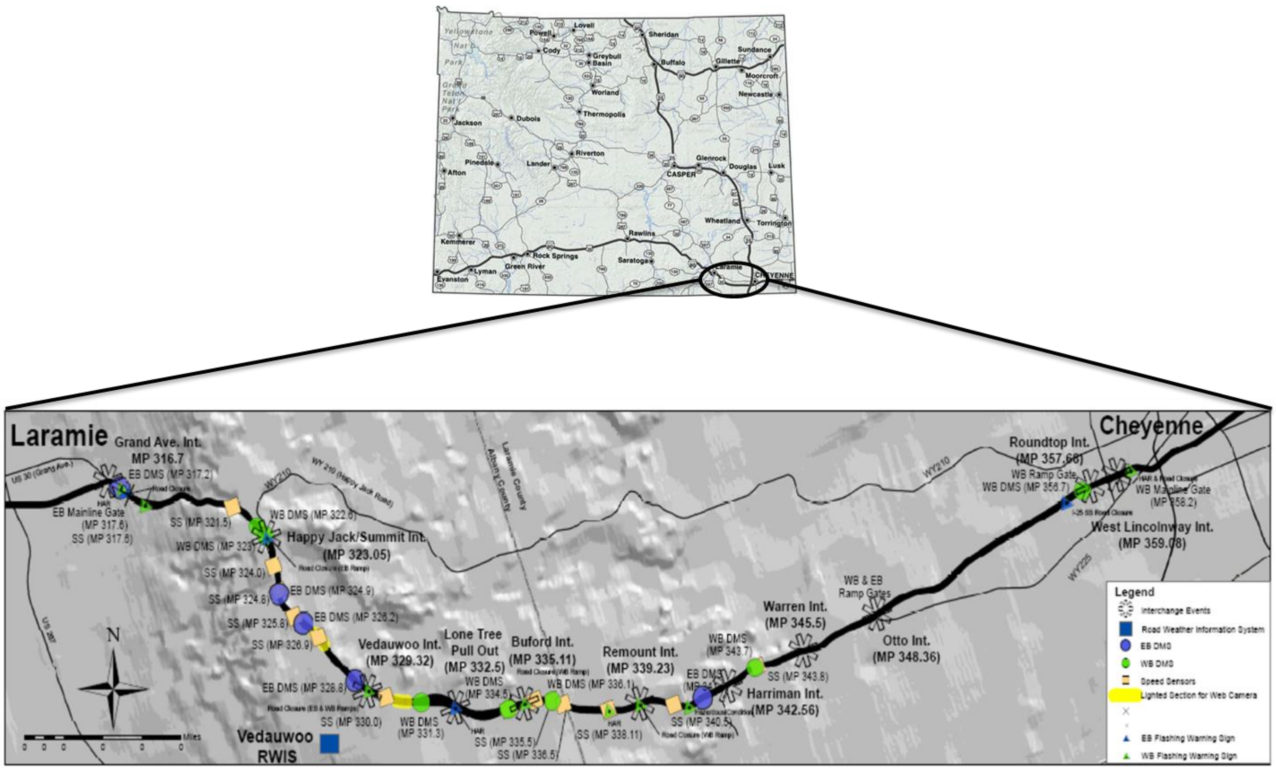


Figure 3.1 I-80 between Cheyenne and Laramie

Figure 3.2 RWIS Station on I-80

3.2 WY-28 between Farson and Lander

State highway WY-28 is 80.25 miles and runs between Farson and Lander. This is a rural two-lane highway, with three climbing lanes. In the eastbound direction, one climbing lane is located at milepost 32.35. In the westbound direction, there are two climbing lanes located at mileposts 49.15 and 58. There is 1,500 feet of elevation change between Lander (5,300 feet) and Farson (6,600 feet). This corridor is mostly used by the oil and gas industry for transporting equipment between drilling rigs, but there are many recreation opportunities for vacationers as well. Recently, new technology was installed in this corridor, which includes nine speed sensors, nine dynamic message signs, 10 variable speed limit signs, three road weather information system stations, and four web cameras. A picture of this corridor can be seen in Figure 3.3.

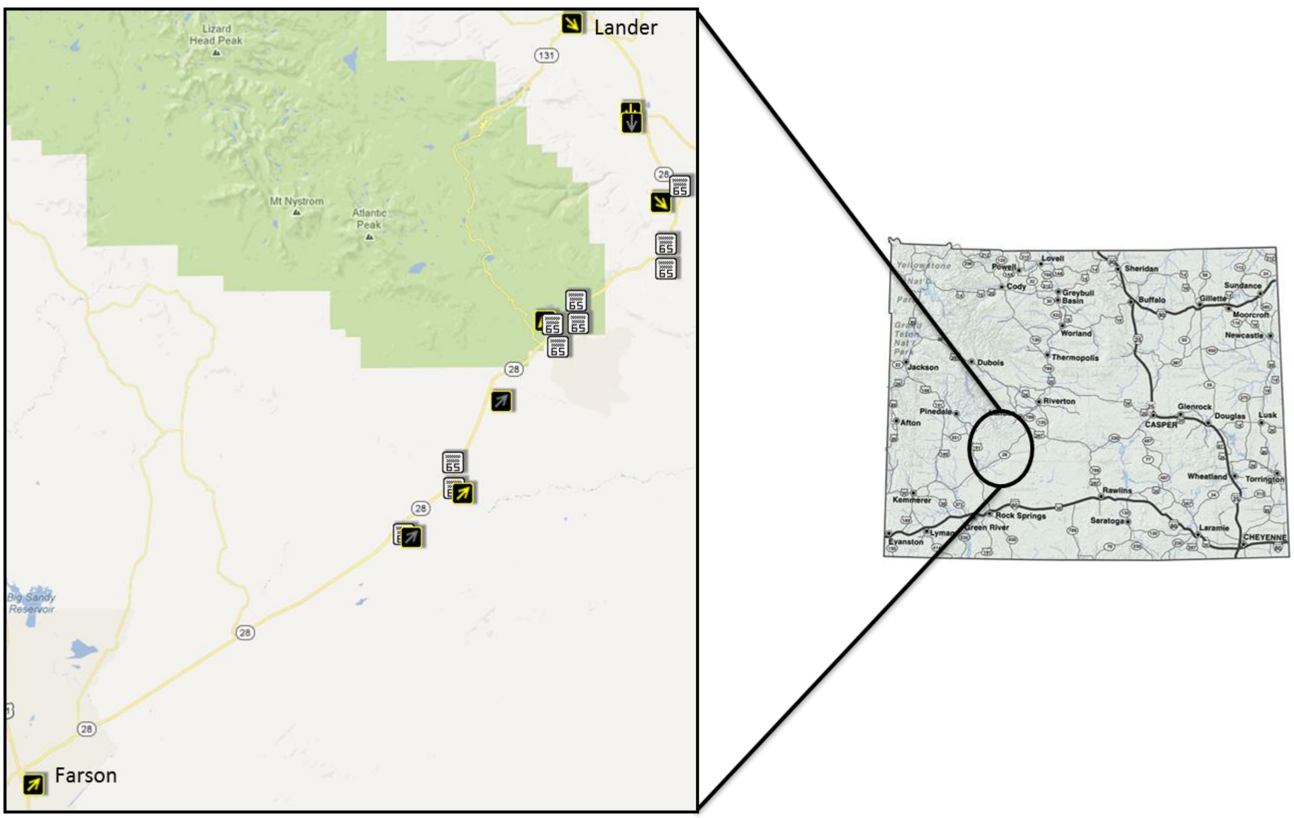


Figure 3.3 WY-28 Corridor between Farson and Lander

The technology being used on this corridor is the exact same as the technology being used on I-80. Table 3.2 lists all mileposts where technology is present, and the shaded areas indicate the type of technology present. Originally, the Bluetooth sensors installed in the Cheyenne-Laramie corridor were going to be relocated to the South Pass corridor for the second half of the winter season, but results showing low penetration rates on I-80 and issues with technology reliability made it infeasible to install the sensors on a low volume and remote corridor.

Table 3.2 Technology Locations along WY-28

Milepost	Dynamic Message Sign	Variable Speed Limit	RWIS	Speed Sensor
0.75 (Farson)	■		■	
30.43	■	■		■
35	■	■		■
41.2	■		■	
46.7				■
47.04	■	■		■
48.8		■		■
49.15		■		■
58		■		■
61.5			■	
62.3	■	■		■
67.91	■			
73.3	■			
81 (Lander)	■			

3.3 Pre-Trip Information Sources

One of the most important goals of this research is to develop a methodology to improve the pre-trip decision-making abilities of travelers through Wyoming. The place this should start is going to be the WYDOT website. People who plan to travel on Wyoming highways can visit http://www.wyoroad.info/ to quickly look at closures, advisories, web cameras, and construction sites across the state. If travelers want to see what the road and weather conditions look like along their route, they can click on the map link and chose a resolution. This will open a map of Wyoming highways, where road and weather conditions are color coded. Figure 3.4 shows an example of this online road and weather conditions map.

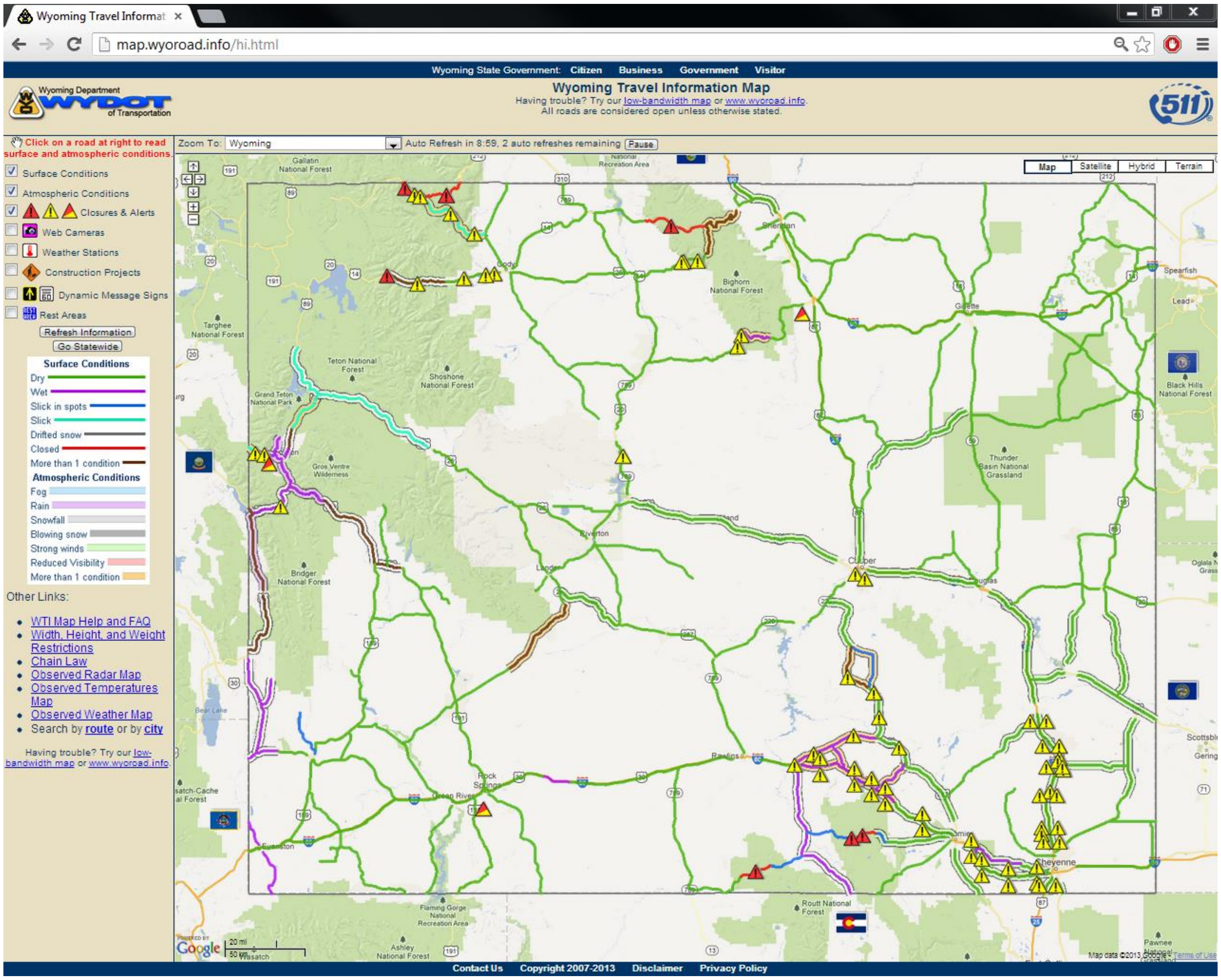


Figure 3.4 Wyoming Travel Information Map (WYDOT)

The Wyoming travel information map shows more than surface and atmospheric conditions. It also posts important alerts if they are necessary. These alerts are indicated by yellow triangles, red and yellow triangles, and red triangles that can be clicked on for additional information. The yellow triangles represent temporary important alerts for the highways in question. An example of these alerts include “No Light Trailer Traffic,” “No Unnecessary Travel,” “Chain Law in Affect,” and “Falling Rock.” The red and yellow triangles report important traveler information that are relative all year round like runaway truck ramp locations, steep grade locations, and highways closed to overweight trucks. The red triangles indicate highways that are closed to vehicular travel. This could mean seasonal closures, where a road is closed during the winter season, or roads that have been closed due to extreme weather conditions.

Another pre-trip information source is 511 phone service. If potential Wyoming travelers are unable to access the Internet at the current location, they can dial 511 and navigate through a series of auditory menus to receive travel condition information. Another option is to subscribe to “511 Notify,” where a person can receive text alerts and email alerts on extreme road conditions around the state. Television and radio announcements also play a role in the pre-trip information system.

3.5 During-Trip Information

The most noticeable sources of during-trip information in Wyoming are the Dynamic Message Signs (DMS) located on the side of the road. DMSs can accommodate one to three lines of information, depending on the type of sign installed, and they can be mounted on the side of the road or on overhead structures. Currently, the most popular messages displayed on the DMS are similar to the alerts displayed on the WYDOT map. A picture of these types of signs can be seen in Figure 3.5 and Figure 3.6.

Figure 3.5 Two Line, Side Mounted DMS on I-80

Figure 3.6 Three Line, Overhead Mounted DMS on I-80

A major complaint about the DMSs is the lack of timely updates. Many travelers have reported seeing dry conditions while the DMS was reporting “Slick” or “Slick in Spots” conditions. Since road and weather conditions are not updated frequently, the most trusted messages on the DMSs are “Turn Off Cruise Control” and “No Unnecessary Travel” (Edwards, 2008). These two messages indicate very severe travel conditions. The methodologies in this research will help streamline the process of changing DMS messages, as well as add some new information that may better convey current traveling conditions.

Another recent addition to Wyoming’s ITS is the variable speed limit (VSL) signs. They are placed in strategic locations around the state where weather has greatly affected traveling conditions. The main purpose of the VSL signs is to encourage and enforce slower speeds during adverse traveling conditions. Since February 2009, the following five VSL corridors in Wyoming have been implemented:

- I-80 between Cheyenne and Laramie (Feb. 2009)
- I-80 between Laramie and Rawlins (Oct. 2011)
- I-80 between Rock Springs and Green River (Feb. 2011)
- I-80 between Lyman and Evanston (Oct. 2011)
- WY-28 between Farson and Lander (Oct. 2012)

The speed limit on the sign is based on road condition observations from Wyoming Highway Patrol or WYDOT maintenance personnel and is controlled manually through the Traffic Management Center in Cheyenne. Although the main focus is on I-80, WYDOT is slowly expanding its ITS across the entire state.

4. DATA SOURCES

Three different types of sensors were utilized for this research: speed sensors, Bluetooth sensors, and road weather information systems (RWIS). The first two sections in this chapter will discuss the methods used to download data from speed sensors, as well as the problems encountered with the data. The next two sections will discuss obtaining, installing, and extracting data, along with the problems experienced with the Bluetooth sensors. The last section will describe the weather data obtained from the RWIS stations, which will be used in a statistical analysis of the correlation between the travel time index and the weather.

4.1 Speed Sensor Data

The first type of sensor used for this research was a Dual Radar speed sensor. These speed sensors are constantly monitoring each lane of the highway by sending out and receiving microwave signals. The sensor knows when a vehicle is present when the microwave signals come back in a shorter amount of time. Then it determines the amount of time it takes the vehicle to travel between two points on the road, which is known by the speed sensor. Once the time and distance is known, then the speed can be determined by taking the distance and dividing by the time. The advantage of using a Dual Radar speed sensor is that it can also measure vehicle characteristics. By using the speed and the amount of time the vehicle was registered by radar, the speed sensor can also calculate the length of the vehicle. The vehicle can be grouped into one of eight different classifications based on its length. Other important factors that these sensors can measure include the direction of travel (eastbound or westbound), traveling lane number (where "Lane 1" is the right-most lane in the direction specified), average headway, average gap, lane occupancy, and traffic volume.

Archived speed sensor data were collected through the "Data Collector" computer in WYDOT's traffic management center (TMC) in Cheyenne. Through the popular remote-connection website GOTOMYPC, data could be downloaded anytime and anywhere. WYDOT uses the software program TranSuite to collect and organize speed sensor data. TranSuite can download average speeds for different speed sensors at aggregated time intervals of one minute, 15 minutes, 30 minutes, one hour, or one day. For this research, speeds were downloaded at 15-minute intervals.

For the I-80 corridor between Cheyenne and Laramie, data were downloaded from 14 speed sensors between October 2009 and October 2010 at 15-minute intervals. This equates to a dataset with 1,420,276 speed records. An example of this data set can be seen in Table 4.1.

Table 4.1 I-80 Speed Sensor Data Example

SampleTime	Int Id	Det Id	Lane #	Dir	Count	Avg Occ	Avg Spd	#of Samples	#of Good Samples	#of non-zero speeds
12/1/09 12:00	36	1	2	w	66	3.56	69.69	30	30	30
12/1/09 12:00	37	2	1	w	26	0.82	76.53	30	30	30
12/1/09 12:00	38	3	1	e	12	0.35	86.32	30	30	30
12/1/09 12:00	39	4	2	e	61	2.82	77.48	30	30	30
12/1/09 12:15	36	1	2	w	58	3.04	70.77	30	30	30
12/1/09 12:15	37	2	1	w	16	0.43	75.42	30	30	30
12/1/09 12:15	38	3	1	e	21	0.4	86.96	30	30	30
12/1/09 12:15	39	4	2	e	65	3.03	75.47	30	30	30
12/1/09 12:30	36	1	2	w	74	4.25	68.89	30	30	30
12/1/09 12:30	37	2	1	w	30	1.16	74.79	30	30	30
12/1/09 12:30	38	3	1	e	11	0.49	83.79	30	30	30
12/1/09 12:30	39	4	2	e	74	3.6	76.92	30	30	30
12/1/09 12:45	36	1	2	w	68	4.36	70.34	30	30	30
12/1/09 12:45	37	2	1	w	33	1.04	76.09	30	30	30
12/1/09 12:45	38	3	1	e	7	0.27	83	30	30	30
12/1/09 12:45	39	4	2	e	49	2.48	76.42	30	30	30
12/1/09 13:00	36	1	2	w	65	3.59	67.5	30	30	30
12/1/09 13:00	37	2	1	w	29	0.94	73.7	30	30	30
12/1/09 13:00	38	3	1	e	10	0.14	79.05	30	30	30
12/1/09 13:00	39	4	2	e	52	2.88	77.98	30	30	30

For each 15-minute interval, there are four different speeds recorded, one for each lane in each direction of travel. Each lane in each direction gets a unique "Int ID" and "Det ID." The "Lane #" refers to the lane which the average speed was recorded. The "Avg Occ" category refers to the percentage of time that a vehicle was registered by the speed sensor in the previous 15-minute interval.

The speed sensors on highway WY-28 first became operational in November 2012. One key difference between the I-80 corridor speed sensor data and the WY-28 data is the one-minute aggregate intervals. When the 15-minute aggregated intervals were downloaded for WY-28, the average speeds recorded were extremely low. The speed limit of the highway is 65 mph, and the average speeds being recorded were in the 30-40 mph range. When the one-minute range was downloaded, the average speed limits were much more reasonable and it was determined that the TranSuite software had a calculation error in its 15-minute aggregation algorithm that was not previously there. An example of speed sensor data from the WY-28 corridor between Farson and Lander is in Table 4.2.

Table 4.2 WY-28 Speed Sensor Data Example

SampleTime	Int Id	Det Id	Lane #	Dir	Count	Avg Occ	Avg Spd	#of Sampl	#of Good	#of non-ze
11/8/2012 0:00	423	1	1	w	0	0	65.43	1	0	1
11/8/2012 0:00	424	2	1	e	0	0	68.15	1	1	1
11/8/2012 0:01	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:01	424	2	1	e	1	0.02	58.78	2	2	2
11/8/2012 0:02	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:02	424	2	1	e	0	0	49.42	2	2	2
11/8/2012 0:03	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:03	424	2	1	e	0	0	49.42	2	2	2
11/8/2012 0:04	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:04	424	2	1	e	0	0	49.42	2	2	2
11/8/2012 0:05	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:05	424	2	1	e	0	0	49.42	2	2	2
11/8/2012 0:06	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:06	424	2	1	e	0	0	49.42	2	2	2
11/8/2012 0:07	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:07	424	2	1	e	0	0	49.42	2	2	2
11/8/2012 0:08	423	1	1	w	0	0	65.43	2	0	2
11/8/2012 0:08	424	2	1	e	0	0	49.42	2	2	2

4.2 Speed Sensor Quality

Speed sensor malfunctions were a common occurrence. When a speed sensor was malfunctioning, the average speed would be displayed as zero or as an error. When the speed sensor was working correctly, the count was greater than zero, therefore the average occurrence was greater than zero, and there was a speed recorded. The record for that 15-minute period of time was then considered complete. This was the case for both I-80 and WY-28. Since I-80 has a much higher traffic volume, it is easier to see where speed sensors are malfunctioning; however, for WY-28, there could be 30 minutes between vehicles. Each corridor needed a different methodology for managing the giant quantities of data.

4.2.1 I-80 Speed Sensor Data Quality

In order to conduct analysis on the I-80 data, a multitude of missing rows had to be deleted. The data were split into eastbound and westbound directions and resorted in order to find the missing data. These missing data could have been a result of malfunctioning equipment, or simply because no vehicles had passed by the detector in that 15-minute period. After removing the missing data, it is clear which speed sensors were the most reliable and which may need maintenance. Table 4.3 shows the percent of data missing from each speed sensor from the I-80 analysis.

Table 4.3 I-80 Speed Sensor Missing Data

Milepost	% of Data Missing	% Complete
317	13.70%	86.30%
321.5	13.89%	86.11%
324	28.40%	71.60%
324.9	17.86%	82.14%
325.9	28.22%	71.78%
326.9	30.87%	69.13%
330	21.67%	78.33%
334.5	55.32%	44.68%
335.5	77.14%	22.86%
336.1	14.16%	85.84%
336.5	60.26%	39.74%
338.1	14.39%	85.61%
340.5	13.38%	86.62%
343.8	14.94%	85.06%

The most unreliable speed sensor on I-80 was at milepost 335.5 (77.14% of data missing) and the most reliable speed sensor was at milepost 340.5 (13.38% of data missing). All 14 speed sensors recorded usable data only 6.33% of the time. This missing data can attributed to either the speed sensor malfunctioning, the transfer of data between the speed sensor and the TranSuite software program, or the aggregating process in the TranSuite program. There is no way of knowing which process has the most problems without having the original speed records.

Other speed sensors can make up for missing data of one speed sensor since the average speed sensor spacing is 2.05 miles/sensor. In order to have more speed data available, more than one speed sensor was made available for one segment of roadway for each 15-minute period. If one speed sensor returned no data, then the next speed sensor along the route was queried. This way, more data could be used in the travel time analysis. The largest spacing between two sensors on I-80 is between milepost 330 and milepost 334.5. The full list of speed sensor spacing on I-80 can be seen in Table 4.4.

Table 4.4 I-80 Speed Sensor Spacing

Speed Sensor Milepost	Distance to next Speed Sensor (mi)
317.2	4.3
321.5	2.5
324	0.8
324.8	1
325.8	1.1
326.9	3.1
330	4.5
334.5	1
335.5	0.6
336.1	0.4
336.5	1.6
338.11	2.4
340.5	3.3
343.8	N/A

4.2.2 WY-28 Speed Sensor Data Quality

With a rural two lane road like WY-28, it is more difficult to determine when the sensor is malfunctioning. Since it is likely there can be 30 minutes between vehicles on this road, speed sensors reporting a "zero count" in a 15-minute interval are a common occurrence. However, there were very clear instances of speed sensor failure on highway WY-28.

One big error in the 15-minute aggregated data was the inaccurate representation of speeds. WY-28 has a speed limit of 65 miles per hour, and the 15-minute aggregated speeds were being reported as low as 30 miles per hour. These 30-mph speeds could be a result of extreme weather, but when these speeds were compared to the one-minute aggregated data, there was a big difference. The one-minute aggregated data were downloaded, and an extra step was added to the process to convert the speeds to an average 15-minute speed similar to the I-80 analysis. Table 4.5 shows the difference between the one-minute aggregated data and the 15-minute aggregated data between 5:30 am and 5:45 am on November 9, 2012.

Table 4.5 One Minute and 15 Minute Aggregated Speed Errors

1 Minute Aggregated Speeds at Milepost 48.8				
SampleTime	Dir	Count	Avg Occ	Avg Spd
11/9/2012 5:30	w	0	0	74.8
11/9/2012 5:31	w	2	0.01	68.1
11/9/2012 5:32	w	0	0	68.1
11/9/2012 5:33	w	0	0	68.1
11/9/2012 5:34	w	0	0	68.1
11/9/2012 5:35	w	0	0	68.1
11/9/2012 5:36	w	1	0.03	68.1
11/9/2012 5:37	w	0	0	68.1
11/9/2012 5:38	w	0	0	68.1
11/9/2012 5:39	w	0	0	68.1
11/9/2012 5:40	w	0	0	68.1
11/9/2012 5:41	w	0	0	68.1
11/9/2012 5:42	w	0	0	68.1
11/9/2012 5:43	w	3	0.05	66.08
11/9/2012 5:44	w	0	0	66.59
11/9/2012 5:45	w	0	0	66.59

15 Minute Aggregated Speed at Milepost 48.8				
SampleTime	Dir	Count	Avg Occ	Avg Spd
11/9/2012 5:30	w	6	0	34.16

The TranSuite program reports the previously reported speed when no vehicles pass by the sensor in a given one-minute interval. Besides the aggregated 15-minute intervals errors, there were also large gaps of data where no speeds were recorded from any speed sensor. Large gaps of data were found at regular intervals over the four-month period. There were smaller gaps of data (between 15 minutes and 30 minutes), but these were ignored since it is typical for this highway to be empty for long periods of time. After removing the small gaps, the larger gaps were compiled and placed into a table. The full table can be seen in Appendix A, but some statistics about the gaps are shown in Table 4.6.

Table 4.6 Statistics from Speed Sensor Data Gaps on WY-28

Largest Gap =	20:45:00
Smallest Gap =	7:30:00
Average Gap =	15:20:13
Standard Deviation =	4:32:09

Overall, there were 1,069 hours and 30 minutes of missing data from all sensors between November 8, 2012, and February 23, 2013. This equates to more than 44 days of missing data out of a total of 81 days that were download. Unfortunately, it is impossible to compare the TranSuite aggregated data with the individual vehicle data collected by the speed sensors since they cannot be recorded simultaneously.

4.3 Bluetooth Sensor Data

Three Bluetooth sensors were purchased from Acyclica Inc. through a distributor, AM Signal Inc. They were placed in traffic cabinets on I-80 at mileposts 317.2, 334.5, and 343.8. Acyclica calls its Bluetooth sensors BlueCompass. These BlueCompass sensors pick up on Bluetooth signals as well Wi-Fi signals being emitted from electronic devices. For marketing purposes, Acyclica is calling this kind of device a “Differential RF” reader, although it uses the same process for reading MAC addresses. The BlueCompass sensor can be seen in Figure 4.1.

Figure 4.1 BlueCompass Sensor from Acyclica

The BlueCompass sensor has an internal antenna with a 100-meter radius range, and an external antenna can be connected to provide more coverage. It also has 4 GB of storage, which equates to about a month and a half of data from the field. For data retrieval, the BlueCompass sensors use a web-based data interface system in order to download MAC address hits and time-stamps. In order to retrieve the data, a computer needs to be connected to the device through an Ethernet cable. Then, the IP address 192.168.30.20 is entered into a web browser’s address box. This brings up a web page where the sensor can be configured and the data can be downloaded. The data are stored in the sensor as a comma separated value (.csv) file and are easily opened in Excel. An example of the raw data from the BlueCompass sensor is found in Table 4.7.

There are five different columns in the raw data. The sample ID labels each MAC address read in numerical order. The time-stamp gives the date and time in which the MAC address was read. The MAC address column gives the unique 12-character code for the electronic device that was discovered. The encrypted MAC address works similar to the normal MAC address, but with the added benefit of privacy for the traveler. There are options in the configuration to only allow the encrypted MAC address to be displayed. The RF Strength column gives the strength of the signal from the electronic device in decibels (the closer the number is to zero, the stronger the signal). The sensor ID column is the unique identification number given to that specific BlueCompass sensor.

Table 4.7 BlueCompass Raw Data

Sample ID	Time-Stamp	MAC Address	Encrypted MAC Address	RF Strength	Sensor ID
1	Mon Sep 17 09:08:01 2012	7c:d1:c3:6e:13:32	5c63bad3c773e976711e49c65606092e	-81	162058
2	Mon Sep 17 09:08:03 2012	00:00:85:ee:60:a3	de5d42b367a5dc7d472713f497db6bcf	-85	162058
3	Mon Sep 17 09:12:52 2012	8c:58:77:cd:30:06	64cd3f0a523df4fcb2a6eacce41ad0ed	-87	162058
4	Mon Sep 17 09:18:12 2012	00:00:85:ee:60:a3	de5d42b367a5dc7d472713f497db6bcf	-83	162058
5	Mon Sep 17 17:03:00 2012	7c:d1:c3:6e:13:32	5c63bad3c773e976711e49c65606092e	-43	162058
6	Mon Sep 17 20:28:21 2012	00:16:a4:01:25:f5	7f81628a2bcfa2d6b7d08b518c2f0743	-89	162058
7	Mon Sep 17 20:33:28 2012	f8:0c:f3:de:b2:90	3e12c20782ab1fd9fa55367fb4315501	-83	162058
8	Mon Sep 17 21:55:08 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-79	162058
9	Mon Sep 17 22:49:13 2012	f0:1c:13:cd:36:27	e917b3672aa31fe2c33001db817b16c0	-83	162058
10	Mon Sep 17 23:08:12 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-79	162058
11	Mon Sep 17 23:43:19 2012	f8:0c:f3:df:30:3a	7f6483e40b65248e993489364b5a1ee5	-79	162058
12	Tue Sep 18 01:06:02 2012	00:16:a4:01:6f:41	bf92b98faf7a326441457a9054f4c2af	-87	162058
13	Tue Sep 18 08:40:42 2012	00:11:20:93:b6:68	e546b3184acb7b412e19317ea426a397	-87	162058
14	Tue Sep 18 09:39:20 2012	00:16:a4:20:54:45	edc11640bd05076e99e0927e4ca040aa	-85	162058
15	Tue Sep 18 10:04:36 2012	00:16:a4:fe:42:af	49694a5f5fdc09565f056b9568bd162f	-89	162058
16	Tue Sep 18 10:45:46 2012	00:0b:6b:b4:21:89	beef5eabd0c0feeed18267cee31a1abd	-87	162058
17	Tue Sep 18 11:00:57 2012	00:16:a4:fe:86:7c	a380515102d16d908bf3d1a200ae6f1f	-87	162058
18	Tue Sep 18 11:56:41 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-89	162058
19	Tue Sep 18 12:10:28 2012	00:16:a4:20:2d:30	a629c63320335ae2dc537d61b8004f19	-87	162058
20	Tue Sep 18 12:25:03 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-85	162058
21	Tue Sep 18 13:13:12 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-83	162058
22	Tue Sep 18 13:45:51 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-85	162058
23	Tue Sep 18 14:12:37 2012	2c:27:d7:a3:a6:00	49988abdbb654f006494b9f760537509	-65	162058
24	Tue Sep 18 14:22:36 2012	f0:1c:13:46:cf:19	441f444db14531d825f13d8375f800aa	-89	162058
25	Tue Sep 18 14:32:18 2012	00:16:a4:20:2b:06	552e9e5c7395e6599864c0a1a97ee732	-87	162058
26	Tue Sep 18 14:34:24 2012	f0:1c:13:46:cf:19	441f444db14531d825f13d8375f800aa	-89	162058
27	Tue Sep 18 14:35:39 2012	00:40:9d:41:a7:cc	5571e4f1070cd71da6c69f5cbe0cab3b	-85	162058
28	Tue Sep 18 14:44:40 2012	f0:1c:13:46:cf:19	441f444db14531d825f13d8375f800aa	-87	162058
29	Tue Sep 18 14:54:47 2012	f0:1c:13:46:cf:19	441f444db14531d825f13d8375f800aa	-85	162058
30	Tue Sep 18 14:57:25 2012	1c:b0:94:7e:c8:9c	7522ca25a29958f1bc1290a5506fe118	-85	162058

Before releasing its first generation of BlueCompass sensors, Acyclica tested its sensor on the I-70 corridor. The results of this study were released in a report on December 1, 2011, and they were extremely positive (Acyclica, 2011). From this report, the "Differential RF" readers found in the BlueCompass sensors were able to collect up to ten times more MAC addresses compared with a standard Bluetooth reader. Figure 4.2 shows a time-of-day frequency chart straight from Acyclica's report on the difference between the Differential RF readers found in BlueCompass and Bluetooth readers.

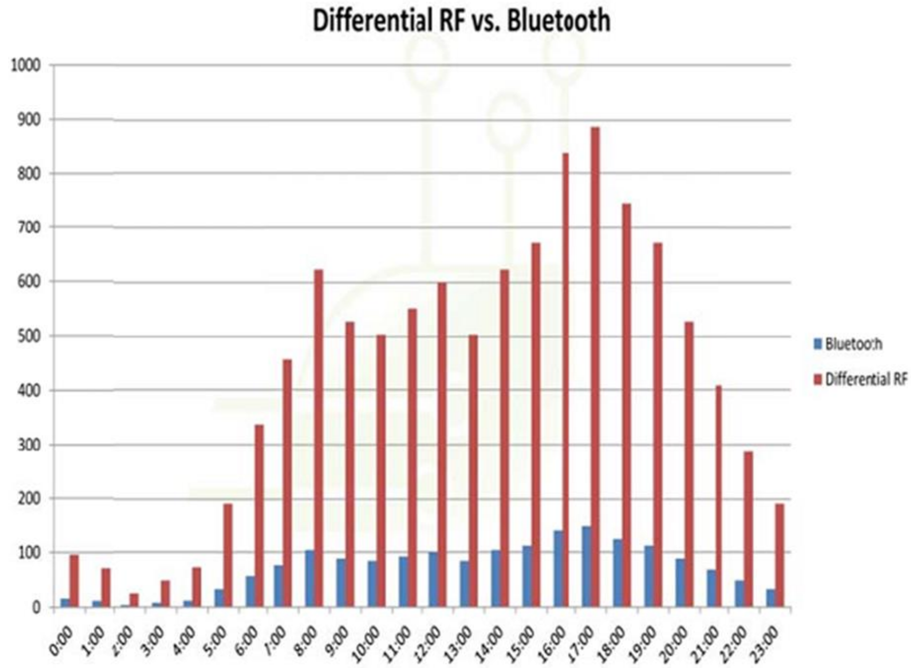


Figure 4.2 Differential RF and Bluetooth Comparison (Acyclica, 2011)

4.4 Bluetooth Sensor Quality

There were many stumbles in the BlueCompass data collection process and Acyclica was helpful in fixing the problems that were found with the BlueCompass sensors. Some of the most common problems encountered with the BlueCompass sensors include: connectivity problems between the computer and the sensor, problems with the sensor storing data, and the power cord receding into the device. To fix these problems, Acyclica generously provided firmware updates to fix connection and storage issues, and they offered replacement sensors to replace the ones with the power cord issues.

After one year of working with the BlueCompass sensors, only ten days of data were downloaded. One measure of quality calculated from these data was the average time between usable MAC address hits. After the MAC addresses were matched between all three sensors, and the unmatched MAC addresses were deleted, a simple statistical analysis was done for the average time between MAC address hits. The result of this analysis is represented in Table 4.8.

Table 4.8 Time Between Usable MAC Address Hits for each Sensor

Time Between Usable MAC Address Hits for each Sensor			
	BC1	**BC2**	**BC3**
Average=	0:10:29	0:12:47	0:16:58
Std Dev=	0:13:53	0:20:24	0:25:25
Max=	4:40:48	6:15:18	7:34:40
Min=	0:00:01	0:00:01	0:00:00

The BlueCompass sensors were very inconsistent in terms of how often a MAC address was read. The average across the three sensors ranged from 10 minutes to 17 minutes, but the standard deviation ranged from 14 minutes to 25 minutes. The standard deviations are larger than the averages for all three cases. Even though the averages were manageable, the maximum time seen between two usable MAC address hits ranged between 4.75 hours and 7.5 hours. This is unacceptable if the BlueCompass sensors are to be used as a backup to the speed sensors for calculating travel times.

These long intervals between each read MAC address could be a result of inefficient software in the BlueCompass sensor, or it could be there are no cars on the road. The next variable that needed to be accounted for was the penetration rate, which is the number of hits from a Bluetooth reader divided by the total number of cars driving by the sensor. So, after the non-usable MAC address hits were filtered out, the BlueCompass sensor data were compared to the vehicle count data from the speed sensors at the same location. The results of this penetration rate calculation, as well as some general statistics about the number of usable MAC addresses recorded by the BlueCompass sensors, are shown in Table 4.9.

Table 4.9 Number of MAC Address Hits and Penetration Rate

Number of MAC Address Hits and Penetration Rate			
Total # of MAC Address Hits for 10 days	Hits per Day	Hits per Hour	Average Penetration Rate
766	76.6	3.2	0.6%

For a highway that carries close to 15,000 vehicles per day, the BlueCompass sensors are only picking up 0.6% of that volume. This 0.6% penetration rate is equal to about one usable MAC address hit for every 175 vehicles that pass by the sensor. Another important aspect of this analysis is the “Time of Day Frequency.” The MAC addresses that were read by all three BlueCompass sensors were placed into a histogram, which is Figure 4.3.

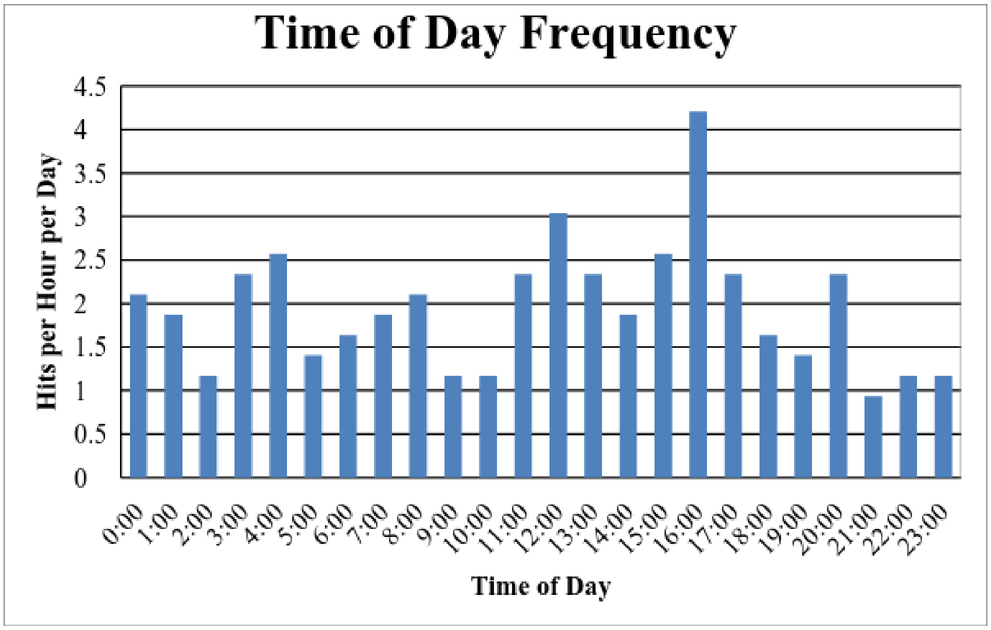


Figure 4.3 Time of Day Frequency for MAC Addresses Read by All Three Sensors

Over the 10 days that the BlueCompass sensors were functional, the range of MAC address hits per hour was only between zero and five. The most successful times for the BlueCompass sensor to collect data were around 4:00 pm and 12:00 pm, where there were 2.5 to 4 usable MAC address hits per hour, per day. The sensors were not installed on WY-28 since the data recorded were such low quality.

4.5 Road Weather Information Sensor Data

In order to perform a statistical analysis between the travel time index and the weather variables, weather data were downloaded from a RWIS weather station located at milepost 329 on I-80. The weather data were downloaded from the same "Data Collector" computer used for the speed sensor data. Instead of using TranSuite, the RWIS data are stored in the software program ScanWeb. There are 11 weather-related measurements done by the RWIS sensor, but not all were used in the analysis due to errors in the data:

- Surface Temperature - The temperature of the pavement at the sensor's location.
- Air Temperature - The temperature of the air at the sensor's location.
- Relative Humidity (RH) - The percent of moisture based on how much moisture the air can hold.
- Dew Point - The temperature at which the air becomes saturated.
- Average Wind Speed - The average speed of wind during the 15-minute period.
- Precipitation - Indicator of whether or not precipitation is present. Reported as none, yes, or other. For analysis:
    - None = 0
    - Yes or Other = 1
- Gust Wind Speed - The maximum speed of wind during the 15-minute period.
- Wind Direction - The average direction of the wind during the 15-minute period. Reconfigured into a categorical variable with the following parameters:

    - North = 0
    - Northeast = 1
    - East = 2
    - Southeast = 3
    - South = 4
    - Southwest = 5
    - West = 6
    - Northwest = 7
- Surface Status (SfStatus) - An indicator of the status of the pavement. Eight different conditions can be reported: dry, trace moisture, wet, chemically wet, ice, ice warning, ice watch, or error (not used in analysis).
- Precipitation Intensity (Precipin) - the rate of precipitation in in/hr (not used in analysis).
- Subsurface Temperature (SubTemp) - the temperature of the pavement 5 inches below the surface (not used in analysis).

An example of the raw data downloaded from the RWIS sensors can be seen in Table 4.10.

In order to simplify the analysis, the cardinal wind directions were converted into a numerical categorical variable, where north equals zero, and the value increases going clockwise around the cardinal directions. The precipitation variable was originally set up to report the type of precipitation (none, rain, snow, hail, etc.), but has only reported three different conditions: none, yes, or other. Therefore, the precipitation variable was converted to a binary variable where zero equals “None,” and one equals “Yes” or “Other.” Another variable added to the analysis is the Day and Night variable. This is a binary indicator of whether or not the 15-minute time period is during the daytime or nighttime. This variable was calculated using nautical twilight as a reference. Nautical twilight is the time at which some visible light is present, but objects are indistinguishable without artificial light. The “DayNight” variable was added by comparing nautical twilight values with the time-stamp of the RWIS data collection. Then it was converted to a binary variable where daytime equals zero, and nighttime equals one. A small excerpt of the long list of data used for analysis, including the travel time index response variable, is shown in Table 4.11.

Table 4.10 RWIS Raw Data Example

Date/Time (MDT)	SfTemp	SubTemp	AirTemp	RH	Dewpoint	AvgWindSpeed	GustWindSpeed	WindDirection	PrecipType	PrecipIntenisity
10/1/09 0:02	30	57	27	68	18	33	40	SW	None	None
10/1/09 0:07	29.8	57	27	67	17	34	43	SW	None	None
10/1/09 0:12	29.8	57	27	66	17	34	43	SW	None	None
10/1/09 0:17	29.8	57	27	67	17	35	46	SW	None	None
10/1/09 0:22	29.7	57	27	67	17	39	50	SW	None	None
10/1/09 0:27	29.5	57	26	67	17	39	50	SW	None	None
10/1/09 0:32	29.5	57	26	67	17	39	48	SW	None	None
10/1/09 0:37	29.3	57	26	67	17	39	49	SW	None	None
10/1/09 0:42	29.3	57	26	67	17	42	52	SW	None	None
10/1/09 0:47	29.1	57	26	67	17	39	52	SW	None	None
10/1/09 0:52	28.9	57	26	67	17	40	50	SW	None	None
10/1/09 0:57	28.9	57	26	67	17	32	48	SW	None	None
10/1/09 1:02	28.9	57	26	67	17	32	44	SW	None	None
10/1/09 1:07	28.8	57	26	67	17	30	44	SW	None	None
10/1/09 1:12	28.8	57	26	67	17	35	47	SW	None	None
10/1/09 1:17	28.8	57	26	67	17	30	47	SW	None	None
10/1/09 1:22	28.8	57	26	67	17	31	43	SW	None	None
10/1/09 1:27	28.6	57	26	67	16	27	43	SW	None	None
10/1/09 1:32	28.8	56	26	67	16	25	40	SW	None	None
10/1/09 1:37	29.5	56	26	67	16	21	34	SW	None	None
10/1/09 1:42	29.8	56	26	66	17	26	37	SW	None	None
10/1/09 1:47	30.2	56	26	67	17	25	37	SW	None	None
10/1/09 1:52	30.6	56	26	66	17	19	32	SW	None	None
10/1/09 1:57	30.7	56	26	66	17	20	32	SW	None	None
10/1/09 2:02	30.9	56	26	66	17	21	32	W	None	None
10/1/09 2:07	31.1	56	26	66	17	20	29	W	None	None
10/1/09 2:12	31.3	56	26	66	17	20	29	W	None	None
10/1/09 2:17	31.5	56	27	65	17	18	26	W	None	None
10/1/09 2:22	31.5	56	27	63	16	23	35	W	None	None
10/1/09 2:27	31.3	56	27	62	16	26	38	SW	None	None
10/1/09 2:32	31.1	56	27	62	16	23	38	W	None	None
10/1/09 2:37	31.3	56	27	62	16	24	34	W	None	None
10/1/09 2:42	31.3	56	27	61	16	27	39	W	None	None

Table 4.11 Statistical Analysis Data Excerpt

Index	SfTemp	AirTemp	RH	Dewpoint	AvgWindSpeed	GustWindSpeed	WindDirection	Precip	DayNight
0	57.2	46.7	71.7	38.0	5.0	7.3	5	0	0
0	57.2	46.7	71.7	38.0	5.0	7.3	5	0	0
0	48.6	44.0	79.0	38.0	3.0	6.0	4	0	0
0	48.6	44.0	79.0	38.0	3.0	6.0	4	0	0
0	50.9	45.3	76.3	38.0	2.0	3.7	3	0	0
0	50.9	45.3	76.3	38.0	2.0	3.7	3	0	0
0	57.2	48.0	66.3	37.7	6.7	10.3	3	0	0
0	57.2	48.0	66.3	37.7	6.7	10.3	3	0	0
0	48.0	43.7	77.7	37.3	4.7	6.3	3	0	0
0	48.0	43.7	77.7	37.3	4.7	6.3	3	0	0
0	45.9	42.0	80.7	37.0	3.7	11.3	5	0	0
0	45.9	42.0	80.7	37.0	3.7	11.3	5	0	0
0	47.3	42.7	79.7	37.0	2.0	5.7	7	0	0
0	47.3	42.7	79.7	37.0	2.0	5.7	7	0	0
0	47.9	44.0	77.3	37.0	1.7	3.0	6	0	0
0	47.9	44.0	77.3	37.0	1.7	3.0	6	0	0
0	44.9	42.0	77.0	35.7	11.0	20.7	5	1	0
0	44.9	42.0	77.0	35.7	11.0	20.7	5	1	0
0	62.2	54.0	46.3	34.0	13.7	19.3	4	0	0
0	62.2	54.0	46.3	34.0	13.7	19.3	4	0	0
0	52.6	36.3	88.7	33.3	13.3	19.0	0	0	0
0	52.6	36.3	88.7	33.3	13.3	19.0	0	0	0
0	52.6	36.3	87.7	33.3	12.3	17.3	0	0	0

5. METHODOLOGY AND RESULTS

This section will describe the methodology and results of the data analysis. The first section will explain the method of calculating travel times with speed sensors and the travel time distributions associated with the calculations. The next section will discuss travel time calculation methods for the Bluetooth sensors and their relationship with the speed sensor data. The third section will explain how the travel time index was created for I-80 and South Pass. The final section will discuss the statistical analysis done between the travel time index and the weather variables downloaded from the RWIS station.

5.1 Speed Sensor Travel and Travel Time Reliability for I-80 and WY-28

The travel time analysis involving speed sensors is split into two sections: the analysis done for I-80 between Cheyenne and Laramie, and the analysis done for WY-28 between Farson and Lander.

5.1.1 I-80 Travel Time Analysis

One year (October 2009 to October 2010) of data from 14 speed sensors was downloaded from the WYDOT servers at 15-minute intervals. The speeds recorded during the time interval are averaged. Travel times were calculated by choosing a beginning speed sensor. The speeds from this speed sensor were the assumed speed of vehicles along the corridor until the next usable speed sensor was reached. The average travel time was calculated between the two speed sensors using the speed from the first sensor. The travel times from these calculations were then summed, yielding an average expected travel time between the beginning and end speed sensors. For reference, the expected travel time between Cheyenne and Laramie at the speed limit of 75 mph would be 34 minutes.

A probability density function was created from these travel times after an entire year's worth of data were downloaded. The most frequent travel times for this particular corridor between October 2009 and October 2010 ranged between 31 minutes and 36 minutes depending on which direction was traveled. The probability distribution function curves from this research can be seen in Figure 5.1 and Figure 5.2.

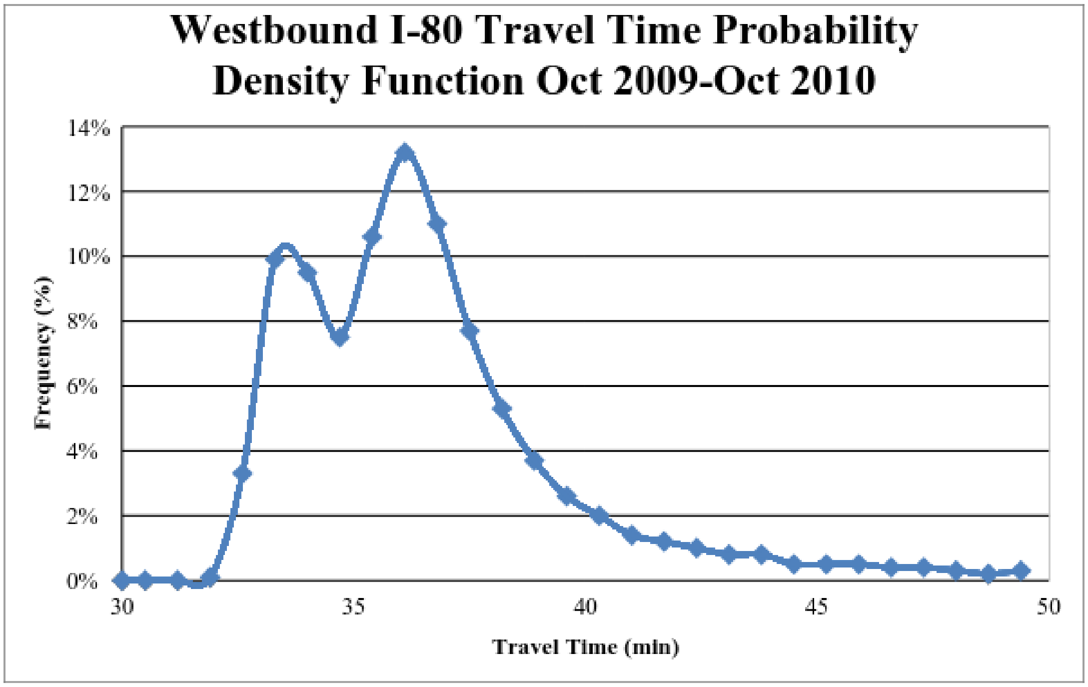


Figure 5.1 Probability Density Function for I-80 between Cheyenne and Laramie, Westbound

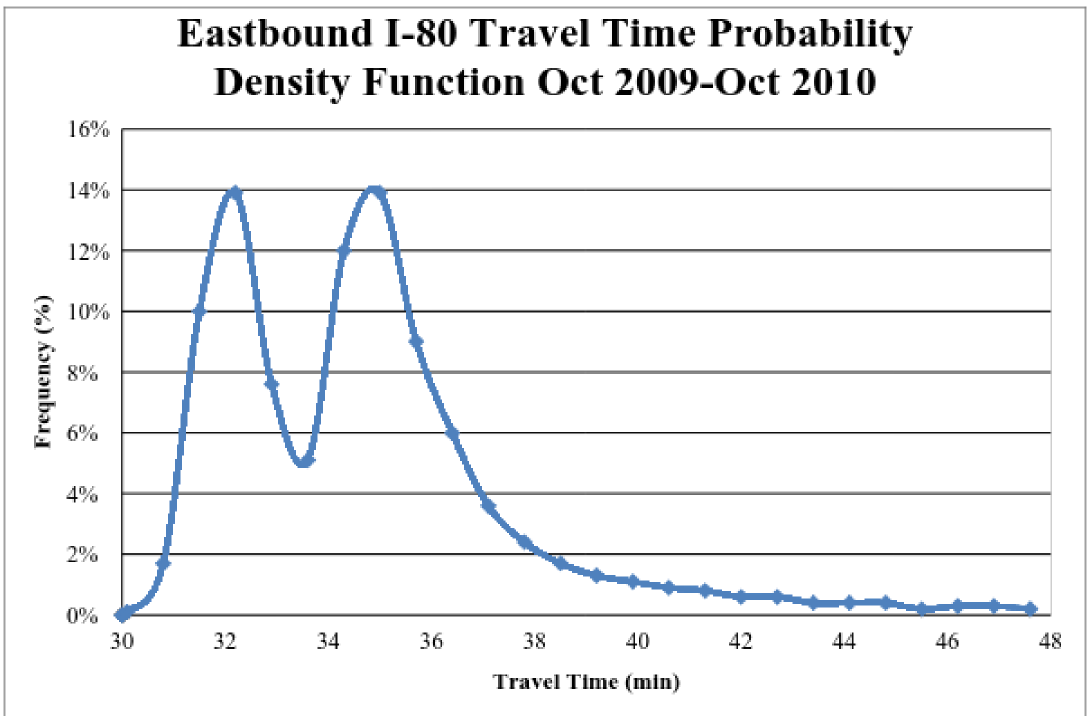


Figure 5.2 Probability Density Function for I-80 between Cheyenne and Laramie, Eastbound

The most curious result from this research was the bi-modal distribution curve. Originally, it was postulated that this bi-modal distribution was the result of daytime and nighttime driving behavior, but no further calculations were initially done. Since the I-80 corridor has such a high population of trucks, this distribution characteristic could also be caused by the different driving speeds between commercial freight vehicles and passenger vehicles.

To investigate the causes behind the bi-modal distribution, first the I-80 data were split into daytime and nighttime driving based on nautical twilight. Nautical twilight is the time at which some visible light is present, but objects are indistinguishable without artificial light. After the data were categorized, the travel time distributions were recalculated for both directions. Figure 5.3 and Figure 5.4 show the new travel time distributions for the eastbound direction. The westbound direction distribution figures are in Appendix B.

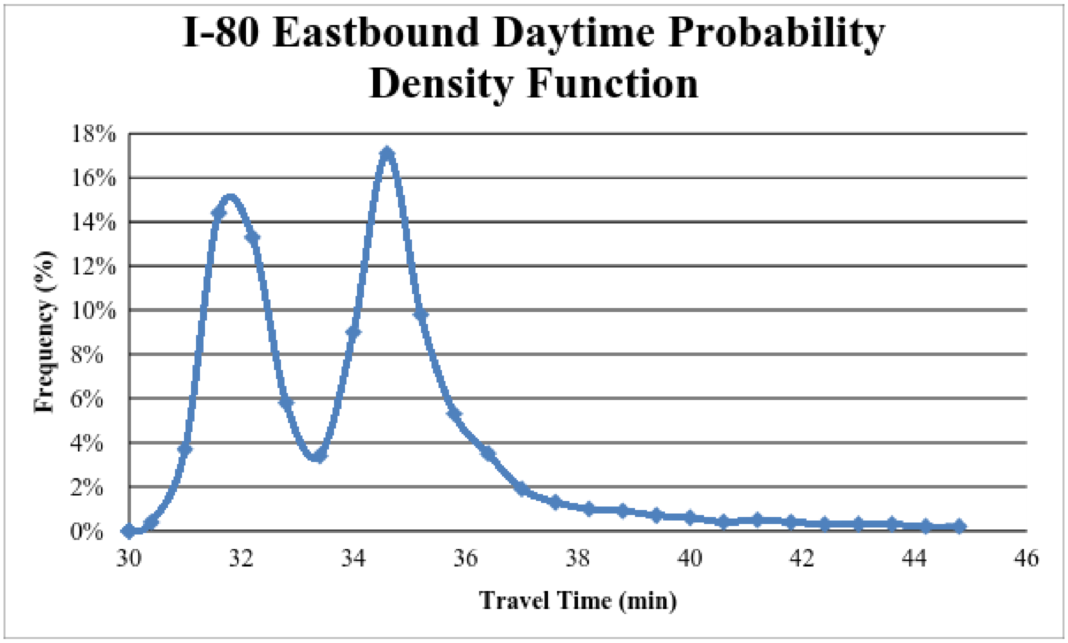


Figure 5.3 Eastbound Travel Time Frequency, Daytime

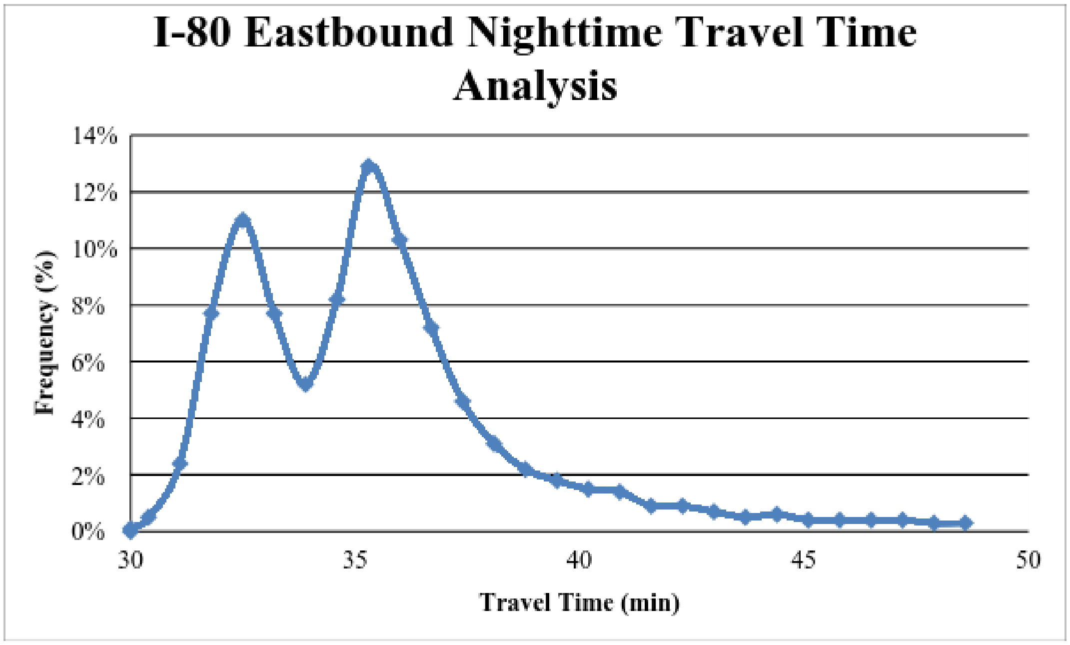


Figure 5.4 Eastbound Travel Time Frequency, Nighttime

After separating the travel times into day and night driving, the bi-modal distribution remained. This means the cause of the bi-modal distribution is not due to daytime and nighttime driving. Actually, the bi-modal distribution is even more extreme than the total distribution curves. Since this is not the solution, the next step was to separate the data into cars and trucks. The 15-minute aggregated data do not include the vehicle length, so other data had to be used. Individual vehicle data were downloaded from the Elk Mountain corridor just west of Laramie, which has similar traffic composition to the Cheyenne-Laramie corridor. Speeds were downloaded from milepost 256.2 (when the conditions were ideal) and separated into passenger vehicles and semi-trucks using a length-based classification. The cars and trucks were separated into two frequency figures, and then combined into a total speed frequency figure. These are displayed in Figure 5.5, Figure 5.6, and Figure 5.7.

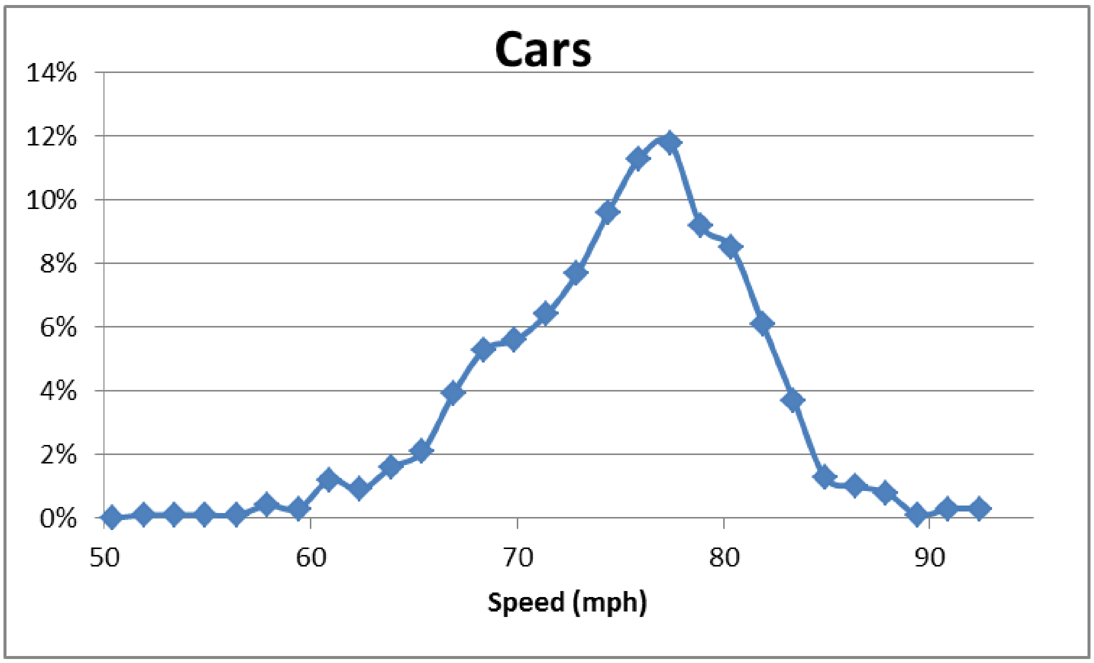


Figure 5.5 Elk Mountain Car Speed Frequency

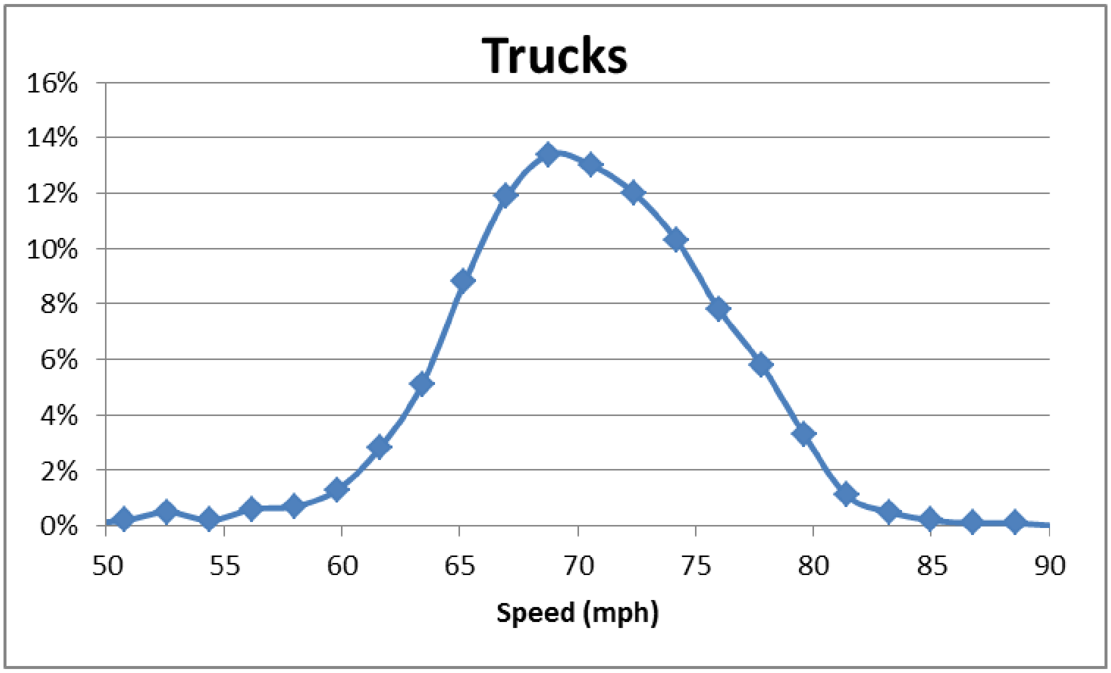


Figure 5.6 Elk Mountain Truck Speed Frequency

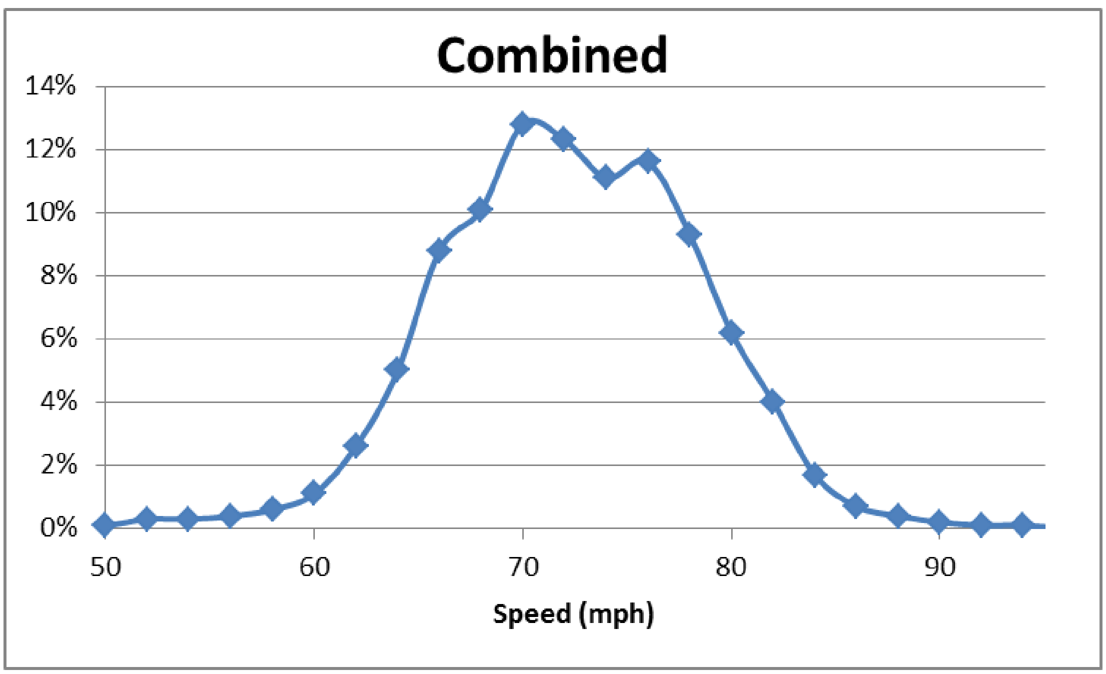


Figure 5.7 Elk Mountain Combined Speed Frequency

The car speed frequency and the truck speed frequency diagrams both have single peaks in their distribution. However, when they are combined, two peaks appear. The two peaks in the combined frequency figure correlate with the single peaks in the car and truck figures at around 78 miles per hour and 69 miles per hour, respectively. The bi-modal distribution is attributed to cars and trucks traveling at different average speeds, as determined by speed sensor data.

Oftentimes, speed sensors data were unavailable due to malfunctioning equipment or a faulty network connection. In these cases, it was important to know how many functioning speed sensors are necessary to accurately represent travel times along a corridor. Table 5.1 shows different densities of speed sensors and resulting discrepancies in travel times when compared with the travel time values calculated with all 14 sensors (considered closest to true travel time).

Table 5.1 Speed Sensor Density Error

# of Speed Sensors Used	14	12	10	8	6	4
Average Eastbound Error	N/A	0.36%	0.77%	0.82%	1.48%	1.95%
Average Westbound Error	N/A	0.18%	0.95%	1.10%	1.11%	1.83%
Resulting Sensor Density (Miles /Sensor)	2.9	3.4	4.1	5.1	6.8	10.1

Even for an average speed sensor spacing of 10 miles, the error in the travel time calculation is very low for rural Interstate corridors. A 2% error in travel time equates to about a 40-second difference in travel time estimations for this particular study. However, it is not recommended that the spacing of the speed sensors for calculation is not spaced more than an average of 10 miles apart due to localized weather effects. When using speed sensors to calculate travel times, it is important to recognize the spacing of the available sensors and to keep that spacing under 10 miles per sensor. This will be important when determining a methodology for reporting travel times to the public. The travel time frequency graphs were recalculated for each direction with the 10 mile/sensor rule in place. This allowed for more observations, but the bi-modal distribution was still present.

5.1.2 WY-28 Travel Time Analysis

Nine speed sensors were installed on WY-28 in the fall of 2012, and they started collecting data on November 8, 2012. Data were gathered at one-minute aggregated intervals between November 8, 2012, and February 24, 2012. The one-minute data was then converted to 15-minute average data. This is equal to 10,464 15-minute intervals for this time period. Unfortunately, due to speed sensor problems, only 1,683 travel times were calculated for the eastbound direction, and 2,031 travel times were calculated for the westbound direction.

Since the aggregated speed sensor data were unreliable, three speed sensors (at mileposts 35, 48.8, and 58) were taken offline to download individual vehicle data. Since WYDOT uses the speed sensors as well, it was not advisable to take all the speed sensors in South Pass offline. Two weeks of data between March 9, 2013, and March 25, 2013, were downloaded from these three speed sensors and added to the travel time calculation data set previously mentioned. For reference, the expected travel time between Farson and Lander at the 65 mph speed limit is 69 minutes. The probability density function graphs for the eastbound and westbound direction are shown in Figure 5.8 and Figure 5.9.

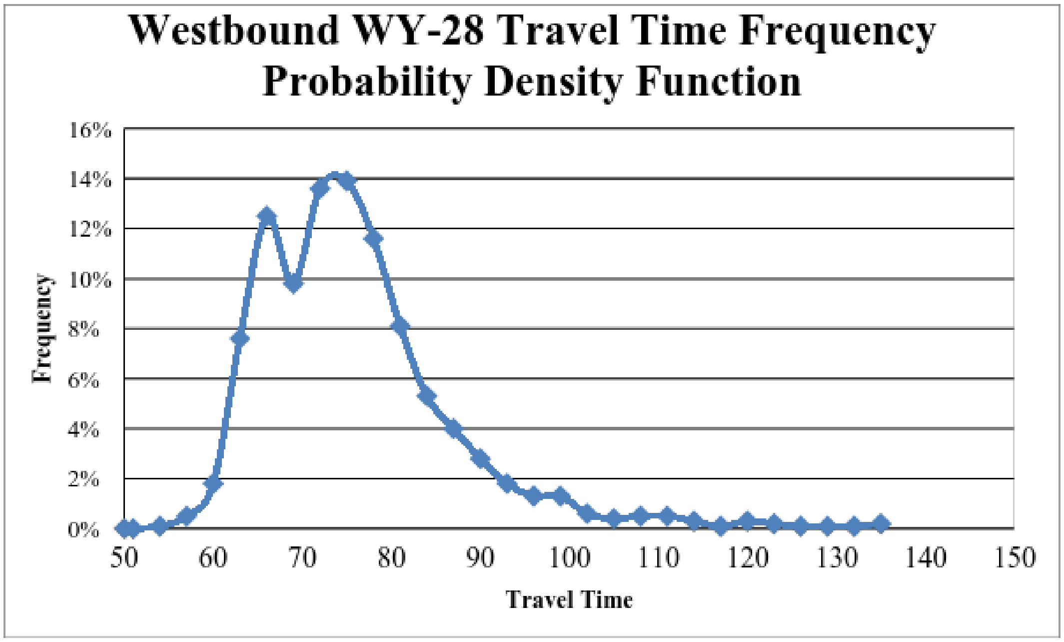


Figure 5.8 Westbound Travel Time Frequency for WY-28

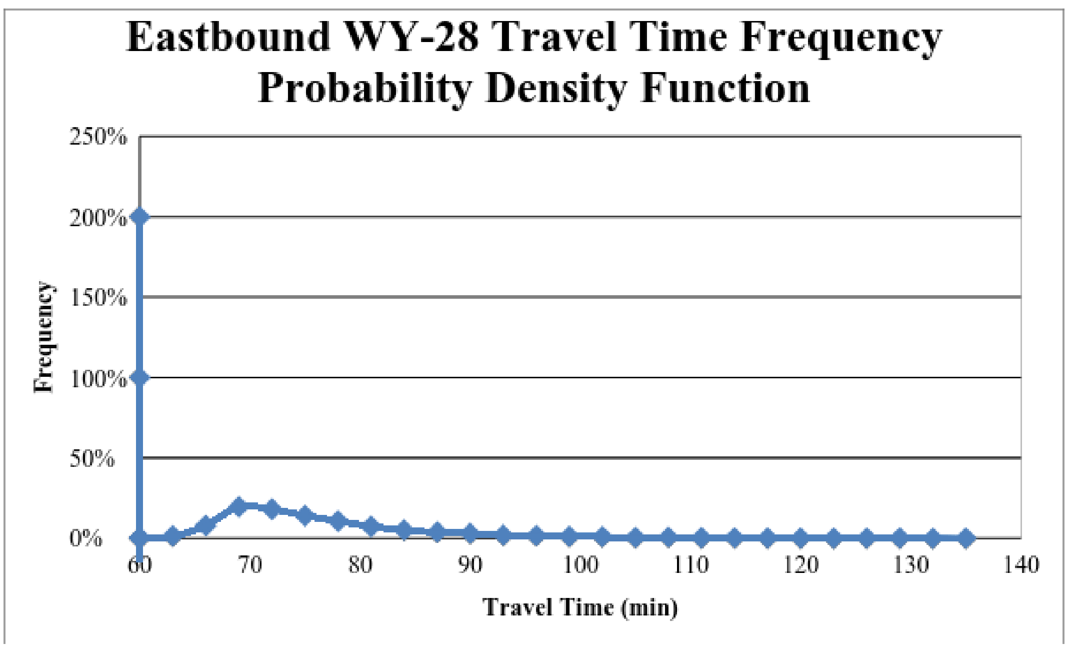


Figure 5.9 Eastbound Travel Time Frequency

The bi-modal distribution is present in the westbound probability density function but is not present in the eastbound. One reason for this may be that there are more steep grades in the westbound direction (1,300 feet of positive elevation change from Lander to Farson), and this slows down the larger vehicles traveling on the road, similar to I-80. The effect of the grade is not seen in the eastbound direction. This could be happening because there has not been enough data collected to see a distinct bi-modal distribution or because all vehicles driving in the eastbound direction are actually traveling at similar speeds. A travel time index cannot be determined from the data because of the insufficient amount of data available. However, trends are beginning to surface about traveling behavior on WY-28 that can help with future research. Some statistics on the reliability of travel times for the corridor can be seen in Table 5.2.

Table 5.2 Reliability Statistics for WY-28

Eastbound		**Westbound**	
Average Travel Time (min)=	75.44	Average Travel Time (min)=	75.07
90th Percentile Travel Time (min)=	88.06	90th Percentile Travel Time (min)=	88.33
Std. Dev.=	11.40	Std. Dev.=	14.07

The average travel time for both directions is already much higher than the expected travel time of vehicles traveling 65 miles per hour between Lander and Farson, which is around 69 minutes. The standard deviations for both directions are very high for the short time the speeds were collected. Since the speed sensors were installed at the beginning of the winter season, large variances and slower speeds were expected. As adverse weather moved in and out of the South Pass area, the travel times fluctuated up and down frequently. If more spring and summer data were added to the data collection, the standard deviation may drop dramatically, and the travel times may begin to move towards the expected travel time at the speed limit.

5.2 Bluetooth Sensor Travel Time Analysis on I-80

One important aspect of this research is to determine the applicability of Bluetooth sensors to measure travel times on rural highways. Unfortunately, the problems encountered with the BlueCompass sensors have limited the amount of usable to data to ten days between September 16, 2012, and September 26, 2012. The data from the BlueCompass sensors were downloaded manually, and the MAC addresses were matched manually in Excel. The “match” function in Excel gives the location of a look-up value in a specified look-up array. This was done across all three BlueCompass sensors in order to determine the travel time for one vehicle along the route. After the matching was complete, travel times were calculated. Some statistics about these travel times can be seen in Table 5.3.

Table 5.3 General Statistics about the BlueCompass Travel Times

Segment between MP 317 and MP 334.8

	Average	**Standard Deviation**	**Maximum**	**Minimum**
Travel Time (min)	18.1	4.8	57.9	13.0
Average Speed (mph)	60.1	9.5	80.6	18.1

Segment between MP 334.8 and MP 343.5

	Average	**Standard Deviation**	**Maximum**	**Minimum**
Travel Time (min)	8.6	1.8	31.3	6.5
Average Speed (mph)	65.8	6.6	86.3	17.9

Total Segment between MP 317 and MP 334.8

	Average	**Standard Deviation**	**Maximum**	**Minimum**
Travel Time (min)	26.8	5.1	66.8	20.7
Average Speed (mph)	62.9	5.3	77.1	35.9

The last part of the analysis involved comparing the travel times calculated from the speed sensors, with the travel times calculated by the BlueCompass sensors. Travel times from both sets of data were calculated at 15-minute average intervals. The 15-minute intervals of time where both the speed sensors and BlueCompass sensors measured travel times were extracted. Then the means of these two data sets were tested against each other using the t-test function in Excel. From the literature review, the null hypothesis for comparing two data sets is that the mean of the two data sets is equal, and the alternative hypothesis is that the mean of the two data sets is not equal. The results of this test for the westbound direction can be seen in Table 5.4, and the results for the eastbound direction can be seen in Table 5.5.

Table 5.4 Bluetooth Travel Times versus Speed Sensor Travel Times, I-80 Westbound

Westbound	*Bluetooth*	*Speed Sensor*
Mean	39.98	34.91
Variance	95.31	0.92
Observations	64	64
Pearson Correlation	0.25	
Hypothesized Mean Difference	0	
df	63	
t Stat	4.24	
P(T<=t) one-tail	3.75E-05	
t Critical one-tail	1.67	

Table 5.5 Bluetooth Travel Times versus Speed Sensor Travel Times, I-80 Eastbound

Eastbound	*Bluetooth*	*Speed Sensor*
Mean	43.48	34.34
Variance	28.67	1.37
Observations	71	71
Pearson Correlation	0.23	
Hypothesized Mean Difference	0	
df	70	
t Stat	14.78	
P(T<=t) one-tail	1.63E-23	
t Critical one-tail	1.67	

It turns out that the hypothesis testing was not needed between these two data sets since the means are visibly different, and the variance in travel times recorded by the Bluetooth sensors is very high. In fact, the mean travel times being reported for each 15-minute interval by the BlueCompass sensors were higher than the speed sensor travel times for all 133 matches. The average speed for the mean travel time calculated by the BlueCompass sensors is 63 miles per hour and 58 miles per hour for the westbound and eastbound directions, respectively, compared with the average speed calculated from the speed sensors, which was between 72 and 73 miles per hour.

One possible reason why the BlueCompass calculated speeds are so low might be due to the abundance of semi-trucks with Bluetooth enabled devices, and the lack of passenger vehicles with Bluetooth enabled devices. An effort was made to try and match the MAC addresses to an electronic device or vehicle type. However, MAC addresses can only be linked back to the vendor that made the electronic device. There are many websites that can convert MAC addresses to the name of the company that produced the electronic device. The website that was used for this research is called http://www.macvendorlookup.com/. Out of the 200 MAC addresses that were used for travel time calculation, 186 were matched with a vendor. Besides one MAC address hit from an Apple product, it is impossible to determine what kind of electronic devices were read by the BlueCompass sensor. Table 5.6 shows a summarized list of the vendors that were matched with the MAC addresses.

Table 5.6 Total Number of Vendors Matched to MAC Addresses

Vendor Name	# of MAC Addresses
Ezurio Ltd.	148
Cisco Systems	11
Motorola	7
Digiboard Inc.	5
Giga-Byte Technology Co. Ltd.	3
Wistron Neweb Corp.	3
AzureWave Technologies Inc.	2
Hon-Hai Precision Co. Ltd.	2
Apple Inc.	1
Intel Corporation	1
Intermec Corporation	1
Pronet GMBH	1
Quatech Inc.	1

There are many reasons why Bluetooth sensors are not ideal for rural highways in Wyoming. First, the time between usable MAC address reads is unpredictable. There could be seconds between reads, or there could be hours. On a highway that accommodates up to 17,000 vehicles a day, it is unacceptable to have multiple hours without any data for travel time calculations. Second, there seems to be a bias toward semi-trucks in the MAC address travel time calculations. Speed sensors do a better job at representing all types of traffic on the highway, and they are more reliable.

5.3 Travel Time Index on I-80

A travel time index was created using the same data from the probability density function graphs in Figure 5.1 and Figure 5.2. The travel time index will help give WYDOT a reliable and consistent method for reporting current traveling conditions to the public. A new histogram was created from these data, with each bin representing a five-minute interval of travel times. The purpose of creating the histogram was to find the natural breaks in the data where longer travel times were more likely. These natural breaks in the data were used to determine the thresholds in the travel-time-based road condition index.

The travel time index worked well for both directions of travel. The natural breaks in the eastbound direction were also found in the westbound direction. There were two natural breaks found: one at 70 minutes and one at 100 minutes. A 70-minute travel time is an average travel speed of 36 mph and a 100-minute travel time is an average travel speed of 25 mph. These two breaks in the data created three indices. However, three indices is not enough information for travelers to discern between passable road conditions and poor road conditions, so the three indices were split into six indices. A table of the index ranges is displayed in Table 5.7. The right tail of the graphs used to determine the natural breaks in the travel time frequency are shown in Figure 5.10 and Figure 5.11.

Table 5.7 Travel Time Index Numbers and Ranges

Index #	Color	Travel Time Range (min)
0	Green	<= 40
1	Blue	40.01 - 55
2	Purple	55.01 - 70
3	Yellow	70.01 - 85
4	Orange	85.01 - 100
5	Red	> 100

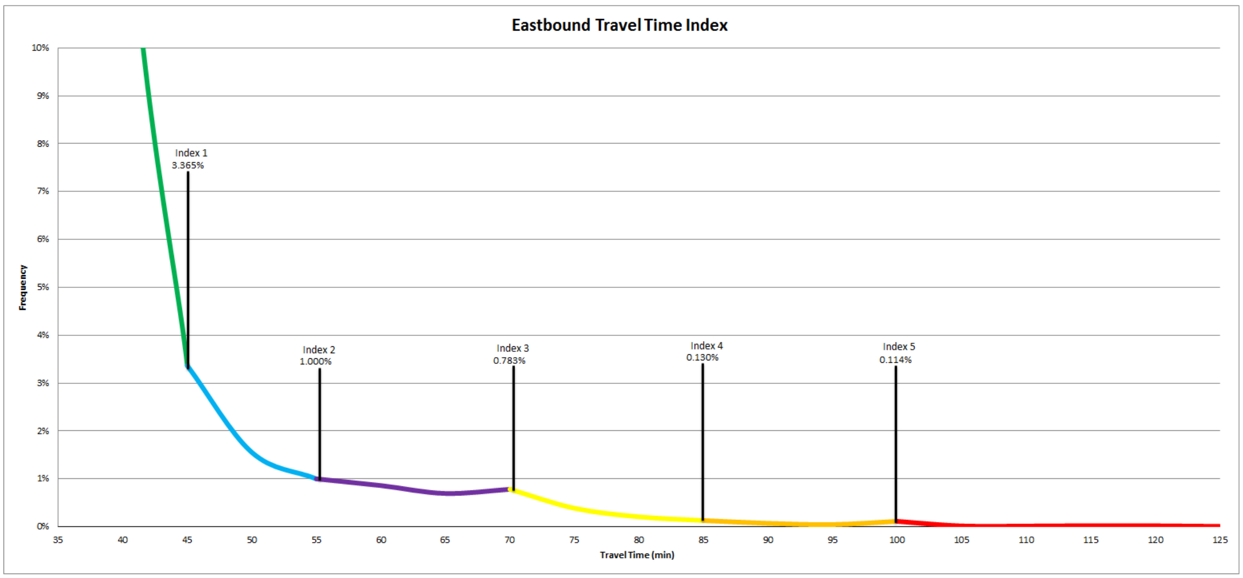


Figure 5.10 Eastbound Travel Time Index for I-80 between Cheyenne and Laramie

Figure 5.11 Westbound Travel Time Index for I-80 between Cheyenne and Laramie

Each index was numbered and colored, with “Index 0” (color coded green) indicating ideal driving conditions for driving on I-80 between Cheyenne and Laramie. Indices one through five were represented with the colors blue, purple, yellow, orange, and red, respectively. Next, the index was applied to the spreadsheet of 15-minute aggregated travel times between October 2009 and October 2010. In many cases, the index would switch back and forth between index numbers for every 15-minute interval. If this were happening while the index was being reported to the public, they may see the new procedure as unreliable. In order to stop this from happening, the travel time index was recalculated on the condition that the measured travel time index of the current interval matched the measured travel time index of the previous interval in order for it to be a reported travel time index. This way the index would have to be measured for two consecutive 15-minute intervals before being reported. After this condition was applied to the data, the indices were recalculated, and the statistics for each were calculated. A full table with the bin numbers and number of travel times observed in each bin is shown in Appendix D. A summary table of each index, for each direction of travel, is shown in Table 5.8 and Table 5.9.

Table 5.8 Eastbound Travel Time Index Summary

Eastbound			
Index #	Range	# of Occurrences	% Observed
0	< 40	27,900	90.62%
1	40.01 - 55	1,822	5.92%
2	55.01 - 70	720	2.34%
3	70.01 - 85	223	0.72%
4	85.01 - 100	71	0.23%
5	> 100	51	0.17%

Table 5.9 Westbound Travel Time Index Summary

Westbound			
Index #	Range	# of Occurrences	% Observed
0	< 40	26,782	86.86%
1	40.01 - 55	2,990	9.70%
2	55.01 - 70	650	2.11%
3	70.01 - 85	265	0.86%
4	85.01 - 100	63	0.20%
5	> 100	83	0.27%

Table 5.10 and Table 5.11 further describe the duration of each index and the percent of time the index was used throughout the year.

Table 5.10 Eastbound Travel Time Index Usage between October 2009 and October 2010

Eastbound				
Index #	**Total Time Used**	**Average Duration**	**Maximum Duration**	**% of Time**
0	6327:45:00	29:59:22	281:45:00	72.237%
1	612:15:00	3:00:58	16:30:00	6.989%
2	144:45:00	1:55:48	10:45:00	1.652%
3	79:30:00	1:56:20	11:30:00	0.908%
4	14:45:00	0:59:00	2:15:00	0.168%
5	10:30:00	3:30:00	7:00:00	0.120%
N/A Data	1570:15:00			
Total Time	8759:45:00			

Table 5.11 Westbound Travel Time Index Usage between October 2009 and October 2010

Westbound				
Index #	**Total Time Used**	**Average Duration**	**Maximum Duration**	**% of Time**
0	6018:45:00	23:03:37	200:45:00	68.709%
1	877:15:00	3:27:13	40:30:00	10.015%
2	148:00:00	1:49:38	6:45:00	1.690%
3	102:15:00	1:53:37	15:15:00	1.167%
4	40:15:00	1:32:53	5:45:00	0.459%
5	19:15:00	1:55:30	4:45:00	0.220%
N/A Data	1554:00:00			
Total Time	8759:45:00			

These tables show that this travel time index can be an effective tool for communicating with motorists. The green ideal driving condition index would have been reported a vast majority of the time over the year, and each increasing index would have a smaller and smaller chance of being reported. This increases the reliability of the travel time index since the larger indices are not reported as often. Only 17% of the data were missing for both directions. As long as the speed sensors are functional, the travel time index could be used to vastly improve WYDOT's road and weather condition reporting system.

A flow chart of decisions and actions was created in order to maintain consistency and to keep the travel time index reliable. This flow chart starts by downloading data from each speed sensor from the past 15 minutes. The data from a speed sensor are then added to or left out of a combined spreadsheet based on count, occupancy, and whether or not a speed was recorded. The minimum number of vehicles required for the speed sensor data to be used is 55. This number is based on the minimum observed AADT (average annual daily traffic) on I-80 between Cheyenne and Laramie in 2011. The lowest AADT in 2011 was observed in February, and it was 5,285 (WYDOT, 2012), which equates to around 55 vehicles every 15 minutes. After this, the speed sensors spacing is calculated (including the origin and destination in question). From previous research on travel time calculations with speed sensors, if the speed sensors are more than ten miles apart from each other, the accuracy of the travel time decreases. If there were data downloaded from the speed sensors, and they were less than ten miles apart, only then is the average travel time calculated for that 15-minute interval.

Next, the travel time index is calculated. The travel time is put into a category based on the travel time index in Table 5.9. However, this is not the reported index. Only if an index has occurred for a time of at least 30 minutes will it be reported to the traveling public. This means a travel time index has to be read for two consecutive 15-minute intervals before it can be reported. The "read" index (the index that is measured from the travel times) versus the "true" index (the index that is reported to the public in the end) is an important factor in this flow chart. Although the "true" and "read" index methodology will help filter outliers, it may not react as quickly as needed. For future research, the algorithm will be coded into the program MATLAB. After it is coded, the index procedure will be adjusted to allow for more frequent changes in the index. The full flow chart that was created for the travel time index is in Figure 5.12.

rdinal

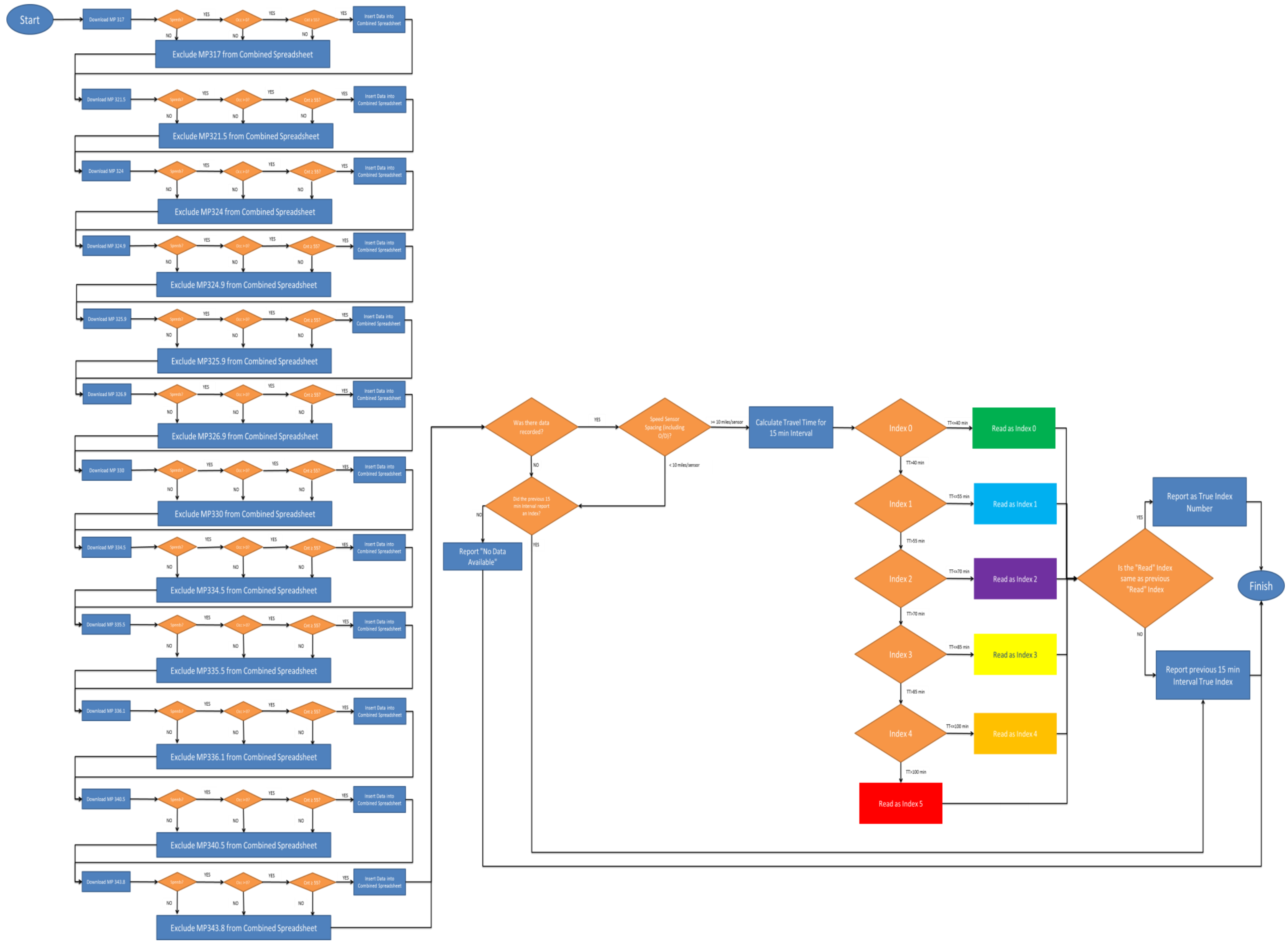


Figure 5.12 Flow Chart for Reporting the Travel Time Index

5.4 Logistic Regression of Travel Time Index and Weather Variables

The goal of this regression analysis is to determine which weather variables are the most important when they are modeled against travel time indices. The final model can then be interpreted to determine if the travel time index methodology is capturing weather conditions adequately. Originally, nine weather variables were selected for the analysis: surface temperature (SfTemp), air temperature (AirTemp), relative humidity (RH), dew point, average wind speed, gust wind speed, presence of precipitation (Precip), and a day-night variable (DayNight). The "Precip" variable is a binary variable where 0 equals no precipitation, and 1 equals precipitation. The "DayNight" variable is also a binary variable, where 0 equals daytime, and 1 equals nighttime. One winter weather event was selected (500 data points between October 26, 2009, and October 31, 2009) and compiled to perform the analysis. This storm event was chosen because it included all six indices, and the index number gradually increased and decreased as the storm event passed over the highway. A Pearson correlation table was created in order to determine if there were any multicollinearity issues between variables. The resulting Pearson correlation table between all the variables is shown in Table 5.12.

Table 5.12 Pearson Correlation Coefficients for Travel Time Index Analysis

Pearson Correlation Coefficients, N = 500

	SfTemp	AirTemp	RH	Dewpoint	Avg Wind Speed	Gust Wind Speed	Precip	DayNight
Index	-0.62957 <.0001	-0.72281 <.0001	0.75132 <.0001	0.08279 0.0643	0.25565 <.0001	0.283 <.0001	0.76588 <.0001	-0.03049 0.4964
SfTemp		0.89176 <.0001	-0.67147 <.0001	0.26338 <.0001	-0.24175 <.0001	-0.25584 <.0001	-0.74053 <.0001	-0.28559 <.0001
AirTemp			-0.77064 <.0001	0.2583 <.0001	-0.21006 <.0001	-0.22253 <.0001	-0.84743 <.0001	-0.06149 0.1698
RH				0.40721 <.0001	0.43782 <.0001	0.4571 <.0001	0.94037 <.0001	0.04343 0.3324
Dewpoint					0.36284 <.0001	0.37135 <.0001	0.18244 <.0001	-0.02606 0.561
Avg Wind Speed						0.98531 <.0001	0.37694 <.0001	-0.02611 0.5602
Gust Wind Speed							0.39296 <.0001	-0.00654 0.884
Precip								0.05237 0.2424

The highlighted portions of the previous table show three instance of severe multicollinearity in this data set with a value greater than 0.85. If two variables are perfectly collinear, their Pearson correlation value would be either a 1 or a -1. The highest value of multicollinearity was between the Gust Wind Speed variable and the Average Wind Speed variable at 0.985. The second highest value was between precipitation and relative humidity. The third highest value of multicollinearity was between air temperature and surface temperature. These three variable interactions played a big part in the variable selection process described later in this section.

Since the desired output for this analysis is a categorical index, where the order matters, the type of analysis selected was an ordinal logistic regression. A logistic regression model predicts the probability of one outcome happening over another. This is different from a linear regression model, which predicts a continuous dependent variable. For ordinal logistic regression, the output is a cumulative probability for the specified category (from the low category to the high category) (Allison, 1999). For this analysis, there were six categories for each of the six indices. The general form of the cumulative logistic equation is displayed in Equation 6, where "π" equals the probability of the response being equal to or less than category "j".

$$log\ (\frac{\pi_{ij}}{1-\pi_{ij}}) = \alpha_j + \beta x_i$$

Equation 6. Cumulative Logistic Model (Allison, 1999)

When this equation is rearranged to solve for "π", Equation 7 is formed.

$$\pi_{ij} = \frac{exp(\alpha_j + \beta x_i)}{1 + exp(\alpha_j + \beta x_i)}$$

Equation 7. Cumulative Logistic Model Solved for π (Allison, 1999)

In order to determine which model had the best fit, the Akaike Information Criterion (AIC) was used. For this criterion, the model with the best fit has an AIC value closest to zero. Many combinations of variables were used, but the multicollinearity issues made variable selection difficult. Through a meticulous process of adding and removing variables from the model, it was determined that the average and gust wind speed, wind direction, and precipitation variables were not significant at a confidence level of α=0.95, so they were removed. After the model selection process, the air temperature, surface temperature, dew point, relative humidity, and day/night variables remained in the model. This model had an AIC equal to 908.

Even though this model had the lowest AIC, multicollinearity between the surface temperature and air temperature variables was causing the coefficient estimates to be the opposite of what was expected. The surface temperature coefficient estimate was negative whereas the air temperature coefficient was positive. In theory, these two temperature coefficient estimates should have the same sign. In the end, the final model contained three variables: air temperature, relative humidity, and day/night, which all had coefficient signs as expected. The AIC of this model was 930 and the estimates are displayed in Table 5.13.

Table 5.13 Cumulative Logistic Regression Analysis Parameter Estimates

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**5**	1	-8.0341	0.9517	71.2618	<.0001
Intercept	**4**	1	-6.7473	0.8558	62.1598	<.0001
Intercept	**3**	1	-4.6518	0.8276	31.5933	<.0001
Intercept	**2**	1	-1.1675	0.8611	1.8383	0.1751
Intercept	**1**	1	1.6758	0.7836	4.5738	0.0325
AirTemp		1	-0.1202	0.0161	55.9316	<.0001
RH		1	0.0666	0.00802	68.9191	<.0001
DayNight	**1**	1	-0.2831	0.0941	9.0466	0.0026

The model in Table 5.13 was selected for a few different reasons. The AIC is larger than the previous model mentioned, but the interpretation of each variable coefficient is much more meaningful. With multicollinearity seemingly eliminated from the model, each coefficient estimate is pointing in the expected direction. Also, the coefficient estimates have more of an effect on the probability for each index. In previous models, the intercept estimates were larger (between -25 and -15) and the variable coefficient estimates were about the same (between 0.007 and 0.4). With the model selected, the intercepts are between -8 and 1, and the coefficient estimates have more of an impact on the probability of each index.

The interpretation of each intercept is slightly different from other model types. Since the output of this model is a cumulative probability for each index, the intercepts are interpreted as the cumulative probability of that index at AirTemp=0, RH=0, and DayNight=0 (Allison, 1999). Since index 0 is the base condition, it would have a cumulative probability of zero. To obtain the probability of each index, e.g., index 5, the cumulative probability of index 5 would be subtracted from the cumulative probability of index 4.

A few other observations can be made from this model:

- As the air temperature decreases, the chances of being in a higher index increase.
- As the relative humidity (RH) decreases, the chances of being in a higher index decrease.
- If it is nighttime, the chances of being in a higher index increase. If it is the daytime, the chances of being in a higher index decrease.

Overall, the goal of the statistical analysis for this research was to construct a model that shows the relationship between weather variables and the travel time index in order to verify the travel time index methodology was adequately describing weather conditions. Multicollinearity issues were found between air temperature and surface temperature, average wind speed and gust wind speed, and precipitation and relative humidity. The best model for interpretation included three variables: air temperature, relative humidity, and day/night. The correlation between these variables and the travel time index is an accurate representation of what is expected. For future research, a prediction model could be created purely from the weather variables by performing discriminate analysis or principal component regression. These two types of analysis can use all the weather variables and eliminate multicollinearity. The model that had the lower AIC is included in Appendix E.

6. PROPOSED INFORMATION DISSEMINATION METHOD AND SURVEY PROCEDURE

This section will discuss the display methods for travel times, average speed, or the travel time index as well as methods that should be used to measure the effectiveness of reporting a travel time and/or travel time index as part of pre-trip or during-trip information. The first section will discuss how travel times, average speed, or the travel time index can be incorporated into WYDOT's current road condition reporting system. The second section will lay out a plan for evaluating the use of travel times for reporting road conditions after it has been implemented.

6.1 Incorporating Travel Times, Average Speeds, or the Travel Time Index into the WYDOT System

As was mentioned in the literature review, the FHWA released documentation concerning the regulation of road weather displaying methods (FHWA, 2012). There are many approved methods on how to report travel times for each type of media. For dynamic message signs (DMSs), it is important not to put too much information on a sign at one time. Since there are two types of DMSs on I-80, two-line and three-line, the message will need to be altered according to the type of sign being used. For the three-line overhead signs, the message should read like the example in Figure 6.1 or Figure 6.2.

TRAVEL TIME TO I-25 50 MIN AT 6:30PM

Figure 6.1 DMS Display Example, Travel Time

AVERAGE SPEED 49 MPH AT 6:30PM

Figure 6.2 DMS Display Example, Average Speed

Since a rural corridor like I-80 is more likely to have users who are unfamiliar with the distances between cities, Figure 6.2 may be a more pertinent option. Since there are so many unfamiliar users, it is not advised to use the travel time index for during-trip information. For more severe weather conditions, this display can also be paired with a second display that reports the type of travel conditions being experienced, along with the traveling index. Two messages, or phases, on one DMS are the maximum number recommended by the FHWA guidelines. There is not a guideline for reporting travel times on two-line dynamic message signs. Since it is difficult to fit travel time information on a two-line sign, they should be used to display average speed information and road condition information. This can be done in one or two phases depending on the number of adverse conditions being experienced on the route. Figure 6.3 is an example of what this might look like.

SLICK ROAD BLOWING SNOW
AVERAGE SPEED 45 MPH AT 10:00AM

Figure 6.3 Two-Line DMS Two Phase Example

Some of the travelers on I-80 are unfamiliar with the distance, and expected travel times between cities. So reporting a travel time on DMS may not be as effective. There are a couple of different options to solve this problem. One way is to report an average speed instead of a travel time. Since the highway has a posted speed limit, an average speed similar to Figure 6-2 may be more relatable to all travelers. Another option would be to report an ideal condition travel time along with the observed travel time. This would allow unfamiliar travelers to quantify the slow travel time. The disadvantage to the latter is that it will need two phases on a three-line DMS. An example of what this might look like is in Figure 6.4.

TRAVEL TIME TO I-25 50 MIN AT 6:30PM
IDEAL TRAVEL TIME 34 MIN

Figure 6.4 Three-Line DMS Travel Time with Baseline

The guidelines also recommend the number of lines of information that can be displayed for certain speeds. For speeds greater than 35 miles per hour, it is recommended that the message be limited to four lines of data. This guideline does not matter for the two-line DMS since the maximum they can hold are four lines in a two-phase message. For three-line DMS, this guideline does need to be considered. This adds another disadvantage to Figure 6.4. During the surveying process, travelers could be asked whether or not this is too much information for them to understand.

Another important source being utilized by travelers is WYDOT's Wyoming Traveler Information Map on the Internet (www.wyoroad.info). The key factor to reporting travel conditions online is consistency while utilizing perceived common knowledge about transportation. For instance, red should be used for extreme caution, yellow for caution situations, and green should be used for normal conditions. As a reminder, the colors chosen for the travel time index were green for index 0, blue for index 1, purple for index 2, yellow for index 3, orange for index 4, and red for index 5. Green and red were chosen as the ends of the index because of their use in the WYDOT road condition reporting system to report dry roads and closed roads, respectively. If the travel index was added to the WYDOT website, Figure 6.5 shows what it might look like with I-80 between Cheyenne and Laramie. At this time it is proposed to display a single travel time for the corridor, but given the coverage of speed sensors, the corridor could be segmented to provide more detailed information about average speeds within the corridor. This would only be proposed for the web-based information since it is

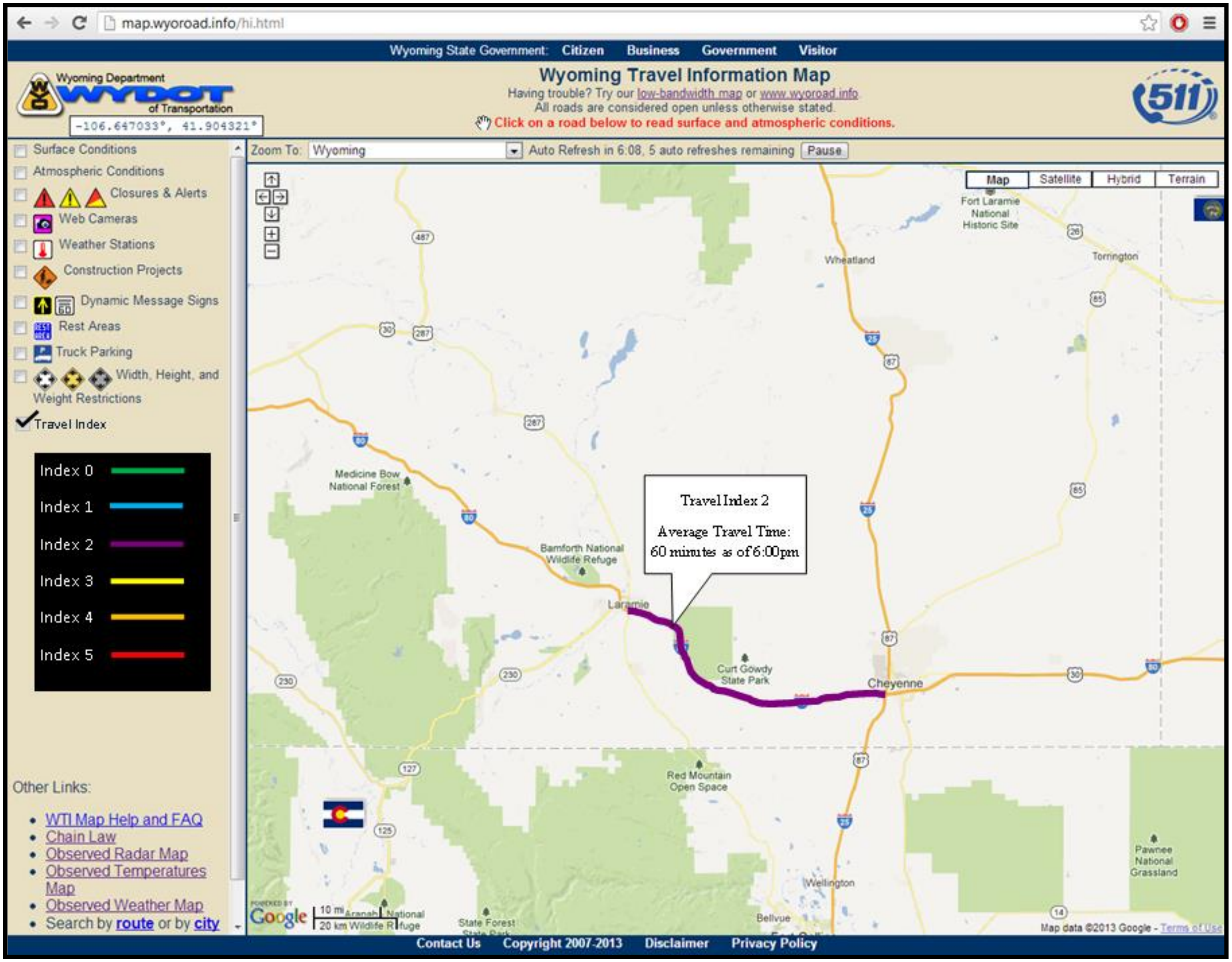


Figure 6.5 WYDOT Road Condition Map with Travel Index

difficult to convey such detailed information to travelers outside of their accessibility to a map environment.

There other forms of media where the travel time index can easily be incorporated. The 511 phone service and highway advisory radio can expand the road condition report for each highway by adding the travel time index, travel time, the time stamp, and an ideal travel time for the highway in question. Reporting travel times through these three types of media will help the public make better decisions before they go on a trip, and during their trip.

6.2 Post-Implementation Survey Method

After the new condition reporting system has been implemented, the public needs to be surveyed to see how these changes affected their decision to drive I-80. There are two different methods that should be used to gather information. The first method is to assemble a frequent traveler focus group. This group would consist of people who frequently travel the corridor between Cheyenne and Laramie, and who are willing to fill out a web survey that is sent to them after storm events.

The frequent traveler group can be formed in a couple of different ways. One way is to post flyers around Laramie and Cheyenne announcing the frequent traveler group with information regarding contact information. Another option is to place an advertisement in newspapers from both cities with the same information as the flyer. The flyer and advertisement would include an email address that could be contacted for more information, as well as a link to a Facebook page. The third option for recruiting for the frequent traveler group is to make an announcement at University of Wyoming athletic events. This would be a great place for recruitment since the people who attend these events are usually from Laramie or travel from Cheyenne. An example of the flyer and advertisement that would be used can be seen in Figure 6.6 and Figure 6.7.

Figure 6.6 Frequent Traveler Focus Group Recruitment Flyer

Frequent Traveler on I-80?

Do you frequently travel on Interstate 80 between Laramie and Cheyenne? A University of Wyoming study is evaluating the traveler information for this corridor and would like feedback on the information provided on the roadside signs, road condition website, and other sources.

To become a member of the frequent traveler, email us at **WYDOTsurvey@gmail.com** or like our Facebook page at **www.facebook.com/WYDOTsurvey** for more information.

As a member of the panel you will be asked to fill out periodic web surveys on the traveler information that was provided for various roadway conditions.

Figure 6.7 Frequent Traveler Focus Group Newspaper Advertisement

After the frequent traveler group is assembled, the next step is to create the survey. The survey should include, but is not limited to, the following questions:

- Did you consult any WYDOT resources on the traveling conditions for your trip today? If so, which ones?
- Which information most drastically affected your pre-trip driving mind set?
    - Travel Time Index, Road Conditions, or Weather Report
- Do you think the travel time index displayed accurately represents the conditions you experienced today?

- On a scale of 0 (great conditions for driving) to 5 (I was extremely uncomfortable driving today), what do you think the travel time index should read?
- What are things that need to be improved in WYDOT's road and weather reporting system?
- Were the messages on the dynamic message signs comprehendible?
- How big of a difference was the travel time/average speed reported on the DMS with what you were experiencing?
- Which would you prefer displayed on the DMS?
    - Travel Time Index, Travel Time, or Average Speed
- Which would you prefer reported on the WYDOT Road Condition Map Online?
    - Travel Time Index, Travel Time, or Average Speed

At the time a person becomes a frequent travel panel member, basic questions for name, age, gender, and preferred method for receiving surveys would be asked. Random traveler surveys should be used in conjunction with the frequent traveler focus group to determine the effectiveness of the travel time index on a user group likely to be less familiar with the corridor and the type of weather conditions that can be encountered. This would involve going to popular traveler destinations, like truck stops, and asking random travelers about their experience on the highway. Surveys would be administered at these truck stops during bad winter weather conditions in order to get the most meaningful answers. Also, an incentive can be added (such as a free cup of coffee) to get more participation. From these questions, the effectiveness of the travel time index can be determined, and further implementation of the index can be discussed.

This surveying procedure is specifically designed for travel time reporting for I-80 between Cheyenne and Laramie. When a travel time and travel time index procedure is created for South Pass, a new surveying procedure should be created. This will be a more arduous task since the traffic volume is so much smaller, and there are a limited number of places where random travelers could be surveyed (as opposed to I-80, which has multiple truck stops available for random traveler surveying). For South Pass, the frequent traveler focus group may have to include oil and gas companies developing in the area. Surveying travelers on WY-28 may be a very difficult task.

7. SUMMARY AND CONCLUSION

The final section of this report will first present a summary from each section of research. Then, each section of research will have its own set of conclusions. Finally, future research will be recommended based on findings in this paper.

7.1 Summary of Research

7.1.1 Summary of Travel Time Frequency Analysis for I-80 and WY-28

Travel time frequency graphs were calculated through speed sensor data from October 2009 to October 2010. One obvious characteristic about these graphs was the bi-modal distribution, which is unusual in existing travel time research. One theory presented for why these data have two distinct modes of travel time was that they were the difference between day and night speeds. The travel times were then separated into day and night, and the travel time frequency graphs were recalculated. The resulting graphs produced an even more predominant bi-modal distribution compared with the total travel time frequency graphs.

The second theory for the bi-modal distribution is the speed preferences between passenger vehicles and commercial trucks. Unfortunately, the yearlong data recorded between 2009 and 2010 were aggregated data, and did not contain information on the vehicle types passing by the sensors. In order to perform these calculations, individual vehicle data were used from the Elk Mountain corridor, located west of Laramie. Speeds were separated into passenger vehicle and commercial truck based on the length measured by the speed sensor. When the speed frequency diagrams were calculated for the cars and trucks, only a single mode was observed. When the speed data were combined, a bi-modal distribution was observed. This indicates that the bi-modal distribution being seen in the travel time frequency graphs is caused by a large difference in speed preferences between passenger vehicles and commercial vehicles on I-80. This will need to be considered if more travel time calculations need to be done.

In addition to the travel time frequency calculated on I-80, travel times were calculated for WY-28 between Farson and Lander. Speed sensors on this corridor were installed and started collecting data on November 8, 2012. Three months of data were downloaded between November and January, and the speeds were converted to travel times for the corridor. There were missing data due to software malfunctions, so three speed sensors were taken offline and used to collect individual vehicle data for two weeks in March. The individual data were combined with the three months of 15-minute aggregated speed sensor data to produce the travel time frequency graphs.

The two travel time frequency graphs for WY-28 tell two disparate stories regarding the traveling behavior on this corridor. There is a bi-modal travel time frequency in the westbound direction but not the eastbound. In addition to the speed preferences between cars and semi-trucks, the bi-modal travel time could also be due to extreme grades present. There is a large increase in elevation when traveling from Lander to Farson (westbound direction). This, combined with the fact that the WY-28 goes through a small part of the Wind River mountain range, causes the design of the roadway to include many steep grades. There are more uphill steep grades in the westbound direction, which could be the cause of the non-uniformity in the travel time frequency in that direction. The eastbound direction travel time frequency is more uniform because it is easier for all types of vehicles to maintain the speed limit going downhill from Farson to Lander.

7.1.2 Summary for the Utilization of Bluetooth Sensors on Rural Corridors

In order to determine the effectiveness of Bluetooth sensors on rural corridors, BlueCompass sensors were purchased from Acyclica and installed at three locations on I-80 between Cheyenne and Laramie. After many complications with the sensors, they were able to collect MAC addresses for ten days. The MAC addresses collected from the three Bluetooth sensors were downloaded, matched, and the travel times were calculated. The travel times from the MAC address matching procedure were compared to the travel times calculated from the speed sensors during the same time period to determine if the travel times were similar.

A simple t-test was performed to determine whether or not the two data sets were familiar. The "equal mean" null-hypothesis was rejected, but this test did not need to be performed since the mean of the Bluetooth dataset was much higher than the speed sensors. The observed average travel times calculated by the speed sensors were 10 minutes lower than the travel times calculated by the Bluetooth sensors. One theory as to why this is happening is that commercial trucks have more electronic equipment compared with passenger vehicles. Since larger vehicles were being read more often than smaller vehicles, the average travel time was higher.

In addition to the travel times being higher than the speed sensor data, the number of vehicles that were tracked along their route was also very low. The amount of time between usable MAC address hits varied between seconds and hours. The Bluetooth sensors measured a very small fraction of the volume being seen on the route and had a low penetration rate. The vehicle count at each speed sensor was compared to the number of usable MAC address hits (MAC addresses that were sensed at all three sensors), and the results of this analysis are shown again in Table 7.1.

Table 7.1 Bluetooth Penetration Rate

Number of MAC Address Hits and Penetration Rate			
Total Hits for 10 days	Hits per Day	Hits per Hour	Average Penetration Rate
766	76.6	3.2	0.6%

In order to determine if the Bluetooth sensor was measuring more commercial vehicles than passenger vehicles, the list of MAC addresses was matched with the company that manufactured the Bluetooth device. There was one instance where an "Apple Inc." product was read, which would indicate a personal device. Other than that, it was impossible to determine what type of electronic device was read by the Bluetooth sensor.

7.1.3 Travel Time Index Summary

The purpose of creating a travel time index was to provide another information option for travelers on the highway. It was important to keep the travel time index as reliable as possible. A traveler might not notice they are five minutes later than expected, but they may notice 15 or 20 minutes of delay due to weather. But if the travel time ranges for each index were too large, then travelers might not be able to discern between manageable road conditions and hazardous road conditions. The travel time index was created by finding natural breaks in the travel time frequency graphs, and then adjusting those natural breaks to increase reliability.

Three natural breaks were found at the same time intervals on both eastbound and westbound frequency charts. These three breaks were used as a foundation for the six indices that were created. These indices were labeled from 0 to 5, where 0 indicates ideal conditions for driving. A reminder of what the range is for each index is shown in Table 7.2.

Table 7.2 Travel Time Index Numbers and Ranges

Index #	Travel Time Range (min)
0	< =40
1	40.01 - 55
2	55.01 - 70
3	70.01 - 85
4	85.01 - 100
5	> 100

If the I-80 corridor between Cheyenne and Laramie was driven at the speed limit for the entire distance, the travel time would be 34 minutes. Even though the upper bound of the ideal travel time index is six minutes slower than the expected travel time, 70% of the travel times measured was categorized as index 0. Fifteen-minute travel time intervals between travel time indices give drivers a more realistic view of the types of conditions that exist.

The travel time index, used in addition to the current road and weather system, could help drastically improve the quality of road condition information. For example, if the road conditions were reported as foggy along and ranked as index 2, travelers would know that the fog is severe enough to delay drivers for up to 30 minutes. On the other hand, if the road conditions were reported as slick in spots along with index 0, the travelers would know that the road is starting to dry and conditions are returning to normal. The travel time index can be used effectively along with the current system to improve traveler knowledge and information system reliability.

7.1.4 Summary of Statistical Analysis

The purpose of the statistical analysis was to determine which weather variables had the greatest impact on the travel time index. The travel time from October 2009 to October 2010 was reduced to a one week storm that contained all six indices. This one week of travel time indices was matched with weather data downloaded from road weather information system stations. In order to compare ordinal data with a variety of different types of variables, ordinal logistic regression was the type of analysis performed. It is important to remember that this type of analysis will not directly give a travel time index based on weather conditions, but rather it will yield a probability for each travel time index.

After multicollinearity was discovered in the correlation table, resolved, and insignificant variables were removed, the model contained three variables: air temperature, relative humidity, and day/night. Some important observations made from the correlation table and from the model estimates are:

- The highest correlated values were average wind speed and gust wind speed at 0.985, precipitation and relative humidity at 0.940, and air temperature and surface temperature at 0.892.
- There is a negative relationship between air temperature and the probability of being in a high index.
- There is a positive relationship between relative humidity and the probability of being in a high index.
- There is a negative correlation between the day/night variable and the probability of being in a high index. Meaning, as night turns to day, the chances of being in a high index decrease.

The three coefficient estimates in the model behaved in the way anticipated. As the air temperature decreases, it is expected that the probability of having a higher travel time index goes up since there is possibility for freezing conditions. As the relative humidity increases, the probability of having a higher travel time index also increases as there is a higher chance for precipitation. Finally, it is more likely that a higher travel time index will be reported at night than during the day because of low visibility. It should be noted that this model should not be used as a method to predict the travel time index. The purpose of the model was to show general relationships between the travel time index and weather variables. Overall, the model gave a realistic representation of what the relationship is between the travel time index that was created and weather variables.

7.1.5 Summary of the Proposed Implementation Plan

Most of the implementation method follows the recently released documentation from the FHWA. For instance, there are multiple guidelines for reporting information on DMSs. These guidelines are in place to ensure that travelers are not overloaded with information as they drive at highway speeds. Reporting the travel time index along with the travel time would be too much information. Later in the implementation, after the public has been informed properly, it might be appropriate to report the travel time index with the current road and weather conditions. This would help better inform the users on the severity of the road conditions they are about to encounter.

After implementation, a survey should be conducted to determine how the travel time index affects traveling behavior. Two types of surveys should be conducted, one with a frequent traveler group, and one at a truck stop where random travelers can be surveyed. The survey would question the travelers about which media they used to receive traveler information and the pre-trip/during-trip decisions they made based on that information. The current system of reporting traveling conditions has too much variability with each condition and is not reported frequently.

Reporting travel times in addition to the current condition reporting system could help travelers better quantify the severity of conditions. For example, the “slick in spots” condition is often an overused report. If a travel time index of zero were reported along with the “slick in spots,” travelers could conclude that the conditions on the route are starting to improve. If a travel time index of two were reported, travelers could conclude that the conditions on I-80 are starting to deteriorate.

7.2 Conclusions

The next five sub-sections contain bulleted lists of conclusions for each part of the research presented in this report.

7.2.1 Conclusion of Travel Time Frequency Analysis for I-80 and WY-28

Conclusions that can be made from the travel time frequency analysis are listed in the following bullet points:

- The bi-modal distribution of travel times seen in the I-80 data and the WY-28 data was caused by the speed discrepancies between commercial vehicles and passenger vehicles.
- A single peak was found for the eastbound direction on WY-28, which suggests a more uniform traveling speed between all vehicle types. More data need to be collected to confirm.

7.2.2 Recommendation for Bluetooth Sensors on Rural Corridors

The analysis done between the travel times calculated from speed sensors and Bluetooth sensors provided the following conclusions:

- Based on a t-test, Bluetooth sensors were reporting different times than the speed sensors with alpha=0.05.
- The travel times observed from the Bluetooth sensors were much higher than the travel times calculated from the speed sensors. This leads to the hypothesis that the Bluetooth sensor was only measuring travel times from large commercial vehicles. However, this could not be confirmed when the MAC addresses were matched with a manufacturer.
- The extremely low penetration rate, skewed travel time results, and the unpredictability made Bluetooth sensors a non-ideal solution for optimizing travel time calculations for rural corridors.

7.2.3 Travel Time Index Conclusions

The travel time frequency discussed in the first section was split into travel time indices, and the conclusions from this analysis are listed below.

- The travel time index gives a consistent and reliable measure of condition severity by separating the ideal condition travel times from non-ideal travel times through natural breaks in the travel time frequency.

- The methodology created for reporting the travel time index can help keep the travel time index reliable, but it may not respond quickly enough to changing conditions.

7.2.4 Conclusions from the Statistical Analysis

The travel time index was modeled with weather data, and the results of this statistical analysis are listed below.

- High levels of multicollinearity between weather variables made variable selection and interpretation difficult.
- The coefficient estimates show that the travel time index is accurately portraying the weather conditions being experienced on I-80 between Cheyenne and Laramie.

7.2.5 Conclusions from the Proposed Implementation Plan

A plan was proposed to ensure that the travel time, travel time index, or average speed was displayed properly for the public. The conclusions from this plan are listed in the bullet points below.

- Reporting a travel time, travel time index, or average speed should be accompanied by a timestamp in order to improve the reliability.
- For dynamic message signs, it is important to limit the amount of information displayed so that travelers are not overwhelmed.
- The overall goal of the post-implementation survey should be to ascertain whether or not travelers are making better decisions with the addition of travel time to the current road condition reporting system.

7.3 Future Research

The research presented in this report is part of a larger research effort to use travel times to improve Wyoming's road and weather information system. The travel time index will continue to be modified over time to fit the wide variety of travel times. The travel time frequency and travel time index research will also continue on WY-28 as the newly installed speed sensors continue to collect more speed sensor data. The implementation of the travel time index, outlined in Section 6, is a big step in providing travelers with real-time travel data. The continuation of this research is crucial for WYDOT's goals of a more efficient travel condition reporting system.

Future research tasks that should be considered include:

- Develop an algorithm to provide real-time index updates for the I-80 corridor between Cheyenne and Laramie.
- Analyze the effect of the travel time index on pre-trip/during-trip decisions through the survey methodology outlined in chapter 6.
- Adjust the travel time index for I-80 based on input from the public and new travel time data from the speed sensors.
- Adjust reporting procedure for travel time, travel time index, or average speed based on input from the public.
- Update the travel time frequency graph for WY-28 as more data become available.
- Develop a travel time index for WY-28 after more data are collected and downloaded.

- Develop an algorithm to provide real-time index updates for WY-28.
- Adjust WY-28 travel time index based on input from the public.
- Investigate methods for using RWIS data and future weather predictions as a backup to calculate the travel time index in case the speed sensors malfunction.

BIBLIOGRAPHY

Acyclica. (2011). *Preliminary Differential RF Performance Results.* Denver: Acyclica.

Allison, P. D. (1999). *Logistic Regression Using the SAS System.* Car, NC: SAS Institute.

Araghi, B., Christensen, L., Krishnan, R., & Lahrmann, H. (2012). Application of Bluetooth Technology for Mode-Specific Travel Time Estimation on Arterial Roads: Potentials and Challenges. Aalborg, Denmark: Aalborg University.

Edwards, M. (2008, December). Evaluation of Traveler Information on Driver Behavior in Southeast Wyoming. Laramie, WY.

FHWA. (2012, June). Guidelines for Disseminating Road Weather Advisory and Control Information. *FHWA-JPO-12-046*.

Haghani, A., Hamedi, M., Sadabadi, K. F., Young, S., & Tarnoff, P. (2010). *Data Collection of Freeway Travel Time Ground Truth with Bluetooth Sensors.* College Park: Transportation Research Board.

Hardigree, M. (2011, August 15). *How Houston uses your Bluetooth phone to Fight Traffic*. Retrieved April 2013, from Jalopnik: http://jalopnik.com/5830870/how-houston-uses-your-bluetooth-phone-to-fight-traffic

KMJ Consulting Inc. (2011, November 28). Using Bluetooth to Measure Travel Time Along Arterial Corridors. Ardmore, PA.

Liu, X., Chien, S., & Kim, K. (2012). "Evaluation of Floating Car Technologies for Travel Time Estimation." *Journal of Modern Transportation*, 50-56.

Lyman, K., & Bertini, R. (2007, November). *Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations.* Washington DC: Transportation Research Board.

Martin, D., Perrin, J., Meldrum, D., & Quintana, I. (2000, June). Utah RWIS Traveler Information Evaluation. Salt Lake City, UT.

McLeod, D., Elefteriadou, L., & Jin, L. (2011, October 27). Travel Time Reliability as a Performance Measure: Applying Florida's Predictive Model on the State's Freeway System. Transportation Research Board.

ODOT/OTREC. (2012). *Wireless Data Collection System for Travel Time Estimation and Traffic Performance Evaluation.* Salem: Federal Highway Administration.

Puckett, D., & Vickich, M. (2010, June). Bluetooth Based Travel Time/Speed Measuring Systems Development. Texas Transportation Institute.

Quayle, S., Koonce, P., DePencier, D., & Bullock, D. (2010). Arterial Performance Measures with Media Access Control Readers. Portland, Oregon.

Ringenberg, P. (2011, July). Expressing Rural Travel Time Reliability on I-80 Between Cheyenne and Laramie in Winter Conditions. Laramie, WY.

Texas Transportation Institute. (1998, March). Travel Time Data Collection Handbook. Federal Highway Administration.

Vo, T. (2011, May). An Investigation of Bluetooth Technology for Measuring Travel Times on Arterial Roads: A Case Study on Spring Street. Georgia Institute of Technology.

WYDOT. (2012). *Automatic Traffic Recorder Report*. Cheyenne: WYDOT.

WYDOT. (n.d.). *Wyoming Traveler Information Map*. Retrieved April 5, 2013, from Wyoming Travel Information Service: http://map.wyoroad.info/hi.html

Wyoming Department of Transportation. (2009). *Interstate 80 Tolling Feasibility Study, Phase 2.* Cheyenne.

Yazici, A., Kamga, C., & Mouskos, K. (2012). *Analysis of Travel Time Reliability in New York City Based on Day-of-Week Time-of-Day Periods.* New York: Transportation Research Board.

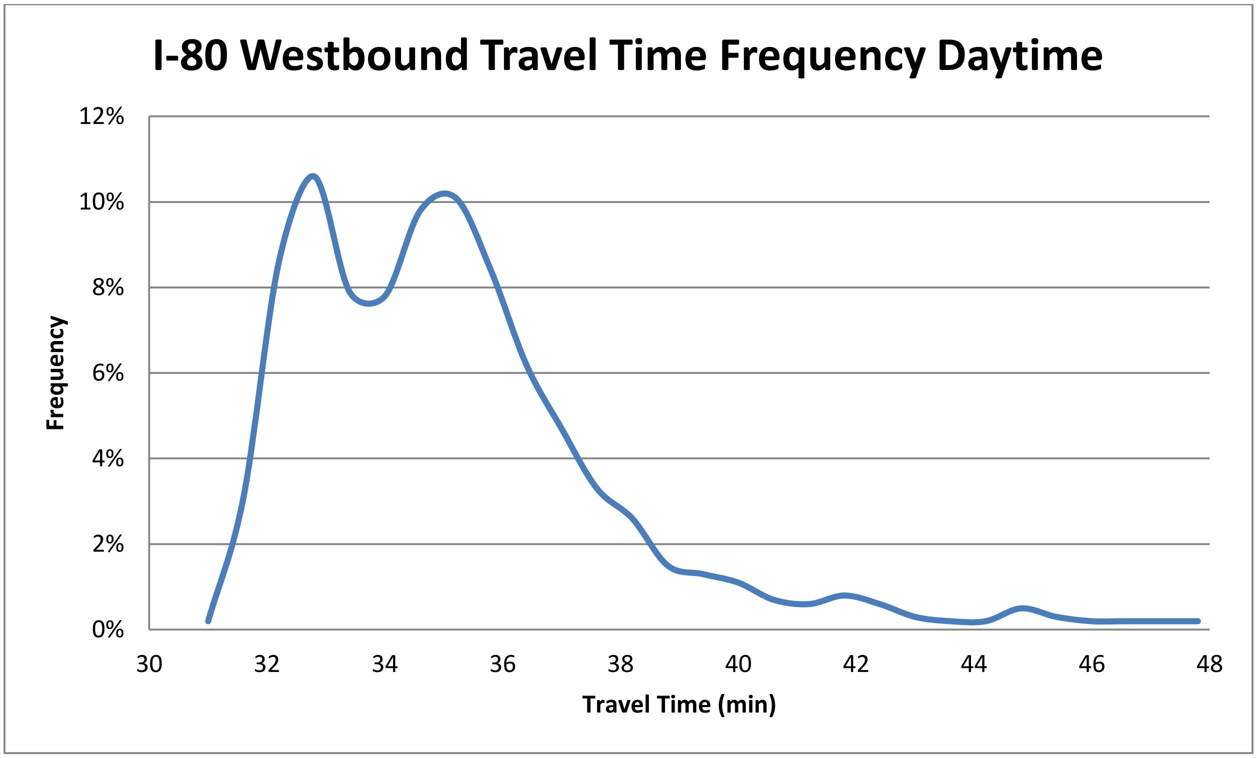
APPENDIX A: GAPS IN THE WY-28 SPEED SENSOR DATA

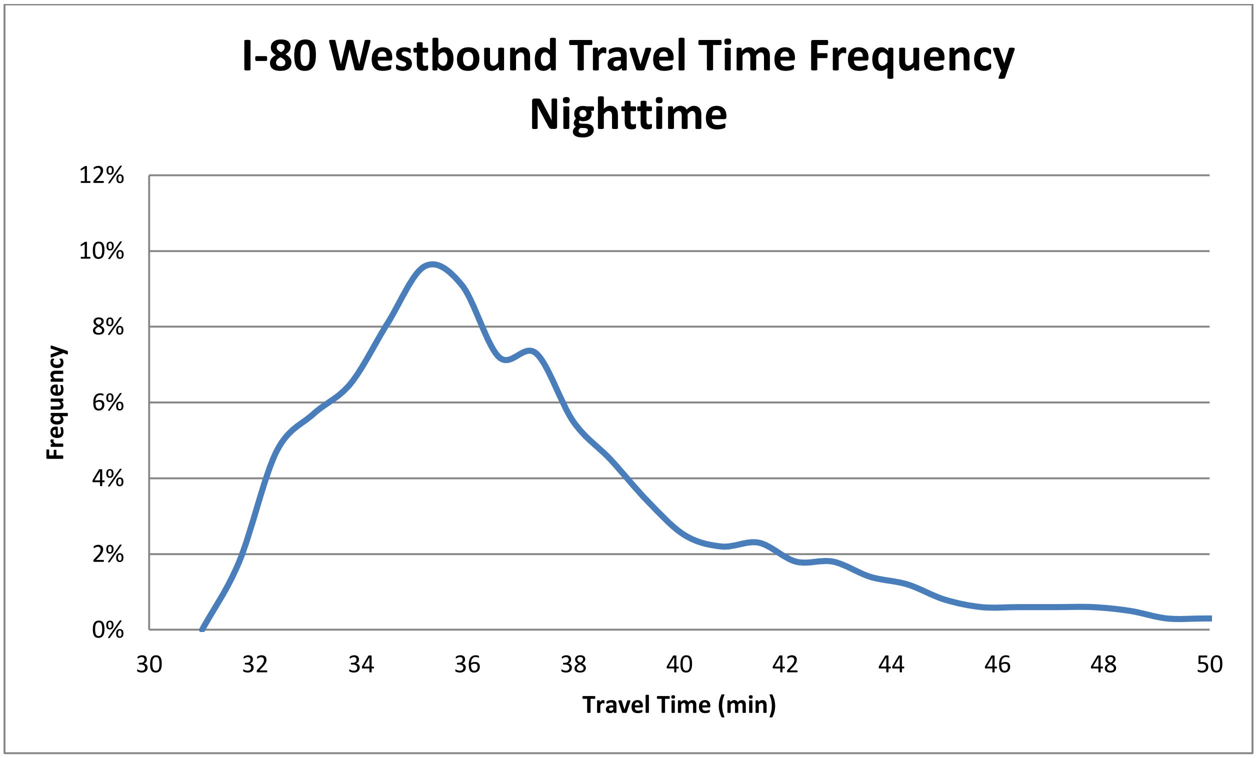
Start Time	End Time	Gap Time
11/8/12 4:00	11/8/12 23:45	19:45:00
11/9/12 12:15	11/9/12 23:45	11:30:00
11/10/12 4:15	11/10/12 23:45	19:30:00
11/11/12 16:15	11/11/12 23:45	7:30:00
11/12/12 12:15	11/12/12 23:45	11:30:00
11/13/12 12:15	11/13/12 23:45	11:30:00
11/14/12 8:15	11/14/12 23:45	15:30:00
11/15/12 3:00	11/15/12 23:45	20:45:00
11/16/12 16:15	11/16/12 23:45	7:30:00
11/17/12 12:15	11/17/12 23:45	11:30:00
11/18/12 4:15	11/18/12 23:45	19:30:00
11/20/12 4:15	11/20/12 23:45	19:30:00
11/21/12 16:15	11/21/12 23:45	7:30:00
11/22/12 4:00	11/22/12 23:45	19:45:00
11/23/12 3:45	11/24/12 0:00	20:15:00
11/24/12 16:15	11/24/12 23:45	7:30:00
11/26/12 12:15	11/26/12 23:45	11:30:00
11/28/12 12:15	11/28/12 23:45	11:30:00
11/29/12 12:15	11/30/12 1:30	13:15:00
11/30/12 4:00	11/30/12 23:45	19:45:00
12/2/12 4:00	12/2/12 23:45	19:45:00
12/3/12 8:15	12/4/12 0:00	15:45:00
12/6/12 3:30	12/6/12 23:45	20:15:00

12/7/12 4:00	12/7/12 23:45	19:45:00
12/8/12 4:00	12/8/12 23:45	19:45:00
12/9/12 4:00	12/9/12 23:45	19:45:00
12/10/12 12:15	12/10/12 23:45	11:30:00
12/11/12 16:15	12/11/12 23:45	7:30:00
12/12/12 4:00	12/12/12 23:45	19:45:00
12/13/12 8:15	12/13/12 23:45	15:30:00
12/14/12 4:00	12/14/12 23:45	19:45:00
12/15/12 12:15	12/15/12 23:45	11:30:00
12/16/12 8:00	12/16/12 23:45	15:45:00
12/17/12 4:00	12/17/12 23:45	19:45:00
12/18/12 12:15	12/18/12 23:45	11:30:00
12/19/12 8:15	12/19/12 23:45	15:30:00
12/20/12 4:15	12/20/12 23:45	19:30:00
12/21/12 12:15	12/21/12 23:45	11:30:00
12/22/12 12:15	12/22/12 23:45	11:30:00
12/24/12 12:15	12/24/12 23:45	11:30:00
12/25/12 8:00	12/25/12 23:45	15:45:00
12/26/12 4:00	12/26/12 23:45	19:45:00
12/27/12 4:15	12/27/12 23:45	19:30:00
12/28/12 16:15	12/28/12 23:45	7:30:00
12/29/12 4:00	12/29/12 23:45	19:45:00
12/30/12 4:00	12/30/12 23:45	19:45:00
12/31/12 4:00	12/31/12 23:45	19:45:00

1/1/13 16:15	1/1/13 23:45	7:30:00
1/2/13 12:15	1/3/13 0:15	12:00:00
1/3/13 3:15	1/3/13 23:45	20:30:00
1/4/13 16:15	1/4/13 23:45	7:30:00
1/5/13 8:15	1/5/13 23:45	15:30:00
1/7/13 4:00	1/7/13 23:45	19:45:00
1/8/13 8:15	1/8/13 23:45	15:30:00
1/9/13 12:15	1/10/13 0:00	11:45:00
1/10/13 8:00	1/10/13 23:45	15:45:00
1/11/13 8:00	1/11/13 23:45	15:45:00
1/12/13 4:15	1/12/13 23:45	19:30:00
1/13/13 8:00	1/13/13 23:45	15:45:00
1/14/13 16:15	1/14/13 23:45	7:30:00
1/16/13 4:00	1/16/13 23:45	19:45:00
1/17/13 3:45	1/17/13 23:45	20:00:00
1/18/13 4:15	1/18/13 23:45	19:30:00
1/21/13 8:15	1/21/13 23:45	15:30:00
1/22/13 8:15	1/22/13 23:45	15:30:00
1/23/13 16:15	1/23/13 23:45	7:30:00
1/24/13 8:15	1/24/13 23:45	15:30:00
1/25/13 4:00	1/25/13 23:45	19:45:00
1/26/13 8:00	1/26/13 23:45	15:45:00

APPENDIX B: I-80 WESTBOUND DAY/NIGHT TRAVEL TIME ANALYSIS





APPENDIX C: TRAVEL TIME INDEX HISTOGRAM AT FIVE MINUTE INTERVALS FOR THE EASTBOUND AND WESTBOUND DIRECTION

Eastbound			
Index	Travel Time Bin	Frequency	% of Total
0	<=25	0	0.000%
0	25.01-30	971	3.154%
0	30.01-35	22127	71.871%
0	35.01-40	4802	15.597%
1	40.01-45	1036	3.365%
1	45.01-50	478	1.553%
1	50.01-55	308	1.000%
2	55.01-60	265	0.861%
2	60.01-65	214	0.695%
2	65.01-70	241	0.783%
3	70.01-75	119	0.387%
3	75.01-80	64	0.208%
3	80.01-85	40	0.130%
4	85.01-90	22	0.071%
4	90.01-95	14	0.045%
4	95.01-100	35	0.114%
5	100.01-105	5	0.016%
5	105.01-110	4	0.013%
5	110.1-115	7	0.023%
5	115.01-120	6	0.019%
5	120.01-125	2	0.006%
5	>125.01	27	0.088%

Westbound			
Index	**Bin**	**Frequency**	**%of Total**
0	<=25	0	0.000%
0	25.01-30	2	0.006%
0	30.01-35	15805	51.260%
0	35.01-40	10975	35.595%
1	40.01-45	1956	6.344%
1	45.01-50	718	2.329%
1	50.01-55	316	1.025%
2	55.01-60	233	0.756%
2	60.01-65	186	0.603%
2	65.01-70	231	0.749%
3	70.01-75	134	0.435%
3	75.01-80	86	0.279%
3	80.01-85	45	0.146%
4	85.01-90	27	0.088%
4	90.01-95	11	0.036%
4	95.01-100	25	0.081%
5	100.01-105	12	0.039%
5	105.01-110	14	0.045%
5	110.1-115	3	0.010%
5	115.01-120	1	0.003%
5	120.01-125	4	0.013%
5	>125.01	49	0.159%

APPENDIX D: ORDINAL REGRESSION ANALYSIS WITH AIC=906

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**5**	1	-25.467	3.6792	47.9149	<.0001
Intercept	**4**	1	-24.177	3.6555	43.7446	<.0001
Intercept	**3**	1	-22.091	3.6473	36.6865	<.0001
Intercept	**2**	1	-18.534	3.6244	26.1485	<.0001
Intercept	**1**	1	-15.298	3.4926	19.1852	<.0001
SfTemp		1	0.00752	0.024	0.0982	0.754
AirTemp		1	0.2781	0.0822	11.4398	0.0007
RH		1	0.2591	0.0402	41.5395	<.0001
Dewpoint		1	-0.4303	0.0864	24.8032	<.0001
DayNight	**1**	1	-0.2904	0.1084	7.1735	0.0074