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Mobile Vehicle Road And Weather Observation Quality Check Methods

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MOBILE VEHICLE ROAD AND WEATHER OBSERVATION QUALITY CHECK METHODS

By

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This thesis, submitted by Daniel Raymond Koller in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Daniel Raymond Koller
DECEMBER 4, 2013

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Tables Page

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ABSTRACT

Today State Departments of Transportation rely more and more on road weather data to make maintenance decisions. Inaccurate data can result in wrong treatment applications or inadequate staffing levels to maintain the roadway at the desired level of service.

Previous methods of road condition data reporting have been limited to static *in situ* sensor stations. These road weather information systems (RWIS) provide varied data about precipitation, winds, temperature, and more, but their siting does not always provide an accurate representation of weather and road conditions along the roadway. The use of mobile data collection from vehicles travelling the highway corridors may assist in the locations where RWIS sitings are sparse or non-existent.

The United States Department of Transporation's "Connected Vehicle" (formally IntelliDrive) research project is designed to create a fully connected transportation system providing road and weather data collection from an extensive array of vehicles. While the implementation of Connected Vehicle is in the future, some of the theories and technologies are already in place today. Several states, as a part of the Pooled Fund Study Maintenance Decision Support System (MDSS), have equipped their winter maintenance vehicles with Mobile Data Collection Automated / Vehicle Location (MDC/AVL)

systems. In addition, since 1996, automobiles sold in the United States are required to be equipped with an Onboard Diagnostic Version 2 (OBDII) port that streams live data from sensors located in and around the vehicle. While these sensors were designed for vehicle diagnostics, some of the data can be used to determine weather characteristics around the vehicle. The OBDII data can be collected by a smartphone and sent to a server in real time to be processed. These mobile systems may fill the information gap along the roads that stationary environmental sensor stations are not able to collect.

Particular concern and care needs to be focused on data quality and accuracy, requiring the development of quality checks for mobile data collection. Using OBDII-equipped automobiles and mobile collection methods, we can begin to address issues of data quality by understanding, characterizing, and demonstrating the quality of mobile system observations from operational and research environments. Several forms of quality checking can be used, including range checks, Barnes spatial checks, comparing vehicle data to road weather models, and applying *Clarus* quality check methodologies and algorithms to mobile observations. Development of these quality checks can lead to the future integration of mobile data into the *Clarus* system, data implementation for improved forecasting, maintenance decision support, and traveler safety.

This paper will discuss the benefits and challenges in mobile data collection, along with how the development and implementation of a system of quality checks will improve the quality and accuracy of mobile data collection.

CHAPTER I

INTRODUCTION

Description of Problem

Unsafe roadways during inclement weather conditions lead to traffic accidents and fatalities. For State Departments of Transportation and Transportation Agencies, knowing road conditions and applying proper maintenance actions is critical to maintaining the required level of service to keep roadways safe for motorists. Inaccurate or unreliable data can result in wrong treatment applications or inadequate staffing levels to maintain the roadway at the desired level of service. The application and improvement of quality checks applied to data used by transportation agencies is expected to improve the maintenance-action decision-making process.

The influences of weather on surface transportation are significant. The National Highway Traffic Safety Administration (NHTSA) estimates that 880,800 vehicle accidents and approximately 3,796 fatalities occurred on U.S. highways in 2009 during adverse weather conditions (NHTSA, 2010). Adverse weather conditions are defined to be rain, snow, sleet, fog, rain & fog and sleet & fog (Goodwin, 2002). Comparing fatalities to the aviation transportation sector and under similar circumstances, only 1,532 occurred (Askelson and Osborne, 2008). In addition to loss of life, adverse weather has impacts on injuries and transportation delays. Approximately 317,000 injuries are attributed annually to crashes that occur during adverse weather conditions (NHTSA, 2010). Highway vehicle crashes also have a significant impact on the economy. It has been estimated that the economic impact from highway vehicle crashes in adverse weather is approximately $42 billion/year (Lombardo, 2000).

To understand how adverse weather affects the roadway, road weather data reporting systems have been developed. Primary methods of road weather data reporting have been limited to static *in situ* sensor stations (Stern et al. 2006). These systems, called environmental sensor stations (ESS), provide varied data about precipitation, winds, temperature, and road conditions. However, their siting does not always provide an accurate representation of weather and road conditions everywhere along the roadway. Some ESS are placed in locations that experience localized weather phenomena like high winds or frequent fog. Mobile data collection from vehicles travelling the highway corridors may therefore assist when ESS are sparse or non-existent--for example in rural areas.

Importance of Mobile Observations

The push for mobile data collection in the realm of consumer automobiles is through the U.S. Department of Transportation "Connected Vehicle" research project (McGurrin, 2012). Connected Vehicle is designed to create a fully connected transportation system--providing assistance with crash avoidance and traffic flow from an extensive array of vehicles. Road and weather data can be collected from this array of vehicles. While the operational implementation of Connected Vehicle is some years away, some of the elements and technologies are being studied today.

Advancements in wireless cellular communications, computers, and instruments have facilitated the development of near real-time wireless mobile observations of road and weather data. The use of Mobile Data Collection with Automated Vehicle Location (MDC/AVL) to monitor maintenance trucks has expanded greatly in the United States in the past decade. Several state members of a Transportation Pooled Fund Study MDSS deployed in excess of 50 MDC/AVL equipped trucks in late 2007, with the intention of deploying fleet wide within a few years (Mewes et al. 2008). These MDC/AVL equipped maintenance vehicles provide important information to State Departments of Transportation (DOT) regarding what they are doing and where they are located (Mewes et al. 2008). Once MDC/AVL units have been deployed, the quality and reliability of the air and pavement temperature values have been questioned.

Since 1996, automobiles sold in the United States are required, through federal regulations (SAE International, 2007), to be equipped with an Onboard Diagnostic (OBDII) port that streams live data from sensors located onboard the vehicle. While these sensors were designed for vehicle diagnostics, some of the data can be used to determine weather characteristics from the vehicle. OBDII data can be collected through various methods, including wireless systems, and sent to a server in real-time to be processed, thus providing a testing structure for research into potential applications of mobile data. Some initial studies raised the question about the quality and biases from the OBDII data. Effective operational techniques for stationary atmospheric sensor data have been developed, yet no techniques exist for operational quality control of surface mobile data (Limber et al. 2010).

Objective

This study includes an in-depth analysis of the current quality checking methods used for road and weather observations collected using stationary environmental sensor stations and the development of quality checks for observations collected using mobile platforms. During development of this new quality check system for mobile road and weather observations, new and modified quality checks, including gap-analysis quality checks, are compared with existing methods. Gap-analysis quality checks use nearby observations to determine whether it is likely that the observation of interest is representative of the environment. The quality checks developed include modified versions of the *Clarus* system checks (Limber et al. 2010) along with additional gap-analysis tests. The performance of the new mobile quality checks is analyzed relative to quality checks used in the *Clarus* system.

The impact of quality checks on these data is evaluated by comparing results with quality-checked observations obtained using stationary environmental sensor stations, which will be considered to provide "truth." Stationary environmental sensor stations may not be perfect, but because their performance characteristics are generally known, they provide a useful baseline for evaluating the quality of mobile data.

CHAPTER II

BACKGROUND

Fundamentals of Mobile Road Weather Observations

Mobile data collection has been used in many meteorological applications. Ships and airplanes are a few of the most prominent mobile platforms. The Aircraft Communications Addressing and Reporting System (ACARS®) is one example that started over 30 years ago with the purpose of collecting air and ground data while communicating them effectively to maximize performance and safety of airline operations (ARINC, 2009). In recent decades, automobiles have begun to be used to collect mobile data. During research on severe summer storms, vehicles called "Mobile Mesonets" were equipped with racks of surface weather instruments on the roof of vehicles (Straka et al. 1996). The types of measurements taken from these stations include wind, temperature, relative humidity, and pressure (Straka et al.1995). The application of roof mounted sensors to data collection is useful when the vehicles are primarily stationary and placed in specific locations. "Prior to any use in the field, the mobile mesonet instruments were checked for being within the factory specifics for tolerance against the Oklahoma Mesonet Calibration facilities" (Straka, Rasmussen, & Frederickson, 1996). The instruments were spot checked twice each day to detect drift. After each field experiment, data-quality assurance was applied. Error flags were applied to known errors, such as those that arose with wind speed and direction when a vehicle was accelerating. In addition, suspect data were determined by using data bounds, standard deviation thresholds, various filters, and instrument time constants.

In 2005, non-intrusive mobile data collection began to take place. An early concept of Connected Vehicle was known as Vehicle Infrastructure Integration (VII) (Petty and Mahoney, 2006). The main goals of VII were to develop an application for the improvement of safety, increased mobility and efficiency along roadways. A secondary goal of VII was "for the weather enterprise to utilize the vehicle data to improve weather and road condition products and to provide those products to transportation system decision makers, including travelers" (Petty and Mahoney, 2007). The purpose of VII was for the vehicle to transmit and collect data from vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). Information collected from VII has included direct measurements (e.g., exterior temperature) and indirect measurements (e.g., traction control or antilock brake system activation) for understanding pavement condition. The potential weather sensing vehicle sensors are included in Table 1.

Table 1. Potential sensors and equipment useful for sensing weather on VII fitted vehicles.

Potential Vehicle-based Elements	
Hours of operation	Impact Sensor
Elevation	Barometric Pressure
Accelerometer data	Fog Lights
Heading/GPS Location	Headlights
Steering Wheel Rate of Change	Anti-lock Brakes system
Exterior Temperature	Traction Control
Windshield Wiper Rate	Stability Control
Rain Sensor	Pavement Temperature
Sun Sensor	Brake Boost
Adaptive Cruise Control Radar	Wiper Status

In 2005-2006, the U.S. Federal Highway Administration (FHWA) began studying use of OBDII vehicles for mobile data collection. They compared data gathered from the OBDII port along with additional temperature sensors placed in other locations around the vehicle to determine the utility of vehicles as mobile meteorological platforms (Stern et al. 2006). The primary research areas were temperature bias vs. vehicle speed, mobile temperature vs. *in situ* observations, importance of sensor placement, thermal characteristics of similar vehicles, and effects of external phenomena on mobile temperatures. The vehicles studied included a moving truck-based mobile laboratory and two 1998 Ford Crown Victorias. Each vehicle was equipped with additional temperature sensors, GPS, and a data logger. The data were collected during wintertime (15 December 2005 – 31 March 2006) and summertime (1 July 2006 – 20 September 2006). The data collection focused on varying weather conditions during morning and evening commutes and midday trips. Results from the tests indicated there were significant differences in biases, even for similar vehicles.

By late 2007 a few State DOTs had begun equipping wintertime maintenance vehicles with MDC/AVL units (Mewes et al.2008). MDC/AVL systems are able to relay information to a central collection location in near real time. If a vehicle is out of cellular communication range, the MDC/AVL system will continue to collect data. Information sent from a MDC/AVL system is sent one of two ways. “In one mode, all data elements are logged to a file at regular intervals (ranging from seconds up to no more than every 5 min) and distributed back to a central collection point for processing into MDSS” (Mewes et al. 2008). The second method logs time and location regularly but other data (road condition, and plow position) are collected only when an event occurs. An event can be the maintenance operator changing a value using the touch screen. For example, if the user enters a road condition of ‘wet’ on a touch screen, that entry and the time it was made would be recorded. The wet road condition would be assumed to be valid from that time/location forward until a different condition is entered, and would be associated with all locations and times during that period (Mewes et al. 2008). The data elements that are recorded from the MDC/AVL units include vehicle identifier, time, location, lane identifier, maintenance data and observations. Maintenance data include the following types of information:

- Plow position
- Material applied
- Material Form

- Application rate
- Application rate units

Observations from MDC/AVL units include the following types of information:

- Road condition
- Road Temperature (Optional)
- Precipitation (Optional)
- Visibility and Obstruction (Optional)
- Air Temperature (Optional)

A complete list of data elements, maintenance data, and observations from MDC/AVL units is provided in Appendix.

In 2009, the National Center for Atmospheric Research (NCAR) conducted a test similar to that conducted by the FHWA in 2005-2006. They were trying to determine how "good" are vehicle observations (Drobot, 2009). The tests included measurements of both air temperature and pressure obtained directly from the OBDII port. The NCAR scientists developed quality-checking tests to verify data coming from the vehicles. The tests developed included a sensor range test, climatological range test, neighboring vehicle test, neighboring surface station test, model analysis test and a remote observation test. They concluded that:

1. The temperature observations are better than the pressure observations.
2. Quality check failures were related to many underlying factors.
3. Vehicle type and weather conditions seem to influence vehicle observation quality.

Some issues noted include 'null' and persistence values reported by some vehicle sensors.

Environmental Sensor Stations

Approximately 30 years ago, ESS started to be installed along roadways. These ESS' provided critical information about the roadways that was not available before. "An ESS consists of one or more sensors measuring atmospheric, pavement, soil, and/or water level conditions" (Manfredi et al., 2005). Types of weather information collected include, but are not limited to, air temperature, dew point, and amount and type of precipitation. The type of surface information collected includes pavement temperature, surface condition (dry, wet, frozen), and chemical concentration. ESS may also contain cameras and additional sensors for a specific use in a desired location (Albercht, 2006). An entire network of ESS connected through a communications network is known as a Road Weather Information System (RWIS). "RWIS consists of the hardware, software, and communications interfaces necessary to collect and transfer road weather observations from or near the roadway to a display device at the user's location" (Manfredi et al., 2005). This information became invaluable to State DOT and transportation managers during adverse weather conditions like rain, sleet, snow, ice, fog, etc. However, unlike radar, satellite, and surface conditions, which are easily accessible via TV and the Internet, ESS data were only available to the State DOTs.

In 2004, *Clarus*, a joint initiative of the USDOT and FHWA, focused on organizing ESS data in a centralized location. The *Clarus* System had four main motivations. The first was to provide a resource of quality checked surface transportation weather and road condition observations for State Departments of Transportation (DOTs). The second was to extend and enhance the existing weather data source for general purpose and weather forecasting. The third was to provide a collection of real-time surface transportation weather observations for supporting real-time operational responses to weather. The final motivation was to use data from surface transportation weather to enhance models to better predict the atmospheric boundary layer (Mixon- Hill, 2009).

Importance of mobile road information

With stationary ESS along many of the U.S. highways, this provides the benefit of gaining a historical climatology at the site, but does have limitations. This leaves gaps along the roadways where road and weather information are not available. Mobile systems are expected to fill the information gap that stationary ESS cannot.

However, the current shortcoming of mobile road and weather observations is the unverified accuracy of the received data. This issue comes from the lack of standards in the interfacing formats and data elements (Mewes et al. 2008). The development of quality checks that focus on the integrity of highway maintenance vehicle and consumer vehicle data will improve the utility of mobile data for critical decision-making.

CHAPTER III

METHOD

Quality Check Algorithm Design

The *Clarus* System implemented their final version of quality checks for stationary ESS in 2010. The stationary ESS quality checks from the *Clarus* System were developed to flag ESS data that were not characteristic of the environment. The quality check tests in the *Clarus* System and proposed mobile ESS quality checks are included in Table 2 (Limber et al. 2010).

Table 2. List of quality checks. *Clarus* System Quality Checks with a "*" denote tests that are used herein.

Clarus System Quality Checks	Developed Mobile ESS Quality Checks*
Sensor range test*	Speed Check
Climate range test	Vehicle-to-Vehicle Spatial Test
Time step test	Pass-by Verification
Climate range test	
Like instrument test	
Persistence test*	
Inter-Quartile Range (IQR) spatial test*	
Barnes spatial test*	

Herein, quality checking algorithm development included the design of various progressive tests used to assess data quality. These tests take many of the qualities from the *Clarus* System quality checks, but are modified to account for a moving observational platform. For the purpose of testing a quality-checking algorithm, each of these tests has been configured to work for air temperature and pavement temperature sensors equipped on many of the mobile ESS platforms. Each of these tests is described below.

The quality checks (Figure 1) begin with the speed check and then continue on to the gross error check. If the speed or gross error checks are flagged, the secondary tests are not run. If both of these checks pass, then the secondary tests are run. The secondary tests include a vehicle-to-vehicle test, a persistence test, and an interquartile range (IQR) test. If the IQR test is flagged or produces an error, then the Barnes spatial test for ESS will run. Otherwise the Barnes spatial test for ESS will not run. The Barnes spatial test is a weighted distance test. More detail describing the quality check tests is provided below.

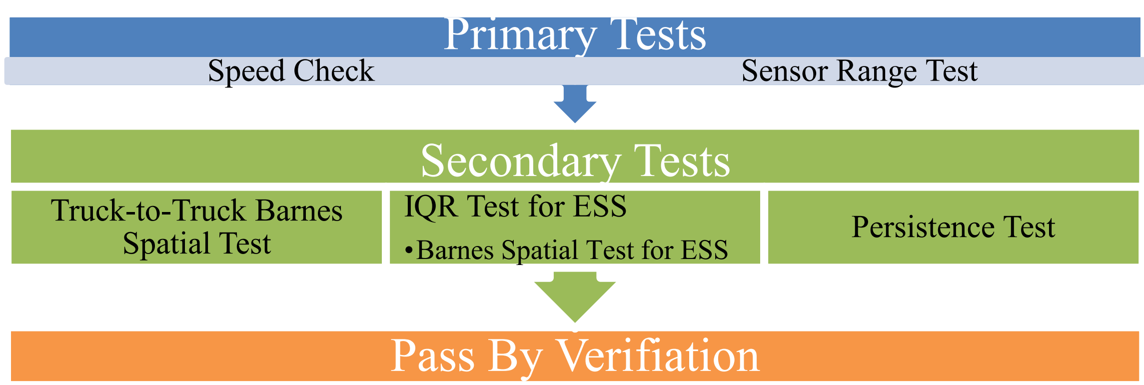

Figure 1. Quality check algorithm flow chart.

Primary Tests

Speed Check tests are applied to determine if the vehicle is moving. This is an issue at times since many of the Mobile Data Collection/Automated-Vehicle-Location

(MDC/AVL) equipped vehicles do not report the actual vehicle speed. This test calculates the distance traveled based upon a previous reported location and time elapsed—as long as the previously reported location occurred in the last 15 minutes.

The speed check is not so much of a quality test as it is a threshold test to determine whether to run subsequent tests. If the speed of the vehicle falls within the defined threshold of 5 mph and 90 mph, the test passes and the observations are allowed to pass into the next tests as shown in Figure 2. If this test determines that the vehicle is not moving or is moving too fast, the next tests are not run and the quality checks for this set of observations are flagged with an error code. This threshold test is used to help account for when the trucks are idling at a stop or more commonly going into a garage and idle while the truck is preparing to go out again. The use of this threshold test is to mitigate the impact in the data from temperature readings influenced by the radiant heat from the engine or by heated garages.

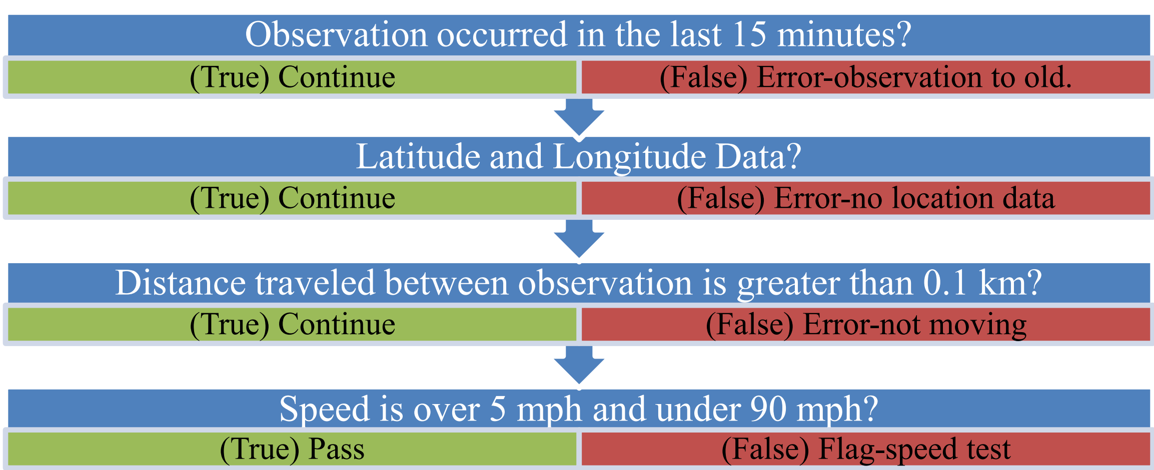

Figure 2. Logic chart showing flow of the Speed Check.

The sensor range test is performed to determine if air or pavement temperature observations fall within a predefined range for the onboard instruments. This test reports an error if no value is reported. If this test flags or reports an error, the subsequent tests are not run and the observation is flagged with an error code.

Each time this test is run, it is given a single observation from a sensor. If the sensor reading is not available, the test returns an error condition that the test failed to run. The sensor provides the sensor range in the form of a maximum and a minimum value. If the observation falls within this range then the test passes. If the target observation is less than the minimum value or greater than the maximum value, then the test does not pass (Figure 3). For the instruments used in these tests the corresponding values were, -50°C to 65 $^{\circ}$C for air temperature and -50°C to 120°C for pavement temperature.

$$Mininum\ Value \leq Observation\ \leq Maximum\ Value \quad (1)$$

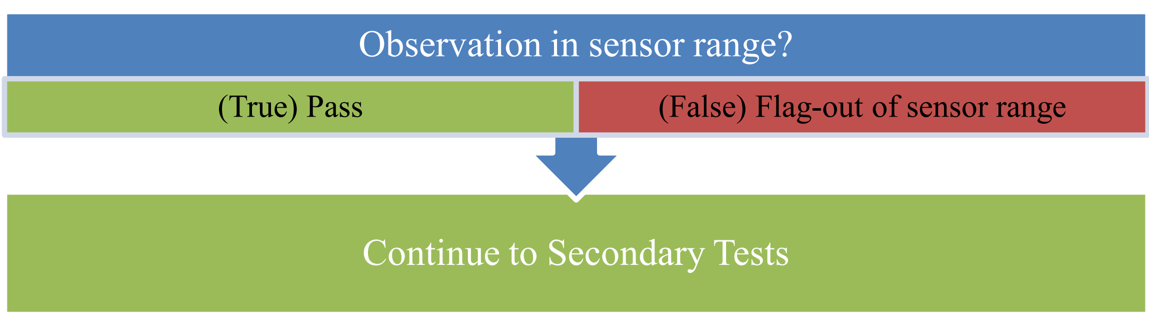

Figure 3. Logic chart showing flow for the Sensor Range Test.

Secondary Tests

The persistence test is used to detect if any of the observed value becomes "stuck" or remains constant for a specified period of time. For example, if the maintenance vehicle's infrared pavement sensor remains unchanged to the precision of the instrument for 15 minutes as the vehicle is moving, the current sensor reading does not pass. Each time the test is run, it is given a single observation from a sensor. Based on the type of observation the test then determines the persistence range for the sensor. Consecutive identical observations readings from the same sensor result in a preliminary flag/error. If one or more of the consecutive sensor observations changes, the current sensor reading passes the persistence test. If the observations remain identical through the persistence range for the sensor, the test is flagged (Figure 4).

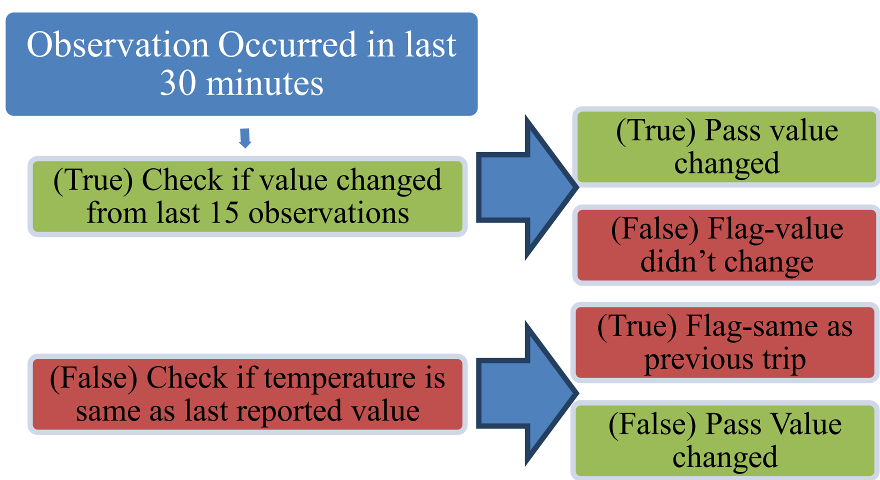

Figure 4. Logic chart showing flow of the Persistence Test.

The Inter-quartile Range (IQR) spatial test checks whether a sensor reading is consistent with the neighboring observed sensor readings. The test checks if the target observation differs by more than a threshold amount from other neighboring sensor observations in a target area.

The target sensor observation does not pass the IQR test if the absolute value between the median of the neighboring readings and the target observation is greater than the higher value from either an adjusted interquartile range or the minimum tolerance bound defined for each observation type (Figure 5). The minimum tolerance bound is a fixed value to each type of observation that bounds a minimum acceptable spread between the target observation and the estimate. To account for sufficient spatial variation from neighboring sensors, adjustable tolerance bounds are used for different observation types. The values for the minimum tolerance bound are initially defined by the values set by the *Clarus* System quality checks, which are 3.5 $^{\circ}$C for air temperature and 10 $^{\circ}$C for pavement temperature.

For the IQR test to be effective there needs to be at least five or more ESS neighbors within the target area. These sensors must be within a radius of influence of 69 miles and have readings within the previous hour. This is an empirically set value and can be adjusted down for areas where dense observations exist. For the tests conducted in this study 69 miles was used to be consistent with the *Clarus* quality checks. Sixty-nine miles was chosen by *Clarus* as a standard radius of influence because it corresponds to 1 degree latitude (Osborne, 2013). The test will not run if these criteria are not met. If the IQR test passes, the Barnes spatial test for ESS is not run. If the IQR test flags or produces an error, the Barnes spatial test for ESS will run (Figure 1).

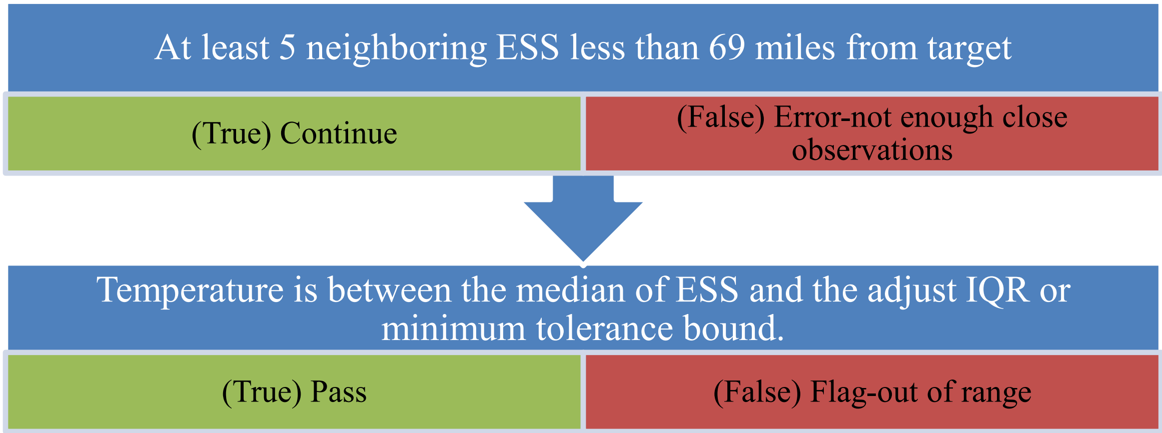

Figure 5. Logic chart showing flow for adjusted IQR Test.

Barnes Spatial Test. Ideally, using an statistical objective analysis scheme would be best for creating a quality-checking test. This scheme would allow one to create uniquely shaped zones where certain background error correlations could be used. The issue with using this method in this study is the lack of availability of the true background and observation error correlations that are needed to successfully run this scheme. Without the true background error correlation the optimum interpolation scheme is rendered worthless. A spatial test, using a distance dependent weighting scheme used in mesoscale analysis (Barnes, 1964), provides a geographical comparison based on tolerance bounds within a region. The Barnes spatial test uses neighboring sensor readings and weights them based upon their distance from the target sensor. At each observation point from the target truck, the values are calculated from surrounding observations. The Barnes scheme allows for the estimation of unstructured/unbalanced data sets. Weather observations that are not a consistent distance apart are considered unstructured/unbalanced data sets. This can cause a bias if the weather observations are clustered together or unbalanced across the radius of influence. Observations that are close together and are a similar distance from the target, but have significantly different values will carry a similar weight.

This method uses distance weighting in order to determine the relative importance of a measurement to determine the value by using a series of Gaussian functions to remove noise. Noise is irrelevant, meaningless data occurring along with desired information. For a given latitude (i) and longitude (j) from a target truck the Barnes scheme function is $g_o(x_i, y_j)$ is approximated by the inverse weighting of the surrounding observations. Weighted values are assigned to each observation point such that,

$$w_{ij} = \exp\left(-\frac{r_{ij}^2}{k}\right) \quad (2)$$

where k is the smoothing parameter—this controls the width of the Gaussian function. The smoothing parameter, k, is controlled by the characteristic data spacing for a fixed Gaussian cutoff radius where R_{ij} is the neighboring observation and σ is the estimated standard deviation:

$$k = 2\left(\frac{R_{ij}}{\sigma}\right)^2 \quad (3)$$

The Barnes scheme for the first pass Barnes function from the measured values $f_k(x, y)$ is given by

$$g_o(x_i, y_j) = \frac{\sum_k w_{ij} f_k(x,y)}{\sum_k w_{ij}}. \quad (4)$$

The weights applied to neighboring observations drop exponentially as the distance from the target sensor increases. This test only takes neighboring stations that fall within a set distance defined using a configurable parameter (Daley, 1996).

Each time this test is run, it is given a single mobile observation. This observation includes its location along with the vehicle identifier and time. If the sensor observation or the location is missing, the test will return an error and the test will not run. If the information is available, then a query of observations for spatial analysis is completed to determine how many observations of the same type are available. If less than two observations of the same type are available, the test returns an error result indicating that it was unable to complete the test.

The target observation is flagged in the Barnes spatial test if the target observation is outside of the range defined by the number of standard deviations from the weighted mean of the neighboring observations (Figure 6). The values used herein are a radius of influence of 69 miles and one standard deviation.

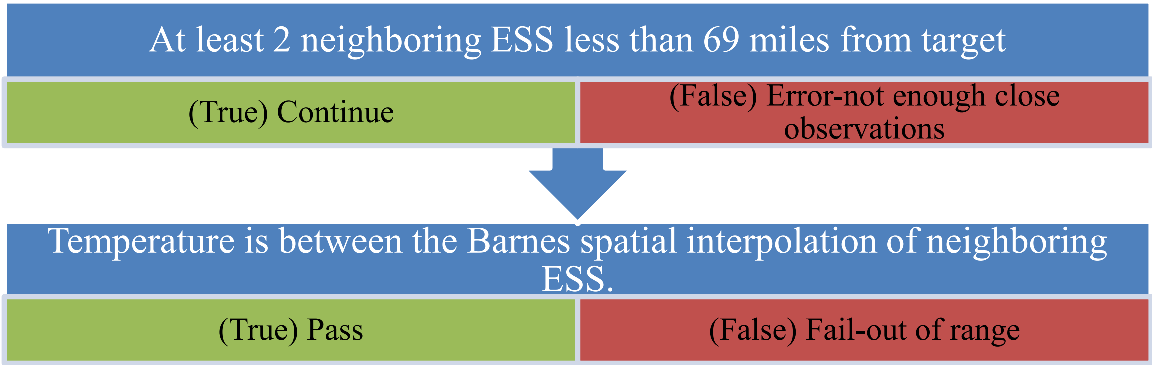

Figure 6. Logic chart showing flow of the Barnes Spatial test.

The vehicle-to-vehicle Barnes spatial test uses a comparison of surrounding vehicle observations to compare against those of the target vehicle. This test uses a technique similar to the Barnes spatial test for ESS. In the vehicle-to-vehicle test, neighboring mobile ESS observations from around the target vehicle from the past hour are weighted based upon their distance from a target observation. The weight of the observation from the neighboring mobile ESS drops exponentially as the distance from the target sensor increases. This test only takes observations from neighboring mobile ESS that fall within a defined radius of influence set in the configuration parameter. A radius of influence is used to help reduce the number of computations need to process the surrounding data.

Each time this test is run, it is given a particular temperature observation. This observation includes vehicle location, vehicle identifier, and time. If the sensor observation, the location, and/or time are missing, the test will return an error and the test will not run. If the information is available, a query of observations is conducted to determine how many mobile ESS observations of the same type are available from the past hour. If less than two observations of the same type are available, then a flag signaling that it was unable to complete the test is returned (Figure 7).

The target observation is flagged in the vehicle-to-vehicle test if the target observation is outside of the range defined by the number of standard deviations from the weighted mean of the neighboring mobile ESS. The configurations for the test are set with a radius of influence of 69 miles from the target location.

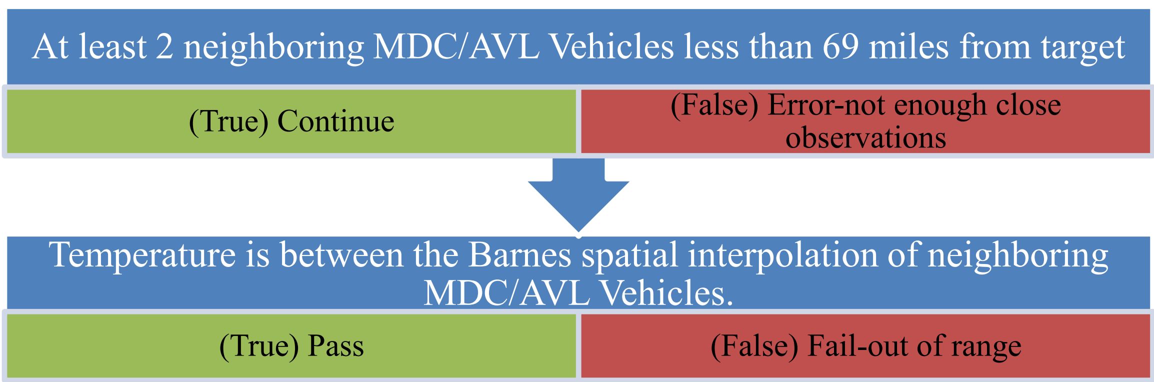

Figure 7. Logic chart showing flow of vehicle-to-vehicle Spatial Test.

A verification "pass-by" check compares against the above checks when a target vehicle passes by an ESS site by using a minimum temperature tolerance bound. The values for the minimum tolerance bound are initially defined by the values set by the *Clarus* System quality checks, which are 3.5 °C for air temperature and 10 °C for pavement temperature. Similar to the checks above, the pass-by check either passes or is flagged as out of minimum tolerance. If the verification pass-by check passes, observations are assumed to be passing until the vehicle passes another ESS site or an hour passes. If the test is flagged, the flagged value is applied over an interval instead of to a specific observation. This test is used herein to verify other quality checks.

CHAPTER IV

RESULTS

The ESS observations for testing the algorithm were extracted from a *Clarus* archive of ESS data maintained at the University of North Dakota Surface Transportation Weather Research Center. A query from the archive provided all available ESS observation for the test dates. The data were processed to separate the observations into air and pavement temperature data for the areas of interest. This was used to reduce the number of processing cycles in the algorithm and to reduce the amount of time to process the truck data.

The truck data from three participating State DOTs were acquired in comma-delimited files by truck. The files included the times of the observations, air and pavement temperatures, and observation latitudes and longitudes.

To keep the data anonymous, the non-maintenance vehicle data were processed with the session ID tag. An OBDII Bluetooth™ adapter connected to the vehicle was paired with a Google™ Android based smartphone/tablet running the application Torque Pro[1]. Torque Pro is a vehicle/car performance/diagnostic tool that communicates with the

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[1]Developed by Ian Hawkins Torque Pro (OBD 2 & Car) October 25, 2013, https://play.google.com/store/apps/details?id=org.prowl.torque

Engine Control Unit (ECU) through a Bluetooth™ OBDII adapter. Within the smartphone/tablet application, it allows for data collection and transmission in near real time to a server. The data transmitted includes location, time, and OBDII observations. The observations that are currently accessible across almost all vehicles include, but are not limited to, vehicle speed, intake air temperature, and ambient air temperature.

Algorithm Testing Methodology

When processing the quality checks for trucks, certain data sources needed to be acquired to complete the tests. These included the *Clarus* System settings used for the IQR and Barnes Spatial tests for ESS. Testing of the algorithm was accomplished using multiple cases from North Dakota, Minnesota, and South Dakota. The data from these states were used to validate the algorithm methodology. The dates of the events are:

Eastern North Dakota

- November 29-30, 2010
- December 30, 2010 - January 1, 2011
- February 8-11, 2011
- March 22-23, 2011
- April 15-16, 2011

St. Cloud, Minnesota

- November 22, 2010
- December 22, 2010

- February 20-22, 2011
- March 22-23, 2011
- April 20, 2011

Black Hills

- December 30, 2010 - January 1, 2011
- January 15, 2011
- February 24, 2011
- March 8, 2011
- March 22-23, 2011

Sisseton Moraine

- February 22-23, 2011

A sample of the results from 8-11 Feb 2011 and 22-23 March 2011 are provided below to validate the algorithm methodology. In the algorithm tests, the air temperature is gathered from all the available ESS within the *Clarus* System for the test date.

Figure 8 denotes truck operational areas from which data were used for algorithm testing. The areas of interest were located near St. Cloud, Minnesota, Interstate 29 between Grand Forks and Fargo, North Dakota, Interstate 29 near the North Dakota/South Dakota border and southward to near Watertown South Dakota, and the vicinity around Rapids City, South Dakota.

Figure 9 provides an expanded view of the Eastern North Dakota area. Data were obtained from four trucks from North Dakota (ND-9311, ND-9372, ND-9644 and ND-9757), two trucks from South Dakota (SD-DT045 and SD-DT116) and four trucks from Minnesota (MN-AT-206572, MN-AT-207576, MN-AT-208562 and MN-AT-208564). As the algorithm processed each truck's data, it produced an output file for the individual truck that included scores for each observation that indicated if it passed tests or if it was flagged by tests.

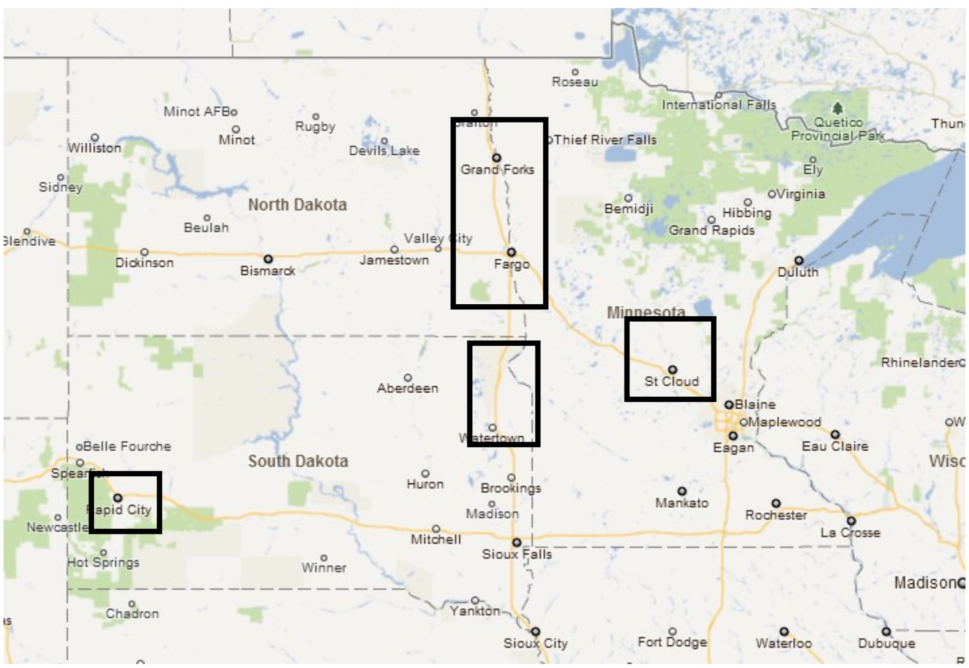

Figure 8. Map of tri state region. Boxes signify the locations of where MDC/AVL data were collected.

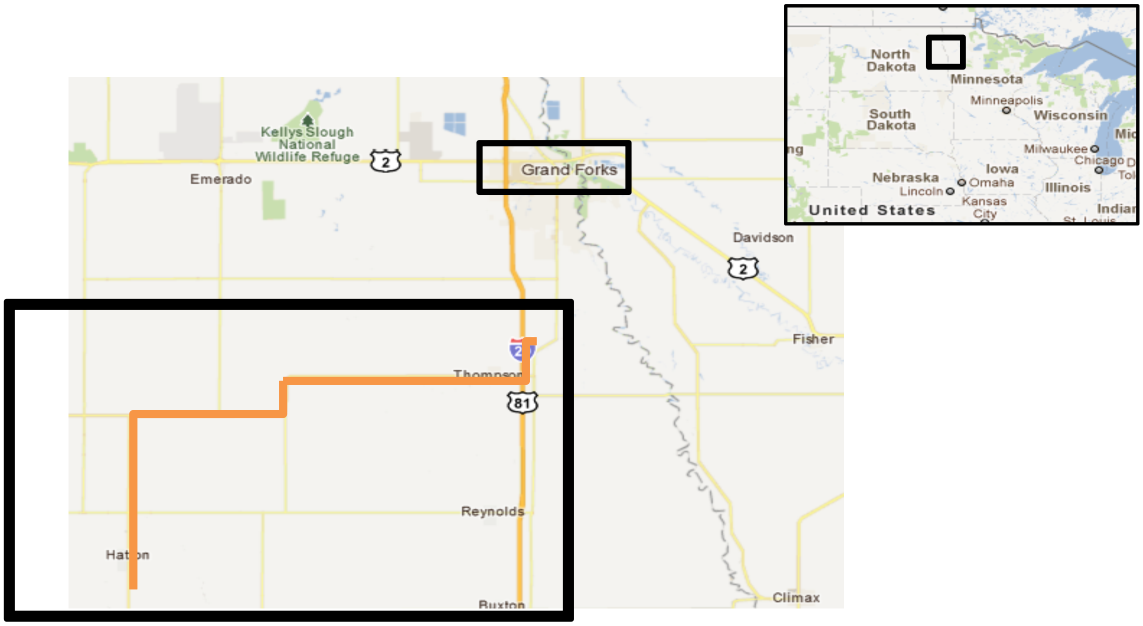

Figure 9. Map of Red River Valley region. Boxes signify the locations of where OBDII data were collected.

Maintenance Truck Results

Even though each test was run on every observation, hourly test data are presented to characterize how the truck performed over specific storm events. On average, for a single truck having 1500 observation points during the period of an event, it takes five to six hours to run through the quality check algorithm. The analysis period of 22-23 March 2011 was one that involved a winter storm that impacted Minnesota, North Dakota, and South Dakota. For sake of clarity, the results presented below have been filtered to show only data that have passed the speed check. The charts below all have similar characteristics. Pass criteria are set as all the tests passed except for the vehicle-to-vehicle test which is depicted on the right Y-axis. The flagged criteria are applied if any one of the tests flagged besides the vehicle-to-vehicle.

North Dakota

Figure 10 shows the truck tracks for the two days data were collected with trucks ND-9644 and ND-9372. Truck ND-9644 traveled Interstate 29 from Grand Forks, ND, to Hillsboro, ND also traveled along US Highway 2 to Emerado, ND. ND-9372 traveled mainly along Interstate 29 and State Highway 15.

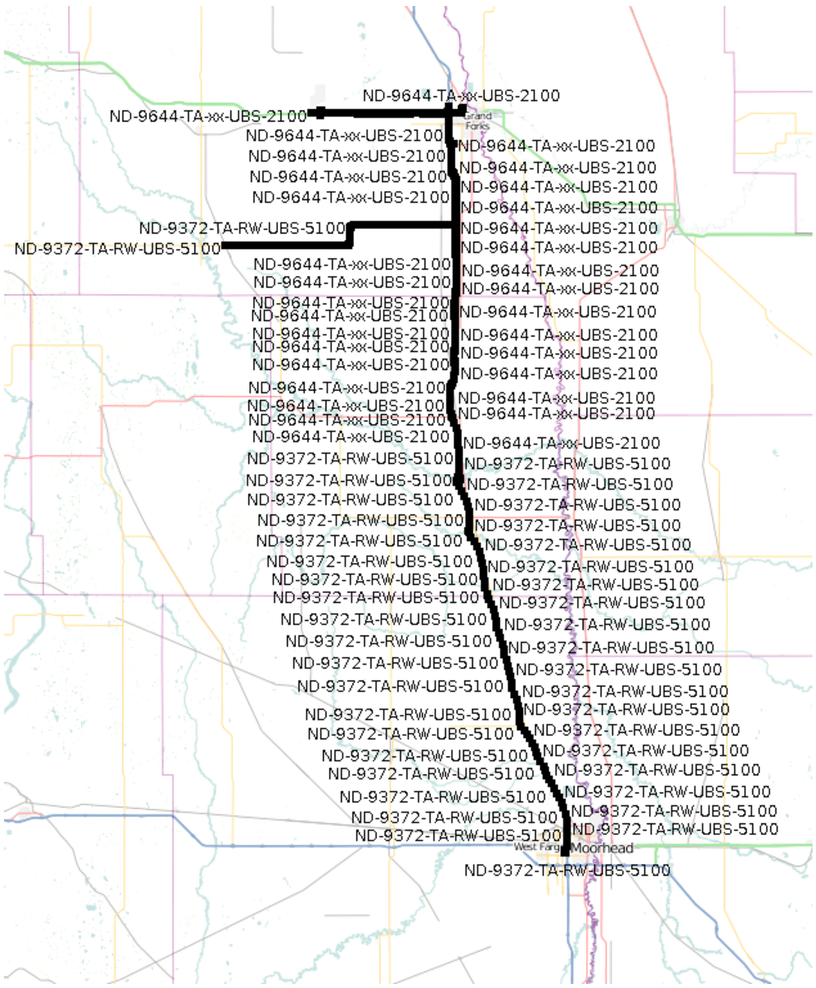

Figure 10. Track for ND-9644 and ND-9372 from March 22-23, 2011.

Figure 11 is an example of results for a truck in North Dakota referred to as Truck ND-9644. The results from this truck show overall good results within the 4.4°C to -

6.6°C air temperature range. Values outside this range were flagged. There were a few hours, specifically during 1:40-2:18 UTC and 10:15-11:13 UTC, on 23 March during which the temperatures do not look suspicious but were flagged. This may be in part to the ESS-based test.

For the vehicle-to-vehicle tests, the results were inconclusive as the data from ND-9644 lined up with that from other trucks in its surroundings and other times the data from truck ND-9644 were outside of/inconsistent with surrounding observations. Persistence scores were 100% for the entire storm, showing that the data from ND-9644 did not persist at any specific value.

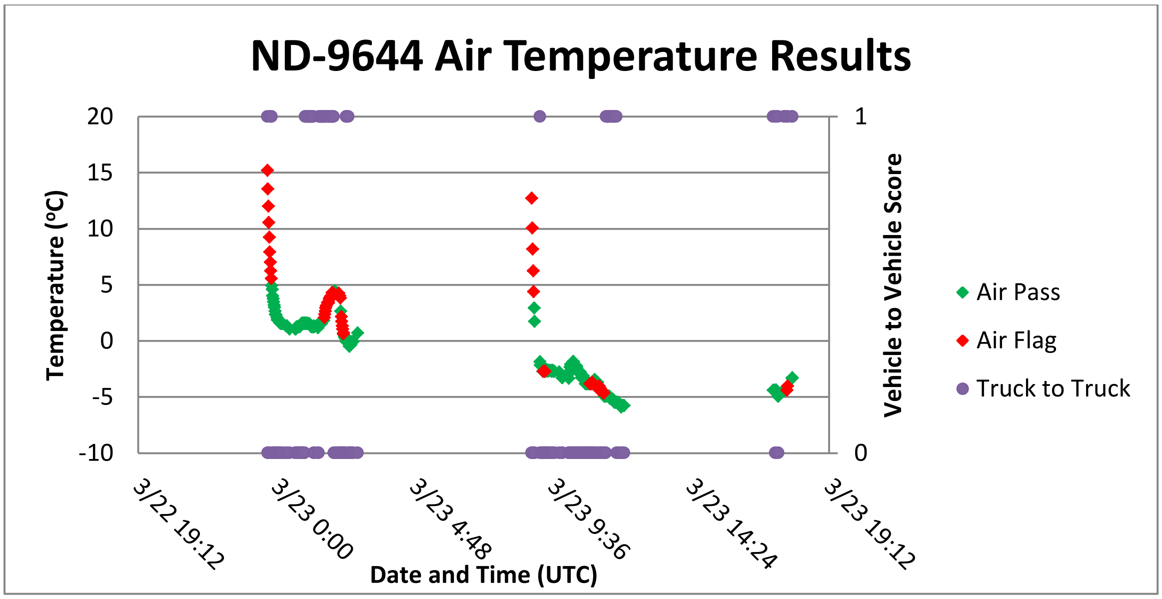

Figure 11. Air temperature results for Truck ND-9644. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Figure 12 indicates that truck observations matched ESS observations during well. At times, observations did not pass because of the lag between a pass-by, but it quickly reacted once the truck passed the ESS site. Specifically on 3/23/2011 between 1:40 to 2:16 UTC a pass-by was recorded and then the readings began to jump to 4.4°C. The point tests caught this and flagged the observations, but the pass-by verification maintained a pass result.

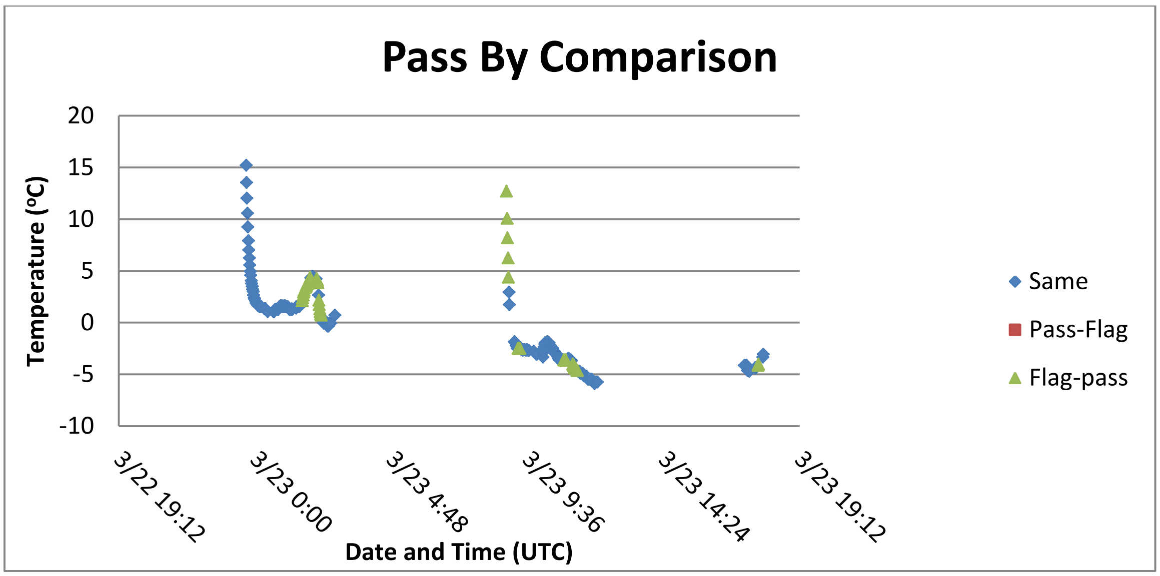

Figure 12.The Air temperature pass-by comparison for Truck ND-9644.Same indicates the results from the other checks and pass by are identical.

Figure 13 is an example of pavement temperatures from Truck ND-9644. The results from this truck show good results from the -9.4°C to 10°C temperature range. Pavement temperatures above this range resulted in flagged scores. During 10:53-11:17 UTC on March 23 the temperatures do not appear to be suspicious but are flagged. For the vehicle-to-vehicle tests, the results for ND-9644 only passed against other trucks when the air temperatures were flagged by the other tests. This was caused by observations from this truck reporting warmer temperatures than the surrounding trucks.

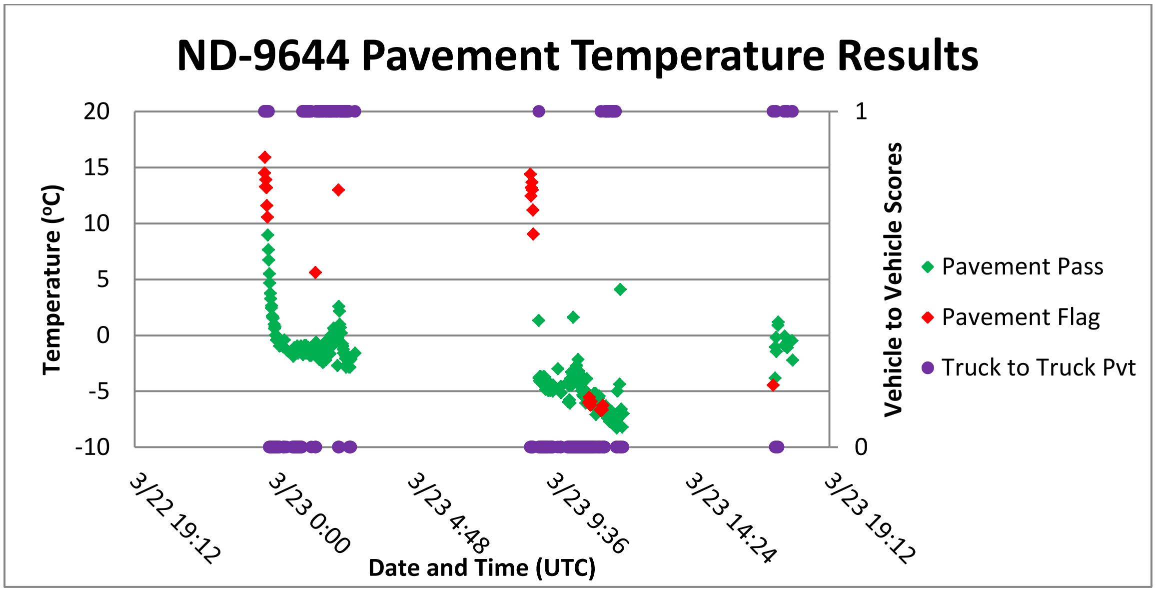

Figure 13. Pavement temperature results from Truck ND-9644. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

From Figure 14 it is apparent that the pass-by verification results are consistent with the other pavement test results. There were a few times between 8:50 and 10:50 UTC on March 23 where the results ended up miss-matching in that the observations were initially flagged and then were labeled as passing.

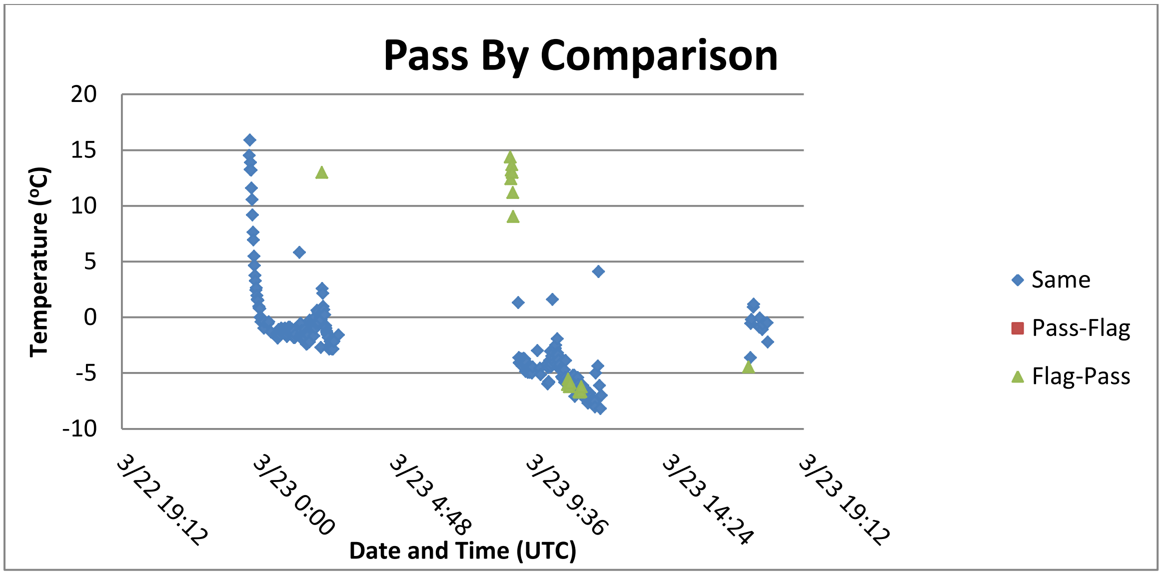

Figure 14. The pass-by comparison for pavement temperatures for Truck ND-9644. Same indicates the results from the other checks and pass by are identical.

Truck ND-9372 experienced at persistent temperature of -17.7°C near the end of the maintenance event (Figure 15). During a few periods the air temperatures passed all tests. The results passed when the reported data were primarily in the -3.8°C to 2.7°C range. For the vehicle-to-vehicle test, results were oftentimes inconsistent relative to other tests. When the data started to develop a problem, the vehicle-to-vehicle test was able to identify it by using data from the surrounding trucks. Around 12 UTC the truck air and pavement temperatures persisted for a prolonged period (Figure 17). At 13 UTC, its air and pavement temperatures dropped to -17.7°C and remained there until the truck quit reporting at 18:35 UTC.

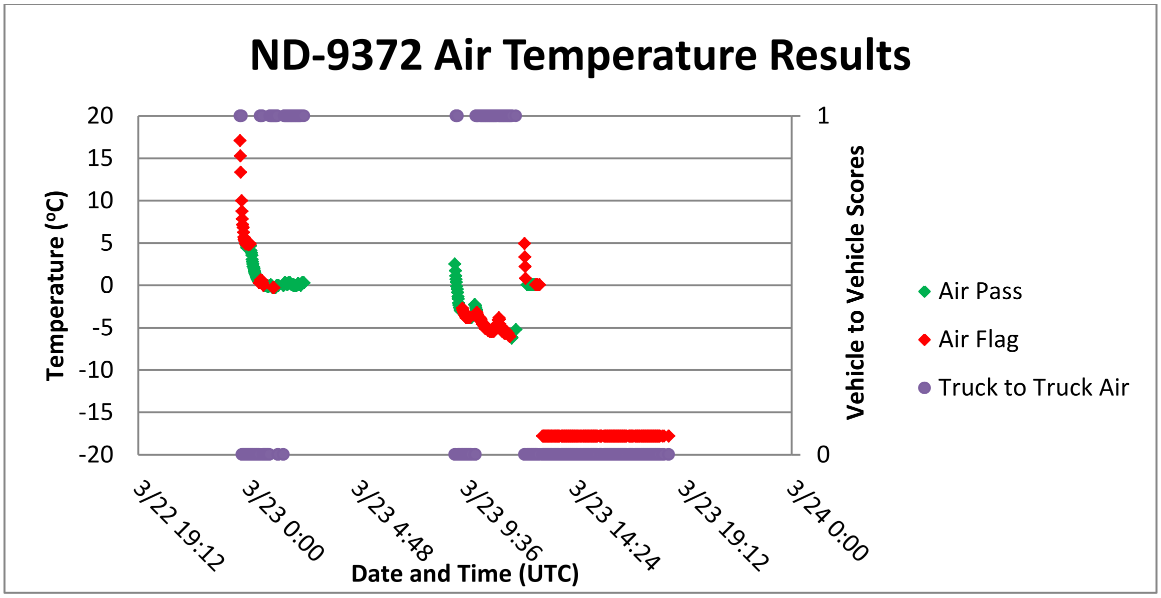

Figure 15. Air temperature results from Truck ND-9372. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

The air temperatures initially verified well relative to the ESS values (Figure 16). When the data began to be flagged frequently from 9:30 UTC and onward on 23 March 2011 the pass-by verification did not fare as well because right before the truck began to report -17.7 °C it passed by an ESS resulting in a pass until it passed by the next ESS along its route 35 miles away. This is evident when the results from the ND-9372 began to report -17.7°C. The point-to-point tests indicated that the data needed to be flagged, but the pass-by verification was delayed 3 hours. Since an ESS was not passed for three hours the pass-by verification was not run causing it to assume the previous score "pass" was still valid.

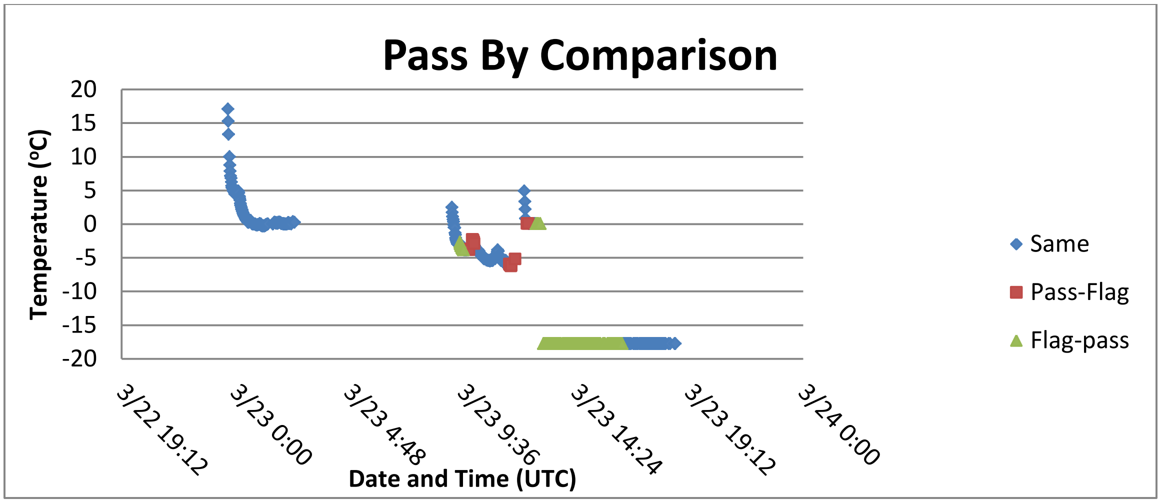

Figure 16. The pass-by comparison results for air temperatures for Truck ND-9372. Same indicates the results from the other checks and pass by are identical.

The pavement temperatures for Truck ND-9372 (Figure 17) generated more passing results than did the air temperatures. As with air temperature, the vehicle-to-vehicle test was able to identify the issue when the pavement temperature dropped to -17.7°C.

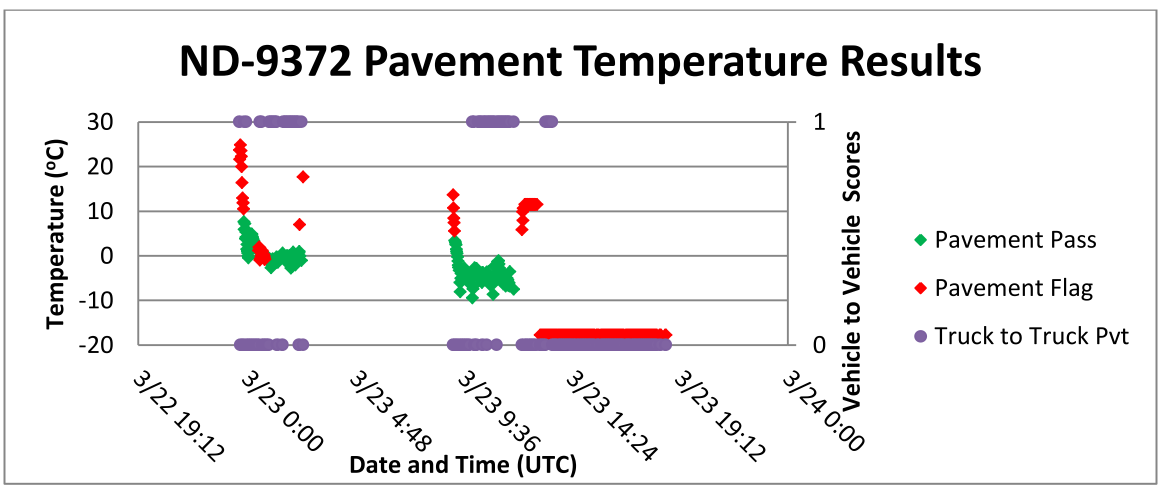

Figure 17. Pavement temperature results from Truck ND-9372. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

The pass-by verification did better for the pavement temperatures than it did for the air temperatures (Figure 18). The reported pavement temperature by ND-9372 at 12:13 UTC was beginning to rise to temperatures higher than that being reported by the closest ESS. By the time the maintenance truck passed the ESS at 12:20 UTC on 23 March 2011, the truck's reported temperature was above 10°C. This was outside of the threshold and triggered the flag on the pass-by verification. When the data became -17.7°C at 13 UTC it was correctly noted to be in the accepted range.

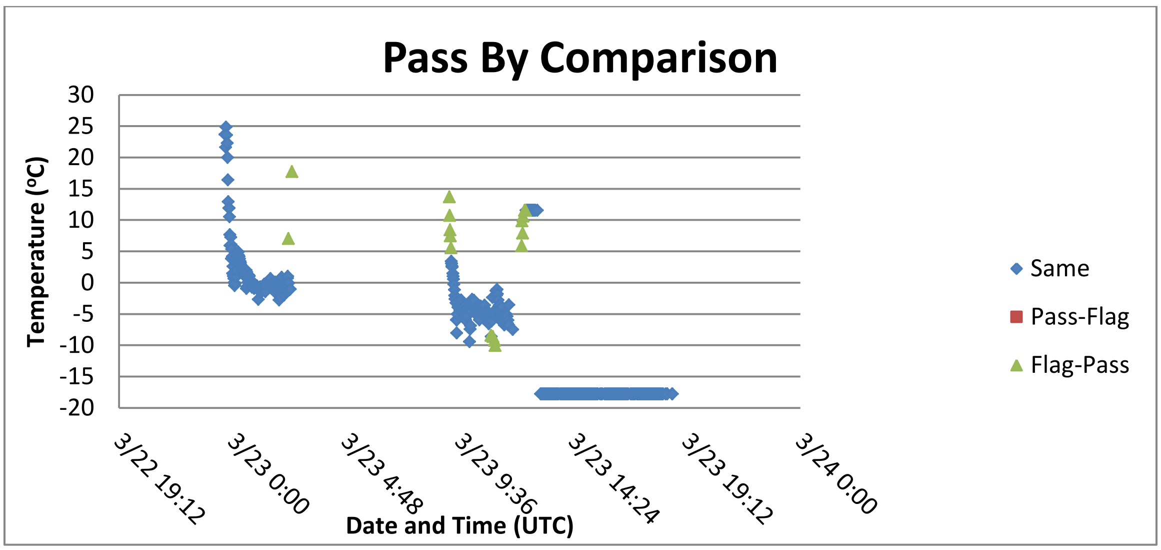

Figure 18. The pass-by comparison for pavement temperatures for Truck ND-9372. Same indicates the results from the other checks and pass by are identical.

South Dakota

Data from SD-DT045 (Figure 19) shows the truck's tracks for the one day data were collected. Truck SD-DT045 traveled on Interstate 29 from Sisseton to Summit, SD, along with traveling briefly on State Highway 15.

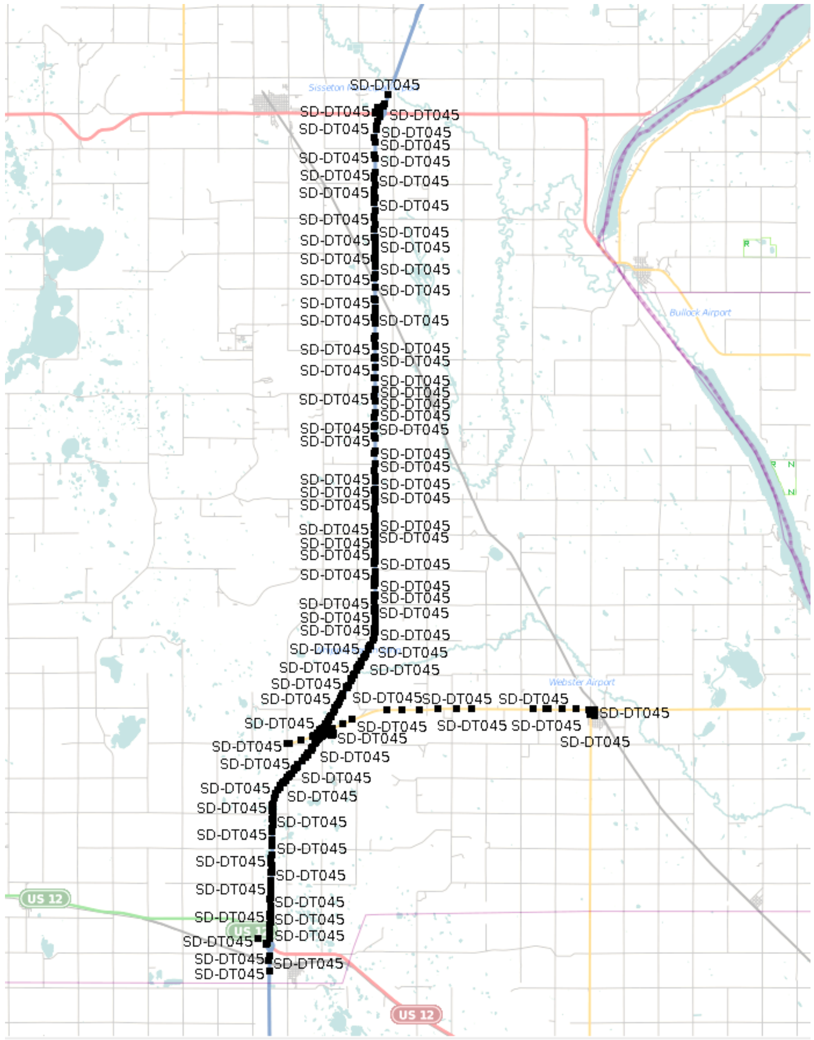

Figure 19. Track for SD-DT045 from 22-23 March 2011.

The data from South Dakota truck SD-DT045 (Figure 20) initially produced passing results. The results became flagged the longer the truck was deployed on its maintenance route. The reason for many of the flagged results after 19:17 UTC was the truck reported lower air temperatures than all of the surrounding ESS. On average, the truck was reporting temperatures that were 2.7°C lower than surrounding values.

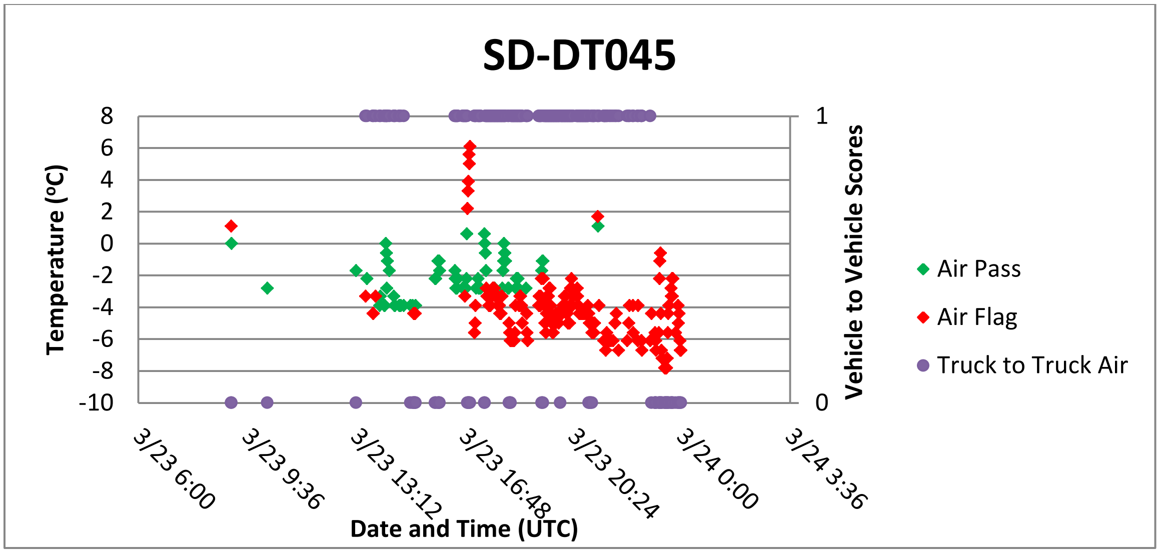

Figure 20. Air temperature results from Truck SD-DT045. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Only the air temperature pass-by verification can be completed because South Dakota ESS are not equipped with pavement temperature sensors. In Figure 21, the pass-by verification matched the point-to-point verification well.

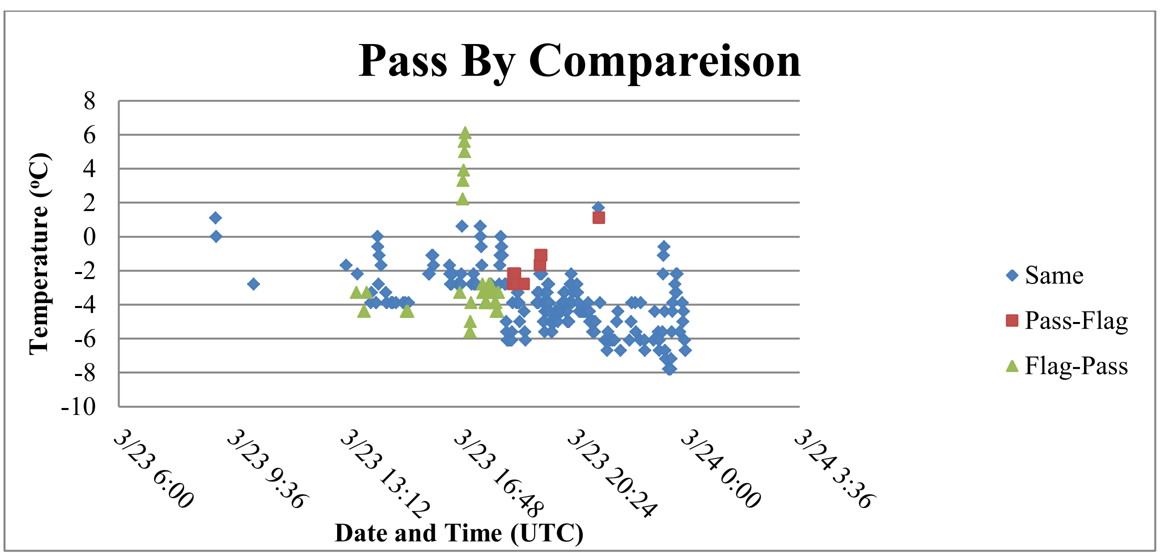

Figure 21. The pass-by comparison for air temperatures for Truck SD-DT045.

For this truck, there were a couple of reasons why some of the tests passed and others were flagged in the pavement results (Figure 22). The reason for many of the flagged results on SD-DT045 is the lack of pavement observations for the IQR test and the Barnes spatial test for pavement temperature. This lack of observations was because South Dakota does not report pavement temperatures through the *Clarus System*. The reason the noted tests passed was because the surrounding states have ESS that report pavement temperature. The vehicle was in range of stations in Minnesota and North Dakota that were reporting pavement temperatures so that the test could be processed. Even then, some of these tests were flagged because the temperature reported from the truck was out of the pass window defined by the test. In addition, there were a few hours in which the truck–to-truck tests were flagged because too few observations from other trucks were available.

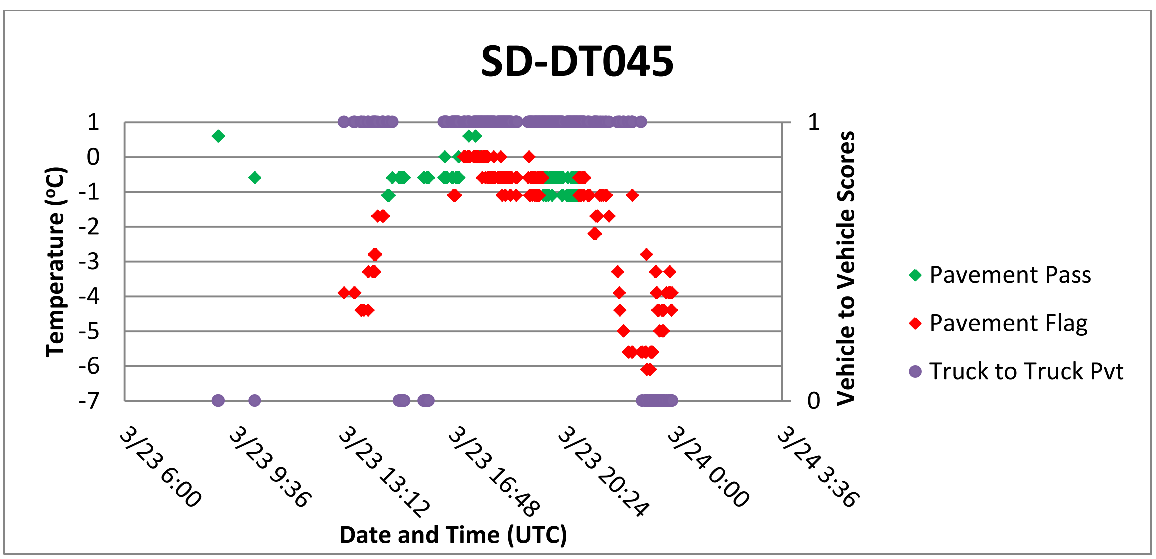

Figure 22. Pavement temperature results from Truck SD-DT045. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Figure 23 shows the truck tracks for SD-DT116 for the test day data were collected. Truck SD-DT116 traveled on State Highway 44 from Rapid City, SD, to US Highway 385.

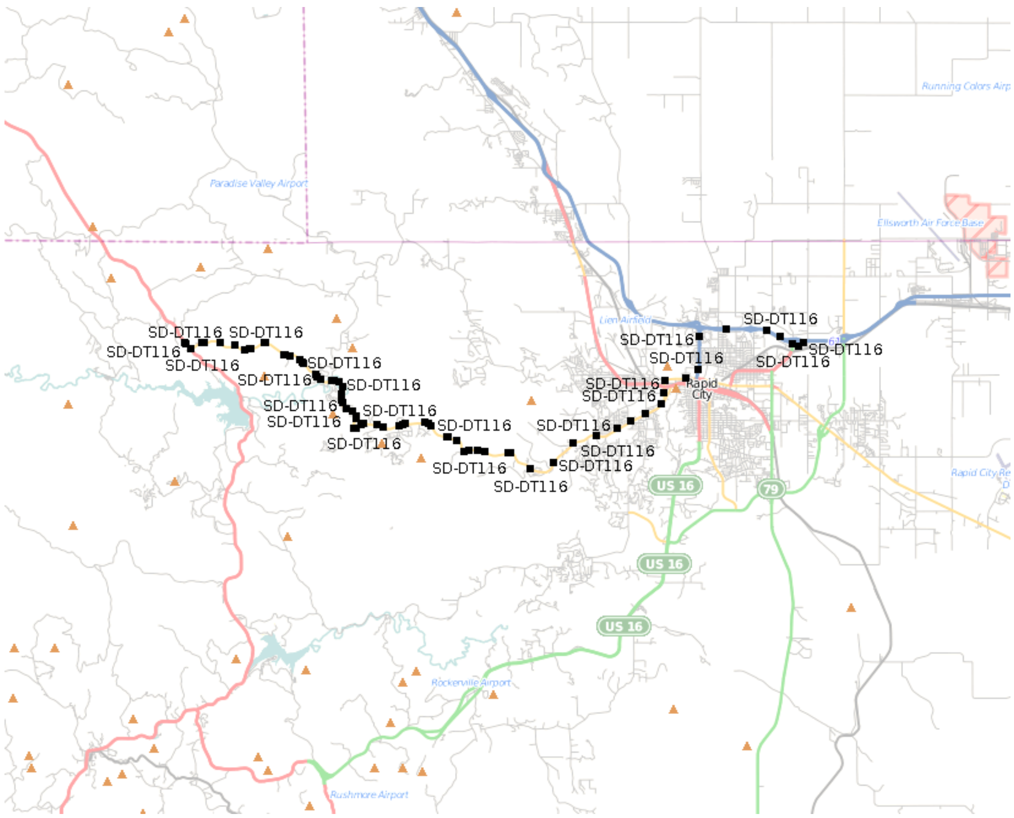

Figure 23. Track for SD-DT116 from 22-23 March 2011.

In Figure 24 the South Dakota truck SD-DT116 only reported for a total of three hours during the evaluated maintenance event. The data generated had overall high marks in all the applicable tests when the air temperature was between -1.6 and -3.8°C. The air temperature IQR tests did not run at all during the last hour. This was due to too few ESS stations being present in the radius of influence to complete the IQR air temperature test. There was no pass-by-verification completed for SD-DT116 because it did not pass close enough to an ESS during the data reporting period.

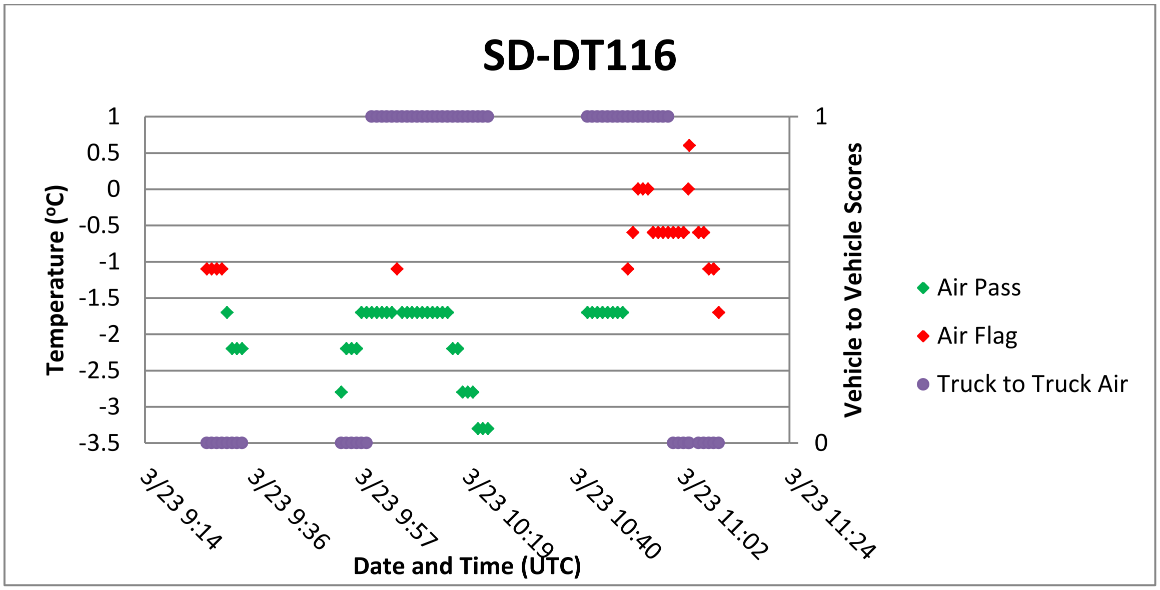

Figure 24. Air temperature results from Truck SD-DT116. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Unlike the air test, the pavement tests did not fair well (Figure 25). The reason for the low IQR pavement test scores was stated previously. The truck temperatures were abnormally higher than those from the surrounding trucks. This caused the vehicle-to-vehicle test to be flagged.

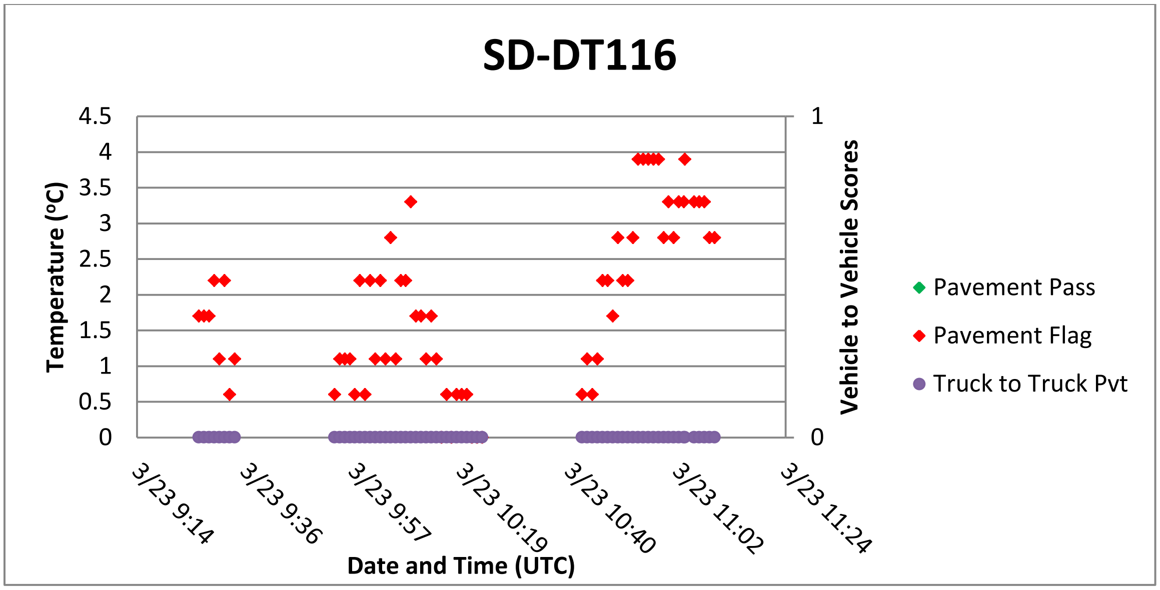

Figure 25. Pavement temperature results from Truck SD-DT116. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Minnesota

In Figure 26 the truck tracks for MN-AT-207576 and MN-AT-208562 are shown. Truck MN-AT-207576 traveled on Interstate 94 from Monticello to Rogers, MN. Truck MN-AT-208562 traveled on US Highway 10 from Becker to Rice, MN. No pass-by verifications were performed with the MN truck data because none of them were close enough to the ESS stations.

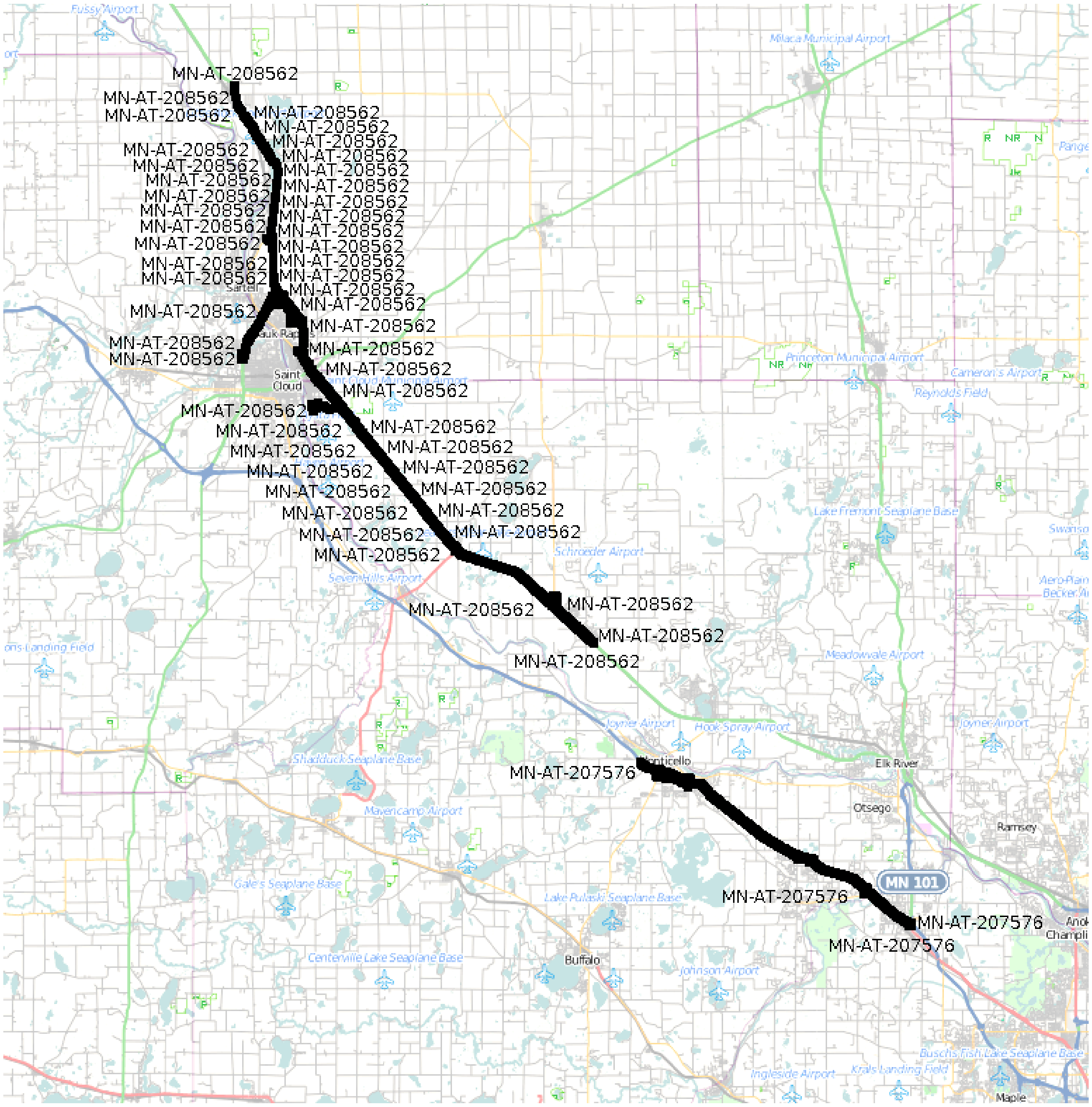

Figure 26. Tracks for MN-AT-207576 and MN-AT-208562 from March 23, 2011

In Figure 27 Minnesota truck MN-AT-207576 reported regularly during the storm event on March 23. In all of the air temperature tests, results scored well except in the last hour for the IQR air temperature test. Even then, the Barnes spatial air temperature test passed when the IQR test was flagging the data as being out of range.

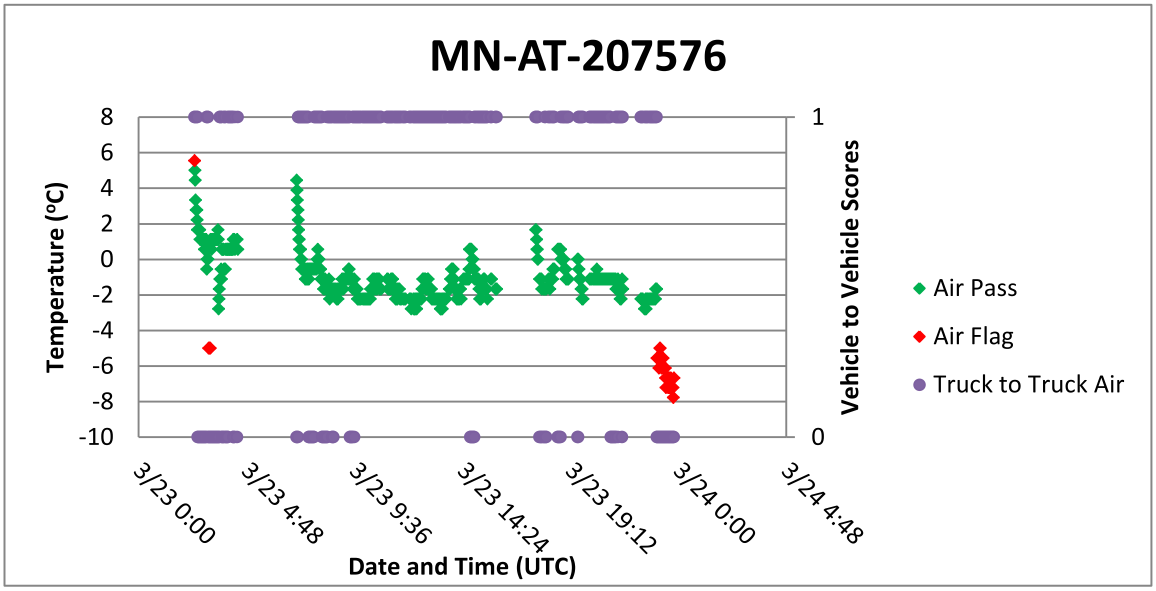

Figure 27. Air temperature results from Truck MN-AT-207576. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

The pavement temperatures for MN-AT-207576 (Figure 28) all passed when compared with values from surrounding ESS stations. The vehicle-to-vehicle results were more inconsistent, however.

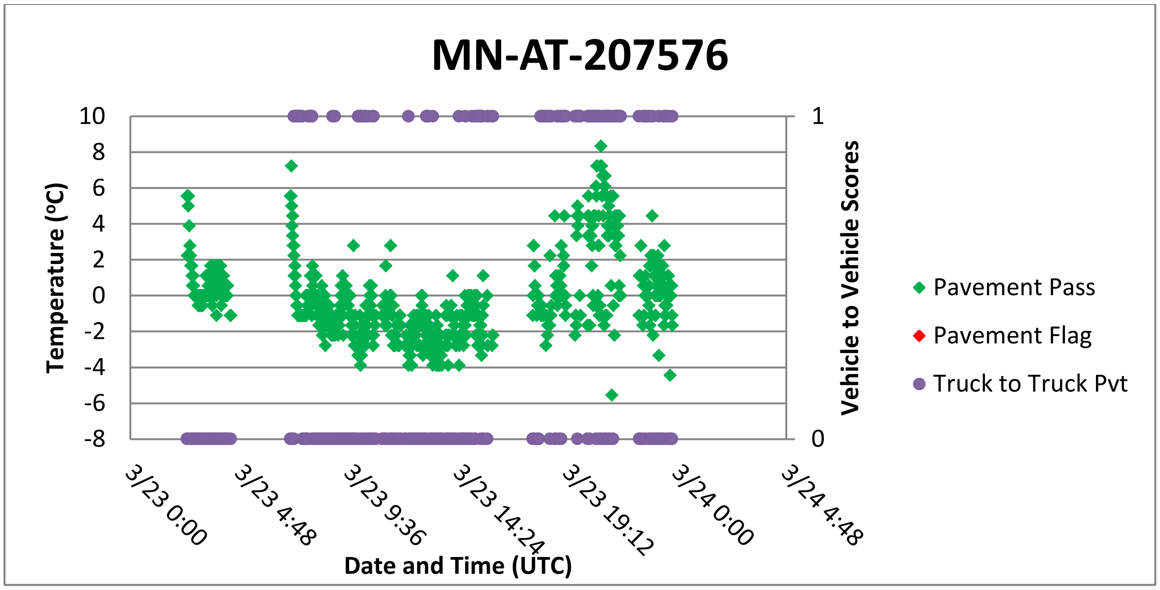

Figure 28. Pavement temperature results from Truck MN-AT-207576. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

In Figure 29 Minnesota truck MN-AT-208562 reported regularly during the storm event of 22-23 March 2011. The only time it did not report was during the overnight hours. In all of the tests, the observations scored well except for a few hours and for the IQR air temperature test. The Barnes Spatial Station air and pavement test passed during the times that the IQR test was flagging the data as being out of range.

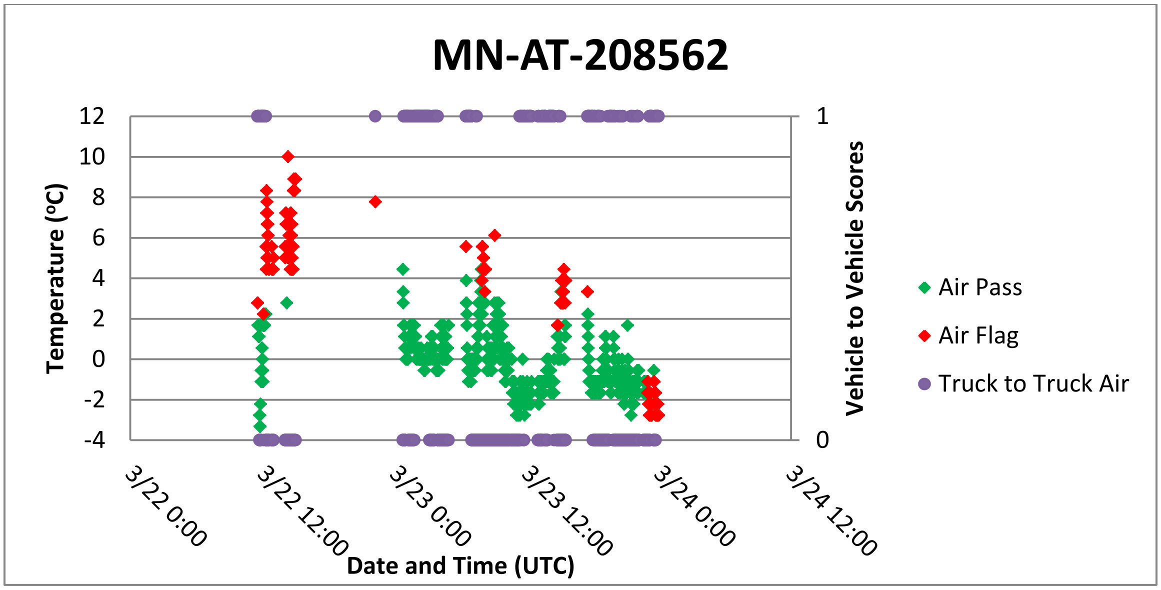

Figure 29. Air temperature results for Truck MN-AT-208562. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Figure 30 shows the pavement temperature results for MN-AT-208562. There were a few times at which the IQR pavement temperature test produced flags, but the values passed all of the other tests. Like truck MN-AT-207576, MN-AT-208562 had similar inconsistent results regarding the vehicle-to-vehicle test results.

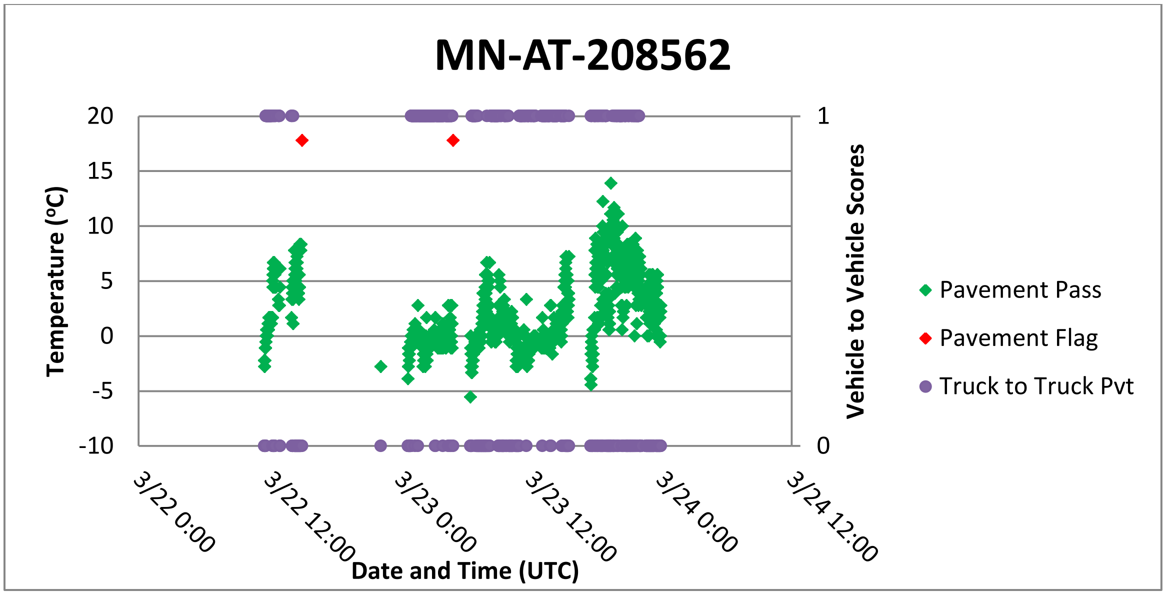

Figure 30. Pavement temperature results for Truck MN-AT-208562. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

OBDII Vehicle Results

The quality-checking tests were also applied to a few consumer vehicles that were equipped with an OBDII port. Unlike the maintenance trucks that had sessions of multiple hours, consumer vehicle session were only 5-15 minutes long, resulting in about 500-1000 observations. Results for the individual observations are depicted below. The analysis period of 8-11 February 2011 was during a period when arctic air propagated from Canada into Minnesota and North Dakota.

The path the OBDII consumer vehicle traveled on 9 February from Hatton, ND, to I-29 by Thompson, ND, is presented as a rural case in Figure 31 below. No pass-by verifications were completed with OBDII vehicle data because none were close enough to the ESS stations.

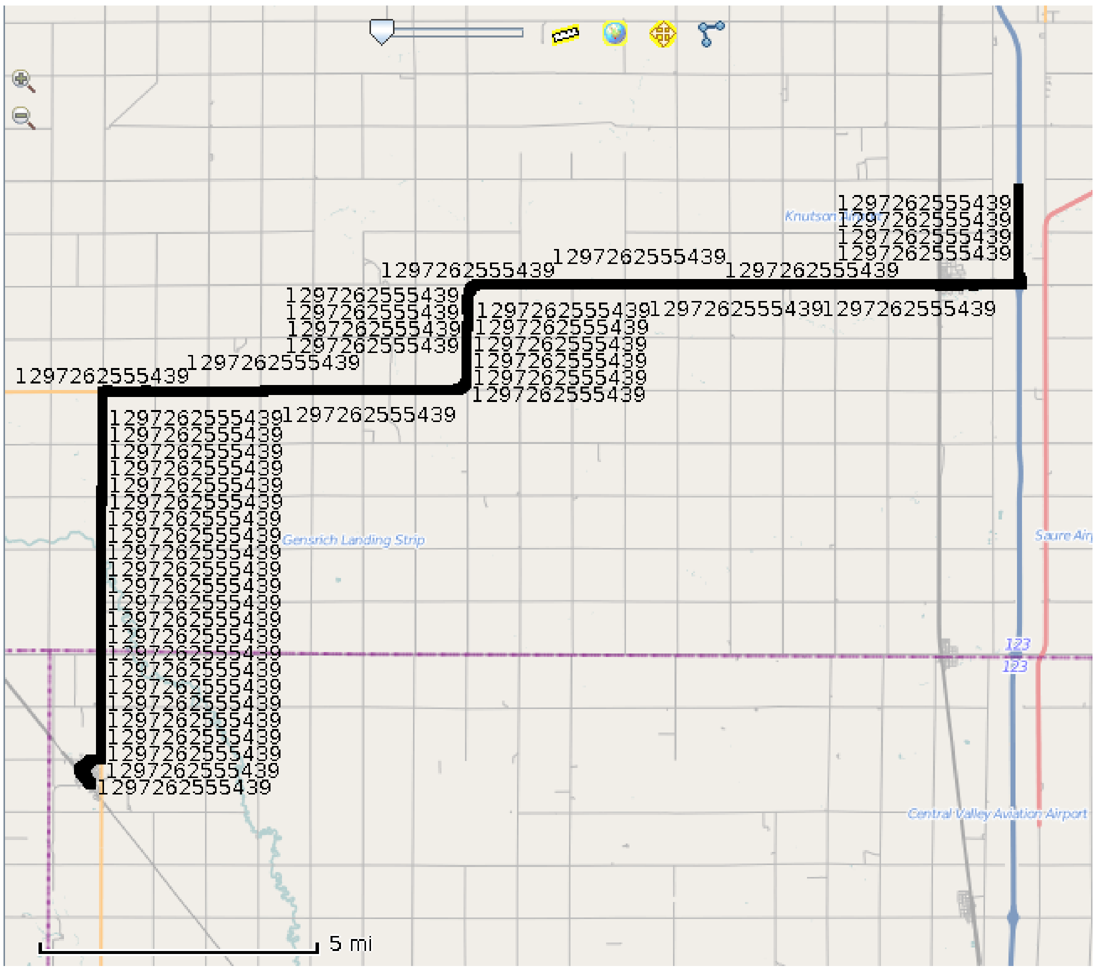

Figure 31. Travel pattern for an OBDII test vehicle during the morning of 9 February 2011.

For this example, the vehicle was reporting ambient and intake air temperature. The data from the ambient air temperature sensor data (Figure 32) passed every IQR test. The intake air temperatures (Figure 33) had mixed results. Intake air temperatures only pass the IQR test from 14:52 to 15:00 UTC, when the temperature was at -19°C and below. During other times, however, the Barnes station test does pass when the IQR test flags values. The main reason for the Barnes station test passing is the standard deviation of the stations near the vehicle was 8-9°C. When looking at the temperatures reported only from the vehicle there are differences between the two sensors. The ambient air temperature average is about 6-9°C lower than the intake air temperature. Also, the intake air temperature did rise and reached into the -12 - -14°C range as the vehicle was traveling 60-70 mph while the ambient air temperature remained at -21°C. The reason for the increase for the intake air temperature compared to the ambient air temperature was the locations where the sensors are located. The ambient air temperature was located in front of the radiator where the ambient air could freely flow around the sensor. The intake temperature sensor is located behind the radiator in the engine bay near the engine. As the air flows through the grill of the vehicle, it passes by the ambient sensor allowing for a unobstructed reading. As the air continues, it passes through the radiator and is heated by the radiator coils. The heated air then passes into the engine bay and is further heated by the heat coming from the internal combustion engine. This causes the engine bay to stay significantly warmer than the environment causing the intake temperature sensor to gain a warm bias once the engine temperature has reached its operating temperature. The vehicle-to-vehicle tests were not included because there were no other observing vehicles present during the time this vehicle was driven.

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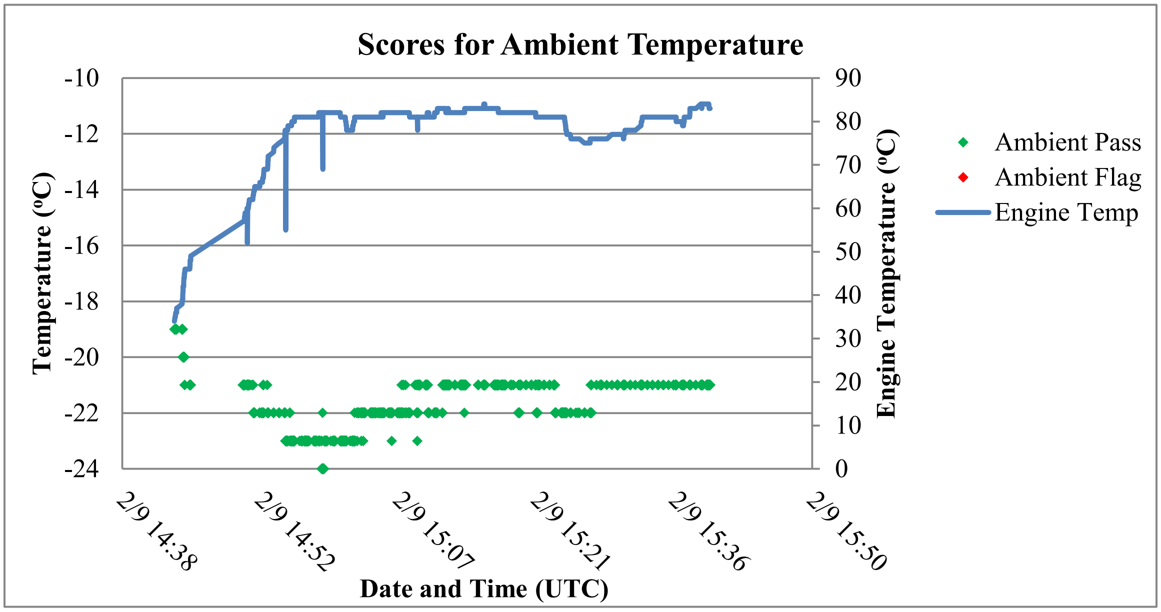

Figure 32. Overview of results from ambient vs. intake case using ambient air temperature. The X-axis is time in UTC. The left Y-axis is temperature. The temperature coloring depicts whether the value passed (green) or flagged (red Values of engine temperature (blue line) from the session is on the secondary Y-axis.

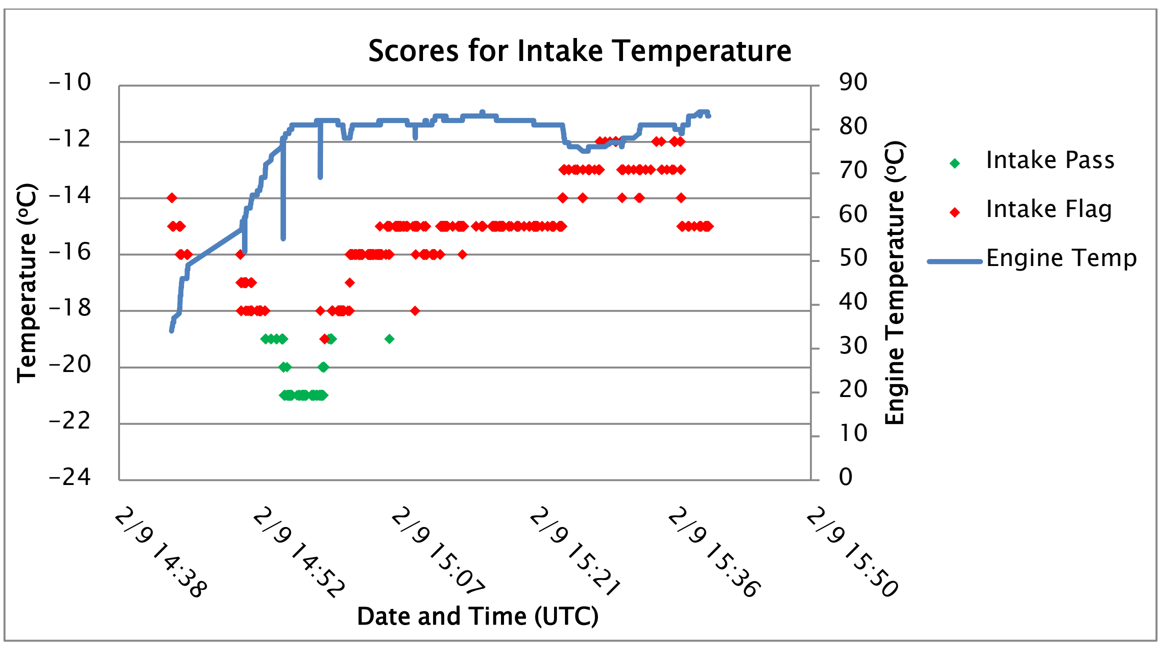

Figure 33. Overview of results from ambient vs. intake case using intake air temperature. The X-axis is time in UTC. The left Y-axis is temperature. The temperature coloring depicts whether the value passed (green) or flagged (red). Values of engine temperature (blue line) from the session is on the secondary Y-axis.

Figure 34 depicts the travel pattern from OBDII-equipped vehicles on the morning of 10 February 2011. The area of focus was along 42nd Street in Grand Forks, ND (circled in red on Figure 34).

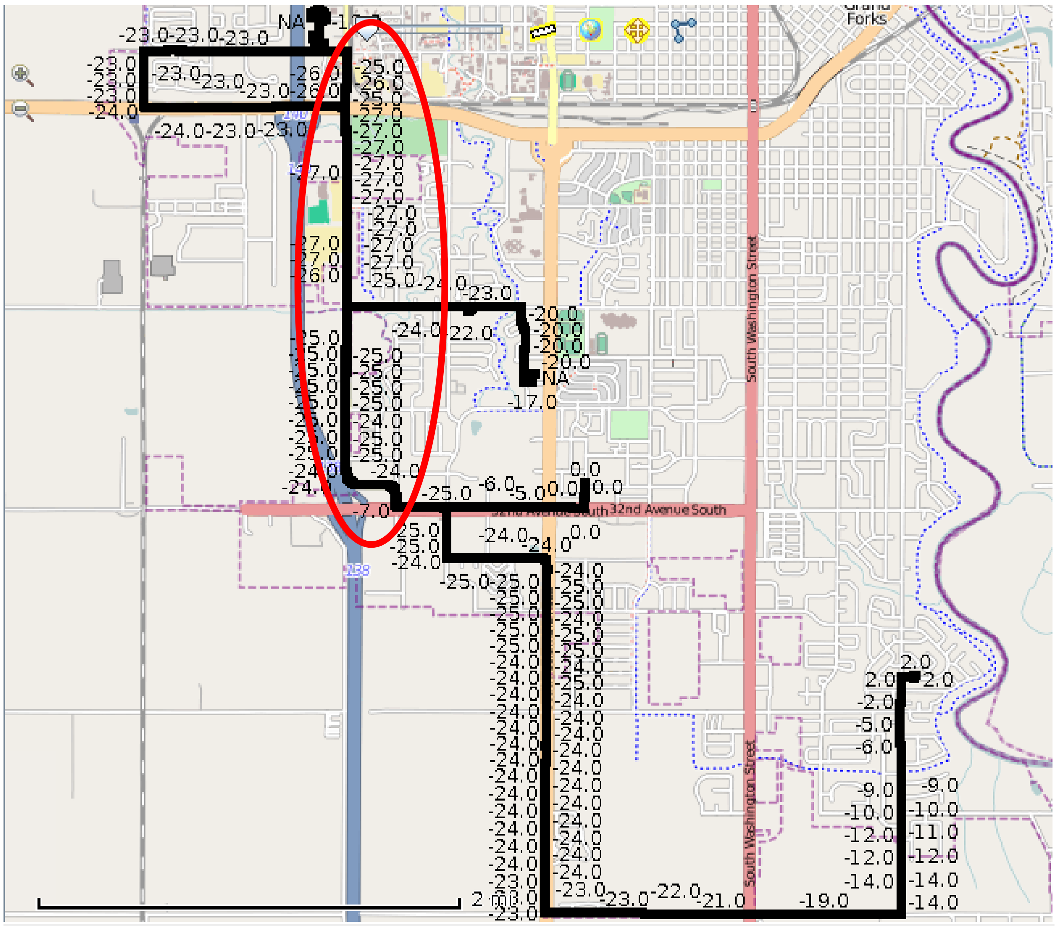

Figure 34. Travel pattern for drivers during the morning of 10 February 2011. Numbers represent the intake temperatures at the specific locations. The red circle on map indicates the focus area 42nd street in Grand Forks, ND.

Figure 35 provides an example of a vehicle starting in a heated garage. The data received from the vehicle were continuous and resulted in the gross check and persistence tests for the air intake to pass at a 100% rate The IQR and Barnes Station tests produced flagged results as the sensor adjusted to the surrounding environment. The sensor had to adjust 24°C degrees before the IQR test passed. Once the sensor adjusted to the surroundings, the IQR test began to pass. However, the vehicle-to-vehicle test produced opposite results. The reason for this was the other vehicles used had higher intake temperatures during this period caused in part by low speeds or stopping and going.

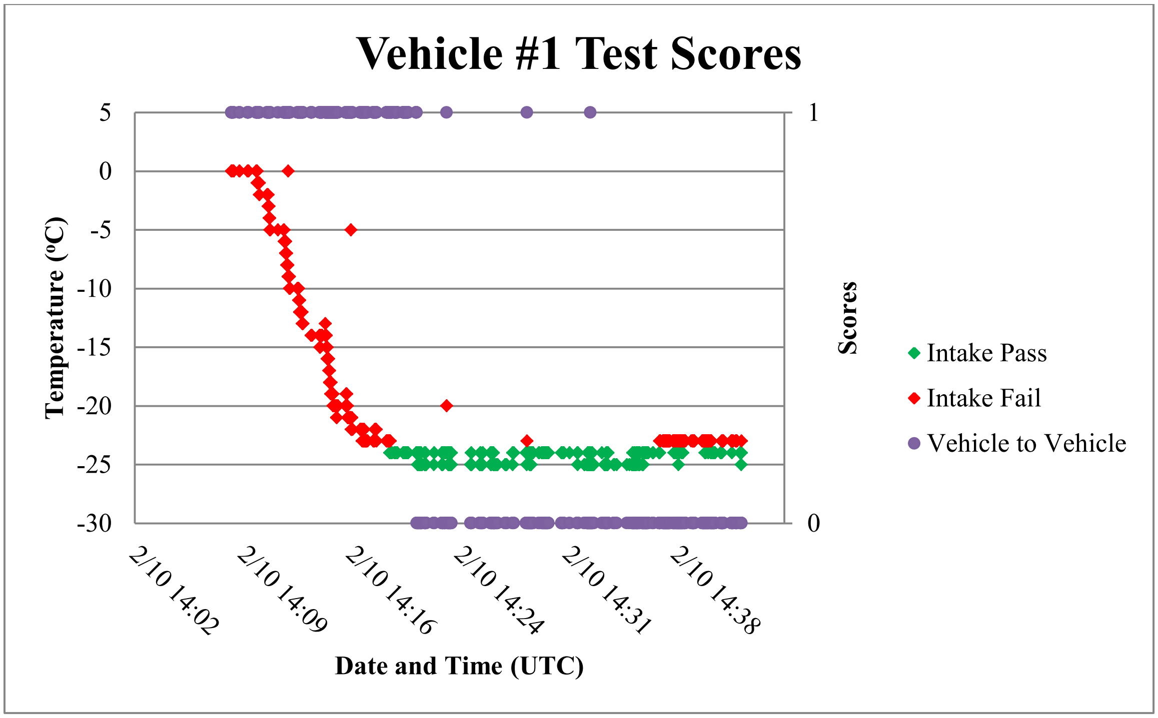

Figure 35. Overview of results from non-idling vehicle including the Vehicle-to-Vehicle test. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

Figure 36 shows an example of one of the vehicles that had an impact on the vehicle-to-vehicle results. This idling case is an example of a vehicle that also started in a garage. But, this vehicle had periods where it came to a standstill and the indirect heat from the engine had some influence on the intake temperature sensor. Gaps within the test results indicate periods when the vehicle was stationary. From 14:14 UTC to 14:44 UTC the temperature continued to drop except for the three times the vehicle was stopped (for a total of 3 minutes). This caused the temperature sensor to stop dropping and at 14:15, the sensor temperature began to rise again. On this vehicle the IQR and Barnes tests all produced flags when comparing against ESS data. The vehicle-to-vehicle tests initially flag the temperatures that were to warm for the environment, but later on after the temperatures reached -6°C and lower this test passed.

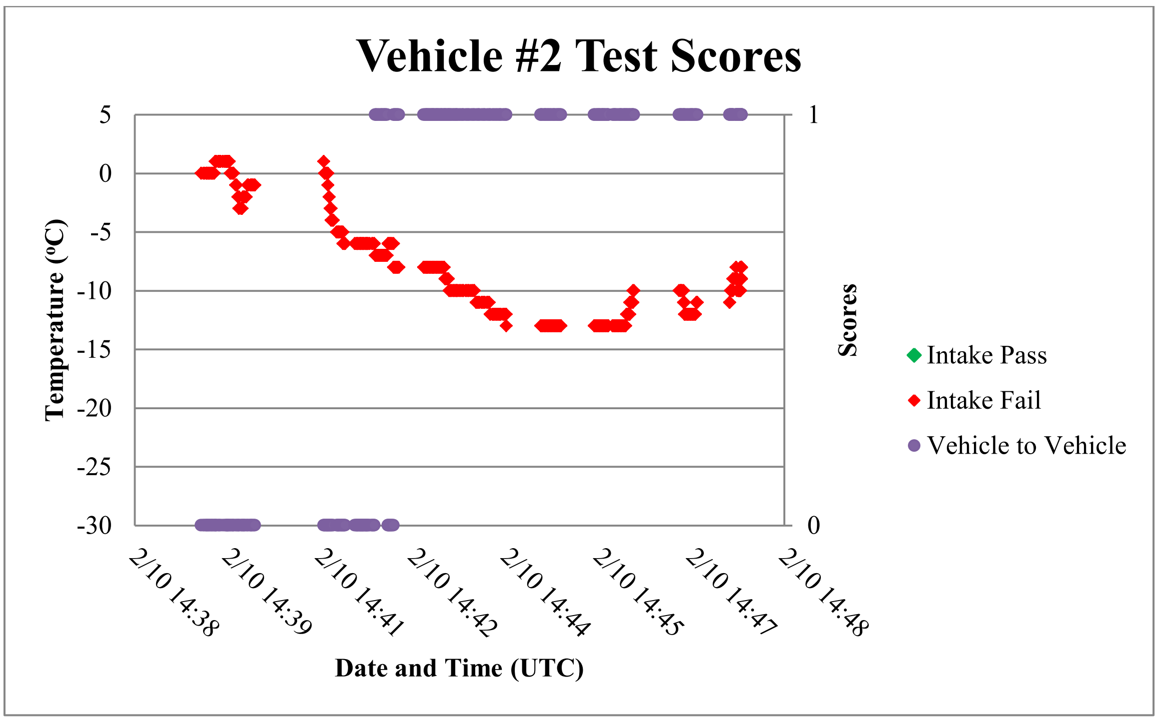

Figure 36. Overview of results from idling vehicle including the Vehicle-to-Vehicle test. The X-axis is time in UTC. The left Y-axis is temperature and the right Y-axis, if applied, is vehicle-to-vehicle results. The temperature coloring depicts whether the value passed (green) or flagged (red).

CHAPTER V

DISCUSSION

This work led to a software application that generates quality check markers for individual mobile observations. The volume of data generated by mobile platforms presents significant challenges in providing timely quality checks. Even after selecting a subset of the available data from a given truck, as was done in this study, the processing time is a significant fraction of the storm event. However, with sufficient computing resources this limitation could be reduced as the processing is expected to be scalable. During the algorithm testing process a few intriguing characteristics of mobile ESS data arose. A few of the more interesting items are presented below.

Amount of included data

This depends upon the sensors installed onboard the vehicle in addition to whether the sensors are operating. Some trucks/vehicles report all available sensor values dependably along with a timestamp and location. Other trucks/vehicles tend to report the timestamp and location reliably and then report additional sensor information occasionally or quit reporting sensor values for long periods of time. The existence of the missing data makes understanding the environment around the truck/vehicle more difficult. In some situations the position information from global position systems provides more detail than might be needed when reporting the observed air and pavement data. An example of this is the Minnesota DOT, which reports air and pavement temperatures every minute and GPS information every 15 seconds. This produces a significant amount of GPS data that can be removed during the preprocessing stage of quality checking.

Timing of data

When working with historical data for specific trucks taken from data archives, the data are rather straightforward and in chronological order. The real-time or operational data received may prove to be more problematic. The data from trucks are sent directly to a third party that collects and redistributes the data to other users. The frequency these data are sent from the third party is dependent upon the third party. In addition, the information that is retrieved is not always complete--some observations are not in chronological order and may not be received until a day later.

The OBDII data used in this study were not received through third party that collects and redistributes the data. However, similar issues are present. One issue is the timing of the data and the cellular network. Sometimes the data are promptly sent to servers while at other times the data may be delayed for a brief period of time. Another issue is completeness of the uploaded data. The data were collected without any issues but the delay in uploading to the server resulted in termination of data uploads and thus in data from only parts of the trip being collected.

Data persisting at -17.7°C (0°F)

This was an issue with a few trucks in this study. The problem is that the sensor readings from a truck appear to become stuck at its last temperature for a period of time. When the truck quits reporting it defaults to -17.7°C (0°F) instead of an empty placeholder. On a few trucks, it is easy to identify this problem since the precision of the temperature data were multiple significant figures after the decimal point and the error didn't report any after the decimal points. This could present serious problems due to being near the melt/freeze point of pure water.

Significant figures in data (xxx.xxx °F or xxx °F)

An algorithm must address inconsistencies across mobile data reporting platforms. The significant figures in data reports from truck sensors differ significantly from state-to-state and vehicle-to-vehicle. Some trucks have significant figures of 2 to 3 after the decimal point while other trucks have one significant figure after the decimal point.

Some states are missing observations to compare against

The tests that utilize data from either fixed or mobile ESS seem to fair well if the reporting truck is near enough to similar types of observations. The issue of spatial tests not running arises when there are not enough similar types of observations for comparison. This makes a specific data type harder to quality control and puts more emphasis on the other quality checks to validate observations.

Limitations

Post or delayed versus real-time is a concern depending upon how the data are to be used. If the data are primarily used to assess current conditions, then real-time processing of the data is needed to determine if any problems are arising with the sensors during maintenance actions. If the data are to be used in prediction models for pavement and/or atmospheric conditions, then the processing of the data only needs be run on a specified interval. In this event the quality checking only needs to be performed at times when the data are going to be ingested into a model. Depending upon the style of processing (real-time versus delayed), the time it takes to complete the processing of the quality checks will vary. Caveats here include:

For real-time use and depending upon the surrounding observations, it may be short if there are few observations. Alternatively, it may take more time than the frequency of the received observations, if there are many observations around the target observation. The advantage of this method is knowing that all of the observations coming from the truck have gone through the tests and that bad data in theory would be flagged.

For the delayed checks, only the observations used during the model initialization need to be checked. This would limit the number of observations that would be run through the quality check tests. The advantage of this is it reduces the amount of processing time. However, this could hinder the identification of transient sensor problems.

Quality Limitations:

With no standards or calibrations for the maintenance truck or OBDII sensors, the quality of the data remains in question across both platforms. This was notable across states. For example, in Minnesota's metro area many ESS sites are available for comparison, which resulted in better quality check performance. In South Dakota and North Dakota the perceived maintenance truck data quality was not the same as Minnesota. There were instances where the data were continually flagged or few of the points passed. In South Dakota and North Dakota the ESS sitings were more limited than in Minnesota's metro area and were taken in a rural setting instead of an urban landscape like the Minnesota metro area.

Barnes Spatial Test limitations:

The Barnes spatial test does have limitations, since it is an objective analysis test. The first is that the test uses surrounding observations to create an estimated temperature value at the point of the vehicle's observation since an actual observation in most cases is not available. This is done by using a weighting scheme that weights the surrounding observations based upon distance from the point of interest. Using the variability of those surrounding observations can help determine a variance. If the observations surrounding the point of interest are in general agreement, then the variance will be small. If the variability between the surrounding observations is great then the variance will be large. In a situation where there are large variances in the surrounding observations it may allow observations that should be flagged to pass. If the variances were small it may flag reported localized phenomenon even though it was valid. Another issue comes from observations that are close together and are similar a distance from the target, but have significantly different values will carry a similar weight. This will cause the standard deviation of surrounding observations in the Barnes spatial test to become larger, thus allowing more data outliers to pass.

The Barnes spatial test also struggles to correctly resolve the background when there are too few surrounding observations. If a mobile observation is influenced by a localized phenomenon, then the Barnes spatial test would flag the observation since it cannot resolve localized phenomenon with limited observations around the mobile observation.

Unbalanced observations is another issue with using a Barnes spatial scheme. A unified or balanced field of surrounding observations would alleviate this issue. The data field from ESS and other vehicles in their current configuration is not evenly spaced. Sometimes, depending on the location of the point of interest, the surrounding data points may all be on one side and/or nearly at the radius of influence. This in turn may result in the estimate at the mobile observation location being poor.

69 Mile Issue

The static radius of influence for the quality checks causes some significant issues for the Barnes spatial tests. One issue is the micro-environments may differ significantly in some areas over this distance. With a static radius of influence of 69 miles this may cause some of the surrounding observations to be diluted if the ESS observation density is great. For a high density ESS observation situation a smaller radius of influence would be more beneficial since observations would focus on only nearby ESS. This difference in number of ESS has an impact on differentiating if a localized observation is legitimate or abnormal.

OBDII specific issues

Idle vehicles impact on Vehicle-to-Vehicle. One issue that did arise when working with the data was the apparent bias that appeared from vehicles that were stationary and idling. The vehicle-to-vehicle tests assimilated surrounding data for both moving and stopped vehicles. This caused a warm bias for the vehicle-to-vehicle tests causing results to be flagged when the ESS-based tests passed.

Ambient Air Temperature filtered and smoothed. Even though the data are being pulled through the OBDII port, the ambient air temperature data are filtered. The raw data are not being pulled; instead the data are smoothed by the engine control unit, which removes some of the variability and noise. This smoothing may have biased some of the results from the OBDII vehicles and must be considered further.

CHAPTER VI

SUMMARY

The goal of the project was to see if mobile data collection observations from vehicles traveling the highway corridors may assist where ESS sitings are sparse or non-existent. There were some events specifically in MN where the data collected from ESS did provided good valid and data along areas where they traveled. These were also areas where ESS sitings were well populated. In North Dakota and South Dakota where it is a more rural landscape and fewer ESS sitings the results from the maintenance truck data were more inconclusive.

Overall these quality checks provide insight on the complexities of developing useful quality checks of mobile observations. The test that provided utility in both the maintenance truck and OBDII vehicle data was the speed test. This test helped filter observations that may have been influence by ambient heat from the vehicles. In addition, the spatial tests seem to work correctly based on reporting ESS. For the maintenance truck data, the pass-by verification did a good job verifying the results from the other tests. For the OBDII data, the ambient sensor appeared to be representative of environmental conditions during moving and idling. The intake temperature sensor gains a warm bias, which is influenced by the engine heat.

Throughout the process of developing the tests and running them, there were many challenges in regards to the data. Some of these challenges include that there were no operational standards for the maintenance truck data or OBDII vehicles for using the data for collecting atmospheric or roadway. Calibration is also an issue faced by maintenance truck and OBDII vehicle data since sensors are generally only replaced if they go bad, but usually not calibrated. This was a problem with comparing road temperature sensors because some non-calibrated sensors may report the road temperature at 1°C but the actual road temperature was at or below 0 °C. Data systems are not always sending data or if something goes wrong and a sensor stops reporting, it usually is not fixed until after a storm event or until it is convenient. This leaves bad data flowing into the quality checking system and is most times caught right away. In other situations, the bad data may continue to pass for a period before the tests begin flag bad data. The data also varied state-to-state as some states provided good data through their trucks and ESS sitings. For other states the data were more variable in regards to quality of the data received.

Other issues regarding the tests include the usefulness from the spatial tests. The large radius of influence and low number of required surrounding observations causes tests to flag observations that were representative to the surrounding environment. An example of this occurred when observations temperatures did not fluctuate, but were passing then became flagged for a brief time and then passed again. In other cases, there were observations that were not representative to the environment. For example, when a maintenance truck leaves the garage, there is a quick drop temperature but during the drop, before the temperature stabilizes to the environment, the tests begin to pass the results. This is because of the sensor response time takes a few minutes to adjust to the environment and the minimum tolerance or the large standard deviation from surrounding observations.

When developing an operational method in quality checking vehicle data, the focus will be in flagging values that fall out of the range of the sensor along with observations that become persistent. The use of the pass-by test is important to see if a vehicle is collecting representative data. This allows for a direct comparison of the vehicle data to the ESS, but the use of the other tests will be used to identify if the vehicle data begins to become unrepresentative to the environment. A dynamic scoring system will need to be applied to the IQR or Barnes tests to account for the number of available surrounding observations when these tests are run.

Currently some of the values required to run the tests, especially in the Barnes and IQR spatial tests used in the quality checks, do not provide good representation of the surrounding environment. When developing the minimum requirement of observations to best represent the environment, use of a background field from a model to test against the quality check spatial tests should be considered. The model output could be used to run the IQR and Barnes check with using the model field in different environments. Reduce the surrounding observations until they fail to represent the target location. This will help define the minimum number of observations required to gain the best consistent results from these test.

In the future, test bed fleets will need to be able to test against different vehicles from different manufactures and types (car, truck, etc.). I recommend looking into the sensors from different manufactures and sensor locations on vehicles, as they may play a role in biases within collected data. Developing an error tolerance to account the differences between the different vehicles will be key in dealing with the bulk data received in Connected Car. Also, vehicle-to-vehicle checks will be important to consider especially when the average vehicle traffic over a mile begins to reach over 100-200 hour. I recommend looking into using statistical methods when comparing vehicle-to-vehicle observations. A statistical method could prove to be useful in determining representative observations and flagging outliers.

APPENDIX

List of potential observations from *Clarus* (Mixon/Hill, Inc., 2011)

Observation Type	Observation Description
essLatitude	Latitude of the ESS station [observation] per WGS-84 datum
essLongitude	East longitude from the Prime Meridian of the ESS station [observation]
essVehicleSpeed	Current speed being reported by the vehicle
essVehicleBearing	Current bearing of the vehicle
essVehicleOdometer	Current odometer reading of the vehicle
essReferenceHeight	Reference elevation of the ESS; height to base of station for permanent ESS height to the ground surface upon which the ESS resides for transportable ESS, or height to surface under vehicle for mobile ESS
essAtmosphericPressure	Force per unit area exerted by the atmosphere
windSensorAvgSpeed	Two-minute average of the wind speed
windSensorAvgDirection	Two-min. average of wind direction (CW from North)
windSensorSpotSpeed	Instantaneous wind speed
windSensorSpotDirection	Instantaneous wind direction (CW from North)
windSensorGustSpeed	Maximum wind gust recorded during preceding 10

	min.
windSensorGustDirection	Direction of max. wind gust during preceding 10 min.
windSensorSituation	Describes the weather and travel situation in terms of wind from staffed stations only. Specific ranges for these values are defined in the Glossary of Meteorology
essAirTemperature	Instantaneous dry-bulb temperature
essWetBulbTemp	Instantaneous wet-bulb temperature
essDewpointTemp	Instantaneous dewpoint temperature
essMaxTemp	Maximum air temperature during preceding 24 hours
essMinTemp	Minimum air temperature during preceding 24 hours
essRelativeHumidity	Relative humidity
essAdjacentSnowDepth	Depth of undrifted & unplowed snow off roadways
essRoadwaySnowDepth	Depth of unpacked snow on roadway surface
essRoadwaySnowpackDepth	Depth of packed snow on roadway surface
essPrecipYesNo	Indicates whether or not precipitation is detected: (1) precip; (2) noPrecip; (3) error
essPrecipRate	Rate of rainfall or water equivalent of snow
essSnowfallAccumRate	Rate of snowfall accumulation
essPrecipSituation	Description of precipitation type & intensity; see NTCIP 1204 for validation rules and text mapping
essIceThickness	Thickness of the ice

essPrecipitationStartTime	Time when most recent precipitation event began
essPrecipitationEndTime	Time when most recent precipitation event ended
essPrecipitationOneHour	Total water equivalent precipitation over preceding 1 hr
essPrecipitationThreeHours	Total water equivalent precipitation over preceding 3 hrs
essPrecipitationSixHours	Total water equivalent precipitation over preceding 6 hrs
essPrecipitationTwelveHours	Total water equivalent precipitation over preceding 12 hrs
essPrecipitation24Hours	Total water equivalent precipitation over preceding 24 hrs
waterLevelSensorReading	Depth of the water from a user-defined point
essTotalSun	Total amount of sunshine during preceding 24 hrs
essCloudSituation	Description of amount of cloud cover; see NTCIP 1204 for validation rules and text mapping
essTotalRadiation	Average total radiation during the radiation period
essTotalRadiationPeriod	Length of time essTotalRadiation is averaged [i.e., accumulated]
essVisibility	Surface visibility
essVisibilitySituation	Describes visibility of travel environment; see NTCIP 1204 for validation rules and text mapping

essSurfaceStatus	Describes pavement surface status; see NTCIP 1204 for validation rules and text mapping
essSurfaceTemperature	Current pavement surface temperature
essPavementTemperature	Current pavement temp. 2-10 cm below surface, specifically at pavementSensorTemperatureDepth
essSurfaceSalinity	Pavement [surface] salinity
essSurfaceFreezePoint	Solution freeze point temperature
essSurfaceBlackIceSignal	Indicates whether or not black ice is detected; see NTCIP 1204 for data validation and mapping
essPavementSensorError	Type of pavement sensor error; see NTCIP 1204 for data validation and mapping
essSurfaceIceOrWaterDepth	Current ice thickness or water depth on roadway surface
essSurfaceConductivityV2	Conductivity of the ice/liquid mixture on the pavement as detected by the sensor
pavementSensorTemperatureDepth	Depth at which the pavement temperature is detected
essSubSurfaceTemperature	Current sub-surface temperature
essSubSurfaceMoisture	Sub-surface moisture expressed as a percentage (e.g., 0 indicates dry, 100 indicates saturated)
essSubSurfaceSensorError	Type of sensor error; see NTCIP 1204 for data validation and mapping

essMobileFriction	Measured coefficient of friction
essMobileObservationGroundState	Prevailing observed ground state of the surrounding environment as determined by the observer; an indicator of past weather conditions; see NTCIP 1204 for data validation and mapping
essMobileObservationPavement	Prevailing observed conditions on the driving surface as determined by the observer; see NTCIP 1204 for data validation and mapping
essPaveTreatProductType	Type of treatment being applied to the road; see NTCIP1204 for data validation and mapping
essPaveTreatProductForm	Condition of the treatment being applied to the road; see NTCIP 1204 for data validation and mapping
essPercentProductMix	Percentage of the total application mix by weight that is of the type specified in essPaveTreatProductType
essPaveTreatmentAmount	Quantity of the treatment being applied
essPaveTreatmentWidth	Width of the spread of treatment
essCO	Concentration of carbon monoxide in the air
essCO2	Concentration of carbon dioxide in the air
essNO	Concentration of nitrous oxide in the air
essNO2	Concentration of nitrous dioxide in the air
essSO2	Concentration of sulfur dioxide in the air
essO3	Concentration of ozone in the air

icePercent	Percent of ice cover on roadway
precip10min	Total water equivalent precip. over preceding 10 min
precipIntensity	Description of precipitation intensity
precipType	Description of precipitation type
essInstantaneousSolarRadiation	The instantaneous ultraviolet, visible, and near-infrared (wavelength of less than 3.0 micrometers) radiation hitting the earth's surface in watts per square meter

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