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Data Mining and Gap Analysis for Weather Responsive Traffic Management Studies

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16. Abstract

Weather causes a variety of impacts on the transportation system. An Oak Ridge National Laboratory study estimated the delay experienced by American drivers due to snow, ice, and fog in 1999 at 46 million hours. While severe winter storms, hurricanes, or flooding can result in major stoppages or evacuations of transportation systems and cost millions of dollars, the day-to-day weather events such as rain, fog, snow, and freezing rain can have a serious impact on the mobility and safety of the transportation system users. Despite the documented impacts of adverse weather on transportation, the linkages between inclement weather conditions and traffic flow in existing analysis tools remain tenuous. This is primarily a result of limitations on the data used in research activities. The overall goal of this research was to identify gaps in the data necessary to develop weather responsive traffic management studies. Activities conducted to achieve this included 1) A comprehensive search and documentation of traffic and weather data in the United States and abroad that could be used for WRTM; 2) surveys, phone calls and site visits with organizations that have suitable traffic data on inclement weather; 3) identification of critical gaps in regards to the collection and processing of traffic data on inclement weather conditions; and 4) recommendation of strategies for gathering and processing data that will be used in WRTM studies. The study found that there are a number of useful research efforts underway both domestically and internationally that are yielding useful data for WRTM analysis. In some cases the scopes are limited and confidentiality issues were found in a number of European studies. There is increasing availability of quality traffic and weather data being generated by transportation and public/private weather information sources in the U.S. The analysis conducted for this project found that this data can be helpful in identifying adverse weather impacts on speed and lane usage. The report recommends that FHWA work closely with agencies as they expand their RWIS to assure that weather data is of adequate quality for WRTM analysis. FHWA also should continue to fund specific research and evaluation activities in conjunction with the Integrated Corridor Management Program or other WRTM initiatives.

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Preface/ Acknowledgements

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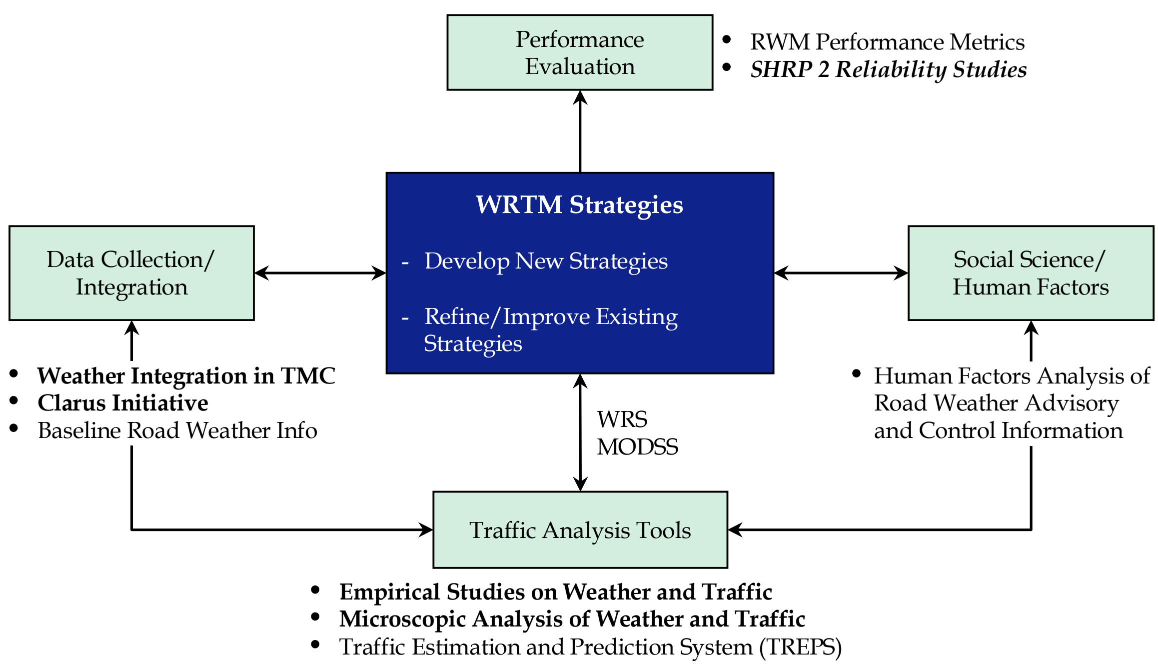
1.0 Introduction

During the past several years, the Federal Highway Administration's (FHWA) Road Weather Management Program (RWMP) has carried out a series of studies to gain a better understanding of travelers' behavior and responses to inclement weather conditions. The FHWA envisions that effective weather responsive traffic management (WRTM) strategies will be developed and implemented based on findings and recommendations generated from the efforts of last several years.

Figure 1.1 depicts the FHWA's overall WRTM framework, consisting of ongoing activities and past efforts. At the center of the framework are the WRTM strategies that transportation agencies can implement to improve the performance of the highway system during adverse weather conditions.

Figure 1.1. Framework for Weather Responsive Traffic Management Program



An important lesson learned from WRTM studies carried out so far is lack of relevant and sufficient traffic and weather data available for the analysis. Efforts were devoted at onset of previous WRTM studies to identify and obtain suitable data, but yielded limited results. Hence, the RWMP decided to add a task that will look into the issues related to 'traffic and inclement weather data'.

1.1 Study Objectives

Four objectives have been identified for this project as listed below:

- Conduct a comprehensive search and documentation of traffic and weather data in the United States and abroad that could be used for WRTM;
- Establish contacts with organizations that have suitable traffic data on inclement weather, and determine procedures/requirements to obtain these data;
- Identify critical gaps in regards to the collection and processing of traffic data on inclement weather conditions; and
- Recommend strategies and generate guidelines for gathering and processing data that will be used in WRTM studies.

The remainder of this report is structured as follows.

Section 2.0 includes the findings of the literature search conducted at the beginning of the project.

Section 3.0 includes the results an analysis of traffic and weather data collected from three cities, Minneapolis-St. Paul, Salt Lake City, and Atlanta. The process of data collection and city selection is documented as well. The purpose of the analysis was to help determine whether readily available data could be used to identify impacts of adverse weather on traffic. Assessments regarding the quality of data were made.

Section 4.0 documents the results of a web survey of Traffic Management Centers (TMC) to determine what weather and traffic data they collect, how it is used and whether they are considering implementation of weather-related traffic management strategies. Seventeen TMCs responded to the survey. This survey was supplemented with a trip to by FHWA and CS to the Utah DOT Traffic Management Center in Salt Lake City. UDOT is a national leader in the integration of weather and traffic information, and their operation represents best practice in a number of weather-related areas. This section also documents the findings of this field trip.

Section 5.0 documents the results of a web survey of domestic and international research institutions about research projects related to weather and traffic. The survey was considered important due to the fact that many research efforts have not yet been published and thus would not be available from the literature search. 39 responses were received and follow up contacts made to obtain more detail on these projects. Both the initial survey results and follow up results are documented in this section.

Section 6.0 includes a summary and recommendations.

2.0 Literature Search

This section includes the results of the first task as identified in the first objective. Included is a literature review of recent and current research related to driver behavior (i.e., lane-changing, car-following, gap acceptance, turning movements, acceleration and deceleration, etc.) on arterials and freeways in various weather conditions. This review also built on earlier literature reviews conducted for the FHWA WRTM Projects. These previous reviews provided results with respect to macroscopic and microscopic traffic studies, including the growing body of naturalistic driving studies focused on individual driver behavior and decision-making.

2.1 Study Methods

Given the previous extensive literature research in this area, the current effort focused on the following:

- International Studies;
- Studies after 2008, although relevant studies conducted prior to that date are included;
- Impact of weather on driver behavior; and
- Data-mining techniques for analysis of weather conditions on travel.

The study entailed the use of the following literature search methods and databases:

- Road Weather Resource Identification (RWRI) tool;
- National Transportation Library – TRIS on-line;
- Transportation Research Board (TRB) Annual Meeting Compendia of Papers on CD;
- Internet search engines (Google and meta search engines); and
- Electronic library resources (e.g., transportation and behavioral science journals).

Study results are presented in tables, with Table 2.1 including the results of the International Scan and Table 2.2, the results of the domestic scan. Included in the table are:

- The year of the study;
- The study title and source;
- The authors, country of origin and affiliations.; and
- An abstract/summary of the studies.

A comment column categorizing the study and its usefulness to the objectives of the WRTM program. This column documents also includes a recommendation for those sources that should be further pursued for data of interest to the WRTM.

The literature was divided into four categories, in descending order of interest to the objectives of the project. These categories were used to prioritize the studies, with Categories 3 and 4 being cited primarily for informational purposes. Since the focus of the project is on the relationship of weather and traffic flow, Category 1 studies were considered most relevant. While the focus of Category 2 studies is somewhat different, the study team considered the possibility that these studies may provide insight into some aspects of traffic flow, particularly those related to incidents:

Category 1 – This category includes studies that address the impact of weather on traffic flow using empirical data. The primary focus is on studies that specifically address driver behavior at a microscopic level or traffic flow on a specific facility, or set of facilities, at a macroscopic level.

Category 2 – This category includes studies that address the impact of weather on crash rates and overall driver safety. Like the traffic flow studies, these may be focused on either individual driver behavior or (macroscopic) crash rates over a larger area.

Category 3 – This category includes studies that address the same topics as Categories 1 and 2, but which do not use empirical data. Some use simulation or modeling techniques, while others simply provide a framework or work plan for analysis.

Category 4 – This category includes all other studies addressing a variety of topics that may be peripherally related to the main objectives.

2.2 Results

Tables 2.1 and 2.2 present a summary of the results of the literature review. The references are presented in reverse chronological order, and the abstracts from the papers are presented. Table 2.1 summarized the results of the international scan and Table 2.2, the domestic scan. As earlier studies extensively documented domestic studies greater emphasis was placed on international studies.

Table 2.1 International Scan Results

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data				
2010	Analysis of Impact of Adverse Weather on Freeway Free-Flow Speed in Spain, TRB 89th Annual Meeting Compendium of Papers DVD, 10-2195 [1]	F. Torregrosa, A. Garcia, and E. Esplugues **"Spain"** Polytechnic University of Valencia, Spain	Weather conditions have an effect over traffic flow characteristics, including speed and capacity. Several previous researches have stated that rain, snow, wind speed, and visibility loss make the speed and capacity to reduce. The knowledge of these relationships is important in order to manage appropriately the traffic flow. In this paper, a new research is presented that evaluates the free-flow speed reduction caused by inclement weather conditions, including rain, snow, wind speed, and visibility loss. There were 15 selected freeway locations in the northwestern Spain. Data was collected in a 15-minute interval by weather and traffic stations during almost three years, from 2006 to 2008. All the individual correlations between the weather and traffic variables were examined in order to select the most important weather variables, and to identify the speed trends and thresholds. All climate conditions were divided into four groups: no precipitation and temperatures above 0ºC, no precipitation and temperatures below 0ºC, rain, and snow conditions. With the final variables choice, a multiple nonlinear regression analysis was performed. Results showed that rain and snow made the speed to reduce in a similar way, but the speed reduction was more dramatic at snow conditions. Wind speed was affected when it was over 8 m/s, while the effect of visibility loss presented a logarithmical form. It also was determined that the location made the variables to affect the speed in a very different way, so for further researches it is recommended to select a big number of sites.	**Category 1 –**The paper investigates the effect of different weather conditions on the traffic speed and flow for different freeways in Spain. It provides direct measurement of traffic conditions at 15-minute intervals under a variety of weather conditions. **Status –** A sample of the data were obtained and reviewed for this project. The results of that review are documented in Section 3.2.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2010	Comparison of Driving Behavior and Safety in Car-Following Platoons Under Icy and Dry Surface Conditions, TRB 89th Annual Meeting Compendium of Papers DVD, 10-0504 [2]	M. Tanaka, and P. Ranjitkat **"New Zealand"** T. Nakatsuji **"Japan"** University of Auckland, Hokkaido University	Road surface condition is one of the most significant factors that influence driving behavior. Drivers often get nervous and drive differently when they encounter an unusual roadway surface and feel they could not control their vehicle, as well as they normally could. There have been many data in the past showing how the roadway friction factor changes on wet, snow, or other unusual surface conditions. However, there are only some data showing how drivers change their car-following behavior on such unusual surfaces. In this study, we utilized rare car-following data on icy surface condition and compared the vehicle safety and car-following behavior on such a slippery surface to the normal dry asphalt surface condition. In order to evaluate the vehicle safety in the car-following conditions, we defined three safety indicators: potential collision index, impact speed, and expected impact speed. Our outcomes in these safety indicators showed a significant difference between the icy and dry surface conditions. We investigated further for what caused this difference even after considering a range of possible maximum deceleration rates and reaction times. We found that speed-spacing relationships were significantly different and drivers were creating much longer spacing to avoid rear-end collisions on the icy surface more than necessary. As a result, the icy surface showed significantly safer indicator values than the dry surface. At the same time, the result let us consider that drivers may have too much confidence and take very high rear-end collision risks on the dry surface.	**Category 1 –** This study addressed car-following behavior under icy conditions in a test track environment. This data was recommended for further evaluation since data on car-following behavior in icy conditions is very difficult to find. In addition, this research was conducted under very rigorous conditions, providing a high level of confidence in the results. **Status –** The authors provided the data to the study team and an analysis was conducted that was documented in the report "Microscopic Analysis of Traffic Flow in Inclement Weather: Impact of Icy Roadway Conditions on Driver Car-Following Behavior," prepared for FHWA by Virginia Tech Transportation Institute and Cambridge Systematics, February 2010.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2010	Variation in Impact of Cold Temperature and Snowfall and Their Interaction on Traffic Volumes, TRB 89th Annual Meeting Compendium of Papers DVD, 10-3182 [3]	S. Datla **"Canada"** University of Regina	Presented in this paper is a detailed investigation of highway traffic variations with severity of cold, amount of snow, and various combinations of cold and snow intensities. Separate analysis for starting, middle, and ending months of winter seasons is conducted to understand the variations in traffic-weather relationships within the winter season. The study is based on hourly traffic flow data from 350 permanent traffic counter sites located on the provincial highway system of Alberta, Canada, and weather data obtained from nearby Environment Canada weather stations, during the period of 1995 to 2005. Multiple regression analysis is used in the modeling process. The model parameters include three sets of variables: amount of snowfall as a quantitative variable, categorized cold as a dummy variable and an interaction variable formed by the product of the above variables. The developed models closely fit the real data with R-square values greater 0.99. The study results indicate that the association of highway traffic flow with cold and snow varies with day of week, hour of day, and severity of weather conditions. A reduction of 1 percent to 2 percent in traffic volume for each centimeter snowfall is observed when the mean temperatures are above 0°. For the days with zero precipitation, reductions in traffic volume due to mild and severe cold are 1 percent and 31 percent, respectively. An additional reduction of 0.5 percent to 3 percent per each centimeter of snowfall results when snowfall occurs during severe cold conditions. Study results show lesser impact of adverse weather conditions on highway traffic volumes during severe winter months and the months thereafter as compared to starting months.	**Category 1 –** This paper investigates the effect of snow and cold on traffic flow variation using empirical weather and traffic flow data; providing the data could be relevant if it will be related to the freeway capacity and car-following models. This report was recommended for evaluation pending further review since models developed for WRTM strategies need to take into account reductions in overall volume that may occur due to adverse weather. It appears this research successfully modeled this relationship in Alberta. **Status –** While the paper provided some useful parameters, the authors could not be reached to obtain the full dataset.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2009	The Impact of Rain on Travel Characteristics in Korean Freeways, TRB 88th Annual Meeting Compendium of Papers DVD, 09-1743 [4]	S. Baek, B. Kim, Y. Lim, and J. Kang **"South Korea"** Korea Expressway Corporation	Several factors such as accidents, road maintenance, and bad weather contribute to traffic congestion. Among them, weather greatly affects road safety through the increased risk of crashes, as well as the increased exposure to weather-related hazards. It also is known that inclement weather conditions decrease the demand for transport while also decreasing the capacities of freeways. However, it is still unclear exactly how much transport demand and freeway capacity decrease under adverse weather conditions. Moreover, traffic congestion that arises due to bad weather may alter the destinations of travelers or cause them to altogether forego their trips. Although information on trips by origin and destination is required for analyzing transportation planning in urban areas, few studies have examined the relationship between weather conditions and travel patterns. This work examines changes in expressway travel patterns that arise due to adverse weather conditions, and analyzes the effect of weather conditions on the volume of traffic and the travel distance. We compare normal travel patterns with those of rainy days with regard to the travel distance for each type of vehicle. Results show that, as expected, the traffic volume and travel distance decrease in rainy days; the findings also reveal differing travel patterns for weekdays as compared with weekends.	**Category 1 –** This study looks at travel patterns and traffic volumes during adverse weather. While it can be termed macroscopic, it is a more general study than others conducted for WRTM in that it addresses broad changes in trip generation and trip distribution. **Status –** As this information appeared to duplicate that in other studies, the dataset was not requested.
2009	Multilevel Assessment of the Impact of Rain on Drivers' Behavior: Standardized Methodology and Empirical Analysis, Transportation Research Record No. 2107 [5]	R. Billot, N. El Faouzi, and F. De Vuyst **"France"** Institut National de Recherche sur les Transports et leur Securite (INRETS), Ecole Centrale de Paris	This study deals with the analysis of the impact of rain on drivers' behavior and traffic operations. First, a generic methodology for assessing the effect of weather on traffic is proposed through a multilevel approach: from individual traffic data, the rain impact is assessed at a microscopic level (time, headways, and spacing). Next, the same data were used to extend the study to a mesoscopic and a macroscopic level. The mesoscopic level deals with the effects of rain on platoons, and the macroscopic level resides in the analysis of the impact of rain on the fundamental diagram enabling weather-responsive macroscopic traffic simulation. Second, following this approach, an empirical study is carried out from individual data collected on a French interurban motorway. Weather data were provided by a weather station located near the test site. The results suggest a significant impact of rain on drivers' behavior and traffic operations, which increases with the intensity of rainfall.	**Category 1 –** This study involved a simulation effort. The impact of rain on traffic flow at microscopic level was estimated using data from a French interurban motorway. The test site included a nearby weather station. **Status –** The detailed dataset was requested but unavailable due to confidentiality restrictions.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2009	Integrating the Effects of Adverse Weather Conditions on Traffic: Methodology, Empirical Analysis, and Bayesian Modeling, European Conference of Transportation Research Institutes, Young Researchers Conference '09 [6]	R. Billot **"France"** Institut National de Recherche sur les Transports et leur Securite (INRETS), Ecole Centrale de Paris	One of the characteristics of an efficient traffic management resides in the abundance of situations to which the road managers are able to adapt and react in real-time. In this respect, as many sources of uncertainty as possible have to be mastered in order to alleviate negative impacts of congestion, and hence increase the level of service of associated networks. Inclement weather conditions are considered as one key factor which can affect traffic operations and safety. Whereas the impact on traffic safety is well known (frequency and severity of crashes), the effects of adverse weather conditions on traffic mobility need to be quantified and account for in the development of weather-responsive traffic management strategies. The objective of the research reported in this paper is twofold: first, it intends to exhibit the significant impact of adverse weather conditions on traffic operations and its quantification based on a rigorous methodology we have proposed in a previous work. More precisely, the assessment of the rain effects on the main traffic characteristics are achieved following a multilevel approach: microscopic level, mesoscopic level, and finally macroscopic one. Second, from an empirical analysis, the quantified adverse weather impact on traffic is then taken into account into a macroscopic traffic stream model to serve as a decision support system for on-line traffic management strategies. The Bayesian approach is used as a modeling framework through the use of particle filtering methods, which are suitable for solving the traffic state estimation issue. The results clearly demonstrate how the knowledge about the weather effects on traffic enables a more accurate traffic state estimation. The potential of the weather-responsive traffic model prototype appears as the core of a new generation of traffic management decision support systems (DSS).	**Category 1 –** This project included the development of a theoretical framework, as well as an empirical analysis of weather impact on traffic flow, using a Bayesian modeling technique. Data were obtained from a motorway in France. **Status –** This dataset was requested but was not available due to confidentiality agreements.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2008	Assessing the Impact of Weather on Traffic Intensity, TRB 87th Annual Meeting Compendium of Papers DVD, 08-1903 [7]	M. Cools, E. Moons, and G. Wets **"Belgium"** Transportation Research Institute, Hasselt University	The investigation of weather effects on traffic intensity is important from a road safety point of view, because traffic intensity is noted as the first and primary determinant of traffic safety. Next to traffic safety, weather conditions affect other predominant traffic variables, namely traffic demand and traffic flow. Therefore, the main objective of this study is the identification and comparison of weather effects on traffic intensity at different site locations. To assess the impact of weather conditions on traffic intensity, the upstream and downstream traffic of four traffic count locations are considered. The traffic intensity data originate from minute data coming from single inductive loop detectors, collected by the Flemish Traffic Control Center. Data concerning weather events were recorded by the Royal Meteorological Institute of Belgium. The main modeling philosophy envisaged in this study to identify and quantify weather effects is the linear regression approach. Most appealing result of this study for policy-makers is the heterogeneity of the weather effects between different traffic count locations, and the homogeneity of the weather effects on upstream and downstream traffic at a certain location. The results also indicated that snowfall, rainfall, and wind speed have a clear diminishing effect on traffic intensity, while maximum temperature significantly increases traffic intensity. Further, generalizations of the findings are possible by studying weather effects on local roads, and by shifting the scope towards travel behavior. Simultaneously modeling of weather conditions, traffic intensity rates, collision risk, and activity travel behavior is certainly a key challenge for further research.	**Category 1 –** This is a study that used detailed, empirical measurements of traffic and weather conditions to address adverse weather impacts. As it parallels some of the macroscopic research being conducted through the WRTM, this dataset could be useful for review and analysis. **Status –** This dataset was recommended for further analysis, but was unavailable due to confidentiality restrictions.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2007	The Impact of Adverse Weather on Travel Time Variability of Freeway Corridors; TRB 2007 Annual Meeting CD-ROM, 07-1642 [8]	H. Tu, J. W. C. van Lint, and H. J. van Zuylen **"Holland"** Delft University of Technology	Over the last two decades, travel-time reliability has become an important aspect of transportation system performance. One group of factors affecting travel-time variability is adverse weather, such as rain, snow, ice, fog, and storm. Empirical investigation on the basis of a large database of travel times on various freeways and one year of weather data shows that adverse weather not only increases average travel time, but clearly also influences travel-time variability of freeway corridors. On average, adverse weather results in twice the travel-time variability compared with that under normal weather conditions. It also is found that rain has little or no effect on travel-time variability below a certain critical inflow, but progressively impacts travel-time variability above it. In general, adverse weather conditions make travel time less reliable. This might imply that different traffic control strategies and applications should be considered under different weather conditions.	**Category 1 –** This study used a large database of travel-time information on various freeways and a year's worth of weather data to estimate the impact of weather on both travel time and travel-time reliability. The research findings indicated that adverse weather did have a significant impact of travel-time variability, but only at higher levels of traffic flow. **Status –** The data were not considered to be of sufficient detail for further research and were not requested.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2005	Impact of Rain to Highway Traffic and Drivers' Deceleration Behavior, Master of Science thesis, Transportation and Logistics Department, Malaysia University of Science and Technology [9]	Tay Hong Yet **"Malaysia"** Malaysia University of Science and Technology	The objective of this research is to study the impact of rain to the surface traffic and to also understand drivers' deceleration behavior by calibrating the car-following model to take into account the effects of rain in slowing down vehicular traffic. The method for collecting and processing data, analysis of the results, and the estimation of the parameters for car-following model are reported. Data was collected using video image processing whilst statistical analysis and parameter estimation were utilized to analyze the results. Theoretically, rain affects traffic flow by reducing visibility, decreasing pavement friction, changing driver behavior, and vehicle performance. Hence, it is important to identify the relationship between rain conditions and traffic parameters. At the fixed flow level, speed and clear gap was decreased up to 28 percent and 45 percent. Gap time has greatest change at 22 percent. However, the equivalent value in time is about 0.38 second, which might not be noticeable for a driver to response differently. Density increased up to 39 percent, which exhibits a transition from stable to unstable region under flow-density relationship. This study is based on data from Video Image Processor (VIP) to conduct calibration for car- following deceleration model. The calibrated car-following deceleration model is important in modeling of vehicles' slow down process during rain. The calibrated model has returned a satisfying result at small error term of -0.089 m/s^2 with standard deviation of 0.13 m/s^2. This model can be used in traffic flow forecast for Intelligent Transportation System (ITS) applications specifically for traffic simulation during rain.	**Category 1 –** This study is of significant interest to the WRTM as it used video-image processing data on a segment of Malaysian freeway to collect data on drivers' deceleration behavior under rainy conditions. A car-following model was calibrated using the data. Estimates were developed of a series of car-following model parameters. The research also captures the effect of rain on the flow-density relationship and deceleration behavior. **Status –** While this study appeared to be potentially useful, the authors could not be contacted to request the data.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2004	Including Weather Condition Factors in the Analysis on the Highway Capacity, TRB 83rd Annual Meeting Compendium of Papers DVD, 04-0548 [10]	N. Okamoto, H. Ishida, and H. Furuya and K. Furukawa **"Japan"** University of Tsukuba, Toyo University	There are many congestion points where the highway structure is considered as one of the main factors of congestion in Japan. The relationship between the structure and the capacity should be analyzed in order to decrease the influence of structural problem on the highway. Moreover, the weather condition is considered as another factor of congestion. But there are few studies which mention the relationship between the weather condition and highway capacity. This paper shows the analysis by modeling on the highway capacity considering the road structure and weather condition. The data on traffic count and the volume of precipitation were used for the modeling. The K-V function is estimated using the variables of precipitation, curvature, clothoid, and gradient. Finally, from the model estimation results, the significant differences of the road capacity with the different weather conditions, as well as the effect of permeable pavement were shown.	**Category 1 –** This study modeled highway capacity as a function of both road structure and weather conditions. Traffic counts and precipitation intensity were used. **Status –** While the study appears to have modeled the impacts of precipitation intensity on weather flow this was not its primary focus and as a result the data were not requested.
2003	Relationship Between Winter Road Surface Conditions and Vehicular Motions, Measured by GPS-Equipped Probe Vehicles, TRB 82nd Annual Meeting Compendium of Papers DVD, 03-0757 [11]	T. Nakatsuji, and A. Kawamura **"Japan"** Hokkaido University, Kitami Institute of Technology	In winter, one of the major concerns of drivers is the current road condition. Taxis, which move around ceaselessly over a wide area, have great potential as a sensor for detecting what the road surface conditions are like across a given area. In order to establish a method to estimate road conditions based on the vehicular motion of taxis, some field experiments were conducted using probe vehicles that fitted with vehicular motion sensors and a GPS device prior to the implementation to taxis. Some preliminary analyses were performed using the data measured on a test track, urban streets, and an expressway. The slip ratio, defined as the relative difference in speed between vehicle and tire wheel, was effective in indicating how slippery roads surfaces were. Taxi vehicular motion data also were collected for more than one month, although unlike the probe vehicles the wheel speed was not measured. Some features of vehicular motion specific to slippery roads were identified; and the discriminability of road conditions, whether icy or dry, without using wheel speed data, also was examined.	**Category 1 –** The researchers used taxis outfitted with GPS devices and vehicular motion sensors to try to estimate vehicular motion parameters specific to dry, wet, or icy road conditions. **Status –** This dataset was not requested due to age.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2002	Effect of Weather Conditions to Traffic Flow on Freeway, KSCE Journal of Civil Engineering, Volume 6, Number 4 [12]	J. Sam, Y. Shim, and Y. Cho **"South Korea"** Korea Institute of Construction Technology, New Airport Highway Company, Chung-Ang University	Traffic speed along a roadway segment is the function of a number of factors like geometry, traffic, and weather conditions. In this paper, the effect of weather conditions on both the speed-flow and flow-occupancy relationships was studied. The data used in the analysis were obtained from traffic management system installed in the Incheon International Airport Expressway. In order to quantify how seriously weather affects traffic flow conditions, the impact in term of traffic speed was described. Regression analyses were performed to select proper models representing the speed-flow and flow-occupancy relationship for congested operation. From the research, weather conditions reduced the slope of flow-occupancy function and caused a downward shift in the speed-flow function. That is, the free-flow speeds are reduced. Increase of traffic volume by weather event at the YeongJong Grand Bridge (site2) is much larger than at the BwangHwa Grand Bridge (site2), which makes travel speed down significantly. The ratio of free- flow speed reduction was observed 7 percent and 2 percent by snow and rain, respectively. Meanwhile, the ratio of speed reduction was shown that snowy and rainy nights are each 5 percent and 6 percent drop. That is, the effect of snowy day and night is similar, while the effect of rainy night is larger than rainy day in terms of speed reduction. In case of site2, during daytime, the ratio of speed reduction in snowy and rainy conditions has no difference. However, the ratio of speed reduction during nighttime was decreased 3 percent and 7 percent in each snowy and rainy condition.	**Category 1 –** This study used empirical data from a major expressway to estimate the impact of weather on speed-flow and flow-occupancy relationships. This study of weather-related adjustment factors is similar to those that recent WRTM research has been exploring but is not recommended for further evaluation due to age of the data. **Status –** This dataset was not requested due to its age.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 2 – Weather Impacts on Safety and Crash Rates				
2009	An Experimental Study on the Luminous Intensity Required for LED Roadway Delineators in Foggy Conditions, TRB 88th Annual Meeting Compendium of Papers DVD, 09-0079 [13]	K. Munehiro, R. Tokunaga, and T. Hagiwara **"Japan"** Hokkaido University and Civil Engineering Research Institute for Cold Weather	Since visibility distances are used in determining the geometric structure of roads, ensuring the visibility necessary for driving is very important in providing safe, comfortable conditions for drivers. However, since foggy conditions make it difficult to ensure the level of visibility needed for driving, a method to make it easier for drivers to see the line of the road is required. For this purpose, retro reflective or light-emitting delineators are installed at roadsides, and delineators with light-emitting diodes (LEDs) are used to improve visibility on routes where high-level service is required for sections with reduced visibility. However, there is no mention of luminous intensity for delineators in any current guidelines, and literature on the luminosity of LED delineators and driver visibility is limited. As a result, the level of luminous intensity required for LED delineators in conditions of poor visibility remains unclear. This study investigated the role that fog plays in reduced visibility, and an experiment was conducted to evaluate the visibility of LED (light-emitting diode) delineators in natural foggy conditions. The experiment was conducted over a two-month period in July and August 2004 on Marine Street, a public road in the Shiranuka area of Hokkaido, using three types of LED delineator. Twenty subjects were tested in each of three cases (one in clear conditions and two in fog) during the day and at nighttime. Based on the results, the luminous intensity required for LED delineators in different conditions of fog was simulated with varying road service speeds.	**Category 2 –** Although this study is focused primarily on the effectiveness of specific technology, the datasets and analysis could be helpful in assessing the impact of low visibility on driver behavior. The WRTM already is utilizing data from Hokkaido University to address driver behavior under icy conditions.
2009	Impact of Snowy and Icy Weather on Freeway Operation and Improvement Countermeasure Studies of South China, TRB 88th Annual Meeting Compendium of Papers DVD, 09-1540 [14]	S. Dong, G. Jianping, Y. Nan, and T. Boming **"China"** Chongqing Expressway Development Corporation and Chongqing Jiatong University	At the beginning of 2008, a serious snow and ice disaster attacked most areas in South China and had great impact on road traffic due to the traditional Chinese Spring Festival holiday, and millions of people cannot go home to reunite with their families. Moreover, the damage caused by the disaster has been incalculable. Chongqing, located in southwest China, was inevitably greater impacted. This paper has made a description about the serious impact by the disaster on freeway transportation, compared the gap in management for the snow and ice disaster between South China and developed countries, pointed out the insufficiency in the emergency management of freeway operation under adverse weather conditions, and then proposed a modern weather disaster prewarning system improving the emergency-response plans. Meanwhile, some constructive proposals are presented.	**Category 2 –** This study addresses safety and emergency response issues during a major disruption resulting from a snow/ice storm. While this study does not appear to include either detailed microscopic or macroscopic analysis, it does include useful findings regarding weather-related traffic management under severe conditions.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 2 – Weather Impacts on Safety and Crash Rates (continued)				
2006	Effects of Winter Weather and Maintenance Treatments on Highway Safety, TRB 85th Annual Meeting Compendium of Papers DVD, 06-0728 [15]	L. Fu, M. Perchanok, L. Moreno, and Q. Shah **"Canada"** University of Waterloo, Ontario Ministry of Transportation	This research has conducted an analysis of the effects of winter weather and maintenance treatments on the safety of highways as related to factors such as weather, road, and treatment characteristics. The ability to assess and quantify these effects is essential for a comprehensive cost-benefit analysis of alternative maintenance strategies and methods and effective communication of the impacts of these strategies and methods to the decision-makers and the public. Two highway routes from Ontario, Canada were selected and data on daily accident occurrences, weather conditions, and winter maintenances operations were obtained for this analysis. A statistical analysis was performed on the integrated dataset with the goal of identifying those weather and maintenance factors that had a significant impact on crash frequency. The modeling results indicate that weather conditions, such as temperature and precipitation (mainly snow fall), had a significant effect on the crash risk. Anti-icing and prewetting operations were found to have improved road safety at one of the study sites. Sanding operations were found to have a positive effect on the safety at both maintenance routes. The research, however, could not statistically confirm the safety effect of conventional maintenance operations – plowing and salting with dry salt.	**Category 2 –** This research used empirical data to assess the impact of different highway maintenance strategies on crash rates.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 2 – Weather Impacts on Safety and Crash Rates (continued)				
2003	A Temporal Analysis of Weather-Related Collision Risk for Ottawa, Canada: 1990 to 1998, TRB 82nd Annual Meeting Compendium of Papers DVD, 03-3488 [16]	J. Andrey, B. Mills, and J. Vandermolen **"Canada"** University of Waterloo	Past research provides evidence that collision and injury risk increase during precipitation relative to normal driving conditions, although estimates vary due to differences in driving context and research methods. Less effort has been devoted to studying how weather-related risks vary over time, and what these variations tell us about interactions between weather and other risk factors. This study examines temporal variations in weather-related collision and injury risk using collision and weather data for Ottawa, Canada, over the period 1990 to 1998. A matched-pair approach was used to define precipitation events and corresponding controls in order to estimate and compare the risk of collision and injury during precipitation relative to normal seasonal conditions for weekdays versus weekends, nighttime versus daytime, peak period versus other daytime; and early winter season versus late-winter season. Results indicate that collision risk increased significantly – by more than 100 percent for rain and approximately 50 percent for winter precipitation events. Injury risk also was elevated, but to a lesser extent. Increases in precipitation-related collision risk during the winter were higher on weekends relative to weekdays. Also, collision risks were especially high during the early part of the winter season.	**Category 2 –** Empirical data were utilized to estimate variation in crash and injury rates for different weather conditions and different temporal periods.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 2 – Weather Impacts on Safety and Crash Rates (continued)				
1998	Weather and traffic accidents in Montreal, Canada, Climate Research, Volume 9, pages 225-230. [17]	M. Andreescu, and D. Frost **"Canada"** McGill University, Concordia University	Impact of weather conditions on traffic accidents is an insufficiently understood and poorly quantified phenomenon in Canada, and recent research results reflect conditions that are not entirely characteristic of the Canadian climatic setting. This study analyzed the effects of rain, mean temperature, and snow on automobile accidents in Montreal, Canada, from 1990 to 1992. Three timeframes were used – monthly, annual, and the entire study period. All three weather variables impacted road accidents significantly. Snow was shown to be the leading variable, as the number of accidents increased sharply with increased snowfalls. This finding is important in light of recent provincial and municipal proposals to reduce spending on winter snow cleaning as a way of cutting operating costs.	**Category 2 –** This study estimated the impact of snow, rain, and mean temperature on automobile crashes in Montreal during the period 1990 to 1992.
Category 3 – Nonempirical Studies Including Simulation and Analysis Frameworks				
2008	Developing Traffic and Weather Responsive Signal Control for Isolated Intersections, TRB 87th Annual Meeting Compendium of Papers DVD, 08-2262 [18]	N. Setala, D. Kosonen, and T. Luttinen **"Finland"** Helsinki University of Technology	Adaptive traffic control systems are used to improve the performance of intersections with highly variable traffic volumes or other conditions. This paper describes a traffic and weather responsive adaptive signal control system developed to enhance an existing intelligent signal control system based on fuzzy logic. Built on top of a real-time microscopic simulation model, the adaptation is carried out not only by changing the signal timings and control schemes of an isolated intersection, but by also adapting the traffic model to fit the current traffic and weather situation. The system has been tested with simulations, and the results suggest that improvements in the performance of intersections as well as in safety can be achieved. Finally, some further research is suggested.	**Category 3 –** This study addresses an important aspect of WRTM, adaptive signal timing. However, the analysis is based on simulation.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 3 – Nonempirical Studies Including Simulation and Analysis Frameworks (continued)				
2008	Modeling Impacts of Adverse Weather Conditions on a Road Network with Uncertainties in Demand and Supply, Transportation Research Part B [19]	W. Lam, H. Shao, and A. Sumalee **"China"** The Hong Kong Polytechnic University, China University of Mining and Technology	This paper proposes a novel traffic assignment model considering uncertainties in both demand and supply sides of a road network. These uncertainties are mainly due to adverse weather conditions with different rainfall intensities on the road network. A generalized link travel-time function is proposed to capture these effects. The proposed model allows the risk-averse travelers to consider both an average and uncertainty of the random travel time on each path in their path choice decisions, together with the impacts of weather forecasts. Elastic travel demand is considered explicitly in the model responding to random traffic condition in the network. In addition, the model also considers travelers' perception errors using a logit-based stochastic user equilibrium framework formulated as fixed point problem. A heuristic solution algorithm is proposed for solving the fixed point problem. Numerical examples are presented to illustrate the applications of the proposed model and efficiency of the solution algorithm.	**Category 3 –** This study addresses several important aspects of WRTM, including adaptive signal timing. However, the analysis is based on simulation.
2006	Performance Measures for Snow and Ice Control in the Province of Alberta, TRB 85th Annual Meeting Compendium of Papers DVD, 06-0548 [20]	L. Falls, R. Jurgens, and J. Chan **"Canada"** Alberta Infrastructure and Transportation, University of Calgary	Performance measurement is a vital component of asset management, which is used in planning and programming to identify assets that are under or over performing and to assess overall performance over time. As part of the move to asset management, Alberta Transportation has implemented performance-based planning and monitoring of the provincial highway network. Three performance measures, based upon technical measurement, have been adopted which characterize network condition, functional adequacy and utilization. However, Alberta, like the rest of Canada, is a winter province, yet no clear suite of performance measure has been developed for snow and ice control. Traditionally, agencies have measured inputs (such as salt or sand) or outputs (such as plowing frequencies), but none of the existing measures address effectiveness. This paper presents the results of a project to develop winter performance measures that address both the planning and operations of a large rural highway network. Preliminary results indicate that traffic volumes and speed data can be used to identify major storm events, and as such may hold promise as repeatable, robust, relevant, and responsive performance measures.	**Category 3 –** The purpose of this effort was to develop a set of performance measures related to snow and ice control. Some of the measures address the data that are being mined in this project, such as traffic volumes and speed. The primary purpose was to identify potential measures; not to actually develop or evaluate them.

Table 2.1 International Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 4 – Other Studies				
2009	Climate Change – A Challenge for Norwegian Roads, TRB 88th Annual Meeting Compendium of Papers DVD, 09-1780 [21]	G. Petkovic, and J. O. Larsen **"Norway"**	This short paper offers some preliminary information about the work on adaptation to climate change currently being carried out by the Norwegian Public Roads Administration." Climate and Transport," a four-year R&D program initiated in 2007, addresses all the topics considered to be important for effective adaptation of planning, design, operation, and maintenance of roads under changed climate conditions. The program consists of seven projects; the results of which will be formulated as amendments to Road Administration manuals and projects on the road network demonstrating necessary action for adaptation to climate change. The main objectives of the program are to evaluate the effect of climate change on the road network and recommend remedial action concerning planning, design, construction, and maintenance of the road network.	**Category 4 –** This paper focuses on long-term impacts of climate change on the roadway network.
2009	Context-Sensitive Design for Nanjing-Changzhou Expressway, TRB 88th Annual Meeting Compendium of Papers DVD, 09-2429 [22]	Q. Guochao, Z. Min, Z.Jiankang, C. Jingya, and C.Jianchuan **"China"**	In recent years, China has made great achievements in expressway construction, which do attract worldwide attention. To enhance expressway's capacity, safety, environmental-friendliness, landscape view and so on, new concepts like context-sensitive solution and flexibility for highway design have been encouraged here. And Nanjing-Changzhou Expressway (hereinafter the NingChang Expy) is just designed with such considerations. Flanking the Expy are varied terrains and unique landscapes along with rich humanistic resources. The present paper focuses upon some of the key technologies employed in its design based on the context-sensitive principle, covering such main issues as safe and harmonious alignment, natural protection engineering, flexible and ecologic drainage, unique landscape, human-centered service area design, as well as public participation. The solutions we propose here aim to further build the NingChang Expy into a fully modernized one characterized by its great safety, satisfying environmental protection, ecological balance, and attractive landscapes for booming tourism, its design believed to be of valuable reference for future projects of the kind.	**Category 4 –** This paper focuses on environmental issues related to design, although safety issues are included.

Table 2.2 Domestic Scan Results

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data				
2008	Long-Term Analysis of Reductions in Traffic Volume Across New Hampshire During Winter Storms, Transportation Research Circular EC-126, Surface Transportation Weather and Snow Removal and Ice Control Technology; Weather 08-011 [23]	M. G. Wellman, S. Miller, S. Gray, and J. Zabransky New Hampshire DOT, Hometown Forecasting Services, Plymouth State University	Snow, sleet, freezing rain, and rain are all common occurrences throughout the northeastern United States. These hazardous weather conditions can paralyze communities statewide. Reductions in traffic volume during these hazardous events can be used to quantify the number of people affected by a particular winter storm, and provide a measure of how people perceive the severity of individual winter storms. Traffic counts were provided by the New Hampshire DOT for 15 locations across the State. These counts were then correlated with nearby weather observations, provided by the National Climatic Data Center and Plymouth State University's on-line database. There were 51 storm events between November 1999 and March 2004. The reductions in traffic volume were calculated hourly and by day, and compared with individual storm characteristics. The hourly reductions were compared to temperature, dew point, relative humidity, wind speed, wind direction, wind gusts, pressure, sky cover, visibility, precipitation type, and precipitation intensity. In addition, the daily reductions were compared to snowfall amounts. A statewide average hourly reduction in traffic volume of 22.2 percent was found for all winter storms. Reductions in traffic volume were found to be most related to storm characteristics related to storm intensity. Storm hours with a northeast wind component were more likely to have the greatest reductions in traffic volume. Likewise, the intensity of snowfall on average across the State doubled the reductions in traffic volume. Reductions in traffic volume also held a strong relationship with visibility: the lower the visibility the greater the reductions in traffic volume. Hourly reductions also were closely correlated to diurnal pattern. The greatest reductions in traffic volume occurred after the evening commute; however, the greatest reductions in vehicles occurred during the evening commute. The comparisons between storm total snowfall and average storm reduction in traffic volume proved to be the most significant relationships. Storm average reductions were found to be related to storm total snowfall. However, they are most related to locations with the greatest average daily traffic volume. In addition, a direct relationship was found between the statewide storm average reductions and the statewide storm total snowfall, and an even stronger relationship with statewide average snowfall amounts greater than five inches.	**Category 1 –** This study compared weather observations from the National Climatic Data Center and Plymouth State University to traffic counts at 15 locations across the State. Fifty-one storm events were evaluated over a two-year period, and reductions in traffic volume correlated with snowfall and visibility reductions. **Status –** This dataset was not requested since data were aggregated over large areas.

Table 2.2 Domestic Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2006	Gap Acceptance for Vehicles Turning Left Across Oncoming Traffic: Implications for Intersection Decision Support Design, TRB 85th Annual Meeting Compendium of Papers DVD, 06-2696 [24]	D. Ragland, S. Arroyo, S. Shladover, J. Misener, and C. Chan **"University of California, USA"**	A left-turning vehicle (Subject Vehicle, SV) attempting to cross the path of an oncoming vehicle (Principal Other Vehicle, POV) at an intersection typically does not have the right-of-way. The main task of the SV driver is to find an adequate opportunity in opposing traffic to initiate the left-turn maneuver. To reduce the probability of a conflict, warning systems, such as Intersection Decision Support (IDS) systems, are being developed. These systems alert drivers of SV vehicles attempting to negotiate a left-turn about traffic approaching from the opposite direction. The current paper 1) describes a video system that was used to assess gap length, gap acceptance, and gap rejection in a Left Turn Across Path/Opposite Direction (LTAP-OD) scenario, 2) describes a way to characterize gap distribution (log-normal) presented to the SV driver, and 3) illustrates how a logistic model often used to describe dose-response curves can be used to characterize gap acceptance by the SV driver. These results are used as the basis for a discussion of implications for IDS systems for alerting left-turning drivers about oncoming vehicles.	**Category 1.** This paper studies left-turn gap acceptance behavior at five different intersections in California. In addition, the IDS (Intersection Decision Support) concept is introduced in this paper. It will be very useful, if the data of this paper are provided for validation purposes of gap acceptance models. **Status –** While the paper could potentially be useful for validation purposes, it does not involve analysis of weather and therefore was not requested.

Table 2.2 Domestic Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2006	The Use of Weather Data to Predict Nonrecurring Congestion, Technical Report, Agreement T2695, Task 54, Washington State Transportation Center (TRAC) [25]	D. J. Dailey Washington State Transportation Center, University of Washington	This project demonstrates the quantitative relationship between weather patterns and surface traffic conditions. The aviation and maritime industries use weather measurements and predictions as a normal part of operations, and this can be extended to surface transportation. Data from two data mines on the University of Washington campus were combined to evaluate the quantitative relationship between freeway speed reduction and rainfall rate as measured by Doppler radar. The University of Washington's Atmospheric Science department maintains an archive of Nexrad radar data, and the Electrical Engineering department maintains a data mine of 20-second averaged inductance loop data. The radar data were converted into rainfall rate, and the speed data from the inductance loop speed traps were converted into a deviation from normal performance measure. The deviation from normal and the rainfall rate were used to construct an impulse response function that can be applied to radar measurements to predict traffic speed reduction. This research has the potential to accomplish: 1) prediction of nonrecurring traffic congestion, and 2) prediction of conditions under which incidents or accidents can have a significant impact on the freeway system. This linkage of weather to traffic may be one of the only nonrecurring congestion phenomena that can be accurately predicted. This project created algorithms and implementations to correlate weather with traffic congestion. Furthermore, it may provide a means for traffic management to determine where and when to proactively place resources to clear incidents.	**Category 1 –** This project used freeway speed data and rainfall rates measured by Doppler Radar to estimate the impact of rainfall intensity on speeds and traffic congestion. The research addressed the possibility of predicting nonrecurring congestion based on weather conditions. While the factors developed may be considered in developing weather-related adjustment factors, the radar data used does not necessarily represent ground conditions. ESS observations would be preferable. **Status –** This dataset was not requested due to the fact that weather radar data were used.

Table 2.2 Domestic Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2005	Impact of Weather on Urban Freeway Traffic Flow Characteristics and Facility Capacity, Aurora Project/Midwest Transportation Consortium, Center for Transportation Research and Education, Iowa State University [26]	M. Agarwal, T. H. Maze, and R. Souleyrette Iowa State University	Adverse weather reduces the capacities and operating speeds on roadways, resulting in congestion and productivity loss. A thorough understanding of the mobility impacts of weather on traffic patterns is necessary to estimate speed and capacity reductions. Nearly all traffic engineering guidance and methods used to estimate highway capacity assume clear weather. However, for many northern states, inclement weather conditions occur during a significant portion of the year. This paper describes how the authors quantified the impact of rain, snow, and pavement surface conditions on freeway traffic flow for the metro freeway region around the Twin Cities. The research database includes four years of traffic data from in-pavement system detectors, weather data over the same period from three automated surface observing systems (ASOS), and two years of available weather data from five road weather information systems (RWIS) sensors at the freeway's roadside. The research classifies weather events by their intensities and identifies how changes in weather type and intensities impact the speed, headways, and capacity of roadways. Results indicate that severe rain, snow, and low visibility cause the most significant reductions in capacities and operating speeds. Rain (more than 0.25 in./hr), snow (more than 0.5 in./hr), and low visibility (less than 0.25 mi) showed capacity reductions of 10 percent to 17 percent, 19 percent to 27 percent, and 12 percent and speed reductions of 4 percent to 7 percent, 11 percent to 15 percent, and 10 percent to 12 percent, respectively. Speed reductions due to heavy rain and snow were found to be significantly lower than those specified by the Highway Capacity Manual 2000.	**Category 1 –** This research utilized traffic speed and volume data and a mix of ASOS and RWIS weather station data to estimate capacity and speed reductions due to adverse weather. Snow, rain, and pavement condition were all evaluated in the Twin Cities region of Minnesota. **Status –** Analysis of this dataset was not considered for this project since the results of this study were documented in other WRTM projects related to driver behavior in adverse weather.

Table 2.2 Domestic Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 1 – Impact of Weather on Traffic Flow Using Empirical Data (continued)				
2003	Analysis of Weather Impacts on Traffic Flow in Metropolitan Washington, D.C., Institute of Transportation Engineers 2003 Annual Meeting and Exhibit, CD-ROM [27]	V. P. Shah, A. D. Stern, L. Goodwin, and P. Pisano Federal Highway Administration (FHWA)	Anyone who uses surface transportation has been affected by delays caused by various forms of weather. Whether it is rain or snow, ice or fog, the result is usually the same. Travel delay rises as traffic congestion increases. The FHWA's RWMP has been sponsoring research into the impacts of weather on surface transportation. One specific research task involved attempting to quantify the amount of travel delay imposed upon drivers due to the effects of inclement weather. This paper describes two different methods used to approximate the average travel delay impacts of weather along approximately 712 directional miles of roadway around metropolitan Washington, D.C. based on weather and travel-time data spanning from December 1999 to May 2001. Each method uses meteorological data sets of differing temporal and spatial resolutions in conjunction with travel-time data archived from a real-time publicly available Internet-based travel advisory source. The average increase in travel time due to precipitation for peak-period traffic in the Washington, D.C. region is estimated to be 25 percent based on radar data specific to particular roadways. The less refined analysis based on regional measurements of weather suggest a 12 percent increase in travel time due to factors of precipitation, visibility, and wind. During the off-peak periods in the daytime, travel time increases by approximately 13 percent due to the array of weather attributes. Measuring the impact of only precipitation, suggests that during the off-peak periods, precipitation causes a 3.5 percent increase in travel time. This estimate, however, is likely to be lower than reality due to the limitations in travel-time data.	**Category 1 –** This study estimated the amount of delay due to inclement weather using three years of data from the Washington, D.C. area. **Status –** This dataset was not reviewed due primarily to age.

Table 2.2 Domestic Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 3 – Nonempirical Studies Including Simulation and Analysis Frameworks				
2009	Safety Effects of Winter Weather: The State of Knowledge and Remaining Challenges, TRB 88th Annual Meeting Compendium of Papers DVD, 09-3353 [28]	C. Strong, X. Shi, and Z. Ye City of Oshkosh, Montana State University	In recent years, there has been growing recognition of the effects of weather on the surface transportation system. Although considerable work has been done in quantifying the effects of weather on the highway system, there is still much that remains unknown about the relationship between weather and highway system performance. This paper synthesizes the findings from some of the major efforts in this area. A table is presented which estimates the change in crash frequency and vehicle travel speed resulting from various winter weather conditions, based on a synthesis of earlier work. Recognizing the lack of comparability between the results of the studies, the paper concludes with a detailed discussion of avenues for future research which could help to address some of the gaps which currently exist.	**Category 3 –** This study is a compendium of various research findings on the impact of weather on traffic flow and concludes with recommendations for further research.
2006	Whether Weather Matters to Traffic Demand, Traffic Safety, and Traffic Operations and Flow, Transportation Research Record 1948, pages 170-176 [29]	T. Maze, M. Agarwal, and G. Burchett Iowa State University	Weather affects many aspects of transportation, but three dimensions of weather impact on highway traffic are predominant and measurable. Inclement weather affects traffic demand, traffic safety, and traffic flow relationships. Understanding these relationships will help highway agencies select better management strategies and create more efficient operating policies. For example, it was found that severe winter storms bring a higher risk of being involved in a crash by as much as 25 times – much higher than the increased risk brought by behaviors that state governments already have placed sanctions against, such as speeding or drunk driving. Given the heightened risk of drivers' involvement in a crash, highway agencies might wish to manage better and restrict use of highways during times of extreme weather, to reduce safety costs and costs associated with rescuing stranded and injured motorists in the worst weather conditions. However, the first step in managing the transportation systems to minimize the weather impact is to quantify its impact on traffic. This paper reviews the literature and recent research work conducted by the Center for Transportation Research and Education on the impact of weather on traffic demand, traffic safety, and traffic flow relationships. Included are new estimates of capacity and speed reduction due to rain, snow, fog, cold, and wind by weather intensity levels (e.g., snowfall rate per hour).	**Category 3 –** This paper includes a literature search that compiles and summarizes research on the impact of adverse weather on crash rates and traffic flow.

Table 2.2 Domestic Scan Results (continued)

Year	Reference	Authors	Abstract/Summary	Category and Comments
Category 3 – Nonempirical Studies Including Simulation and Analysis Frameworks (continued)				
2004	Temporary Losses of Highway Capacity and Impacts on Performance: Phase 2, ORNL/ TM-2004/209 [30]	S. M. Chin, O. Franzese, R. C. Gibson, D. L. Greene, and H. L. Hwang University of Tennessee	This report describes the second phase of the Temporary Losses of Capacity (TLC) study (TLC2). Oak Ridge National Laboratory, sponsored by the FHWA, made an initial attempt to provide nationwide estimates of the capacity losses and delay caused by temporary capacity-reducing events (Chin et al. 2002). This study, called the Temporary Loss of Capacity (TLC) study, estimated capacity loss and delay on freeways and principal arterials resulting from fatal and nonfatal crashes, vehicle breakdowns, and adverse weather, including snow, ice, and fog. In addition, it estimated capacity loss and delay caused by suboptimal signal timing at intersections on principal arterials. It also included rough estimates of capacity loss and delay on Interstates due to highway construction and maintenance work zones. TLC2 improves upon the first study by expanding the scope to include delays from rain, toll collection facilities, railroad crossings, and commercial truck pickup and delivery (PUD) activities in urban areas. It includes estimates of work zone capacity loss and delay for all freeways and principal arterials, rather than for Interstates only. It also includes improved estimates of delays caused by fog, snow, and ice, which are based on data not available during the initial phase of the study. Finally, computational errors involving crash and breakdown delay in the original TLC report are corrected.	**Category 3 –** This report was part of a research effort to estimate TLC on a national basis. Weather was only one of a wide range of factors examined. Others include breakdowns, construction activity crashes, and poor signal timing.

2.3 Summary

The literature search revealed a good variety of recent studies that have used empirical data to assess the impact of adverse weather on traffic flow and safety. A number of these studies, mostly in the international arena, have produced datasets that could be of interest to the research goals and objectives of the WRTM program. Characteristics of desired datasets include:

- Availability of detailed traffic flow data at 15 minutes intervals or less, preferably five minutes, with speed and traffic volume data by lane;
- Availability of detailed weather station data within close proximity to the traffic count stations, including precipitation intensity;
- Data accessible in a standard database format with documented quality control procedures;
- Data includes a variety of weather conditions, including dry, rain, snow, and ice; and
- Pavement condition data available.

Due to the limited scope and budget of many studies, all of these criteria could not be met. However the literature search identified a number of promising datasets, as listed in the tables above. These are summarized below in Table 2.3.

Table 2.3. Recommended Datasets for Further Evaluation

Year	Reference	Authors	Category and Comments
2010	Analysis of Impact of Adverse Weather on Freeway Free-Flow Speed in Spain, TRB 89th Annual Meeting Compendium of Papers DVD, 10-2195 [1]	F. Torregrosa, A. Garcia and E. Esplugues **"Spain"** Polytechnic University of Valencia, Spain	The paper investigates the effect of different weather conditions on the traffic speed and flow for different freeways in Spain. It provides direct measurement of traffic conditions at 15-minute intervals under a variety of weather conditions. **Status –** A sample of the data were obtained and reviewed for this project. The results of that review are documented in Section 3.2.

Table 2.3 Recommended Datasets for Further Evaluation (continued)

Year	Reference	Authors	Category and Comments
2010	Comparison of Driving Behavior and Safety in Car-Following Platoons Under Icy and Dry Surface Conditions, TRB 89th Annual Meeting Compendium of Papers DVD, 10-0504 [2]	M. Tanaka, and P. Ranjitkat "New Zealand" T. Nakatsuji "Japan" University of Auckland, Hokkaido University	This study addressed car-following behavior under icy conditions in a test track environment. This data was recommended for further evaluation since data on car-following behavior in icy conditions is very difficult to find. In addition, this research was conducted under very rigorous conditions, providing a high level of confidence in the results. **Status –** The authors provided the data to the study team and an analysis was conducted that was documented in the report "Microscopic Analysis of Traffic Flow in Inclement Weather: Impact of Icy Roadway Conditions on Driver Car-Following Behavior," prepared for FHWA by Virginia Tech Transportation Institute and Cambridge Systematics, February 2010.
2010	Variation in Impact of Cold Temperature and Snowfall and Their Interaction on Traffic Volumes, TRB 89th Annual Meeting Compendium of Papers DVD, 10-3182 [3]	S. Datla **"Canada"** University of Regina	This paper investigates the effect of snow and cold on traffic flow variation using empirical weather and traffic flow data; providing the data could be relevant if it will be related to the freeway capacity and car-following models. This report was recommended for evaluation pending further review since models developed for WRTM strategies need to take into account reductions in overall volume that may occur due to adverse weather. It appears this research successfully modeled this relationship in Alberta. **Status –** While the paper provided some useful parameters, the authors could not be reached to obtain the full dataset.

Table 2.3 Recommended Datasets for Further Evaluation (continued)

Year	Reference	Authors	Category and Comments
2008	Assessing the impact of weather on traffic intensity, TRB 87th Annual Meeting Compendium of Papers DVD, 08-1903 [7]	M. Cools, E. Moons, and G. Wets **"Belgium"** Transportation Research Institute, Hasselt University	This is a study that used detailed, empirical measurements of traffic and weather conditions to address adverse weather impacts. As it parallels some of the macroscopic research being conducted through the WRTM, this dataset could be useful for review and analysis. **Status –** This dataset was recommended for further analysis, but was unavailable due to confidentiality restrictions.
2009	Multilevel Assessment of the Impact of Rain on Drivers' Behavior: Standardized Methodology and Empirical Analysis, Transportation Research Record No. 2107 [5]	R. Billot, N. El Faouzi, and F. De Vuyst "France" Institut National de Recherche sur les Transports et leur Securite (INRETS), Ecole Centrale de Paris	This study deals with the analysis of the impact of rain on drivers' behavior and traffic operations. First, a generic methodology for assessing the effect of weather on traffic is proposed through a multilevel approach: from individual traffic data, the rain impact is assessed at a microscopic level (time, headways, and spacing). Next, the same data were used to extend the study to a mesoscopic and a macroscopic level. The mesoscopic level deals with the effects of rain on platoons, and the macroscopic level resides in the analysis of the impact of rain on the fundamental diagram enabling weather-responsive macroscopic traffic simulation. Second, following this approach, an empirical study is carried out from individual data collected on a French interurban motorway. Weather data were provided by a weather station located near the test site. The results suggest a significant impact of rain on drivers' behavior and traffic operations, which increases with the intensity of rainfall. This study involved a simulation effort. The impact of rain on traffic flow at microscopic level was estimated using data from a French interurban motorway. The test site included a nearby weather station. **Status –** The detailed dataset was requested but unavailable due to confidentiality restrictions.

3.0 Weather and Traffic Dataset Analysis

This section focuses on traffic and weather-related datasets that could be used to better understand the relationship between traffic flow and weather. These datasets fall into two primary categories.

Research datasets that are generated under controlled, experimental conditions – While these datasets may not provide a precise replication of "real-world" conditions, they provide precise measurement of specific hypotheses. These research efforts are generally documented through professional journals and conference presentations so most have been discussed and prioritized in the earlier memorandum [31]. A summary of datasets identified during the project is presented in this memorandum.

Real-time traffic and weather data – Traffic volume and speed data from ITS systems along with increased deployment of both private and public weather observation stations, is providing improved opportunity to assess the impact of weather on real-time traffic flow. In a 2006 FHWA study [32], weather and traffic data from three cities were collected and used to estimate weather-related adjustment factors that could apply in simulation models. Datasets from Baltimore, Minneapolis-St. Paul, and Seattle were utilized in this effort. Traffic speed and volume data were obtained from local ITS system detectors while weather data were obtained from National Weather Service Automated Surface Observation Systems (ASOS) at local airports. One of the major challenges of this effort was the limited geographic scope of available weather data and the limited capabilities of many available weather stations. For example, many of the road weather stations operated by state transportation departments do not measure precipitation intensity; making it difficult to assess the impact of rain or snow on traffic volumes. Since ASOS stations were generally limited to major airports distances between traffic and weather observation points were often significant, and not adequate to capture local variations in precipitation levels.

A study conducted by CS and VTTI for FHWA in 2006 to 2008 [33] involved collection of weather and traffic data from three cities (Baltimore, Minneapolis-St. Paul, and Seattle). One of the activities required to meet the objectives of this project was to assess whether increased deployment of ITS systems and weather stations over the past three years would provide improved datasets for evaluating the impact of weather on traffic flow. After an initial screening process, which is documented below, three cities were recommended for further evaluation in this report; Atlanta, Salt Lake City, and Minneapolis-St. Paul. Further discussion of available weather and traffic sets is included in this section.

3.1 Summary of Dataset Criteria

The literature search and data review revealed a good variety of recent studies that have used empirical data to assess the impact of adverse weather on traffic flow and safety. A number of these studies, mostly in the international arena, have produced datasets of potential interest to the research goals and objectives of the WRTM program. Characteristics of desired datasets include:

- Availability of detailed traffic flow data at 15-minute intervals or less, preferably five minutes, with speed and traffic volume data by lane.
- Availability of detailed weather station data within close proximity to the traffic count stations, including precipitation intensity. Data on visibility level also are desirable.
- Data accessible in a standard database format with documented quality control procedures.
- Data includes a variety of weather conditions, including dry, rain, snow, and ice.
- Pavement condition data available.
- Similar criteria are applied in this section to datasets generated by ITS and weather data sources.

3.2 Datasets Identified From Literature Search

The literature search identified several research datasets that are of interest to the project. All of the new recent datasets identified were from non-U.S. sites. One concern was to identify any factors that might make the results less valid for modeling the behavior of U.S. drivers. It should be noted, however, that there is great variation in driving behavior within the United States; particularly between cold and warm weather locations, and between large urban, small urban and rural locations. Comparison of the data collected from domestic Traffic Management Centers and weather stations helped to provide a benchmark. Table 2.3 listed the preferred datasets identified through the literature search, review of papers from the 2010 TRB Annual Meeting and discussions with researchers.

Only two of the above datasets listed in Table 2.3 were available for review, the study conducted by the University of Valencia in Spain [1] and the Hokkaido study [2]. Others could not be obtained due to either confidentiality agreements or lack of response to requests by the researchers. The Hokkaido study was used for a microscopic analysis of driver behavior, documented in the report, "Microscopic Analysis of Traffic Flow in Inclement Weather: Impact of Icy Roadway Conditions on Driver Car-Following Behavior," prepared for FHWA by Virginia Tech Transportation Institute and Cambridge Systematics, February 2010 [34].

The data from the Valencia study were analyzed as part of this project. In this study, 15 locations from two Northwestern freeways in Spain have been studied in order to analyze the influence of adverse weather into traffic conditions. Weather stations and traffic stations were used to collect data between January 2006 and November 2008. Traffic stations collected data in a one-hour-based period, while weather stations collected data in a 15-minute period. In order to not lose precision, traffic intervals were split into four similar 15-minute intervals. Seven of those locations were from the A-6 10 freeway, covering 94.3 km; while eight stations belonged to the A-52 freeway, covering 57.4 km.

Both freeways are located in the Northern Spain, influenced by the Atlantic Climate. This region is the most cloudiest and wettest of Spain, with annual rainfall between 800 and 1,500 mm. Average temperatures are 9 ºC in winter and 18 ºC in summer.

Each one of the traffic stations was separated by an average distance of less than 100 m from its corresponding weather station. Thus, it can be considered that the weather conditions registered in the weather stations were the same than the registered on the road. Traffic data was registered in one-hour intervals, while meteorological data was registered in a 15-minute interval. In order to analyze and correlate traffic weather data, traffic data was split into 15-minute aggregation periods. While there were major limitations in the data, largely due to the rural location of the study area, regression models did show that rainy conditions resulted in speed reductions from 5.5 km/h to 7.0 km/h, depending on its intensity. Speed reduction due to snow varied from 9.0 to 13.7 km/h. A more detailed description of this dataset and the analysis conducted is included in this report as Appendix D.

3.3 Additional Datasets Identified Through Research

Additional research-oriented datasets were identified from domestic research programs. Two of them, the SHRP 2 Project L03 and the California PATH Nonrecurrent Congestion Study were identified as important studies, along with others, but most have not yet producing enough information to be helpful in analyzing weather impacts on traffic flow. These studies are summarized in Table 3.1 and it is recommended that these datasets be tracked in the future for the possibility of additional analysis.

Table 3.1 Additional Datasets Identified through Research

Organization	Research Program	Description
Strategic Highway Research Program/ National Cooperative Highway Research Program (SHRP/ NCHRP) [35]	SHRP 2 Project L03: Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies, Cambridge Systematics, Inc. 2009	The weather data for SHRP 2 L03 project was obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). The hourly Local Climatological Data from NCDC for Atlanta, Houston, Minneapolis/St. Paul, San Diego, Los Angeles, San Francisco, and Seattle. The basic weather elements in the hourly data files are: • Sky condition – Cloud height and amount (clear, scattered, broken, overcast) up to 12,000 feet; • The weather data for SHRP 2 L03 project was Visibility (to at least 10 statute miles); • Basic present weather information – Type and intensity for rain, snow, and freezing rain; • Obstructions to vision – Fog, haze; • Pressure – Sea-level pressure, altimeter setting; • Ambient temperature, dew point temperature; • Wind – Direction, speed, and character (gusts, squalls); and • Precipitation accumulation; and selected significant remarks, including variable visibility, precipitation beginning/ending times, rapid pressure changes, pressure change tendency, wind shift, and peak wind. These weather characteristics have been summarized into the following annual totals that would be used in statistically models for travel reliability analysis. • Number of hours with precipitation amounts greater than or equal to: 0.01 inches, 0.05 inches, 0.10 inches, 0.25 inches, and 0.50 inches. • Number of hours with measurable snow. • Number of hours with frozen precipitation. • Number of hours with fog present.

Table 3.1 Additional Datasets Identified through Research (continued)

Organization	Research Program	Description
Strategic Highway Research Program/ National Cooperative Highway Research Program (SHRP/ NCHRP) [35] (continued)	SHRP 2 Project L03: Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies, Cambridge Systematics, Inc. 2009 (continued)	The SHRP 2 Project L03 dataset also includes traffic volume and speed data for roadway segments in a variety of cities. Additional data was collected on incident type, frequency, and duration. Where available, freeway service patrol logs were used to help confirm incident impacts and durations. The primary purpose of this project was to evaluate travel time reliability mitigation strategies. Reliability is generally measured over long periods of time. **Status –** This dataset was used in the gap analysis for Salt Lake City that is documented later in this section. The analysis shows that it can help to supplement some of the data collected from ITS and weather systems, including *Clarus*. However, the fact that it is hourly limits its usefulness.
University of Michigan Transportation Research Institute (UMTRI)[36]	Integrated Vehicle-Based Safety Systems Project	UMTRI is engaged with the Weather Systems and Assessment Program, Research Applications Laboratory of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado and plans to post process radar data that is obtained from the National Climatic Data Center with the assistance of NCAR. NCAR processes code that will allow UMTRI to calculate active precipitation from the radar data using GPS time and location information recorded on-board the vehicles. This data can be then used in conjunction with windshield wiper state from the vehicle data to determine any potential influence that active precipitation has on driver behavior, particularly whether drivers respond to warnings provided in the vehicle, and if they respond, how quickly. **Status –** This is a promising dataset but was not far enough advanced to meet the schedule for this project. An initial report on the heavy truck portion of the project was issued in August 2010. A presentation of the general results was held in October 2010.

Table 3.1 Additional Datasets Identified through Research (continued)

Organization	Research Program	Description
University of Michigan Transportation Research Institute (UMTRI)[37]	IntelliDrive/ Vehicle Infrastructure Integration (VII)	Scientists at the National Center for Atmospheric Research (NCAR) are testing an innovative technological system in the Detroit area that will help protect drivers from being surprised by black ice, fog, and other hazardous weather conditions. The prototype system is designed to gather detailed information about weather and road conditions from moving vehicles. Within about a decade, it should enable motor vehicles equipped with wireless technology to transmit automated updates about local conditions to a central database, which then will relay alerts to other drivers in the area. **Status –** This is a promising dataset but is a long-term project and therefore not far enough advanced for this project**.**
California PATH [38]	California Smart Call Box Study	This FOT replaces a box's existing controller card with a "smarter" card. After this swap, the boxes provide ITS services, such as performing traffic counts, detecting incidents, monitoring weather conditions, and hosting slow-scan closed circuit television cameras. **Status –** This is an older study from the late 1990s. Increase in cell phone penetration has reduced interest in call boxes since that time and this technique for collecting weather and traffic information together has not caught on.
California PATH [39]	Finding and Analyzing True Effect of Nonrecurrent Congestion on Mobility and Safety	This report summarizes empirical research about the causes and impact of nonrecurrent congestion. A method is presented to divide the total congestion delay in a freeway section into six components: the delay caused by incidents, special events, lane closures, and adverse weather, the potential reduction in delay at bottlenecks that ideal ramp metering can achieve, and the remaining delay, due mainly to excess demand. **Status –** The results were not available in time for this study but it is recommended for further evaluation when closer to completion since it provides some information on delays related to weather.

3.4 Data Collection for Gap Analysis

In addition to the research studies discussed in the previous section, this project included collection of data from three U.S. cities. During the FHWA study written by Hranac, et al. in 2006, a number of cities were approached for both traffic and weather data. A number of gaps in the data were identified at that time, including:

- Most of the Environmental Sensor Stations (ESS) owned by DOTs did not report precipitation intensity, making it difficult or impossible to assess the impact of precipitation on traffic flow.
- Many DOT ESS's had reliability problems, resulting in significant gaps in the data.

As a result of the problems identified with ESS's, ASOS data from major airports were used in the earlier study. These stations were often located at some distance from traffic detector locations, creating potential time gaps between traffic and weather data.

Reliability problems with traffic detector data were identified in many locations. These can generally be smoothed over when looking at long-term system performance, but a higher level of detail is required when evaluating the impact of weather events on traffic flow.

Desired traffic data reporting frequency for this analysis is 5 minutes, with a 15-minute maximum. Many detector stations summarize data at lower frequencies such as 30 or 60 minutes.

Ultimately, data was used from Minneapolis-St. Paul, Seattle, and Baltimore to develop weather-related traffic flow adjustment factors. Although the gaps identified above did exist in the data from these cities, the quality of data overall was acceptable, and the sample of those three cities reflected a good variety of weather conditions. Since this analysis was conducted approximately three years ago, there have been significant advances throughout the United States in the deployment of both traffic detection technologies and ESS. These developments are encouraging in that they can provide more data and higher quality data for use in evaluating impacts of weather on traffic and include:

- Expansion of ITS in many metropolitan areas into high-growth suburban and exurban corridors;
- Replacement of loop detectors with nonintrusive detection systems that are less prone to failure and which can be repaired more rapidly;
- Rapid entry of the private sector into the traffic detection arena, resulting in a significant increase in speed and travel time data;
- Replacement of airport AWOS stations with ASOS technology that provides surface condition data;
- Increase in the number of ESS in many States; and
- Implementation of FHWA's *Clarus* system, which provides a standard format and quality control for ESS observations from over 30 states and several Canadian provinces.

The gap analysis documented in this task was designed to help FHWA determine whether these developments have provided greater opportunity to evaluate the impact of adverse weather on traffic with data that is being collected on a regular basis. While this would not eliminate the need for specialized data collection, it may at least reduce that need, as well as enabling researchers to spend more resources on analysis and less on original data collection.

The section below describes the characteristics of traffic and weather data that would help to meet the goals of this project. An initial review of available data sources was conducted in order to recommend three cities for further analysis. This review focused on criteria proposed and documented in Task 2 (Literature Search), including:

- Availability of detailed traffic flow data at 15 minutes intervals or less, preferably five minutes, with speed and traffic volume data by lane;
- Availability of detailed weather station data within close proximity to the traffic count stations, including precipitation intensity;
- Data accessible in a standard database format with documented quality control procedures;
- Data includes a variety of weather conditions, including dry, rain, snow, and ice; and
- Pavement condition data available.

Our initial review of sites, documented below yielded the preliminary recommendation to approach Minneapolis-St. Paul, Salt Lake City, and Atlanta. A number of cities were identified as back-up if the three original selections did not yield satisfactory datasets.

3.5 Traffic Data

Through the work on FHWA's Mobility Monitoring Program and other various state DOT projects, traffic data archives have been collected from numerous traffic management centers around the country. These traffic data are collected at ITS vehicle detection stations along major Interstates in more than 10 metropolitan areas. These stations are usually spaced at one-third mile apart.

The types of data collected include traffic volume and speed for each directional traffic lane. While 5-minute is the most common collection interval, 15-minute interval also is used in some cities.

3.6 Weather Data

Three types of data were reviewed for this task. The first is the roadway surface weather data archived by FHWA's *Clarus* project, the second is the National Weather Station archives collected at National Climatic Data Center, and the third is private commercial weather archives. The latter represents a promising source in that the number of private weather sources has been increasing rapidly and the quality of the data has been improving. The drawback is that these data must be purchased and compiling large datasets required for analysis of weather impact on traffic could be prohibitively expensive for public agencies.

3.6.1 FHWA Clarus Initiative

The *Clarus* system, developed and operated by FHWA through its contractor, Mixon-Hill, collects near real-time atmospheric and pavement observations from various state DOTs' road weather information systems. Most of the stations report at 20-minute intervals, while some report at 10-minute intervals. The types of climate data collected at each station varies, while in general they include:

- Air Temperature;
- Atmospheric Pressure;
- Dewpoint Temperature;
- Maximum Temperature;
- Minimum Temperature;
- 24-hour precipitation;
- 1-hour precipitation;
- 6-hour precipitation;
- 3-hour precipitation;
- 12-hour precipitation;
- Relative Humidity;
- Subsurface Temperature;
- Subsurface Temperature;
- Surface Temperature;
- Total Radiation;
- Wet Bulb Temperature;
- Average Wind Direction;
- Average Wind Speed; and
- Wind Gust Speed.

Archives since December 2008 can be obtained from http://www.clarus-system.com.

3.6.2 National Weather Stations

The NWS Automated Surface Observing System (ASOS) stations are located at major airports and recently have been expanding to smaller airports as well. Many ASOS stations have one-minute data archives. One-minute reports are computed from data accumulations over the following time periods prior to the report:

- Cloud Height 30 seconds;
- Visibility 1 minute;
- Photometer 1 minute;
- Present Weather 1 minute;
- Freezing Rain 1 minute;
- Temperature/Dew Point 1 minute;
- Wind 2-minute average;
- Pressure 1 minute;
- Precipitation Accumulation 15 minutes; and
- Lightning 1 minute.

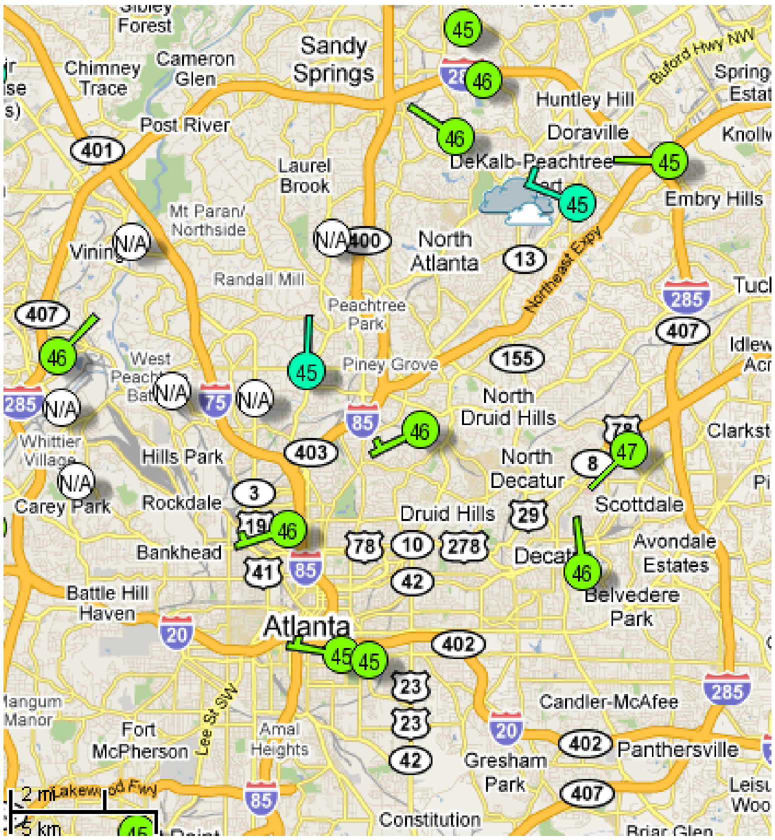
The archives can be obtained from http://www.ncdc.noaa.gov/oa/climate/climatedata.html#asosminutedata.

3.6.3 Commercial Weather Archives

We examined sample weather archives maintained by weatherunderground.com. Their stations are much more densely spaced than NWS' ASOS stations, so it is easier to find a weather station that is close to freeway traffic detection stations.

Many of these weather stations collect data continuously, and weather data collected include: precipitation rate, daily rain, temperature, dew point, pressure, wind direction, wind speed, humidity, and clouds. Figure 3.1 shows a sampling of Wunderground stations in the Atlanta area.

Figure 3.1 Wunderground Stations in Atlanta Region



3.7 Gap Analysis of Weather and Traffic Data

Based on work conducted for the Mobility Monitoring project, a number of cities were identified that could serve as one of the three sites for the gap analysis. This initial analysis included a mix of warm and cold weather cities. However, given the lack of information on impacts of snow and ice on traffic flow, more emphasis was placed on cold weather cities in later review and additional cities were added to the list. The result of this initial review is documented in Table 3.2.

Table 3.2 Initial Screening of Cities for Gap Analysis

City	Traffic Data Granularity	Numbers of Nearby National Weather Stations
Atlanta, Georgia	Lane level, 5-minute	6
Tampa, Florida	Lane level, 1-minute	6
Orlando, Florida	Lane level, 1-minute	4
Fort Lauderdale, Florida	Lane level, 1-minute	3
Miami, Florida	Lane level, 1-minute	1
Salt Lake City, Utah	*Data source in transition from DOT to traffic.com (see update in Table 3.4)	2
Minneapolis-St. Paul, Minnesota	*No data feed since September 2009 (see update in Table 3.3)	4
Portland, Oregon	Lane level, 15-minute	3
Detroit, Michigan	Lane level, 5-minute	2
Seattle, Washington	Lane level, 5-minute	5

Three cities, Atlanta, Georgia; Salt Lake City, Utah; and Minneapolis-St Paul, Minnesota were recommended for analysis pending further review of the data. These cities all had a good, reliable set of traffic data with varying levels of weather data. Two of the three cities, Minneapolis-St. Paul and Salt Lake City, regularly experience winter weather. Table 3.3 shows the selecting criteria for the three cities.

Table 3.3 Data Characteristics of Recommended Cities

City	Frequency of Data Collection and Temporal Distribution			
		Weather Data		
	Traffic Data	*Clarus*	ASOS	Wunderground
Atlanta, Georgia	Lane level, 5-minute	N/A	15-minute	Continuous
Salt Lake City, Utah	Lane level, 5-minute	10- to 20-minute	15-minute	Continuous
Minneapolis-St. Paul, Minnesota	Lane level, 5-minute	10- to 20-minute	15-minute	Continuous

Tables 3.4 through 3.6 show the characteristics of traffic and weather data obtained from the three cities. During an early stage of the gap analysis, the availability and reliability of the data was reviewed to make sure that it met criteria.

Table 3.4 Traffic Detector and Weather Station Geographic Scope and Density in Recommended Cities

City	Geographic Scope and Density			
	Traffic Data	Weather Data		
		Clarus	ASOS	Wunderground
Atlanta, Georgia	On freeways, stations spaced at one-third miles	N/A	3 stations	11 stations
Salt Lake City, Utah	On freeways, stations spaced at one-third miles	3 stations	1 stations	10 stations
Minneapolis-St. Paul, Minnesota	On freeways, stations spaced at one-third miles	3 stations	4 stations	15 stations

Table 3.5 Traffic and Weather Data Elements in Recommended Cities

City	Data Elements			
	Traffic Data	Weather Data		
		Clarus	ASOS	Wunderground
Atlanta, Georgia	Volume, speed	N/A	Precipitation ID, amount	Precipitation rate
Salt Lake City, Utah	Volume, speed	Precipitation amount	Precipitation ID, amount	Precipitation rate
Minneapolis-St. Paul, Minnesota	Volume, speed	Precipitation type, amount	Precipitation ID, amount	Precipitation rate

Table 3.6 Cost and Quality Control Procedures for Traffic and Weather Data Sources

	Other Criteria			
	Traffic Data	Weather Data		
		Clarus	ASOS	Wunderground
Data availability and cost	Text files, ready for processing, free.	Text files at Clarus FTP site, free	Text files at NCDC FTP site, free	Text files, $80 per month 10 kilometers area all PWS data from the circle. Minimum 10 areas. One-year minimum term.
QC	All raw data must pass QC procedures listed in the Scope.	To be determined	To be determined	WU uses three separate checks to ensure the quality of PWS data. 1. First, make sure the data is physically plausible, removing such reports as temperatures colder than Antarctica's record low and wind speeds greater than those found in tornadoes. 2. Check to see if the rate of change also is reasonable, this prevents observations from flip-flopping between say 50 and 80 degrees in the span of five minutes (this pattern is attributable to instrument failure). 3. For temperature, check the temperature against nearby stations to see if it is unusually warm or cool compared to its neighbors. If a station fails any check, they do not display the observation.

Earlier work conducted under the RWMP program highlighted the possibility that data may not be available due to nonworking field equipment or other factors. As a result, several back-up cities were identified, all of which have significant snowfalls but limited number of ESS surface observations available. The cities and their data sources are listed in Table 3.7.

Table 3.7 Other Potential Cities for Data Collection Effort

City	Traffic Data	Weather Data
Boston	Lane level, 5-minute; Volume, speed; On freeways, stations spaced at one-third mile	Clarus: Available ASOS and Wunderground: available
Chicago	Lane level, 5-minute; Volume, speed; On freeways, stations spaced at one-third mile	Clarus: Stations appear to be off-line ASOS and Wunderground: available
Detroit	Lane level, 5-minute; Volume, speed; On freeways, stations spaced at one-third mile	Clarus: N/A ASOS and Wunderground: available
Pittsburgh	Lane level, 5-minute; Volume, speed; On freeways, stations spaced at one-third mile	Clarus: N/A ASOS and Wunderground: available
Providence	Lane level, 5-minute; Volume, speed; On freeways, stations spaced at one-third mile	Clarus: N/A ASOS and Wunderground: available

3.8 Tests of Traffic Data and Weather Wunderground Archives

This section documents sample tests of traffic and weather data from Atlanta, Salt Lake City, and Minneapolis-St. Paul. This provides a prototype methodology for the gap analysis that could be conducted in many major cities with the available weather and traffic data. The primary objectives of these tests were: 1) to determine what type of relationship between weather conditions and traffic data can be discerned from existing data; and 2) recommend methods to fill the gaps that are identified.

3.8.1 Atlanta Data Test

A preliminary test of the methodology was conducted in Atlanta using a Wunderground weather station and a nearby detection station on I-285. The location of both the Wunderground and the traffic detector station are shown in Figure 3.2.

Figure 3.2 Location of Traffic Detector and Weather Station

The Atlanta test was used to focus on a methodology and used data from Sunday, August 24, 2008. Use of a Sunday for the first test eliminated the impact of the heavy congestion that occurs throughout the Atlanta region during peak periods. The traffic speed data is at five-minute intervals for each traveling lane, and the rain precipitation rate data also is at five-minute intervals.

Figure 3.3 demonstrates the rain's impact on traffic speed. Two major spikes in rainfall are shown on the graph with rates reaching three inches an hour around 5:00 p.m. and four inches per hour around 8:00 p.m. Traffic was running at 65 to 70 mph right before the first spike but slowed down to 50 mph on the southbound side and 40 mph on the northbound side with the increase in rainfall rate. Although it continued to rain at just over one-half inch per hour after that, speeds recovered to previous levels. During the second spike at 8:00 p.m., speeds slowed down even further to less than 40 mph on the southbound side and under 30 mph on the northbound side. Rainfall continued at around one inch per hour until around midnight and speeds in both directions leveled off during this period at between 50 and 60 mph. It is likely that darkness had some impact on speed as well as the rainfall. This graph indicates that compiling this information over time could provide some functions.

Figure 3.3 Relationship of Rainfall Levels to Traffic Speeds and Lane Selection

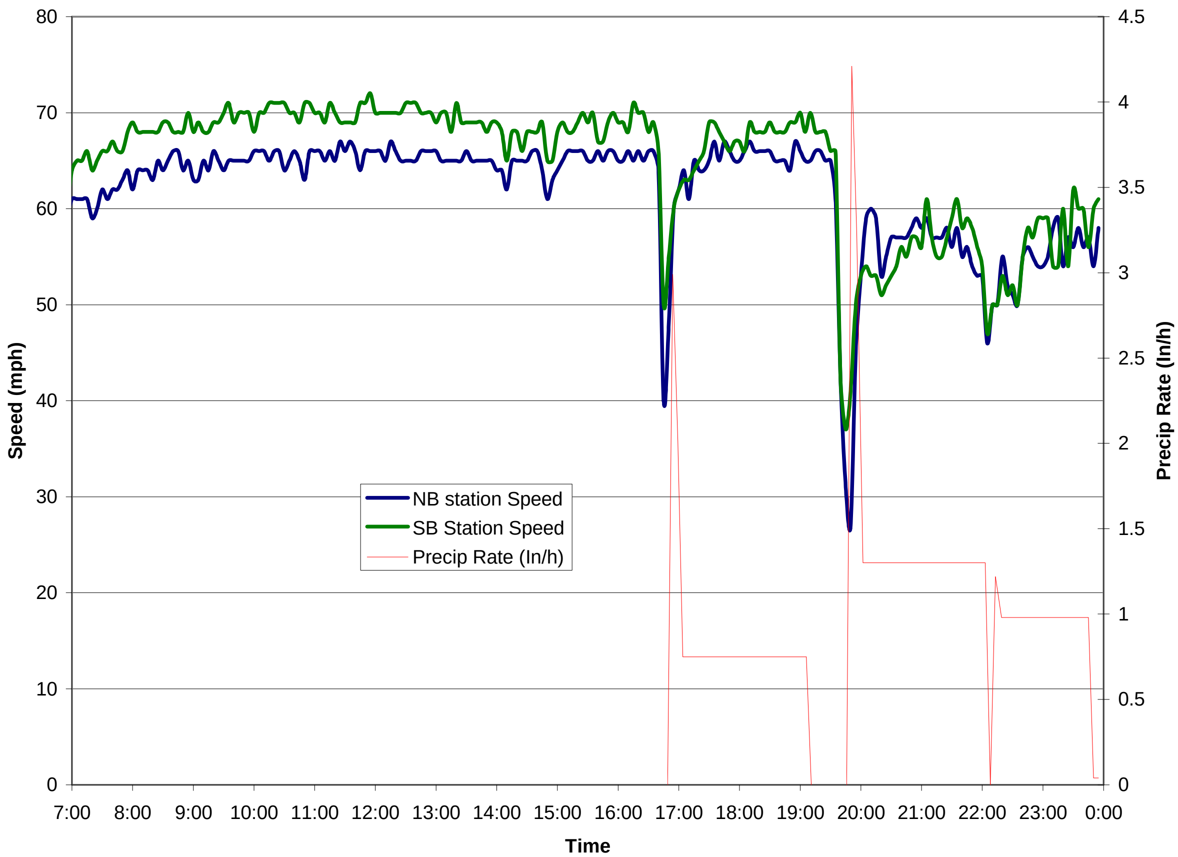
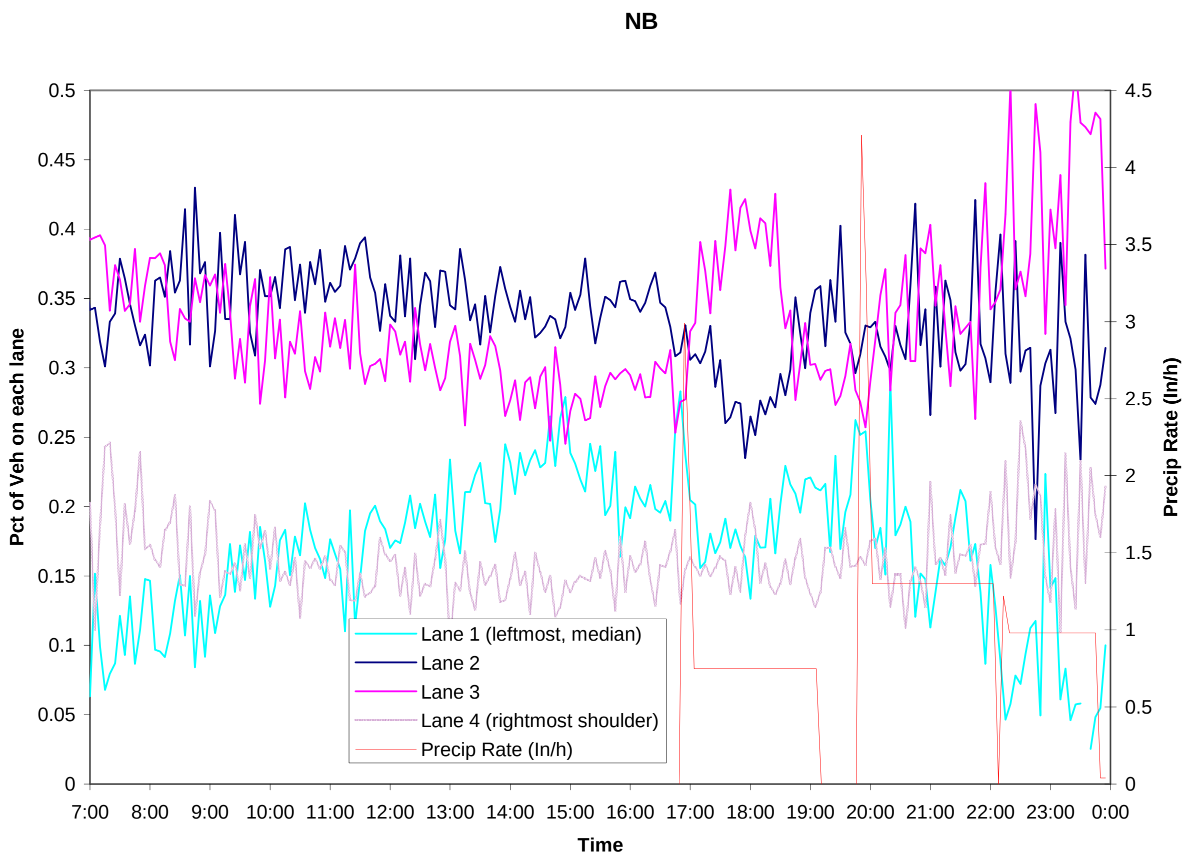


Figure 3.4 shows the rain's impact on the percentages of vehicles on each lane in the northbound direction. The impact on lane distribution is harder to discern than the impact on speed. During the first spike in rainfall, at 5:00 p.m., there is a clear movement of traffic out of the left lane and the third lane along with a significant increase in the second lane. This pattern continues in part during the next three hours with traffic moving from the third lane to the second lane. This may be an impact of both wet pavement and night fall. During the 8:00 p.m. spike in rainfall it is difficult to discern any significant changes in lane use, although there is an indication of more frequent lane-changing.

Figure 3.4 Impact of Rain on Lane Distribution



3.8.2 Salt Lake City Sample Tests

Test Sites

Two sites were tested in the Salt Lake City region, which has an extensive weather station network, including a large number of stations operated by UDOT. The first test site included is located near Salt Lake City International Airport (Figure 3.5) in a heavily developed area, and the second test site is near Parleys Summit (Figure 3.6), mountain pass in a more rural region east of Salt Lake City. These sites represent different environments and roadway alignments and were chosen because of the proximity to weather stations, the completeness of data coverage, and the uniformity of traffic patterns in each site. All the traffic stations in test areas experience limited traffic congestion, even during commute peak hours, which makes it easier to isolate weather's impacts on traffic. Table 3.8 shows the detailed information for the eight traffic stations selected in the test area.

The nearby National Weather Station KSLC supplied weather data through SHRP2 Reliability Study and the NWS ASOS data archive web site. UDOT has weather stations located on I-15 at 500 S and on I-80 at Parleys Summit.

Table 3.8 Salt Lake City Area Traffic Stations

Location	STN_ID	Milepost	Latitude	Longitude	Number of Lanes
NB I-215-W at 500 N	24740	23.35	40.779952	-111.949003	3
SB I-215-W at 500 N	24354	23.35	40.779955	-111.949221	3
NB I-215-W at 100 N	24757	22.8	40.772052	-111.949097	3
SB I-215-W at 100 N	24407	22.8	40.772047	-111.94938	3
EB I-80 at Redwood Road	24787	118	40.765945	-111.936623	3
WB I-80 at Redwood Road	24634	118	40.76608	-111.936595	3
EB I-80 at Lambs Interchange	24414	136.94	40.74336111	-111.6587333	3
WB I-80 at Lambs Interchange	24737	136.95	40.74373056	-111.6586333	3

Dates and Hours

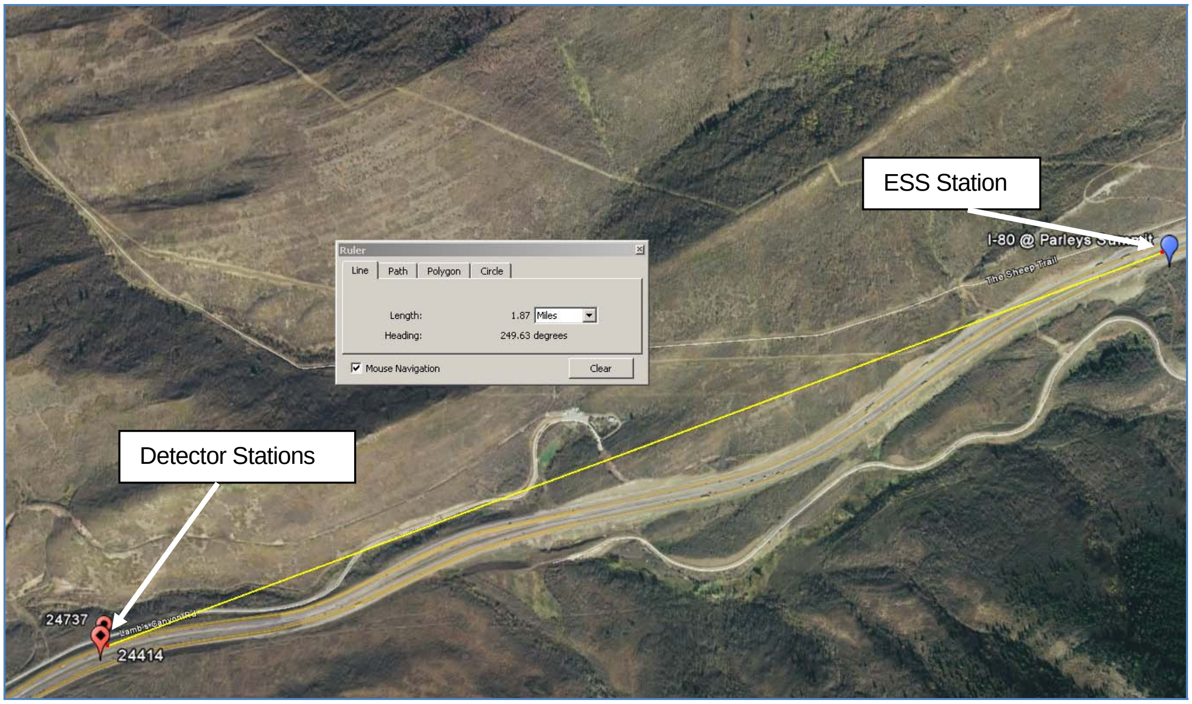
Four days were chosen because of their unique traffic and weather patterns.

- Thursday, January 1, 2009: no inclement weather;
- Friday, January 2, 2009: Snow in test site 1 and test site 2;
- Friday, June 26, 2009: Rain in test site 1 and test site 2; and
- Saturday, June 27, 2009: no inclement weather.

Hours included in the analysis are from 12:00 p.m. to 11:00 p.m.

Figure 3.5 Stations near Salt Lake City Airport

Figure 3.6 Stations near Parley's Summit



Weather Data

Snowfall:

- UDOT (*Clarus*) stations do not have precipitation data for January 2009.
- Both of the hourly national weather station archives from SHRP2 study and the ASOS data archives downloaded from NWS web site show snowfall started in the airport location around 6:50 p.m. on June 26, 2009.

Rainfall:

- *Clarus* archives for June 26 precipitation data are plotted in the following Figures 3.7 and 3.8. These figures show that rainfall started around 7:30 p.m. at I-15, and around 8:00 p.m. at Parley's Summit with both locations experiencing peak rainfall between 8:30 p.m. and 9:00 p.m.
- Both of the hourly national weather station archives from SHRP2 study and the ASOS data archives downloaded from NWS web site show rainfall started in the airport location around 6:40 p.m. on June 26, 2009.

Figure 3.7 Rainfall at I-15 at 500S

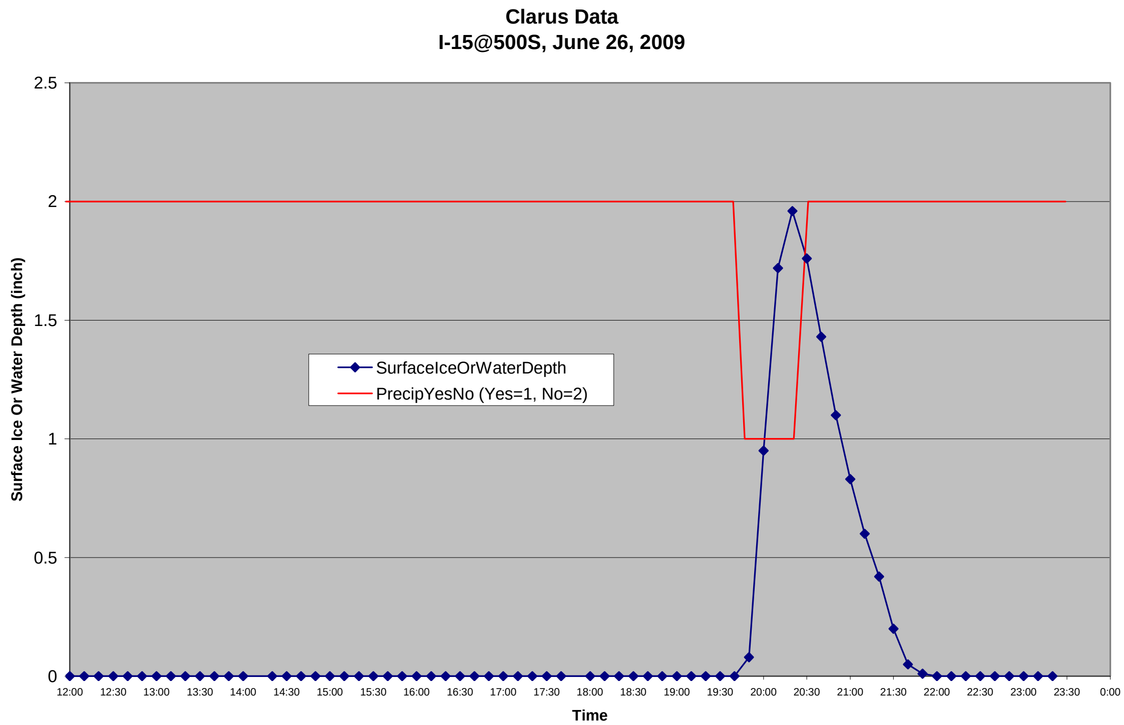
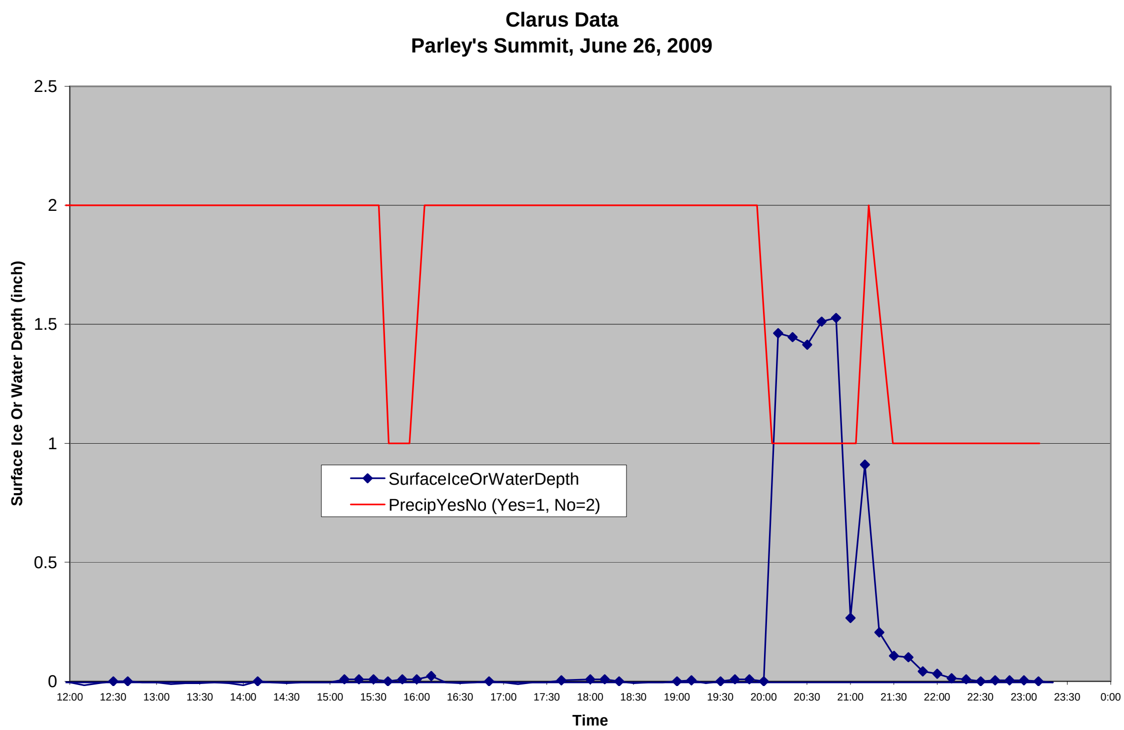


Figure 3.8 Rainfall at I-80 at Parley's Summit



Traffic Speed

Figures 3.9 and 3.10 compare speeds on two consecutive days on I-15 near the Salt Lake City airport. Figure 3.9 represents the speed profile on the rainy day graphed in Figure 3.7, June 26, while Figure 3.10 shows speeds on the following day June 27, which was dry. The graphs show a clear speed reduction on the evening of June 26 between 7:00 p.m. and 8:00 p.m., about the time of heaviest rainfall. Figure 3.10 shows that during the same period the following day there was no change in speed during that period, which in any case occurred after peak hours.

Figure 3.9 Traffic Speed on I-15 on June 26/Wet Weather

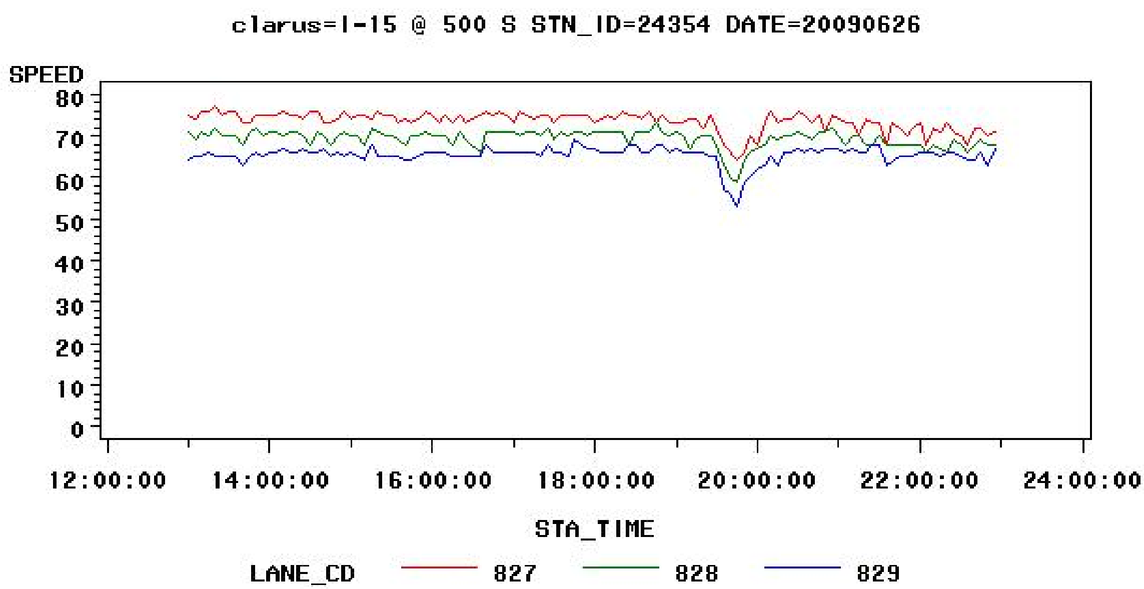
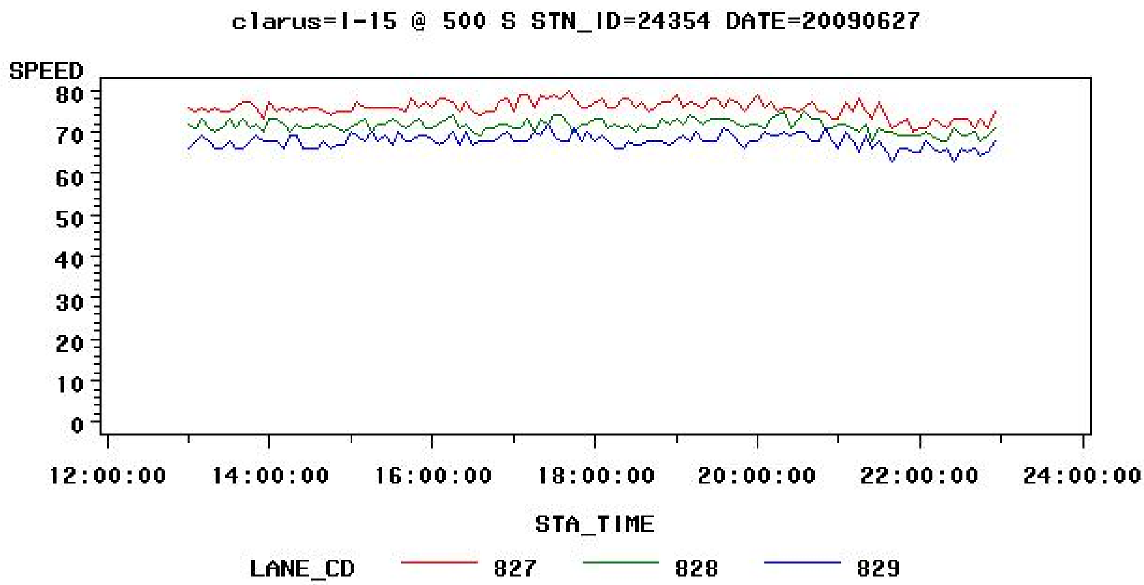


Figure 3.10 Traffic Speeds on I-15 on June 27/Dry Weather



Figures 3.11 and 3.12 show the parallel data for the Parley's Summit ESS Station. Detector data are taken from the westbound side of the highway, which has a downhill grade. There is a slight decrease in speed during the rainy period on June 26, but unlike the I-15 stations the change in speed when compared to the dry condition is small.

Figure 3.11 Traffic Speeds on I-80 Parley's Summit on June 26/Wet Weather

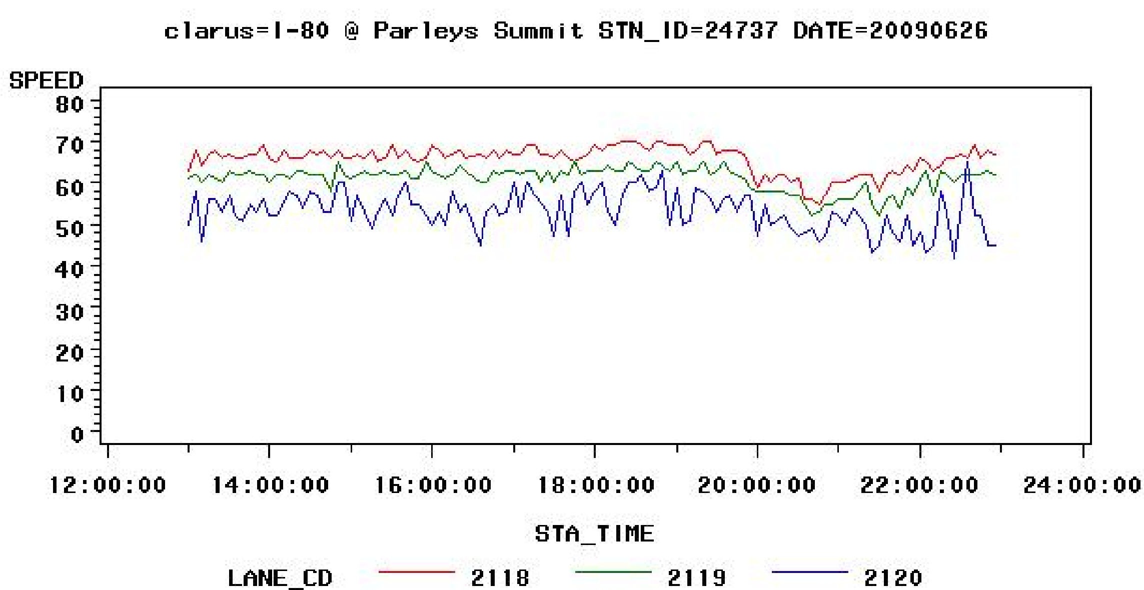
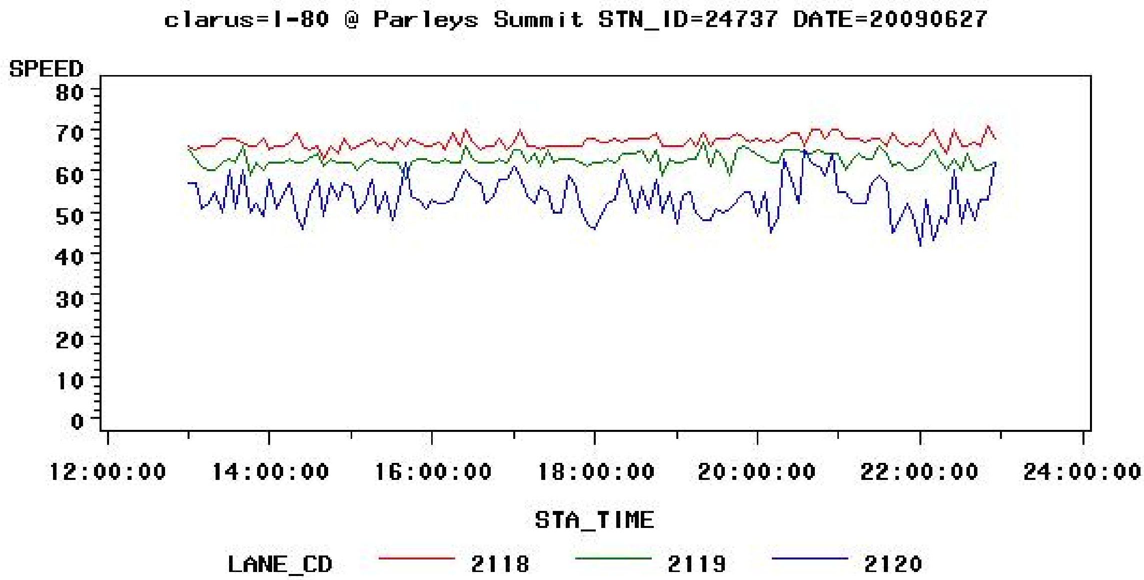


Figure 3.12 Traffic Speeds on I-80 Parley's Summit on June 27/Dry Weather



Figures 3.13 and 3.14 show the impact of snow travel speeds on I-15. Hourly snowfall data were not available but data from the NWS at Salt Lake City Airport indicated that snowfall started just before 7:00 p.m. on January 2 at the Salt Lake City Airport. Figure 3.14 indicates a significant drop in speed during the evening hours of January 2, when compared with speeds at the same time on the previous day. Speeds dropped from over 70 mph to the 30 to 40 mph range at around 8:00 p.m. and stabilized at around 50 mph after that. Figures 3.15 and 3.16 show the change in lane distribution between the same two periods. Figure 3.16 indicates that the snowfall resulted in a shift of traffic from the high-speed lane into the middle lane at around the same time that speeds dropped. This pattern lasted for a relatively short time, however, and it is important to note that lane shifts could be impacted more by the location of snowplows than by the snowfall itself. A much larger set of data from multiple storm events would be required to analyze lane-changing behavior during snowfall.

Figure 3.13 Traffic Speeds on I-15 on January 1/Dry Weather

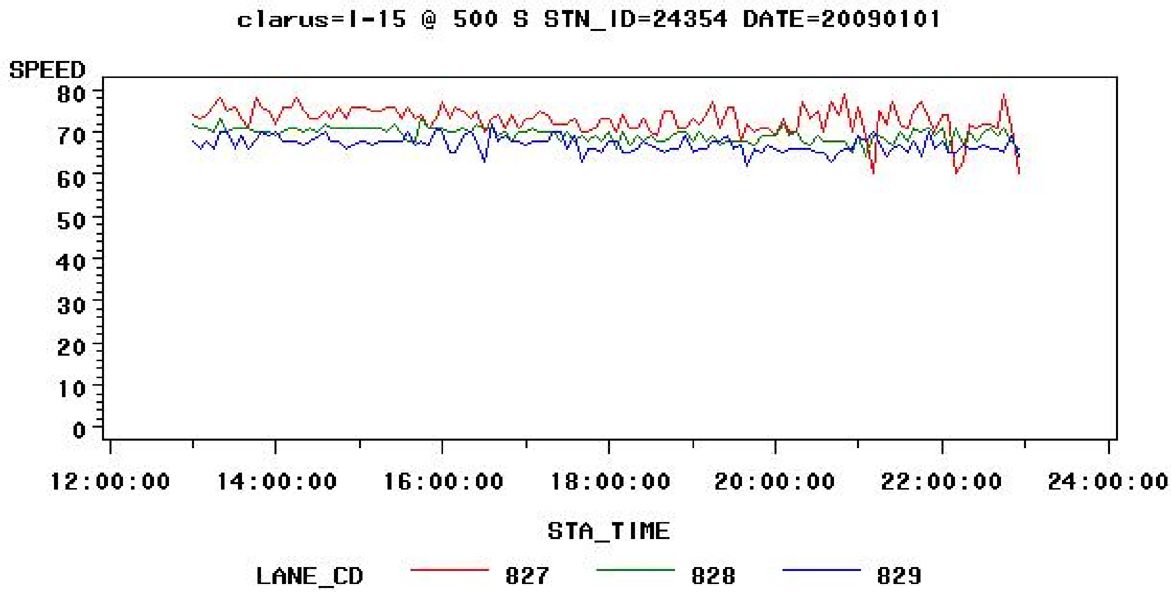


Figure 3.14 Traffic Speeds on I-15 on January 2/Snowy Weather

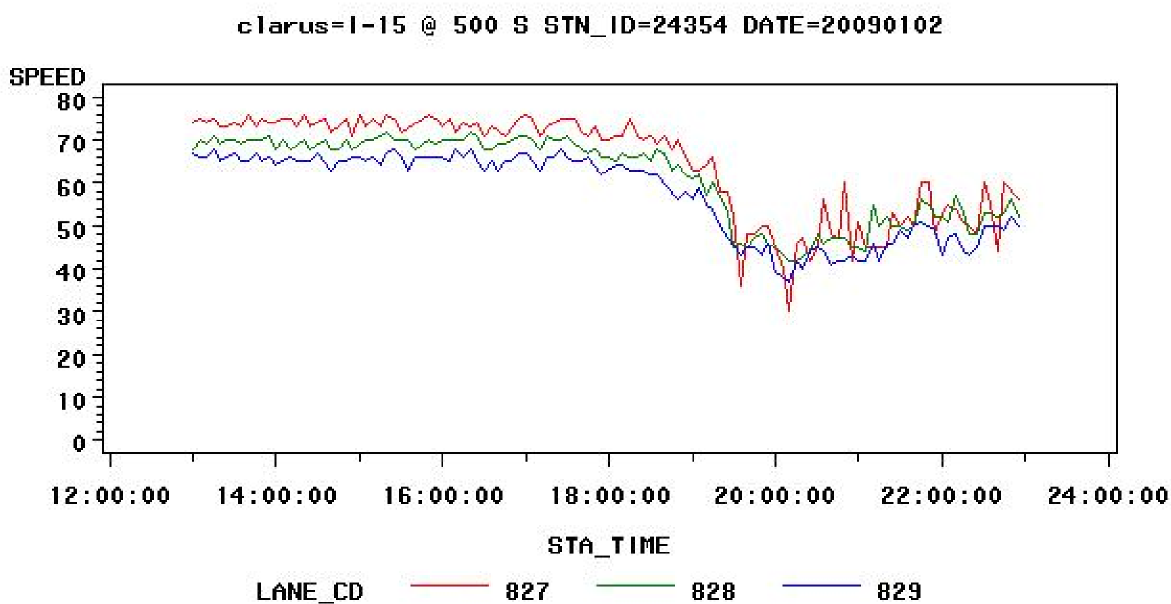


Figure 3.15 Lane Distribution of Traffic on January 1/Dry Weather

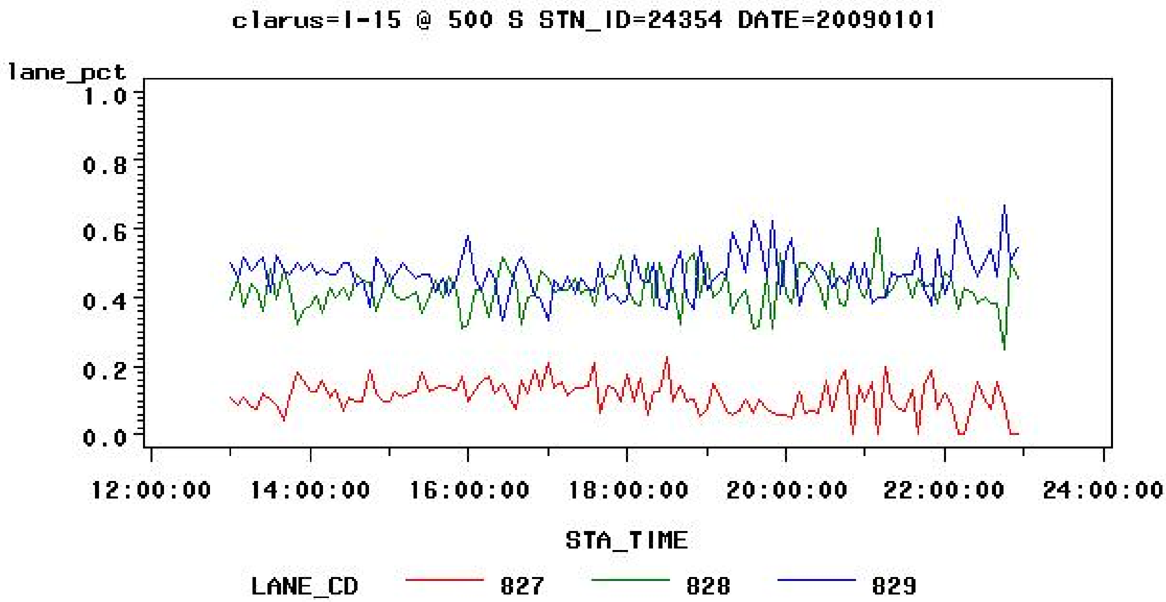
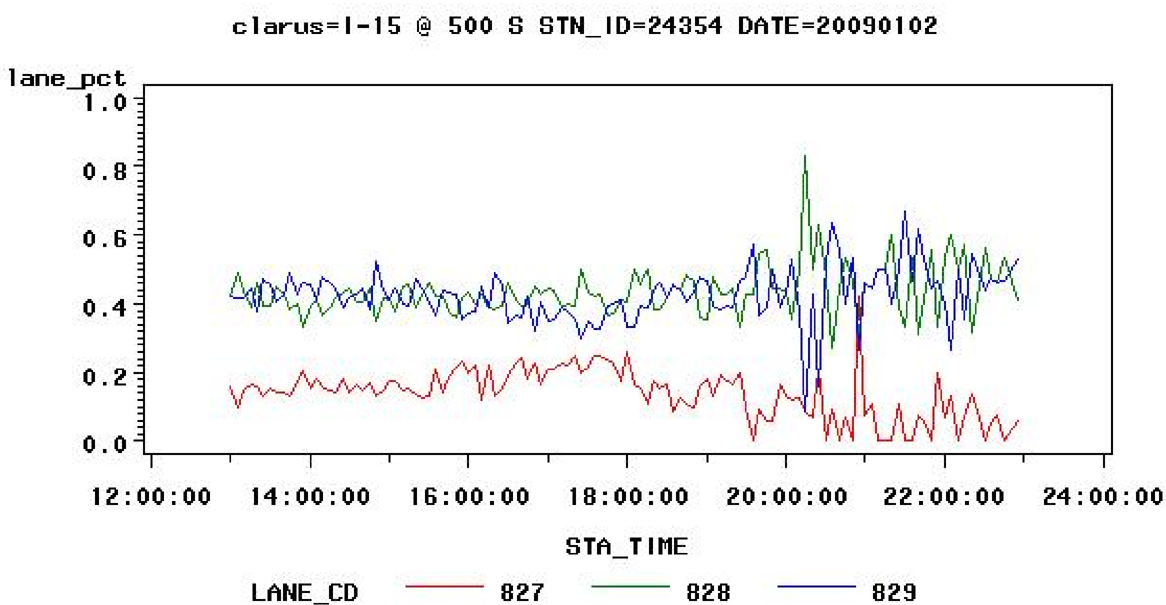


Figure 3.16 Lane Distribution of Traffic on January 2/Snowy Weather



A set of graphs parallel to those shown above in Figures 3.13 to 3.16 is shown below for I-80 at the Parley's Summit station (Figures 3.17 through 3.20) in the mountains east of Salt Lake City. These graphs show a similar but more distinct pattern with greater speed reductions and more significant and consistent lane shifts during the snowfall period. This result is anticipated given the grades found in this area and the fact that it is darker than the urban area along I-15. Speeds during the evening of January 2 drop down to around 20 mph just before 7:00 p.m. and stay around 30 mph for the remainder of the evening. For much of the snowfall period it appears that traffic shifted from the left lane to the middle lane. Heavier snowfall, steeper grades, plowing sequences, and less lighting are all possible explanations for the greater shift.

Figure 3.17 Traffic Speeds on I-80 on January 1/Dry Weather

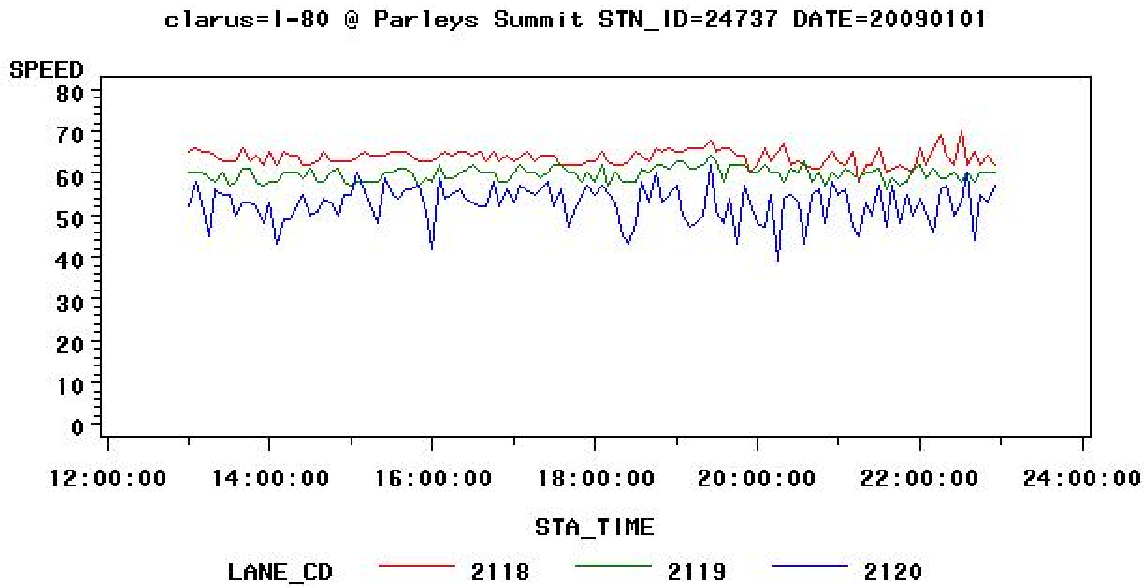


Figure 3.18 Traffic Speeds on I-80 on January 2/Evening Snowfall

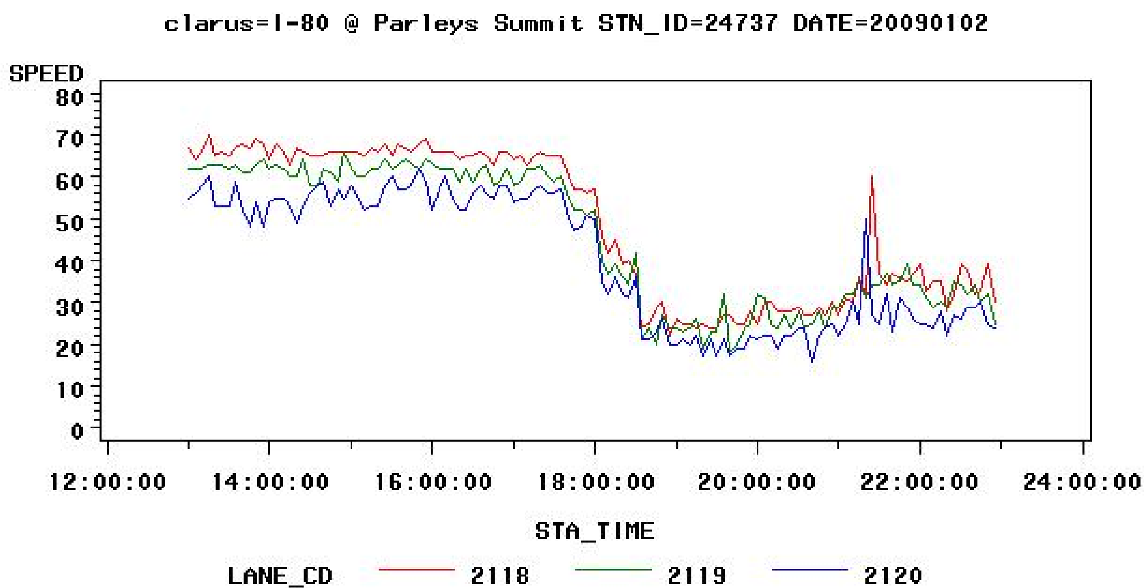


Figure 3.19 Lane Distribution on I-80 on January 1/Dry Weather

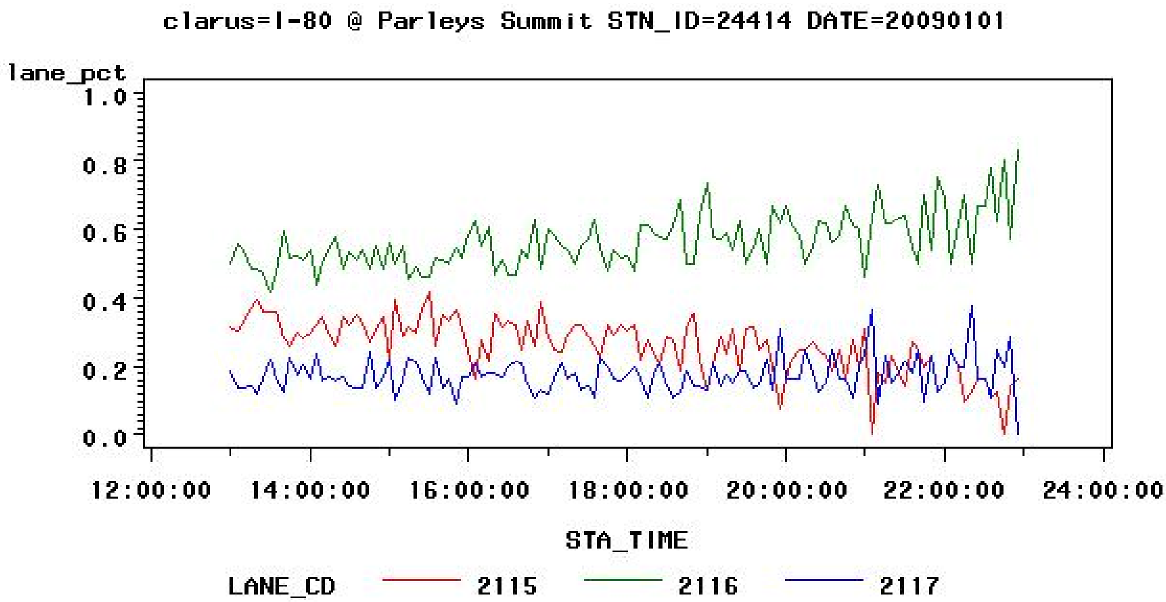
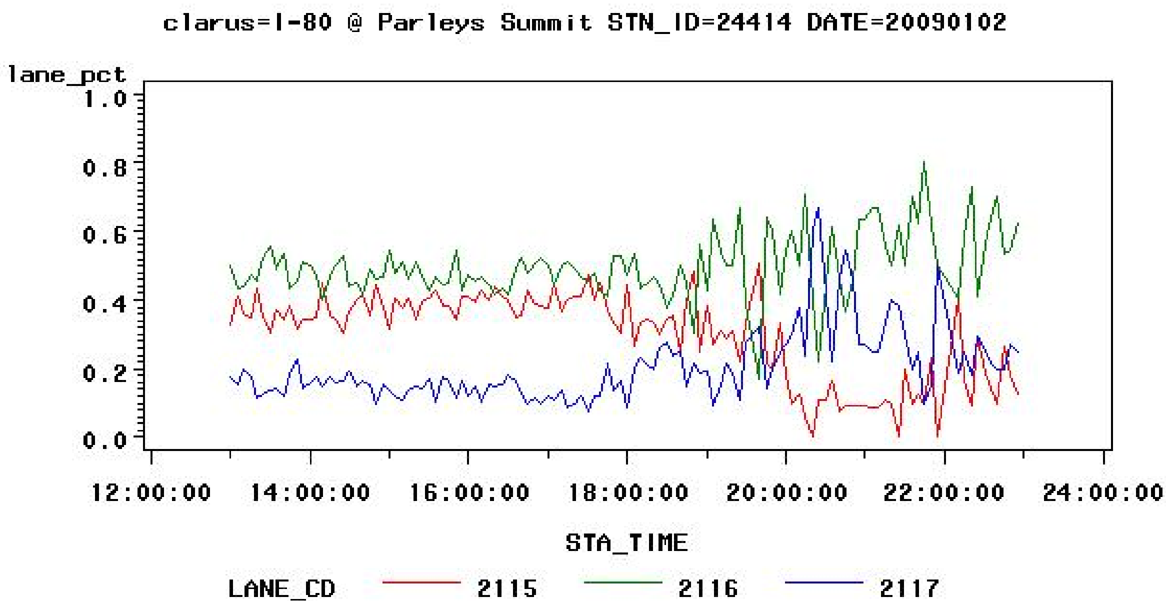


Figure 3.20 Lane Distribution on I-80 on January 2/Evening Snowfall



3.8.3 Minneapolis St. Paul Area Sample Tests

Test Site

One test site was used in Minneapolis-St. Paul, located near Minneapolis St. Paul International Airport (Figure 3.21). Two traffic stations sites were chosen because of the proximity to weather stations, and the completeness of data coverage. Table 3.9 shows the metadata for the two traffic stations selected in the test area. Peak afternoon traffic occurs in the westbound direction. The nearby National Weather Station KMSP supplied weather data through SHRP2 Reliability Study (http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2179) and the NWS ASOS data archive web site. MnDOT has a weather station located on I-495 at MN-5.

Table 3.9 Traffic Stations

Location	STN_ID	Milepost	Latitude	Longitude	Number of Lanes
EB I-495 at 34th Avenue	493	1.96	44.8619	–93.2290380283	5
WB I-495 at 34th Avenue	506	1.92	44.8623	–93.229026977	5

Dates and Hours

Two days were chosen for analysis because of their unique traffic and weather patterns.

- Tuesday, June 16, 2009: rainfall; and
- Wednesday, June 17, 2009: no inclement weather.

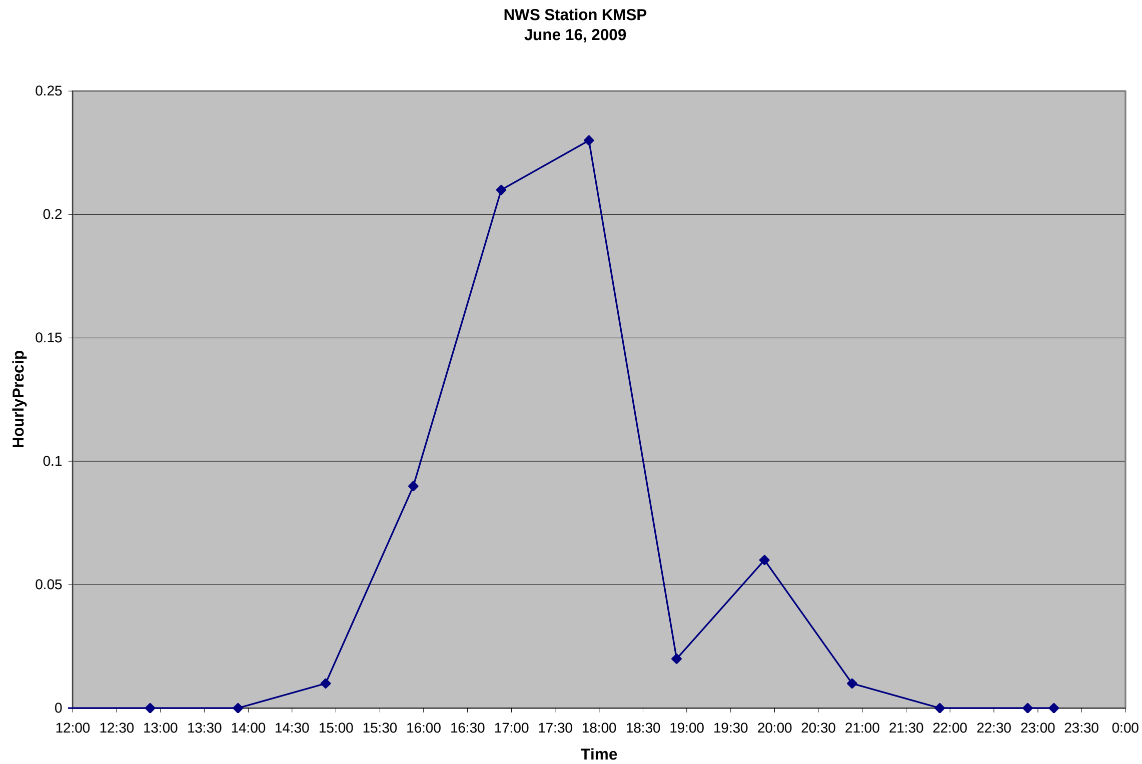
Hours included in the analysis are from noon to 11:00 p.m.

Figure 3.21 Stations near MSP Airport

Weather Data

Both of the hourly national weather station archives from SHRP2 study and the ASOS data archives downloaded from NWS web site show rainfall started in the airport location around 3:20 p.m. on June 16, 2009 as shown in Figure 3.22. *Clarus* archives from the MnDOT ESS for June 16 could not be used for comparison as they showed zero precipitation.

Figure 3.22 Rainfall at MSP Airport



Traffic Speed

The following graphs (Figures 3.23 and 3.24) show the average station speed on the two test days with the green line representing dry conditions (June 17) and the red line rainy conditions (June 16). Both of the two stations showed speed drops when rainfall started. However, the westbound station 506 showed a significant decrease in speed on the rainy day and a much longer peak period. A series of graphs were developed showing lane distribution. These are presented in Appendix A, but did not provide conclusive evidence of lane shifting during rainy conditions.

Figure 3.23 Comparison of Traffic Speeds on I-494 Eastbound on June 17 (Dry/Green Line) and June 16 (Rain/Red Line)

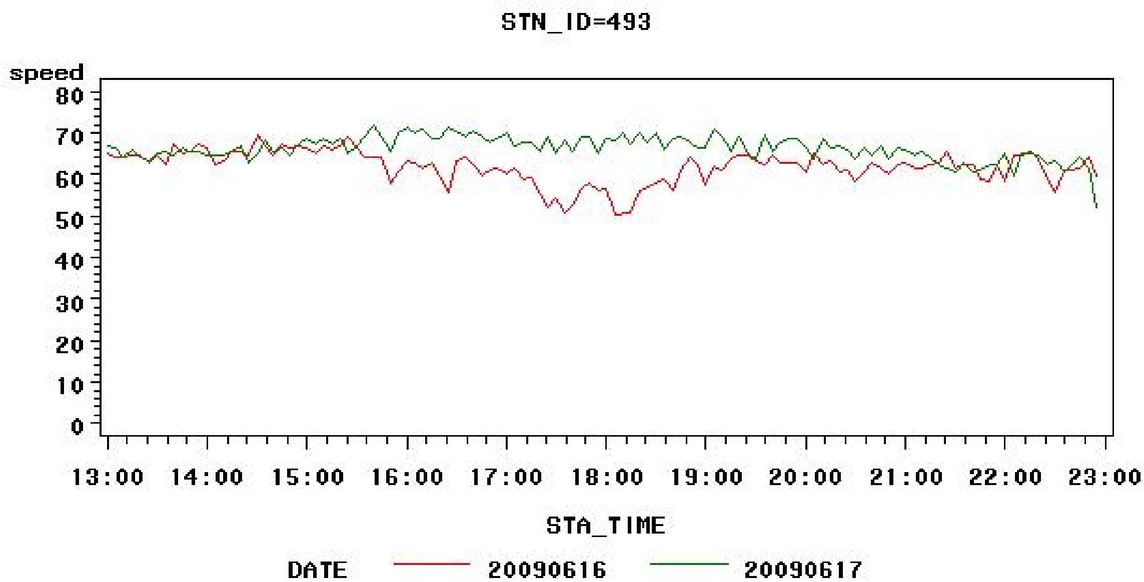
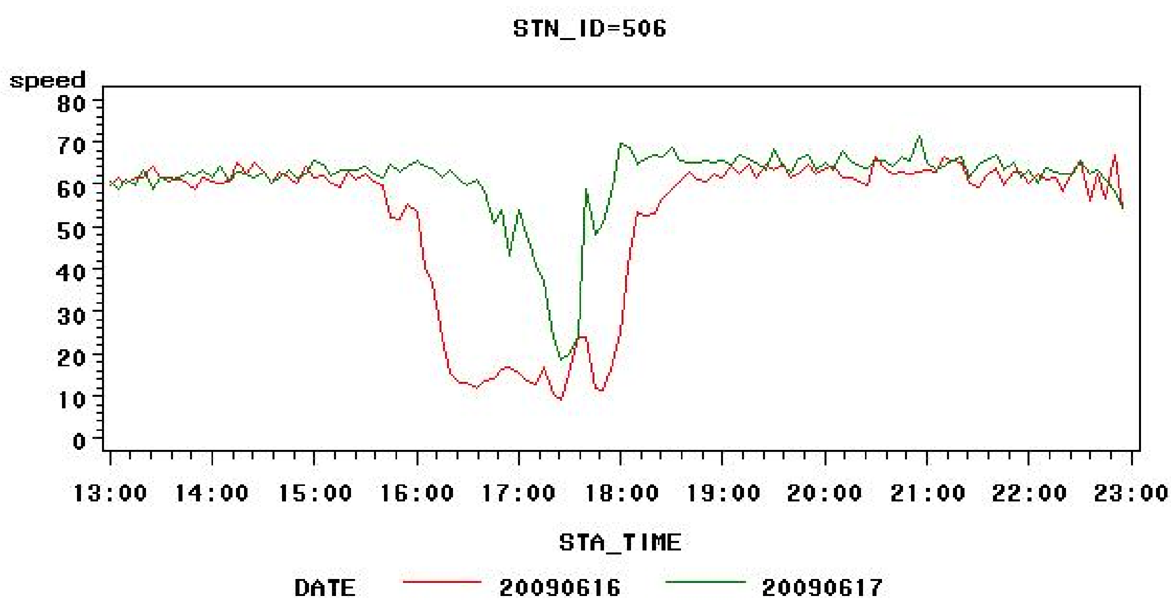


Figure 3.24 Comparison of Traffic Speeds on I-494 Westbound on June 17 (Dry/Green Line) and June 16 (Rain/Red Line)



3.9 Conclusion and Next Steps

This purpose of this exercise was to conduct quick analysis of data from several cities to determine.

- How the quality and quantity has changed since a similar effort was conducted over three years ago; and
- To determine whether data selected could be used to show changes in traveler behavior (speed and lane changes) during adverse weather.

The analysis concluded that there has been an improvement in the quantity and quality of data available. This is particularly true of weather data, due to greater detail provided by NWS and a proliferation of weather observations sites through private sources. Deployment and maintenance of DOT ESS is quite uneven across the country with funding a major limitation. In addition, many of the DOT ESS stations only report precipitation occurrence, not precipitation intensity. The latter is necessary to be able plan and operate WRTM. The density and quality of traffic data available has improved as well. One of the major developments is improvement in the quality and density of speed data. This is due to the deployment of nonintrusive detectors, many of which have multiple capabilities. The proliferation of private sources of data, primarily providing point-to-point travel times, is a relatively new phenomenon that has not yet been fully tapped for analysis and research.

The analysis clearly indicated that the data could identify changes in speed and lane usage due to adverse weather. Development and analysis of much larger datasets could help transportation agencies identify parameters for weather-responsive traffic management particularly freeway-based strategies such as variable speed limits and ramp metering.

There are several implications of these findings for the Weather Responsive Traffic Management Program. While the amount and quality of both weather and traffic data are improving, data are collected primarily for operational purposes, not for research. Developing weather-related traffic management strategies requires extensive testing and simulation under a variety of both traffic and weather conditions. Multiple weather events must be included in the analysis. As a result FHWA should take two paths to continue this effort:

Work with agencies as they expand their ESS and traffic detection systems. Agencies should be encouraged to collocate detectors and should be made aware of FHWA's ESS Siting Guidelines (http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/14447.htm). Agencies should be encouraged to collect data, such as precipitation intensity, that provide adequate detail for this type of research.

Continue to support specific research projects that provide intensive measurement of driver response to adverse weather and traffic control strategies. Use of mobile sensors can help to provide the detailed data required for these measurements. Specific priorities for research activity will be determined through the FHWA's five-year weather research program, which currently is being defined.

4.0 Information from Traffic Management Center Survey

As part of the effort to identify data gaps, the CS/VTTI team conducted a web-based survey of Transportation Management Centers around the U.S. All are operated either by state DOT staff or by private vendors under contract to state DOTs. Approximately 35 TMCs were contacted via e-mail and 17 responded to the survey.

In addition representatives of CS and FHWA conducted a site visit to the Utah DOT TMC in Salt Lake City, which serves the entire State. With an in-house meteorological staff in place UDOT represents best practice in the integration of traffic and weather operations.

4.1 Traffic Management Center Survey Summary

The first part of this section summarizes the results of the TMC survey. Full results are included in Appendix B. Table 4.1 lists the survey respondents.

Table 4.1 List of the TMCs that Responded to the Survey (Question #1 – TMC Survey)

Agency	TMC
Florida DOT	District 4 Fort Lauderdale
Florida DOT	Headquarters, Tallahassee
Indiana DOT	Headquarters, Indianapolis
Minnesota DOT	Metro Region, St. Paul
Florida DOT	District 7, Tampa
Michigan DOT	West Michigan TMC, Grand Rapids
Niagara International Transportation Technology Coalition (NITTEC)	Multi-Agency, Buffalo, New York
Kansas City SCOUT	Missouri DOT and Kansas DOT, Lee's Summit, Missouri
North Carolina DOT	Metrolina Regional Transportation Management Center, Charlotte
New York State DOT	INFORM TMC, Long Island
New York State DOT	Capital Region TMC, Albany
New Hampshire DOT	Statewide TMC, Concord
Mississippi DOT	Statewide TMC, Jackson
Missouri DOT	TMC, St. Louis
Georgia DOT	Statewide, Atlanta
Michigan DOT	Metro Region TMC, Detroit
Texas DOT	Austin District

Most of the respondents were involved in TMC operations either directly or from a supervisory position. Respondents were asked what types of weather and traffic data they collect. About half the TMCs reported that they collect basic weather information, including air temperature, precipitation status, precipitation intensity, and wind speed/direction. Other weather data are collected by a much smaller number of agencies, including items such as road surface temperature and visibility, both of which are important to WRTM strategies. Table 4.2 summarizes the types of weather data collected from the TMC.

Table 4.2 What types of weather data does your TMC collect and use? (Question #4 – TMC Survey)

Air Temperature	9	(53%)
Road Surface Temperature	5	(29%)
Road Subsurface Temperature	1	(6%)
Precipitation Status	10	(59%)
Precipitation Intensity	8	(47%)
Snow Depth	3	(18%)
Dewpoint/Relative Humidity	3	(18%)
Barometric Pressure	3	(18%)
Wind Speed and Direction	9	(53%)
Visibility	4	(24%)
Other	4	(24%)
If other, please specify	4	(24%)

Agencies also were asked what traffic data they collect, and as this is their primary purpose, virtually all respondents collect basic information such as speed, volume, incident detection/clearance times, and video data. Well over half also collect point-to-point travel times, a growing area of interest with the recent entry of multiple private contractors into the market. Data falling into the "other" category includes occupancy, performance measures, and customer satisfaction surveys. Table 4.3 shows the breakdown of traffic data collected and used by TMCs.

Table 4.3 What types of traffic data does your TMC collect and use? (Question #5 – TMC Survey)

Traffic volumes	16	(94%)
Speeds	17	(100%)
Point to point travel times	11	(65%)
Incident detection and clearance	17	(100%)
Video data	15	(88%)
Other	3	(18%)
If other, please specify	3	(18%)

Agencies were asked their main source of weather data. Virtually all agencies use National Weather Service forecasts and a number use specialized services such as e-mail reports. Most agencies utilize the Weather Channel and local media outlets in addition to reports off the Internet. Some agencies also make use of observations from field personnel and phone calls from the traveling public. Only 6 of the 17 respondents currently use RWIS or other field sensors but three additional agencies are in the process of planning and/or deployment.

Agencies were asked how they utilize weather and traffic data in weather-related traffic management activities. Thirteen of the 17 respondents reported that they provide weather-related traffic information while nine use the information in deciding which areas to monitor more closely with CCTV or detection equipment. Nine agencies also reported using the information to allocate duties to field personnel or TMC staff. Only three agencies reported more active weather-responsive traffic management activities such as variable speed limits, ramp metering or signal control. These agencies were Kansas City SCOUT, New Hampshire DOT, and Georgia DOT. Responses to this question are shown below in Table 4.4.

Table 4.4 How are these information sources used in the TMC? (Question #7 – TMC Survey)

Provide traveler information and advisories/warnings on road weather conditions (through 511, VMS/DMS, HAR, etc.)	13	(76%)
Implement weather responsive traffic control strategies (signal timing, ramp metering, variable speed limits)	3	(18%)
Decide which weather-affected or prone areas (e.g., icy roads, flooding) to monitor with CCTVs, detectors and other resources	9	(53%)
Set priorities and strategies for snow removal or other maintenance activities (wind damage, flooding, etc.)	5	(29%)
Scheduling and planning of winter maintenance activity? Nonwinter maintenance activity (striping, pothole repair, etc.)? (This is similar/related to 6d above, combine them.)	1	(6%)
Reposition/reallocate TMC staff or field maintenance personnel	9	(53%)
Other	3	(18%)
If other, please specify	3	(18%)

Many agencies currently do not have the infrastructure available to implement these strategies. A question was asked about whether agencies had an interest and/or plans to implement these strategies in the future. Five respondents expressed an interest in implementing weather responsive traffic management strategies, with small numbers of positive responses given to the other questions. Responses are shown below in Table 4.5.

Table 4.5 Are there weather-responsive traffic management strategies you currently are not using, that you would like to implement? If yes, which strategies? (Question #8 – TMC Survey)

Provide traveler information and advisories/warnings on road weather conditions (through 511, VMS/DMS, HAR, etc.)	1	(6%)
Implement weather responsive traffic control strategies (signal timing, ramp metering, variable speed limits)	5	(29%)
Decide which weather-affected or prone areas (e.g., icy roads, flooding) to monitor with CCTVs, detectors and other resources	1	(6%)
Set priorities and strategies for snow removal or other maintenance activities (wind damage, flooding, etc.)	3	(18%)
Scheduling and planning of winter maintenance activity? Nonwinter maintenance activity (striping, pothole repair, etc.)? (This is similar/related to above, combine them.)	1	(6%)
Reposition/reallocate TMC staff or field maintenance personnel	2	(12%)
Other	0	(0%)
If other, please specify	0	(0%)

Three of the responding agencies indicated that they had collected background information or done studies on possible implementation of WRTM strategies and two of the 17 respondents, Indiana DOT and Kansas City SCOUT, answered that they are sponsoring research studies on the traffic impacts of weather. While INDOT's study is not yet available, KC SCOUT has documented their Weather Integration Self-Evaluation in an extensive report. While the report does not go into great detail in addressing the data requirements for WRTM, it does lay out a strategy for implementation of WRTM.

http://www.kcscout.net/downloads/Reports/Annual/WeatherIntegrationPlan.pdf

Finally, 12 of the agencies responding indicated plans to expand traffic and weather data collection activities. These are summarized in Table 4.6.

Table 4.6 Plans for Expanded Weather and Traffic Data Collection (Question #12 – TMC Survey)

Agency	Plans/Comments
Florida DOT District 2	Have RWIS on all FDOT bridges and up to one RWIS every two miles
Minnesota DOT District 4	Conducting an informal study on precipitation for variable speed limits
Michigan DOT	Deploying RWIS in some regions
Texas DOT	Planning RWIS deployment
Florida DOT District 5	Installing visibility detection system on remote portion of I-4
Kansas City SCOUT	Currently assessing services available from third-party providers to integrate advanced weather technologies into our ATMS system as digital/polygon and road-specific elements to getter enable advanced warning using DMS and web-based notifications
North Carolina DOT MRTMC	Planning ice detection on high-rise flyovers
New Hampshire DOT	Looking to increase the number of RWIS sites and looking to develop a weather operations training program for its TMC operators
Mississippi Department of Transportation	Future plans may involve wind speed detectors in coastal areas and ice detection on bridges
Georgia DOT	Weather stations were taken off-line due to communications problems and aging equipment. Media and NWS currently are adequate for needs

In summary, virtually all responding TMCs collect a basic set of traffic data, while about half collect a basic weather dataset. Many of the agencies that do not collect weather data are located in warmer-weather states but they are showing increasing interest in specific weather information since they are impacted by phenomena such as bridge icing, reduced visibility, and high winds. For the most part weather data are used for traveler information purposes, although there is increasing interest in weather responsive traffic management studies. The survey indicates there are a number of agencies with data available to conduct analysis of weather impacts on traffic. However, limitations of this information have been demonstrated elsewhere in this report with data obtained from Atlanta, Minneapolis-St. Paul, and Salt Lake City. Several agencies such as Utah DOT and Minnesota DOT, which employ in-house meteorological staff provide the most promising opportunity to develop improved analysis datasets.

In spite of current limitations there are great opportunities emerging to develop good research datasets from TMC-based archives and from real-time data as well. ITS deployments are being expanded and many older systems are now being replaced with more modern equipment that uses IP, providing possible opportunities for direct data feeds to research institutions. While most agencies still make limited use of archived data, there is increased interest in this area due to upcoming Federal regulations that will require more extensive and detailed reporting of performance measures. Geographic expansion of ITS infrastructure, greater use of probe data and increase in the number and sophistication of DOT-owned ESS also are likely to provide better opportunities.

While targeted research is still required to develop effective WRTM strategies, this research is expensive and time-consuming, particularly in the data collection phase. If researchers can work directly with TMC operations personnel to use archived and real-time data scarce research funds can be leveraged. In addition this approach will help develop relationships that will enable WRTM strategies to be tested and evaluate more quickly in the field. These efforts can be expedited by bringing TMC operators and researchers together in workshops or summits. Dissemination of best practices, such as the UDOT example which follows, also will encourage further cooperation. The TMC survey indicates that this approach has great promise.

4.2 Utah DOT Site Visit

4.2.1 Introduction

One of the objectives of the project was to identify some of the more advanced agencies in the collection and integration of weather and traffic data. As discussed in Section 3.0 the consultant team identified transportation operations agencies that are most advanced in the collection and integration of weather and traffic data. Analysis was conducted on data from three cities, Atlanta, Minneapolis-St. Paul, and Salt Lake City. After this initial review and consultation with FHWA, the project team decided to conduct a site visit to an agency which was actually using weather-related data for traffic management purposes. After considering several sites the project team settled on the Utah DOT Traffic Management Center (TMC) in Salt Lake City for a site visit. UDOT employs a team of meteorologists in the TMC and utilizes weather data in a number of operational activities. The visit was conducted on June 7 to 8, 2010 by a representative of FHWA and a representative of the consultant team.

4.2.2 Operations Center Overview

The UDOT Traffic Operations Center (TOC) is located in Salt Lake City (see Figure 4.1) but serves the entire State of Utah.

Figure 4.1 Utah DOT Traffic Operations Center

The TOC Tracks state highways through CCTV and a variety of detection equipment, including loop detectors, radar, and ultrasound. About 600 of the 700 CCTV statewide are located in the Salt Lake Valley, the State's major population center. The remainder are scattered throughout the State, with many in mountain passes and others at major interchanges along the rural Interstate system. The UDOT ITS has been expanded over the years by building ITS into new road projects and this continues today.

The TOC operation is described as "near 24/7." Operators are on duty at all times except the 1:00 to 5:00 a.m. shift during early part of the week. There are generally three operators during peak periods. Operators rotate through CCTV feeds are part of their normal duties except when incidents take priority. The TOC provides data to CommuterLink which is the brand name for UDOT Traveler information web site. Communication with motorists on the highway occurs through Dynamic Message Signs (DMS). The default usage for DMS is travel times between prespecified points. UDOT interpolate speeds between adjacent detectors to obtain travel times and has found that the density of detection equipment is adequate to accurately report times. UDOT has recently been installing Wavetronix nonintrusive detectors which provide speed data as well as count information. TranSuite (TransCore) is used as the TMC Operations software and the PeMS system is used for archived traffic data. A picture of the main TOC control is shown in Figure 4.2.

Figure 4.2 Utah DOT Traffic Operations Center Main Control Room

One station in the TOC is reserved for a traffic signal engineer who manages signal timing for 1,200 of 1,700 total signals in the State. The traffic engineer works jointly with municipalities on signal timing, a relationship that is helped by the fact that software and systems are compatible.

The Utah Highway Patrol has a dispatch center in the TOC, which enables TOC operators to have direct access to incident information reported through CAD/911. TOC and UHP personnel communicate directly during major incidents or as otherwise is necessary.

ClearChannel communications has room adjacent to TMC for traffic reporting. The presence of media within the TOC gives UDOT another way to get information out to the public. Colocation allows good communication, assuring that the information will be accurate. The TOC and ClearChannel have good working relationship. One of the benefits for UDOT is exchange of data and support from ClearChannel personnel in developing UDOT announcements.

4.2.3 Weather-Related Issues for UDOT

UDOT has a full staff of meteorologists located in the TMC. Weather is a major focus of UDOT activity for a number of reasons:

- Average snowfall is approximately 60 inches per year in Salt Lake Valley but can reach up to 600 inches per year in some of the mountainous areas. In addition to snow removal, avalanches are major safety hazard that UDOT must address. Staff includes an avalanche forecaster on staff and an avalanche control team within the DOT.

- Surface temperature data are considered critical in making winter maintenance decisions. UDOT can realize significant savings by prioritizing winter maintenance activities efficiently.
- Depending on snowfall levels and spring rains, mudslides can be severe in canyon areas, resulting in closed and/or damaged roads.
- Severe thunderstorms occur in Utah, which can be very localized. Road flooding occurs; often in spot locations.
- High winds are major issue on I-80 west of Salt Lake City and in some other areas of the State. Heavy commercial vehicle volumes make overturned trucks a major danger. High winds also stir up dust storms which can limit visibility and result in run-off-the-road or chain-reaction crashes.
- Areas of thick fog develop around Great Salt Lake and in mountain valleys.
- Wildfires can reduce or entirely eliminate visibility in certain parts of the State.
- Extreme heat can cause buckling of concrete joints resulting in road closure and repair.

UDOT Weather-Related Activities

To help address the numerous issues identified above, UDOT hired a staff meteorologist to manage its weather-related activities, including a contract with Northwest Weathernet, Inc. Northwest provides seven meteorologists as well as forecasting services to both the TOC and UDOT operations and maintenance. Northwest also provides forecast service for Nevada and Wyoming using UDOT as operating base. This results in cost savings for all three agencies and helps UDOT fund contract that are critical for UDOT to know weather developing in other states, especially Nevada. Figure 4.3 shows one of the meteorological work stations in the TOC.

Figure 4.3 Utah DOT Traffic Operations Center Meteorological Station

Northwest is responsible for maintenance of ESS around the State. Maintenance is conducted on each ESS minimum of twice per year. A dedicated maintenance bay for ESS has been set aside on UDOT property next to TOC.

Over time, UDOT has designed customized ESS that use equipment from a variety of vendors. Campbell Scientific provides controllers and software for the system. Significant cost savings have been achieved by 1) being able to tailor each ESS to specific needs at the site and 2) having UDOT own the data rather than a private vendor. Figure 4.4 shows a new ESS recently installed north of Salt Lake City along with an inside look at the cabinet. UDOT also utilizes a mobile ESS in order to test the feasibility of different locations, or address a temporary need. A picture of the mobile station is shown in Figure 4.5. This was installed along I-80 west of Salt Lake City, where high winds have been a problem.

Figure 4.4 New Permanent ESS Installation

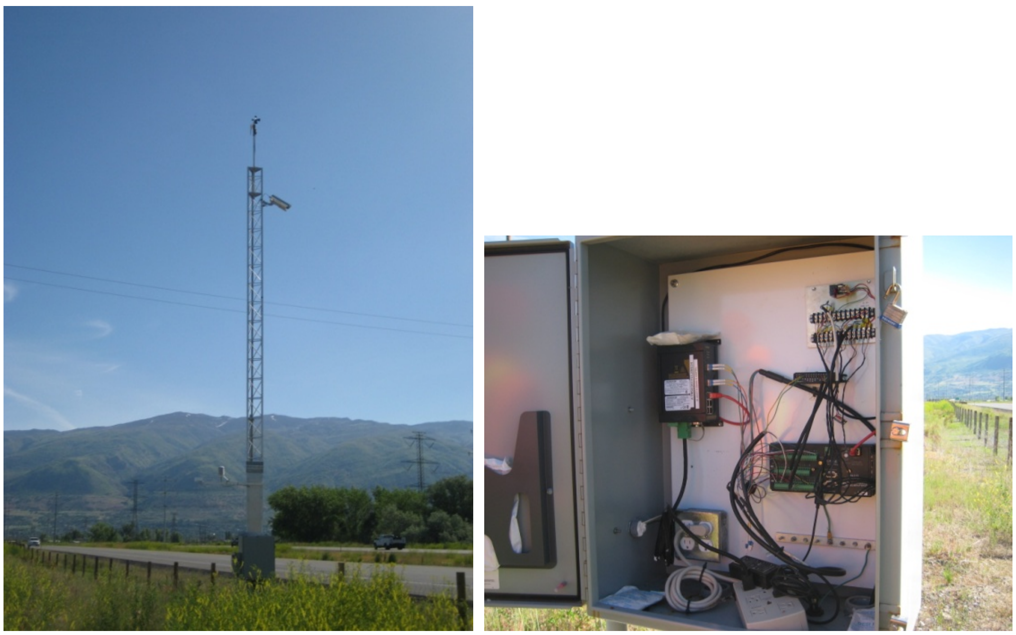
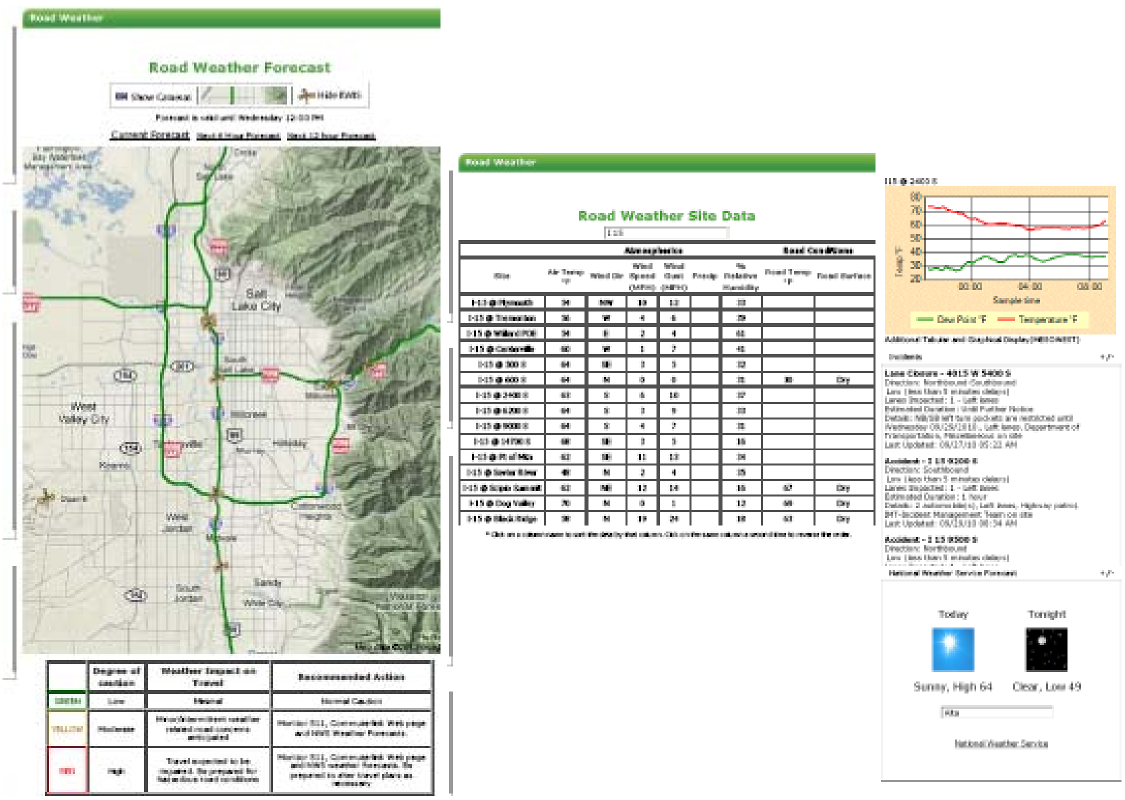


Figure 4.5 Mobile ESS

One of the recent integration initiatives of UDOT has been to develop a set of traveler information messages based on the weather forecast. A recently hired Northwest staff member has been assigned to this project. UDOT is making significant effort to develop weather-related messages that are useful to traveling public and easily understood. The meteorological staff uses three-color coding scheme to classify road conditions – green, yellow, red. Detailed color-coded maps are provided to TOC operators and other operations personnel and copies are kept as an historical record. Figure 4.6 show examples of RWIS information available to the public on the UDOT Commuterlink web site.

Figure 4.6 UDOT CommuterLink Web Site – Weather Forecast



UDOT Weather-Related Partnerships

UDOT recently initiated a project with the National Weather Service and the University of Utah (UU) to determine what messages are most effective with public, including messages delivered through the web and DMS. UU will be doing surveys of travelers to find out how the public responds to different types and formats of weather warning messages. A subsequent activity of UDOT will be to determine what level of weather data is required to provide effective messaging. Specific activities of the project include:

- Targeted surveys related directly to three events; 400 per event;
- Assess levels of awareness among the public, sources of information used and responses to road/weather information; and
- Evaluate and identify strategies for communicating critical information.

UDOT already has developed a draft agreement with UHP regarding weather-related messages for DMS. The agreement covers a wide range of conditions, including ice, wet roads, snow, and high winds. Emergency scenarios and special events are included as well as weather. Using DMS for advisory speeds has been discussed, but UHP is opposed due to a concern that they can be confused with legal speeds. UDOT and UHP have collaborated on a set of wind warning messages with recommended actions based on wind speed. UDOT is working with UHP to prohibit truck traffic where there is severe danger of overturning an effort that also involves a freight planner who is evaluating the impact traffic restrictions on the commercial vehicle industry. The goal is to avoid negative economic impact unless absolutely necessary. There is some discussion of automating wind warning signs.

UDOT's partnership with local National Weather Service has been very beneficial. UDOT participates actively in NWSChat and has worked with NWS on message wording. NWS grid forecasts are available on both CommuterLink and 511. The most recent collaboration is on Winter Weather Road Impact Project which includes:

- A review of the travel time index (deviation from mean travel time) during specific days and peak periods. They were able to determine that the only events that had a major impact on system reliability were winter storms and holidays.
- Detailed analyses were conducted on two separate storms to identify the factors that influenced travel time reliability. They found that both snowfall amounts and road surface temperatures, as well as level and timing of mitigation activities, could have a major impact.
- They used sensor data to obtain a good estimate of the impact of winter storms on travel demand. There appeared to be a major reduction in discretionary travel, especially during p.m. peak.
- As mentioned earlier, this effort includes development of a common message on travel warnings from NWS, UDOT, Northwest Weather net and the media.
- They continue to look for ways to increase the level of detail in weather information allows, which will allow more specific messages to be delivered. For example thunderstorm warnings could be provided on a limited number of DMS when a very localized area is impacted.

One of the more advanced capabilities of the UDOT TOC is the implementation of weather-responsive signal timing plans by the TOC Traffic Engineer. The basis for modifications is a 2001 University of Utah study which estimated a 30 percent speed reduction on arterials during snow events. There are three to four different weather responsive plans for each corridor which vary by time of day which generally involve a change in splits or offsets. A slightly different strategy is used on one road, the Baumgartner Highway, where signal timing changes are made to facilitate plowing of intersections. There is SCATS system in Park City which provides some potential to implement weather-related plans.

4.2.4 Research/Partnership Opportunities

A number of research and partnership opportunities were identified for FHWA and UDOT to work together on filling data gaps related to weather and traffic.

- A large volume of data is potentially available to estimate the impact of adverse weather on both demand and microscopic traffic flow. UDOT has CCTV and detection on some major arterials as well as freeways. They do not record video as policy but there is a possibility of exception for research purposes.
- With weather-related timing plans in place, a unique opportunity exists to look at benefits of weather-responsive arterial signal timing. Some detection would have to be added to arterials but this could provide some very useful input to the FHWA Road Weather Management Program.
- UDOT's work on weather-related messaging, including messages and format of delivery, could be leveraged by FHWA to help identify best practices in this area.
- UDOT's approach to development and deployment of ESS, as well as their meteorological staff, is another example of best practice that could be leveraged by FHWA.

5.0 Weather Responsive Transportation Management (WRTM) Survey Summary

A web-based survey was conducted to reach out to the research community, primarily Universities, to learn about projects related to analysis of weather and traffic data, as well Weather-Related Traffic Management strategies transportation researchers may be evaluating.

E-mails were sent to 170 addresses and 39 responses were received. Respondents were asked if they had conducted analysis using weather data and the type of analysis they did. Twenty-five (64 percent) out of the 39 respondents indicated that they have conducted research using weather data. Section 5.1 summarizes the results of the initial survey while Section 5.2 summarizes the follow-up survey. The full set of results is included in Appendix C.

5.1 Initial WRTM Research Institution Survey

Table 5.1 summarizes the type of analysis these researchers conducted. In addition to the predefined categories, 21 percent of researchers chose "Other." The Other category included "descriptive statistics of weather pattern," "road maintenance," "performance measures for winter operations," "resources used during emergency events," "behavior of different sensor systems," in the "other" category.

Table 5.1 What analysis have you conducted using weather data? (Question #6 – Initial Research Survey)

Traffic flow impacts	18	(46%)
Traffic control	6	(15%)
Safety	13	(33%)
Human behavior	7	(18%)
Other	8	(21%)
If other, please specify	8	(21%)

Respondents were asked how the data analysis was conducted. More than half of the analysis was done by "collected field data." Table 5.2 exhibits the details of the responses. Data falling into the "other" category includes "archival weather data," "material withdraws from accounting system, e.g., salt," "GPS data," "crash reports," "video detection," and "wireless magnetometers."

Table 5.2 How was your data analysis conducted? (Question #7 – Initial Research Survey)

Collected Field Data	23	(59%)
Used a Driving Simulator	1	(3%)
Used Loop Detector Data	8	(21%)
Used In-Vehicle Data	4	(10%)
Used Traffic Simulation	8	(21%)
Other	8	(21%)
If other, please specify	7	(18%)

When being asked what sources of weather data they used, the respondents indicated a wide range of sources as shown in Table 5.3.

Table 5.3 What sources of weather data did you use to conduct your analysis? (Question #8 – Initial Research Survey)

In-site weather stations	14	(36%)
Weather forecasting web sites	7	(18%)
Airport weather forecasting reports	3	(8%)
ASOS/AWOS automated observing systems	1	(3%)
Used Clarus weather database	1	(3%)
Used Road Weather Information System (RWIS)	6	(15%)
Other	8	(21%)
If other, please specify	7	(18%)

As for the weather variables analyzed, 62 percent of the respondents responded “precipitation.” Other commonly used variables included “Temperature,” “Ice,” and “Visibility.” Variables listed in the “other” category included “sunshine duration,” “thunder storm,” “humidify,” “weather event duration,” “status of road surface,” “water film thickness,” etc.

Table 5.4 What were the weather variables that you analyzed in your analysis? (Question #9 – Initial Research Survey)

Precipitation (Rain/Snow)	24	(62%)
Visibility	9	(23%)
Ice	10	(26%)
Wind Speed/Direction	8	(21%)
Barometric Pressure	3	(8%)
Temperature	14	(36%)
Other	7	(18%)
If other, please specify	6	(15%)

About one-third of the respondents, 11 out of 38, indicated that they did not have problems or restrictions at all in accessing the weather data. When being asked "What were the limitations that you encountered with the weather data," the respondents stated issues, including accessibility of data, accuracy in locating weather station with respect to the considered road section, unnecessary data, reliability of data, and comprehensiveness (lack of data covering a whole city).

We also asked "what types of data analysis would you like to conduct using weather data in the future." The answers from the respondents are listed in Table 5.5. The largest number of respondents reported that either Traffic Flow Impacts or Safety were the focus of their study. The types of analysis listed in "other" include "road maintenance," "pavement design," "performance measures," and "correct material usage."

Table 5.5 What types of data analysis would you like to conduct involving the use of weather data in the future? (Question #12 – Initial Research Survey)

Traffic flow impacts	28	(72%)
Traffic control	18	(46%)
Safety	30	(77%)
Human behavior	14	(36%)
Other	5	(13%)
If other, please specify	5	(13%)

At the end of the survey, suggestions for future weather data collection were asked. Twenty-one respondents answered this question. The suggestions are mainly focused on the following aspects: Open source data; improve the reliability, and finer grained weather data in order to match with the frequency of traffic counting.

In summary, majority of the respondents have conducted research or are interested in conducting research using weather data. The research involving weather data has a wide range of topics. However, quality of current weather data is not quite satisfactory. Researchers are expecting weather data to be more accessible, more reliable, more accurate, and to cover more locations.

5.2 Follow-up WRTM Research Institution Survey

Due to the strong response to the original survey a follow-up survey was conducted to provide more detail on research efforts. The follow up survey was sent to respondents who offered to provide more information and 18 responses were received. A summary of results is presented in this section and full details are presented in Appendix C.

Sixteen of the 18 respondents, 89 percent, would like to use the weather information to study the impact of inclement weather on traffic stream behavior. Majority of them, 11 out of 18 (61 percent), would like to develop inclement weather traffic control strategies using the weather information. Details are exhibited in Table 5.6. In addition to the listed research topics, respondents propose research topics such as road surface conditions, driving behavior, including speed and acceleration, etc.

Table 5.6 What would you use weather information for? (Question #5 – Follow-Up Research Survey)

Study the impact of inclement weather of traffic stream behavior	16	(89%)
Study the impact of inclement weather on travel demand	7	(39%)
Study the impact of weather on driver departure time and route choice behavior	6	(33%)
Develop inclement weather traffic control strategies (signal timing, ramp metering, variable speed limits)	11	(61%)
Other	4	(22%)
If other, please specify	4	(22%)

The level of resolution in weather data required by the researchers varies. Most of the researchers prefer more detailed weather information than currently available data. Some required the capability of aggregating weather data as they need (Table 5.7).

Table 5.7 For the analyses identified in previous questions, what level of resolution in weather data would you require? (Question #6 – Follow-Up Research Survey)

Less than 5 minutes	5	(28%)
5 minutes	4	(22%)
Between 5 minutes and 15 minutes	8	(44%)
Other	8	(44%)
If other, please specify	8	(44%)

Respondents were asked about the type of traffic data they need to conduct their analysis. Most of them, 13 out of 18, need aggregate loop detector data. Sixty-one percent (11 out of 18) wants disaggregate vehicle trajectory data such as naturalistic data or GPS data. Four respondents specified their requirements for traffic data as "travel survey data," "disaggregate detector data," or "ADT by route."

While being asked about the level of accuracy and resolution required in the traffic data to conduct analysis, researchers indicated several levels of details. They believed that level of accuracy for traffic data should depend on the type of analysis or the focus of the analysis. The accuracy of traffic data should be comparable to weather data. In general, for traffic data (speed, density, and flow), a minimum of two-to-five minutes aggregated data is required by most of the researchers. For vehicle trajectory data, a higher resolution, one-to-five seconds, is desired.

Respondents were asked the type of data required to integrate weather and traffic data. According to the answers, location and time information are indispensable. Researchers also asked for data on such items as traffic intensity, speed limit, probe-vehicle data, road surface condition and IntelliDrive-based weather information, etc.

At the end of the follow up survey, researchers were asked about the sampling size issues they need to address to conduct their research. The following issues were highlighted:

- Distance between weather station and traffic count station is too far;
- The sampling time length is not long enough;
- The data resolution is not high enough;
- The sites are too few; and
- Weather types are not covered comprehensively.

In summary, researchers are looking forward to more detailed weather data. An efficient linkage of weather data with accidents, work zones, video, and other types of data is highly desired. RWIS data, road surface condition reports, and probe data were other needs identified by the respondents. Researchers also made suggestions on further weather data collection in the aspect of a more open data warehouse, fewer errors in data sensors, and more reliable vehicle-based data.

6.0 Findings and Recommendations

This goal of this project was to identify gaps in weather and traffic data that can be used to help implement weather-responsive traffic management strategies. Several activities were undertaken to accomplish this, including:

1. A comprehensive search and documentation of weather-related traffic studies was conducted. This effort built upon previous literature searches but focused heavily on international studies. A number of test datasets were identified and requested.
2. Representatives of the client and consulting team attended the 2010 TRB Annual Meeting and through session attendance and committee meeting attendance were able to identify additional studies. These efforts and those of the literature search were documented in a technical memorandum.
3. The project team conducted a review of available weather and traffic data from major metropolitan areas. A set of criteria were established, including proximity of weather and traffic stations and a variety of weather conditions. Weather datasets were drawn from a variety of sources, including National Weather Service, *Clarus,* and state DOTs. Traffic data were obtained from datasets collected for FHWA's Mobility Monitoring program and directly from state DOTs.
4. Datasets were screened based on the criteria established and three cities were selected for further testing; Atlanta, Salt Lake City and Minneapolis-St. Paul.
5. An analysis of the impact of weather on travel speeds and lane usage in the three selected cities using the weather and traffic datasets obtained. Locations were selected where ESS and traffic detectors were found in close proximity. Dry and rainy conditions were tested in all three cities while data on snow conditions also were tested in Salt Lake City.
6. A survey of Traffic Management Centers (TMC) regarding the collection and use of weather and traffic data was conducted. TMC managers were asked what types of weather and traffic data were collected, whether data were used or being considered for use in Weather-Responsive Traffic Management and whether any research activities were planned or underway. Seventeen TMCs responded to the questionnaire, representing a good cross-section of urban areas and climatic conditions.
7. A similar survey of research institutions regarding ongoing studies of the impact of weather on traffic flow. Thirty-nine institutions responded providing information on a variety of studies. Eighteen agreed to a follow-up survey.
8. Two members of the project team conducted a site visit to Utah DOT which is a national leader the integration of weather and traffic management. Meetings were held with TMC management and members of the meteorological staff, which provides forecasting services to UDOT and also maintains their RWIS system. Lessons learned were documented in detail in this report.

9. Based on the activities above, data gaps were identified and incorporated into the findings and recommendations documented below. The activities in this section are referenced by number below in the findings and recommendations.

6.1 Findings

1. There are many efforts underway attempting to establish relationship between weather and traffic flow variables, particularly in research institutions. Studies involve rates of precipitation and surface condition, both of which are important to WRTM strategies (activities 1, 2, 7).
2. Research studies tend to be limited in scope, however. Many of the studies are subject to confidentiality agreements, which limit their ability to be used for operational purposes. These limitations seem to be most common in international studies (activities 1, 2, 7).
3. The analysis conducted for this project indicated that relationships between weather conditions and travel speeds could be established with readily available data and relatively basic analysis tools. However, greater sophistication will be required to establish operating procedures for WRTM strategies such as variable speed limits and weather-related traffic signal plans (activities 3, 4, 5).
4. Compared to three to four years ago, more agencies are collecting both traffic and weather data, due to gradual expansion of ITS and RWIS. However, funding is a major hurdle in expansion as well maintenance of existing systems and equipment. Legacy ESS often does not collect precipitation intensity data, which are important to WRTM. Many agencies are now purchasing travel time data from private vendors, a change that enables them to greatly increase the road-miles covered. However some of these agreements include confidentiality restrictions on this information, making it more difficult to use for research purposes (activity 6).
5. In conducting research on weather impacts on traffic, particularly fast changing events such as snowstorms and thunderstorms, it is important to have weather data at frequent temporal intervals, preferably five minutes. Conditions can change dramatically during these events over very short periods of time. The sources of surface weather data that are generally most reliable, ASOS stations are located primarily at airports which may not be optimal for roadway condition analysis (activities 3, 4, 5, 6).
6. The activities of Utah DOT provide a good prototype demonstrating how investment in road weather information and staff can be leveraged effectively. UDOT staff includes a full-time staff meteorologist. The meteorologist is responsible for procurement and supervision of a private contractor that provides meteorological staff and services, including both forecasting services and maintenance of ESS statewide. UDOT been able to leverage this capability and reduce costs through actions such as an innovative ESS design that utilizes components from various vendors. In addition adjacent States have contracted with UDOT's vendor, reducing costs to UDOT through resource sharing and providing more timely information on weather conditions in adjacent states. It also should be noted that UDOT is one of the few agencies to have implemented a WRTM program; modification of traffic signal timing along several major corridors during winter storms (activity 8).

6.2 Recommendations

1. FHWA has been effectively disseminating information on its research activities through brochures, technical papers, conferences, and webcasts. It is important to stay current with other research efforts, both domestic and international, and try to leverage these studies wherever possible. A recent example was provided in the FHWA study "Microscopic Analysis of Traffic Flow in Inclement Weather," where a dataset on icy road conditions developed by Hokkaido University was obtained by FHWA and evaluated by the Virginia Tech Transportation Institute (activities 1, 2, 7).
2. It is recommended that a separate research effort be conducted into confidentiality agreements, focusing on Europe, where this seems to be common practice. This effort should identify the source and reasons for confidentiality agreements, and identify any initiatives that can be taken to make datasets more available (activities 1, 2, 7).
3. FHWA should continue its efforts to develop weather-related parameters for microsimulation models and should conduct tests of WRTM strategies with those models. After an initial set of tests the models could be installed in several TMCs and simulations conducted in parallel with actual TMC operations. A subsequent step would be to use the simulation results and test actual strategies implemented by transportation operating agencies. Agencies involved in the tests would require a "before" period to collect detailed data on traffic flow during weather events so that the impact of the strategies could be identified (activities 3, 4, 5).
4. FHWA has several active projects in this area, including guidelines development of WRTM and microscopic analysis of traffic flow during adverse weather. The latter research project has been conducted at arterial intersections using video and Environmental Sensor Stations. A data collection program is recommended for several freeway corridors. Changes in traffic flow parameters need to be monitored continuously over a period of time so the impacts of congestion and changing demand can be identified. Several corridors could be selected that already have good coverage of traffic detectors and ESS and then supplemented where necessary. It is possible that some of the Integrated Corridor Management projects currently being funded by FHWA could be used to leverage funding (activity 6).
5. FHWA should look at ways to leverage data from NWS, other government agencies, the IntelliDrive program and private weather sources to obtain higher-quality, more detail observations on road weather and surface conditions. While state DOT RWIS are expanding, this expansion is relatively slow due to funding constraints. In addition, many agencies are finding it difficult to maintain legacy ESS due to funding constraints. Development of a plan would be an important step in accomplishing this. Much of the input data required already has been collected by FHWA and its contractors (activities 3, 4, 5, 6).
6. These best practices of UDOT and other agencies should be disseminated through brochures and other forums such as conferences and webcasts (activity 8).

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APPENDIX A. Sample Tests of Weather Impacts on Freeway Traffic in Salt Lake City Area

A.1 Test Sites

The first test site is located near Salt Lake City International Airport (Figure A.1), and the second test site is near Parleys Summit (Figure A.2). These sites are chosen because of the proximity to weather stations, the completeness of data coverage, and the uniformity of traffic patterns for each site. All the traffic stations in test areas experience little or no traffic congestion, even during commute peak hours, which could made it easier to isolate weather impacts on traffic. Table A.1 shows the detailed information for the eight traffic stations selected in the test area.

The nearby National Weather Station KSLC supplied weather data through the SHRP 2 Reliability Study and the NWS ASOS data archive web site. UTDOT has Clarus weather stations located on I-15 at 500 S and on I-80 at Parleys Summit.

Table A.1 Traffic Stations

Location	STN_ID	Milepost	Latitude	Longitude	Number of Lanes
NB I-215-W at 500 N	24,740	23.35	40.779952	-111.949003	3
SB I-215-W at 500 N	24,354	23.35	40.779955	-111.949221	3
NB I-215-W at 100 N	24,757	22.80	40.772052	-111.949097	3
SB I-215-W at 100 N	24,407	22.80	40.772047	-111.94938	3
EB I-80 at Redwood Road	24,787	118.00	40.765945	-111.936623	3
WB I-80 at Redwood Road	24,634	118.00	40.76608	-111.936595	3
EB I-80 at Lambs Interchange	24,414	136.94	40.74336111	-111.6587333	3
WB I-80 at Lambs Interchange	24,737	136.95	40.74373056	-111.6586333	3

A.2 Dates and Hours

Four days have been chosen because of their unique traffic and weather patterns:

- Thursday, January 1, 2009: no inclement weather;
- Friday, January 2, 2009: snow in test site 1 and test site 2;
- Friday, June 26, 2009: rain in test site 1 and test site 2;
- Saturday, June 27, 2009: no inclement weather; and
- Hours included in the analysis are from 12:00 p.m. to 11:00 p.m.

Figure A.1 Stations near Salt Lake City Airport

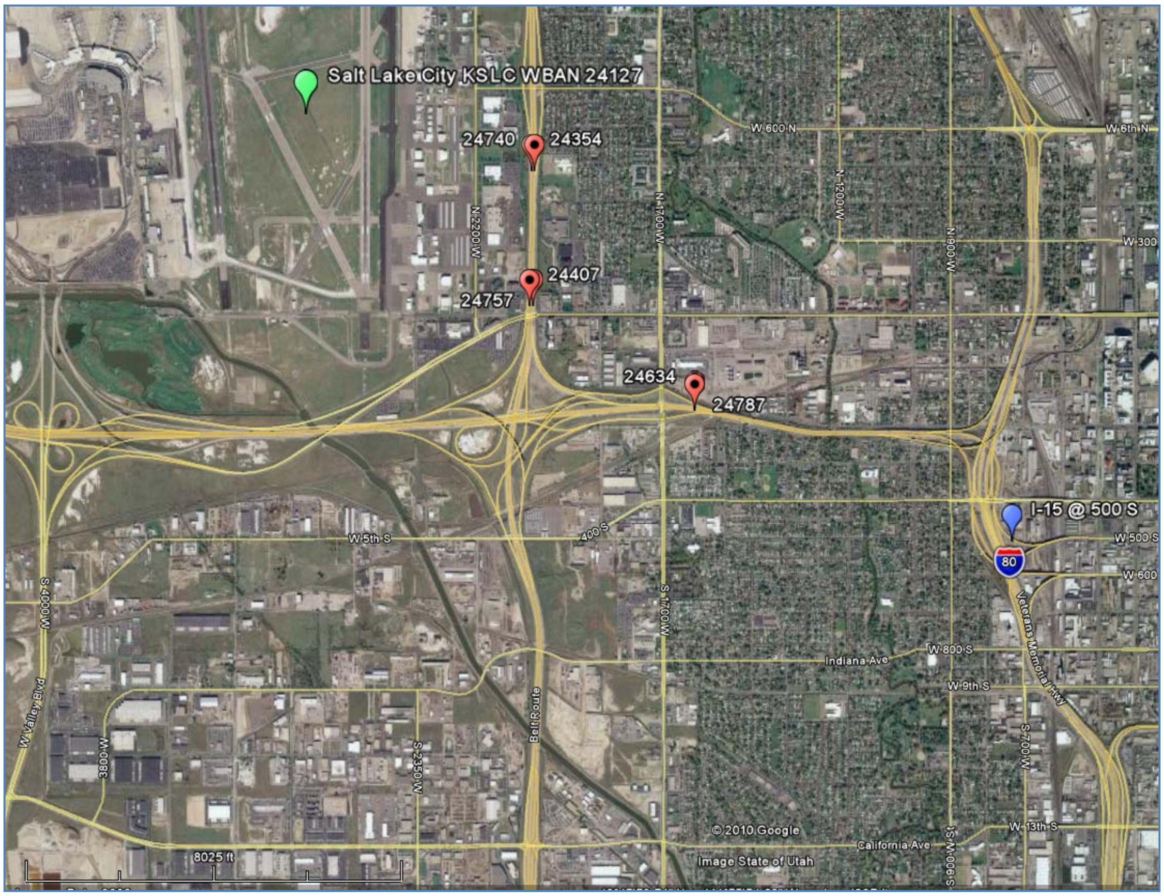
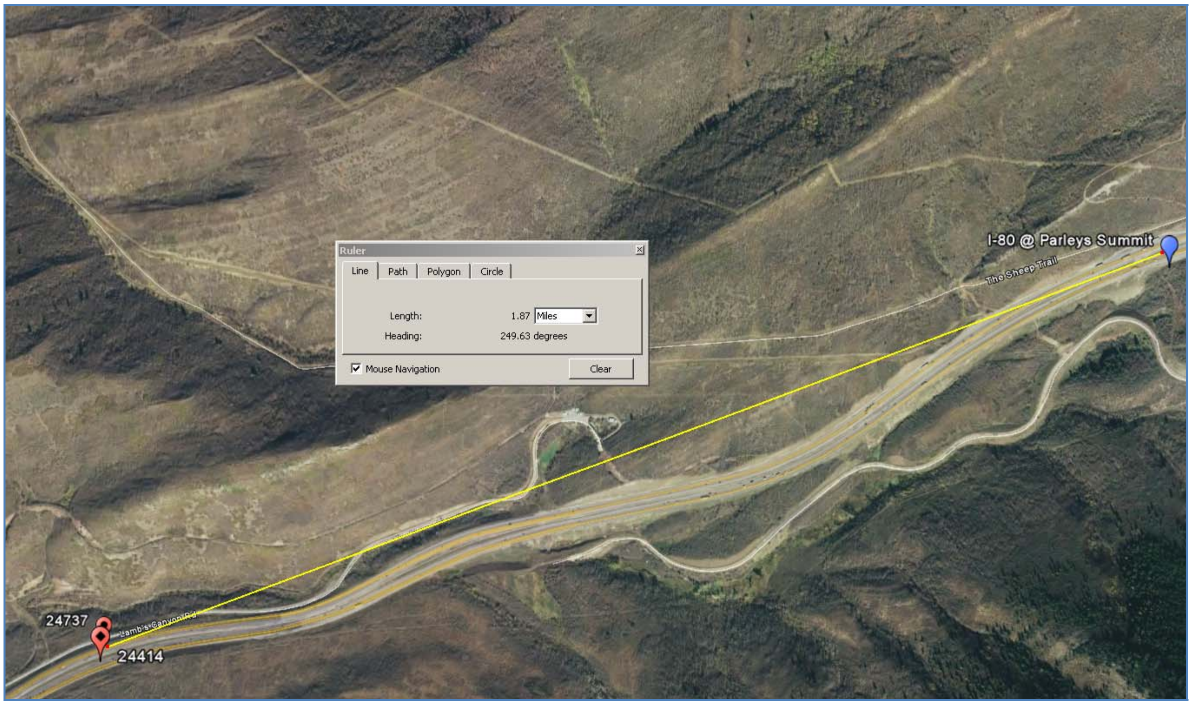


Figure A.2 Stations near Parley's Summit



A.3 Weather Data

Snowfall

Clarus stations do not have precipitation data for January 2009.

Both of the hourly national weather station archives from SHRP 2 study and the ASOS data archives downloaded from NWS web site show snowfall started in the airport location around 6:50 p.m. on June 26, 2009.

Rainfall

Clarus archives for June 26 precipitation data are plotted in the following figures. These figures show that rainfall started around 7:30 p.m. at I-15, and around 8:00 p.m. at Parley's Summit.

Both of the hourly national weather station archives from SHRP 2 study and the ASOS data archives downloaded from NWS web site show rainfall started in the airport location around 6:40 p.m. on June 26, 2009.

Figure A.3 Rainfall at I-15 at 500S

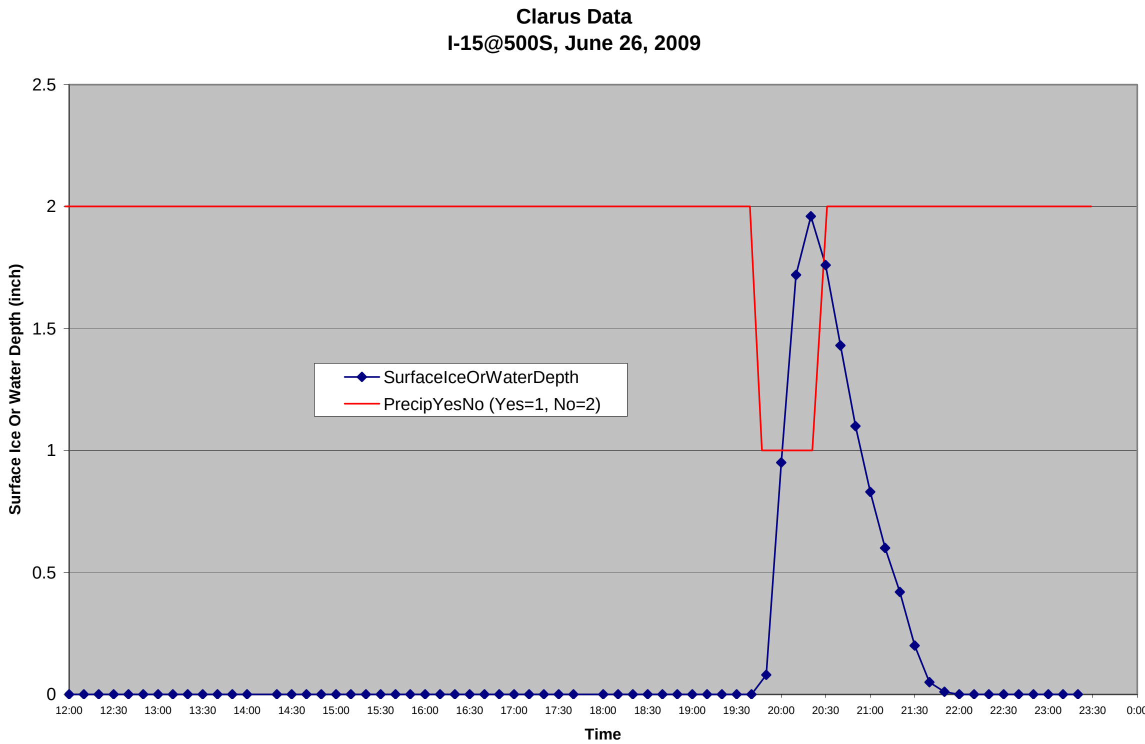
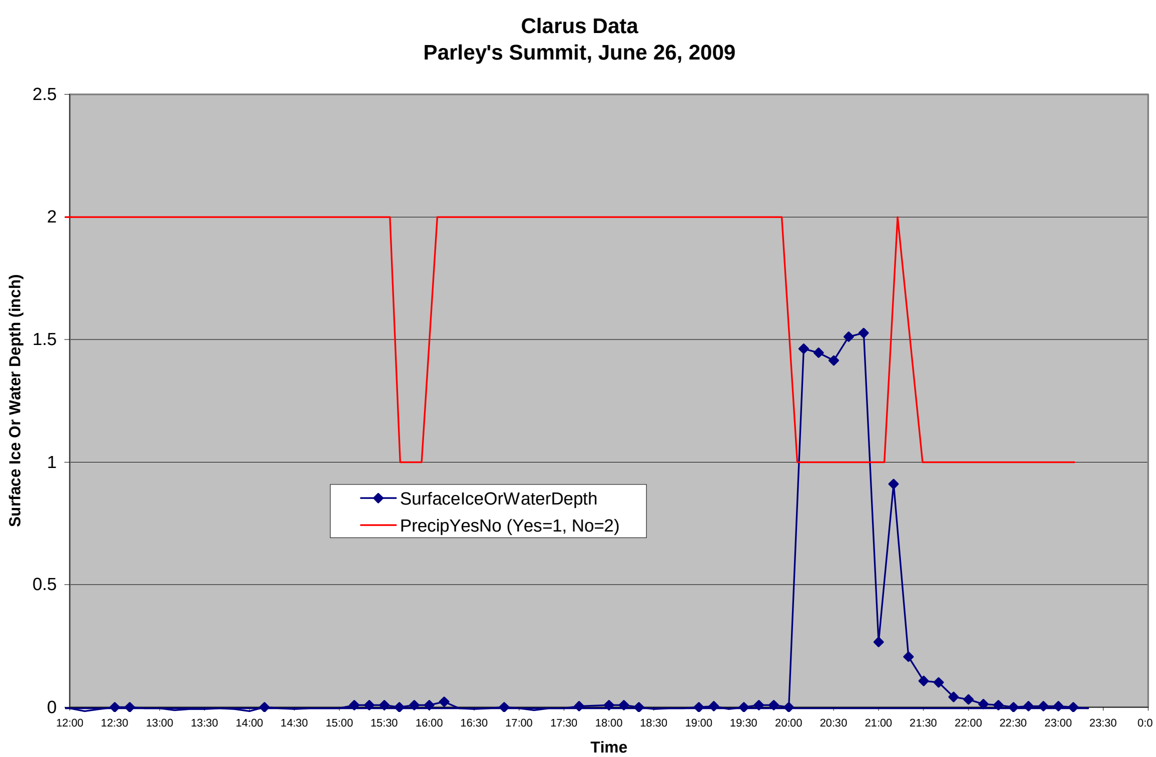


Figure A.4 Rainfall at I-80 at Parley's Summit



A.4 Traffic Speed

The following graphs show the traffic speed on each lane at each station on the four test days. Lane CD is numbered from leftmost lane (close to median) to the rightmost (close to shoulder) at each station.

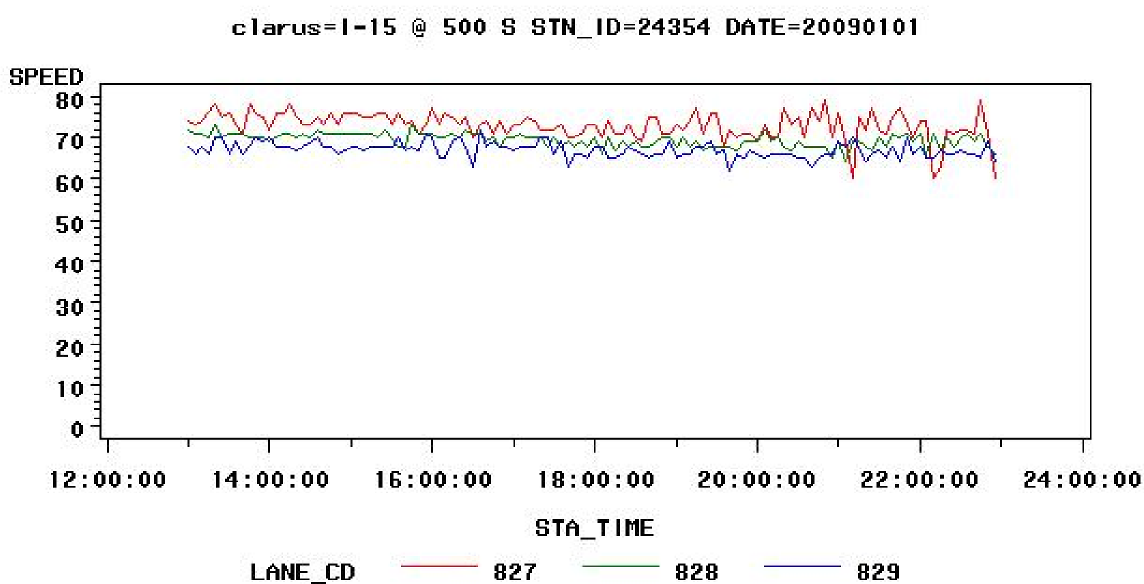
All stations have distinct differences between days with inclement weather and the regular free-flowing traffic patterns.

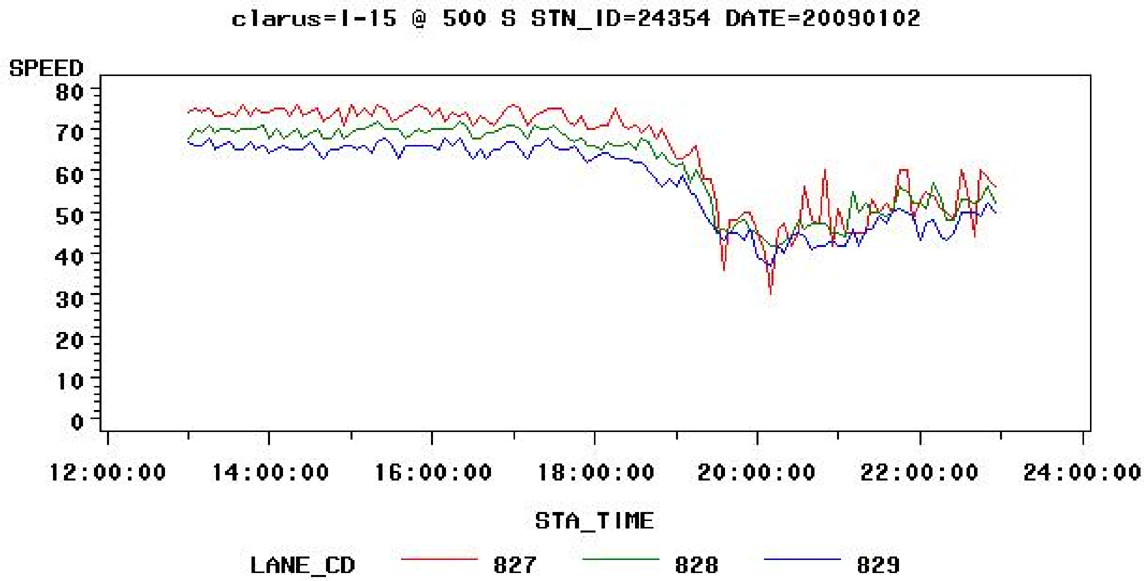
All the stations have speed drops when snowfall started, and stations in the mountain seem to have sharper speed decline.

All the stations also have speed drops when rainfall started, and rainfall seems to have bigger impacts on stations around the airport than those stations up in the mountain. But that could be explained by the fact that the rainfall around the airport was heavier than the rainfall in the mountain on June 26, 2009.

Key to Lane Designations

Red – Inside lane
Green – Middle lane
Blue – Outside lane

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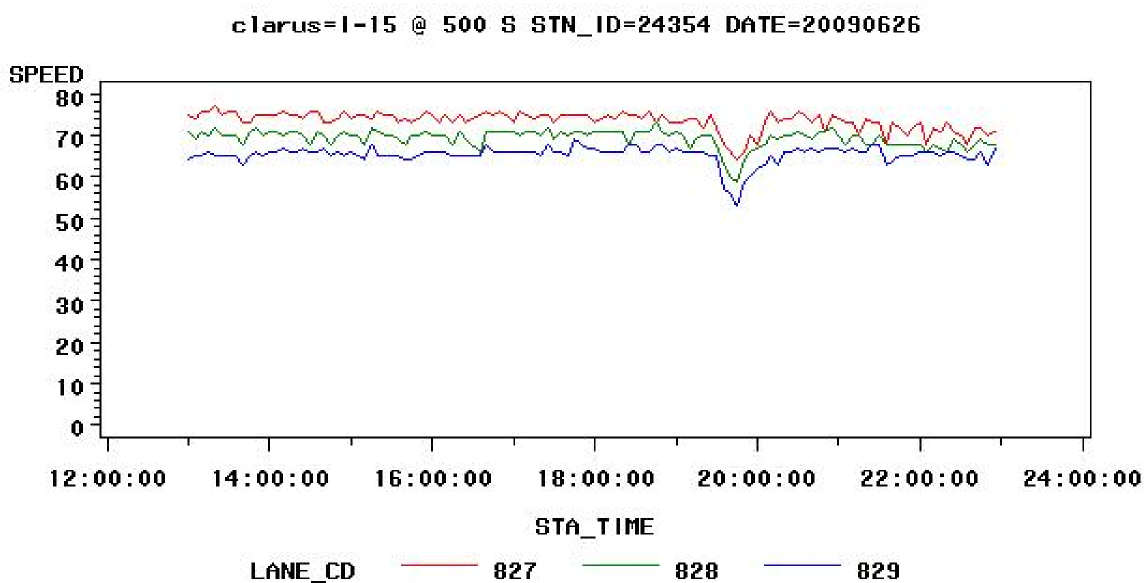
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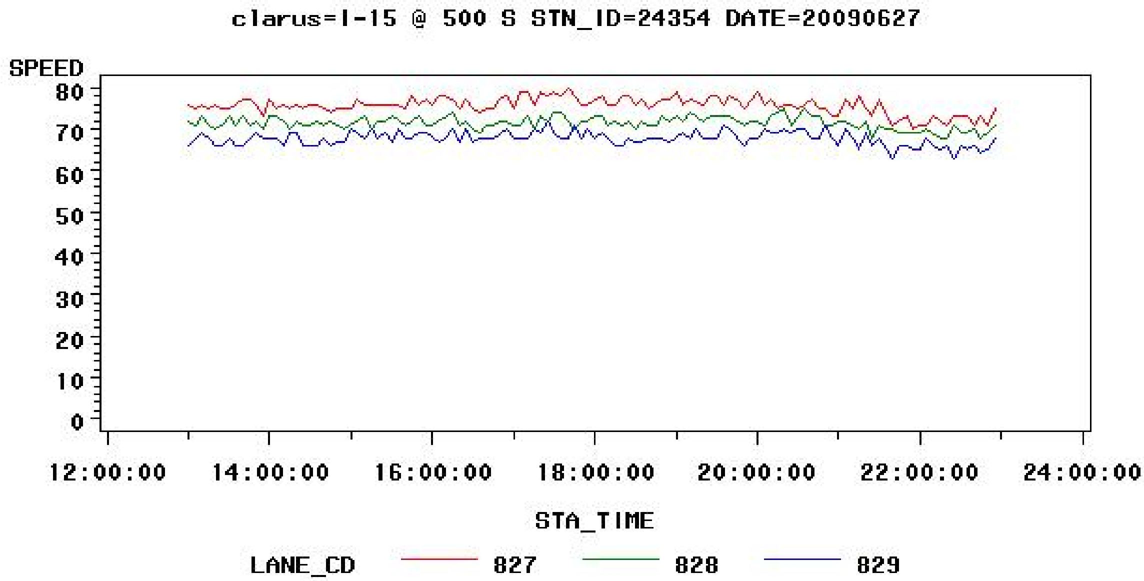
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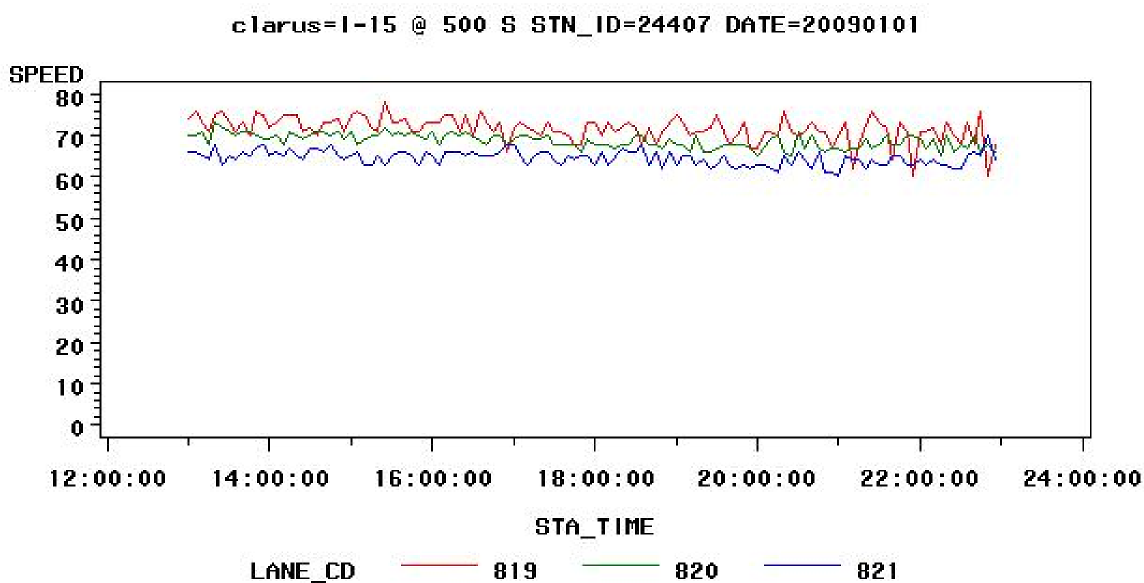
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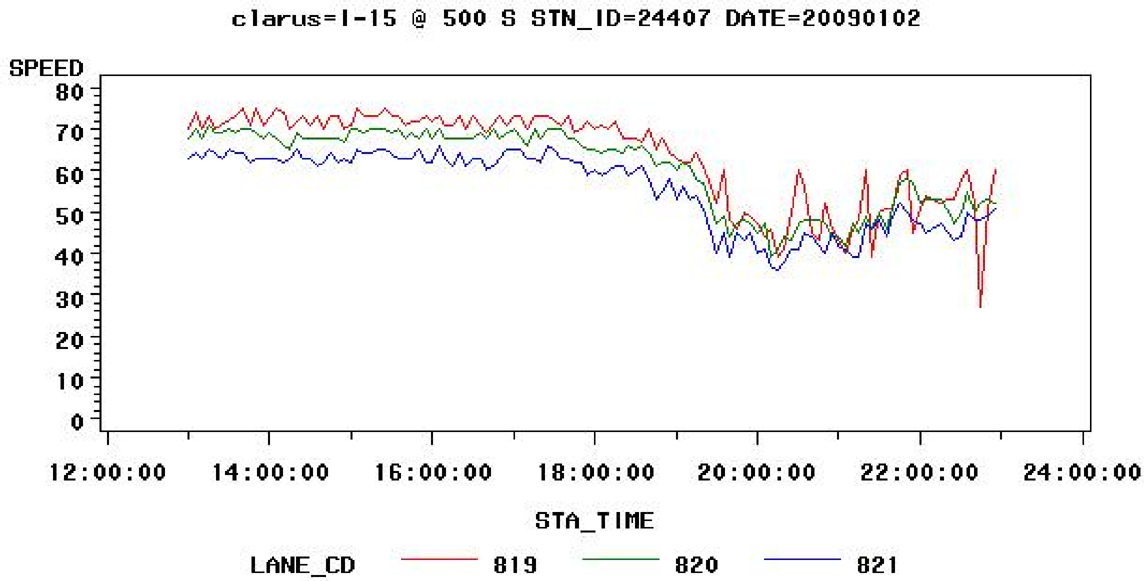
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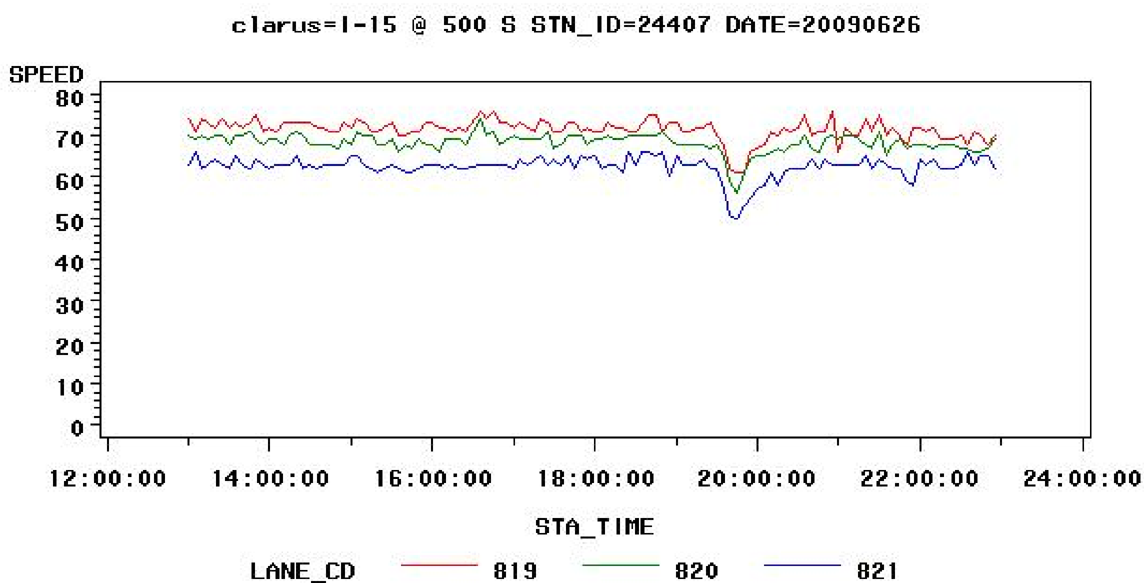
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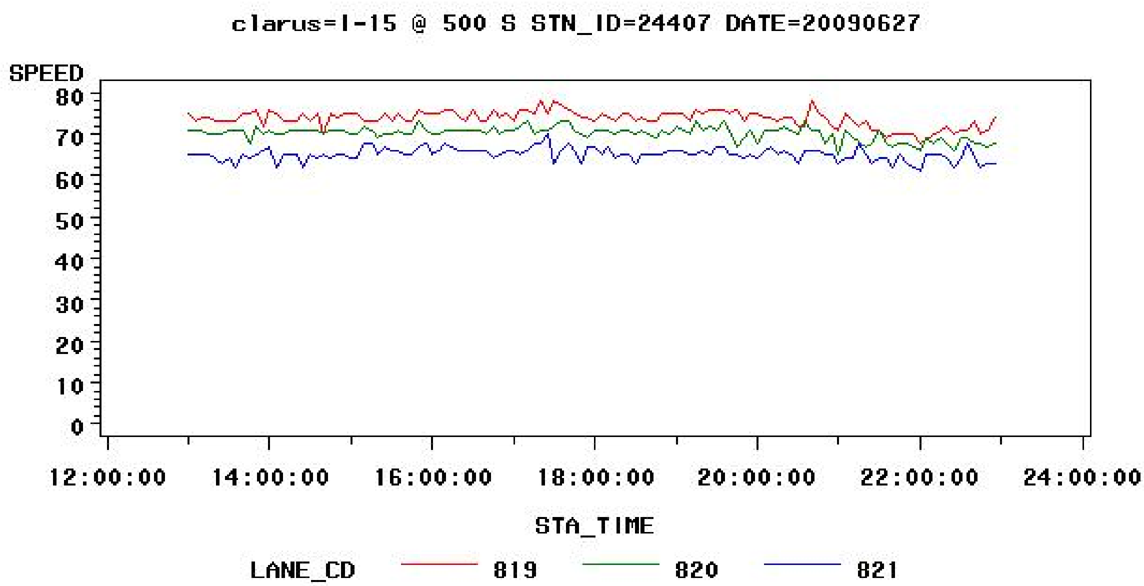
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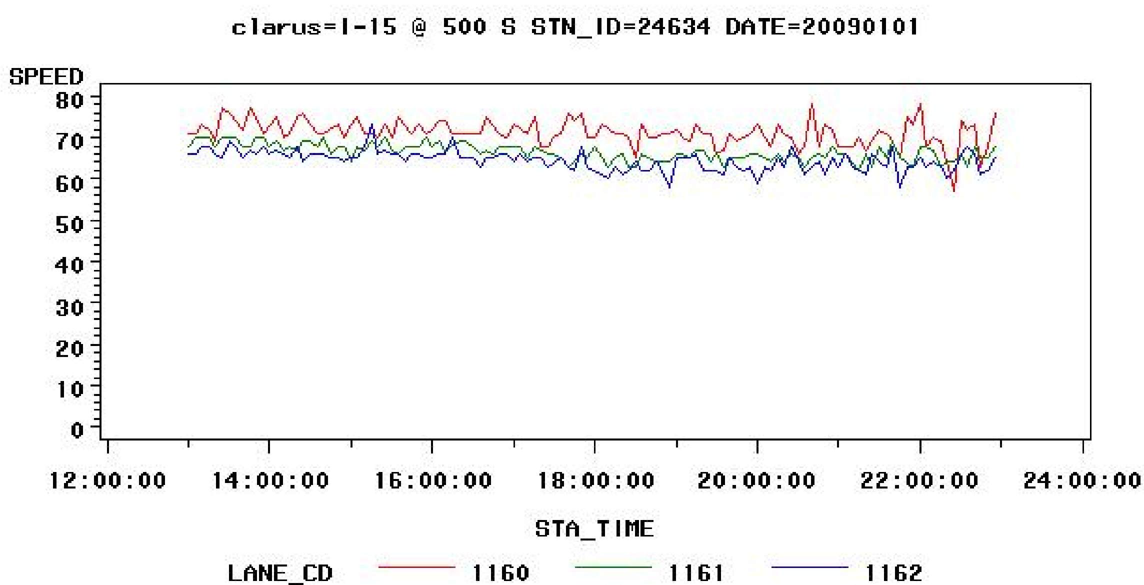
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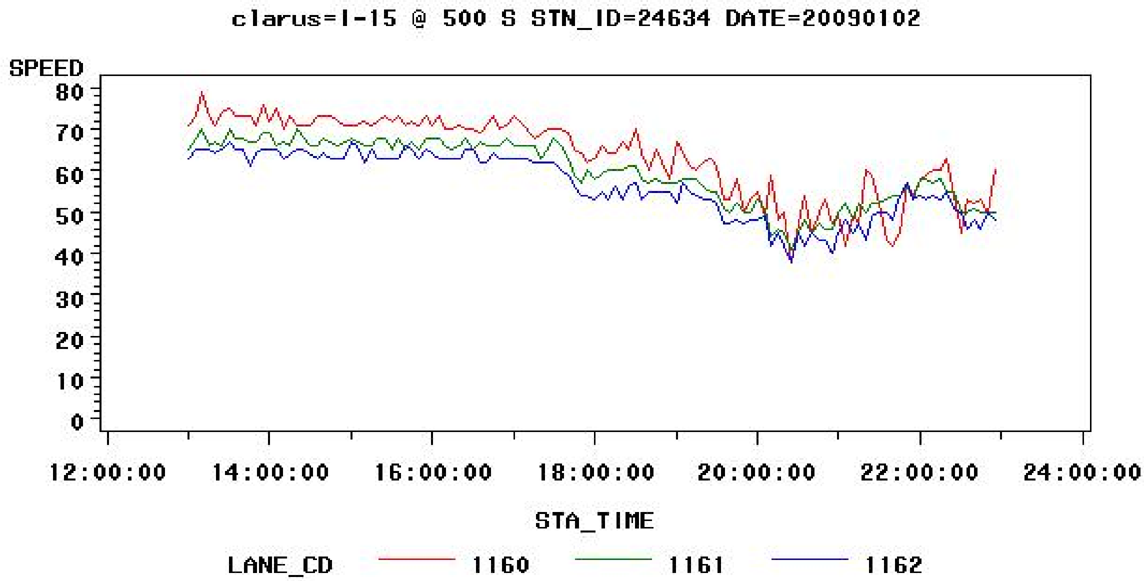
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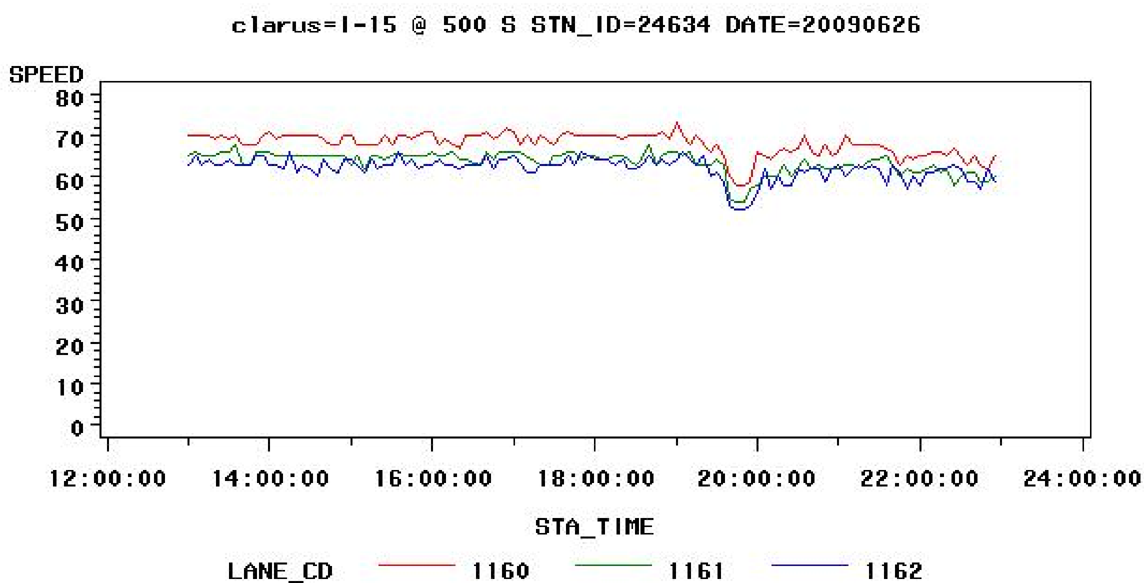
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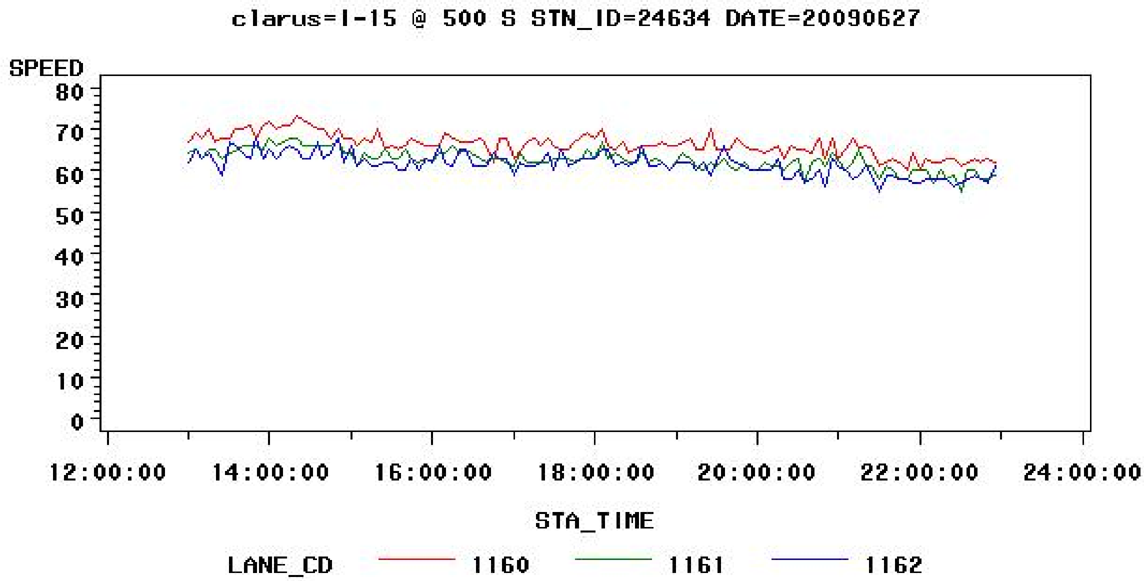
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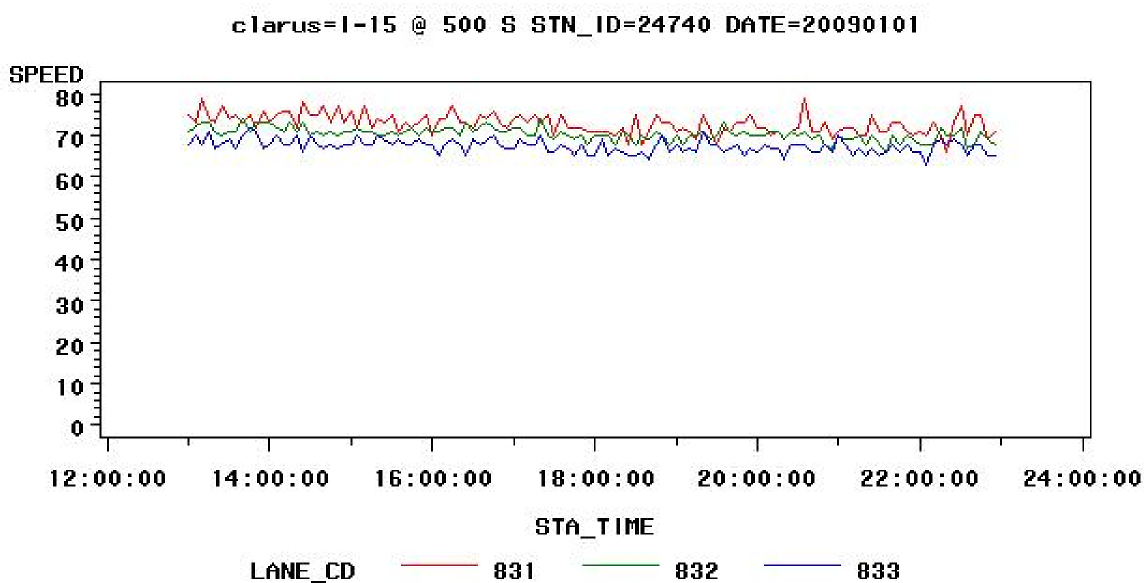
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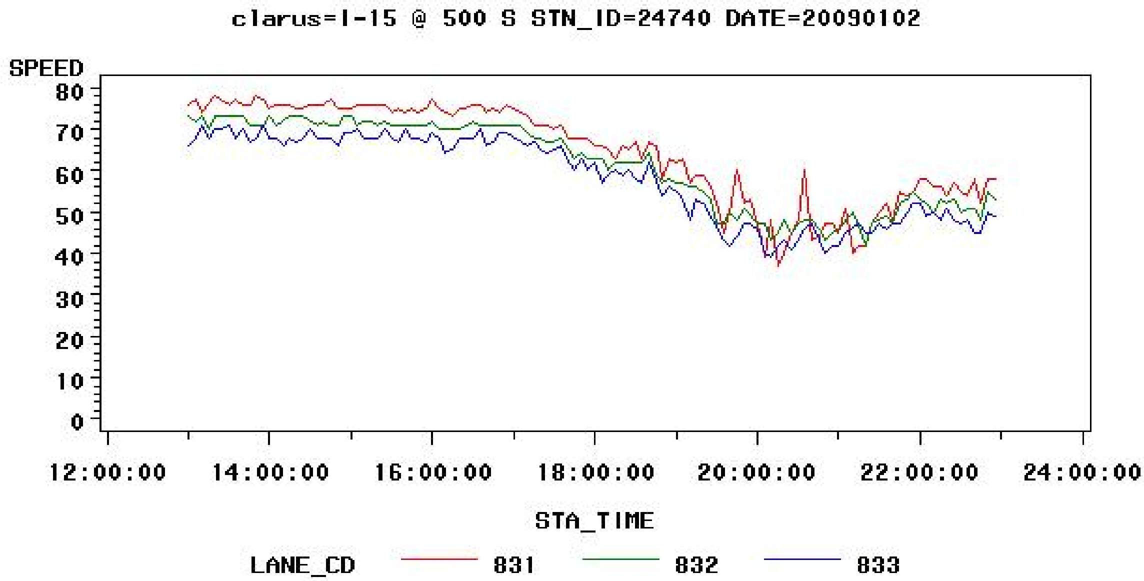
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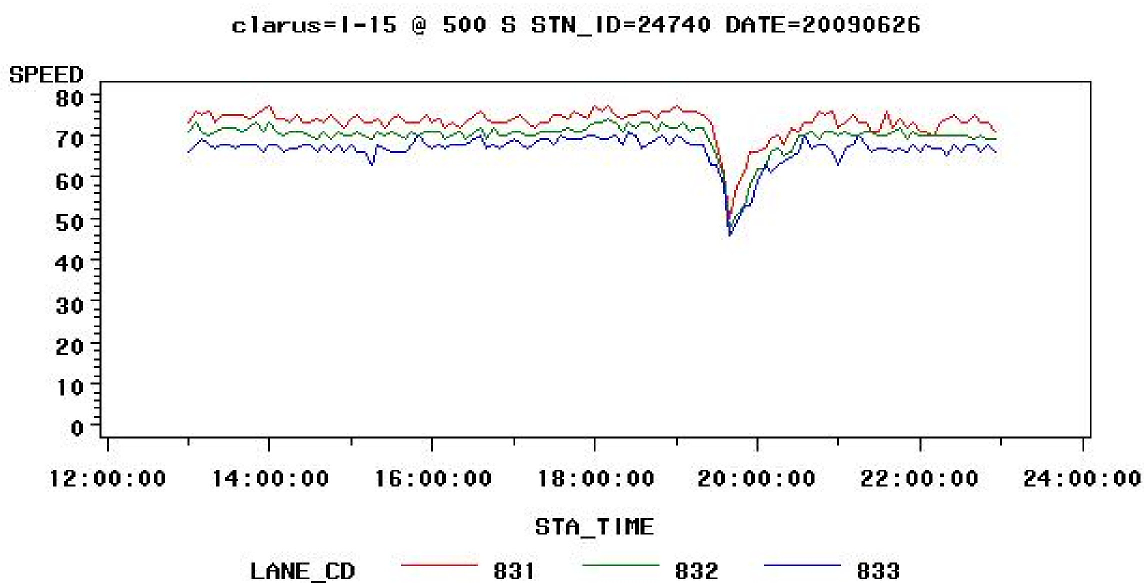
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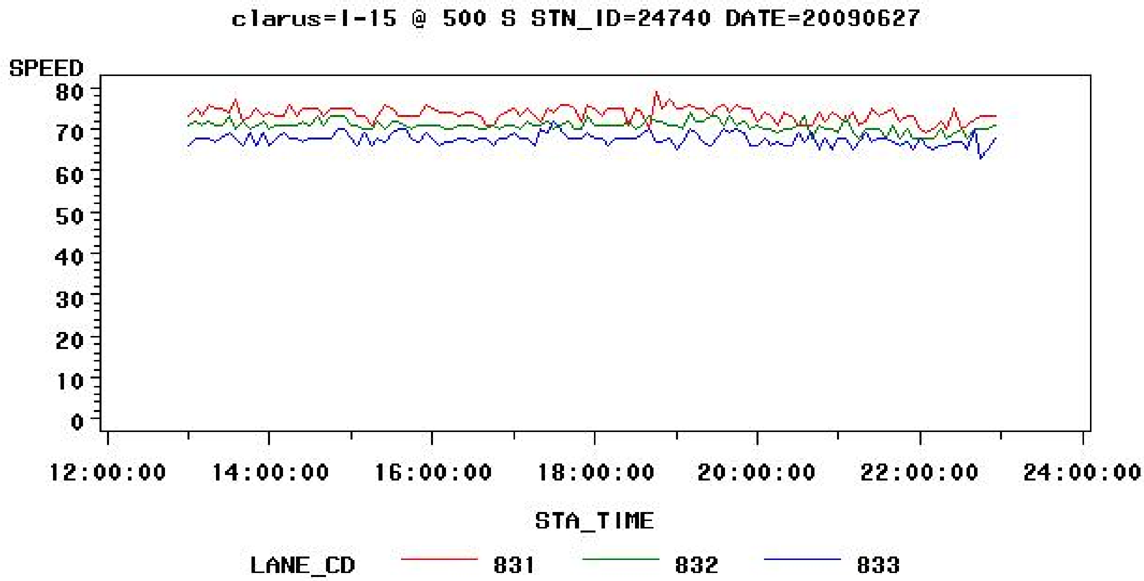
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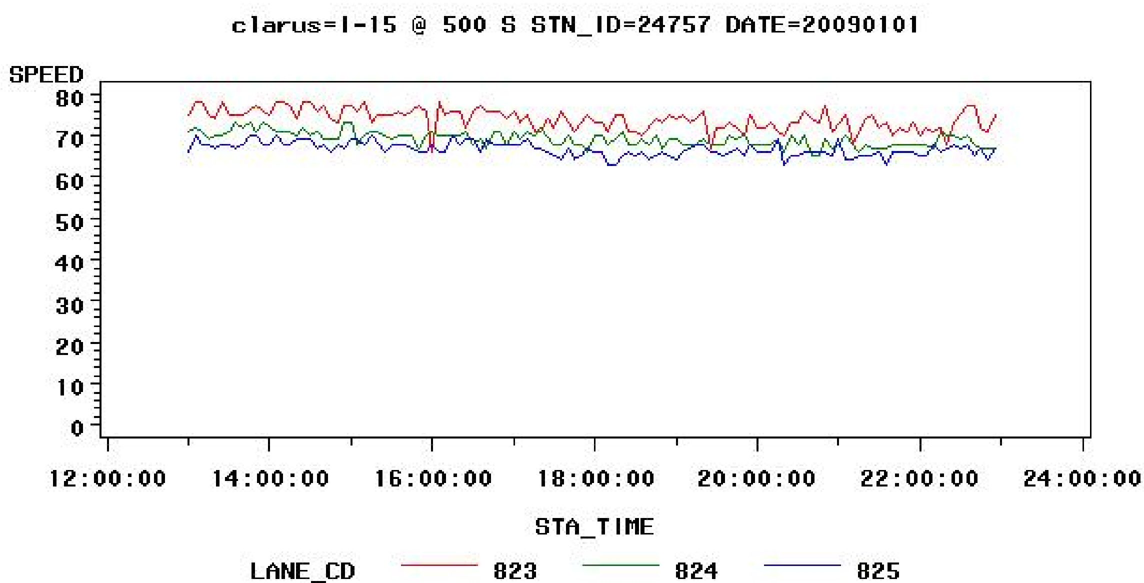
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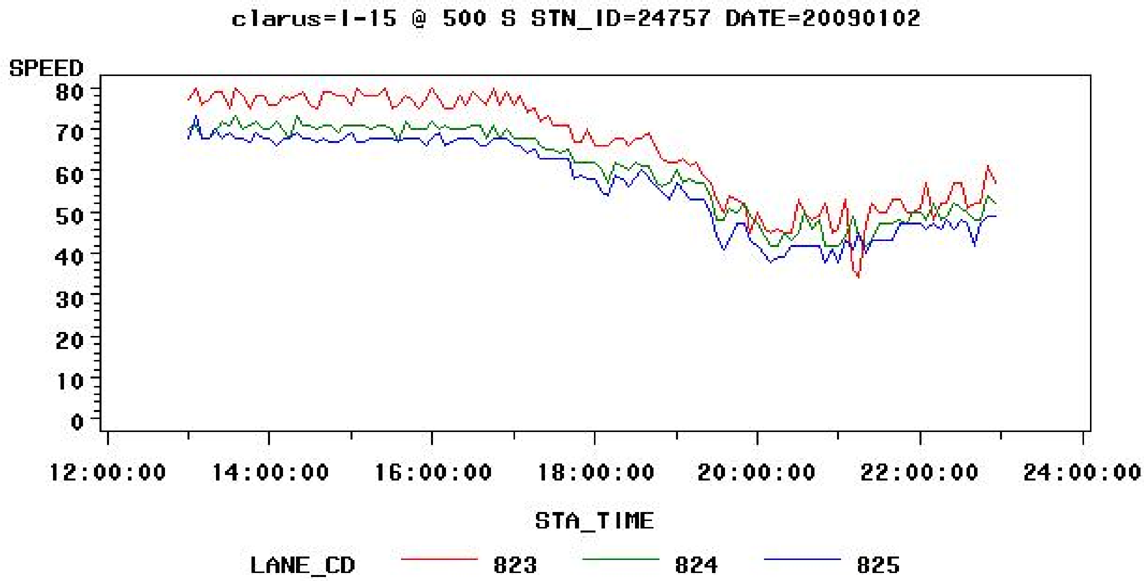
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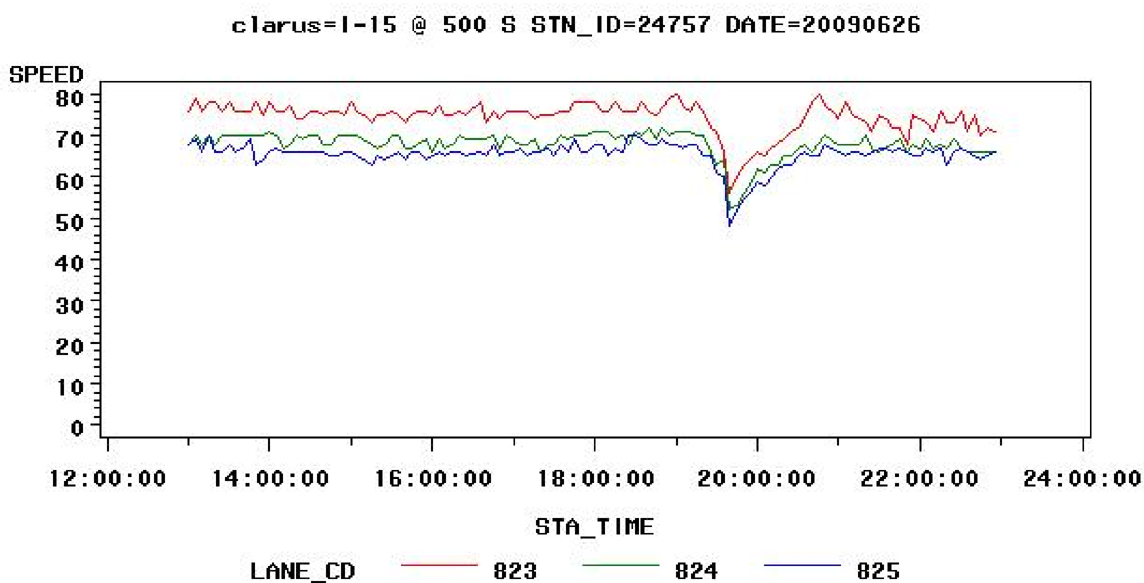
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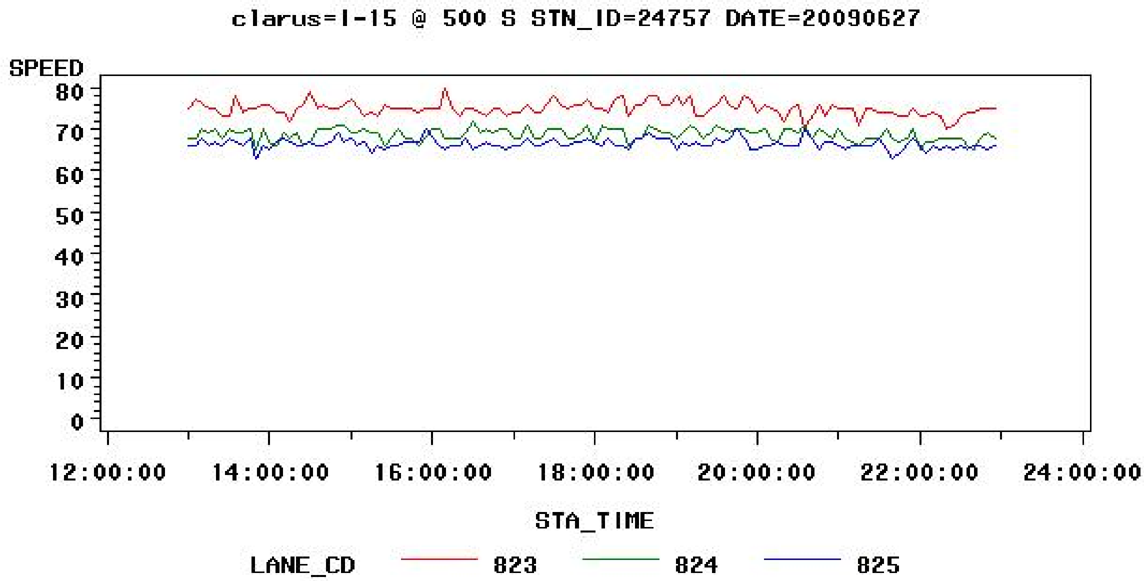
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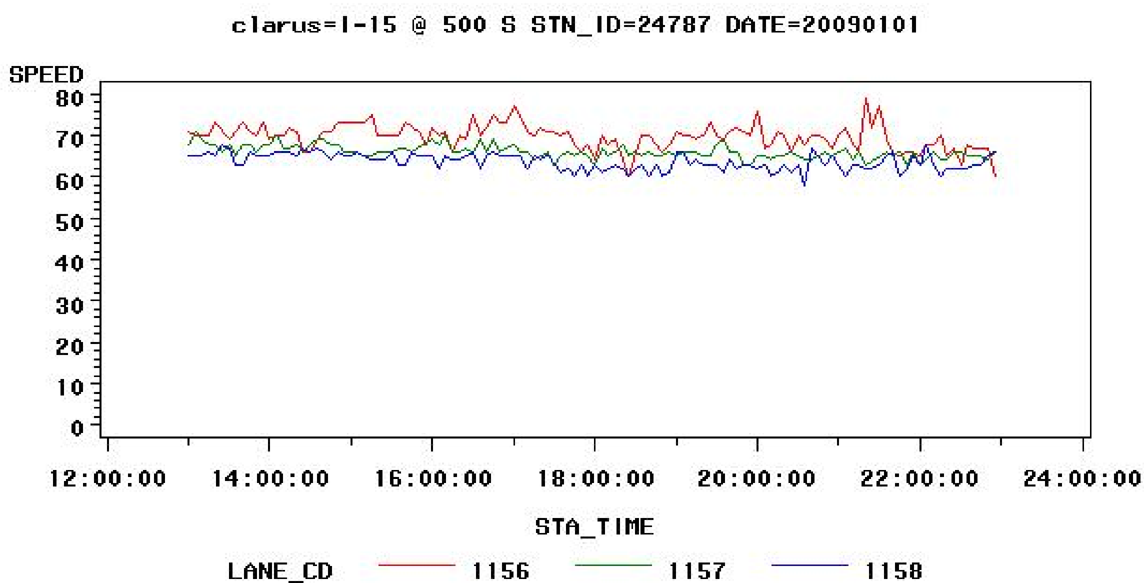
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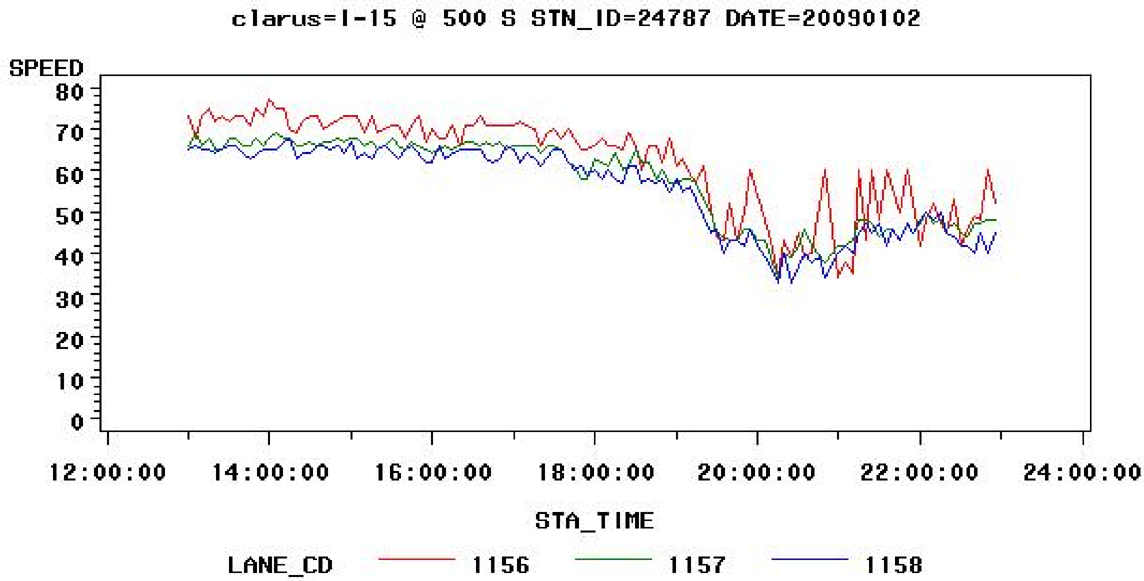
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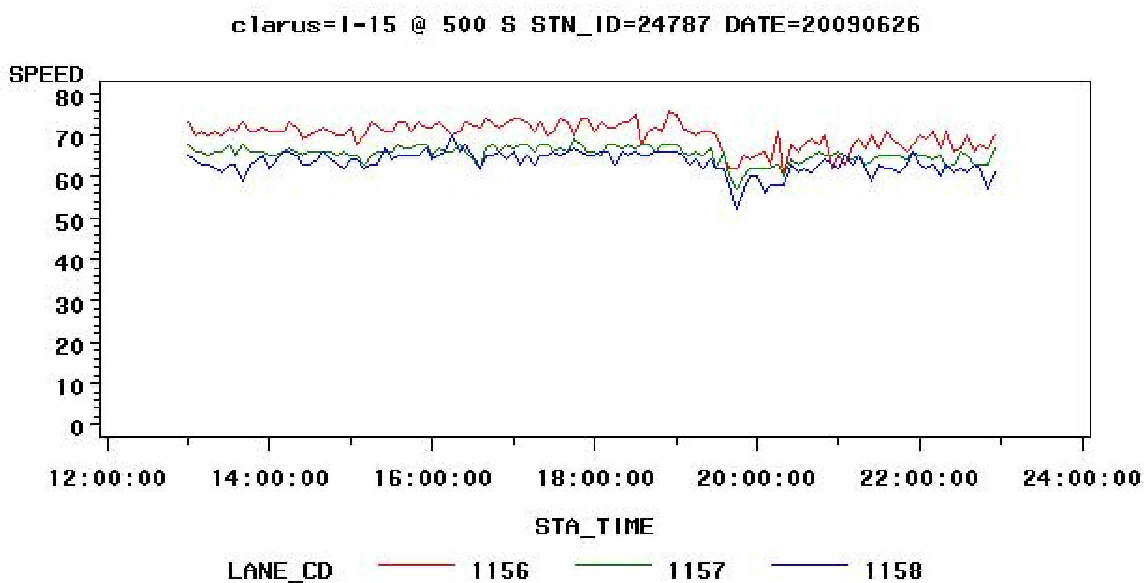
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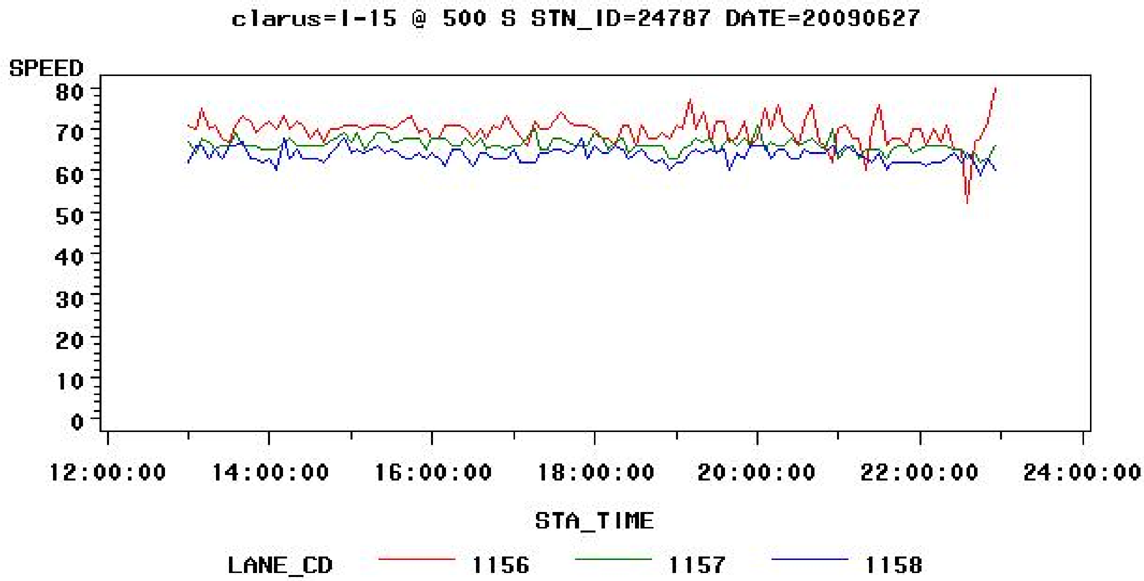
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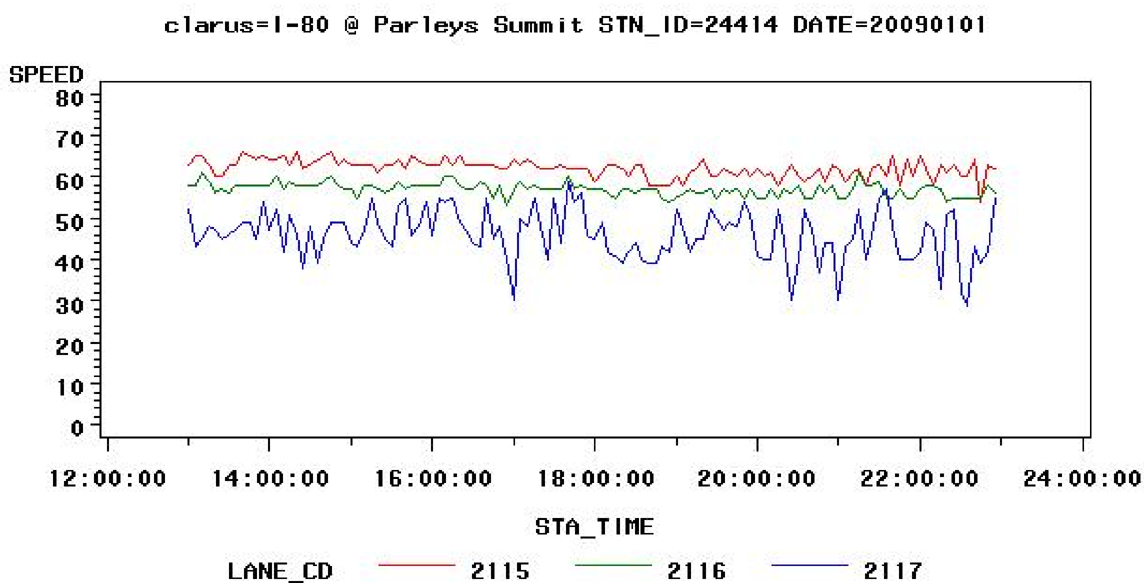
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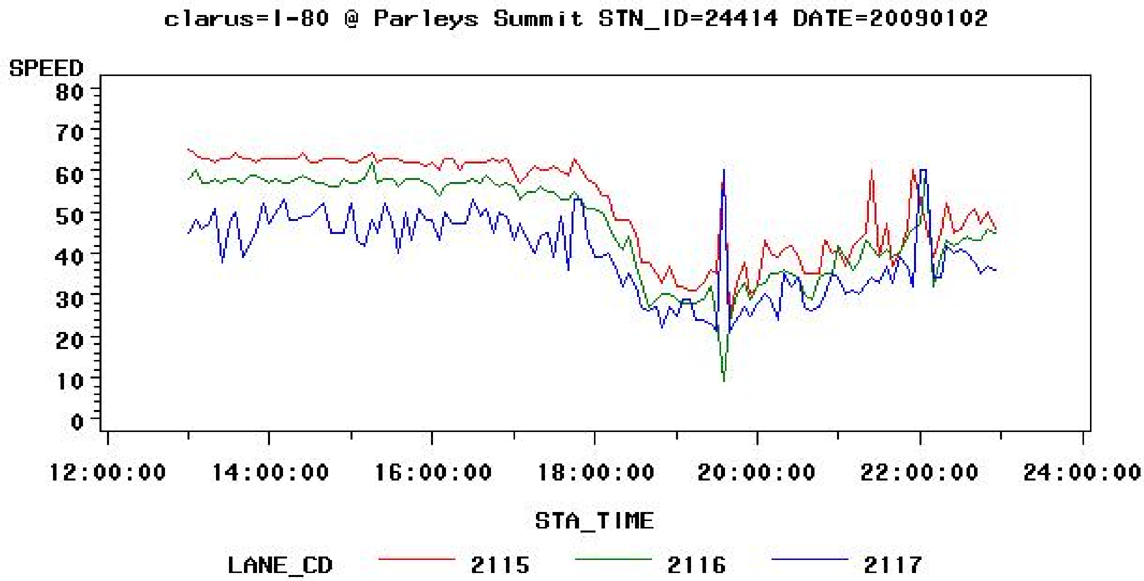
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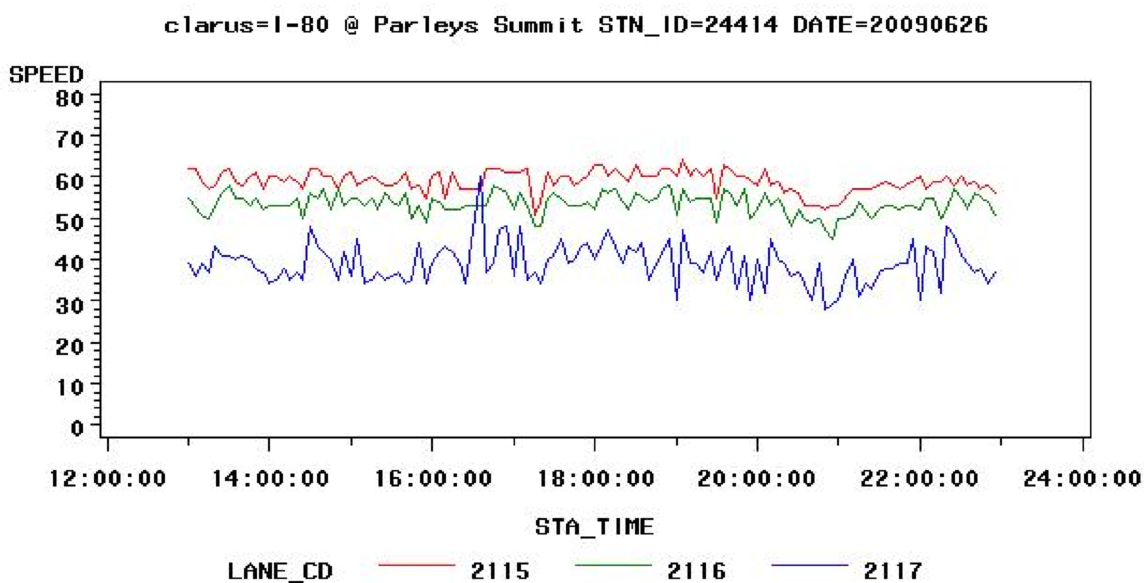
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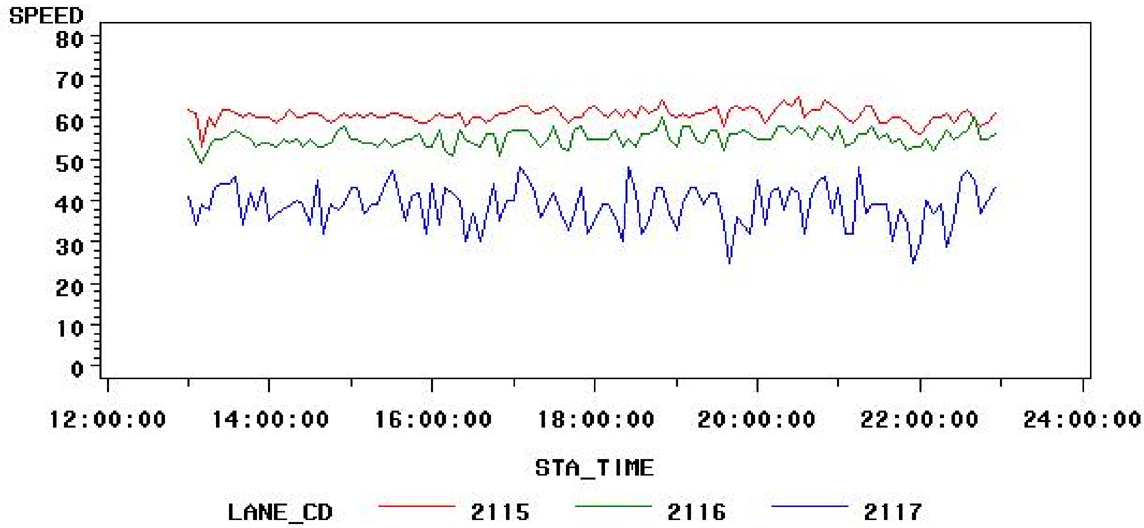

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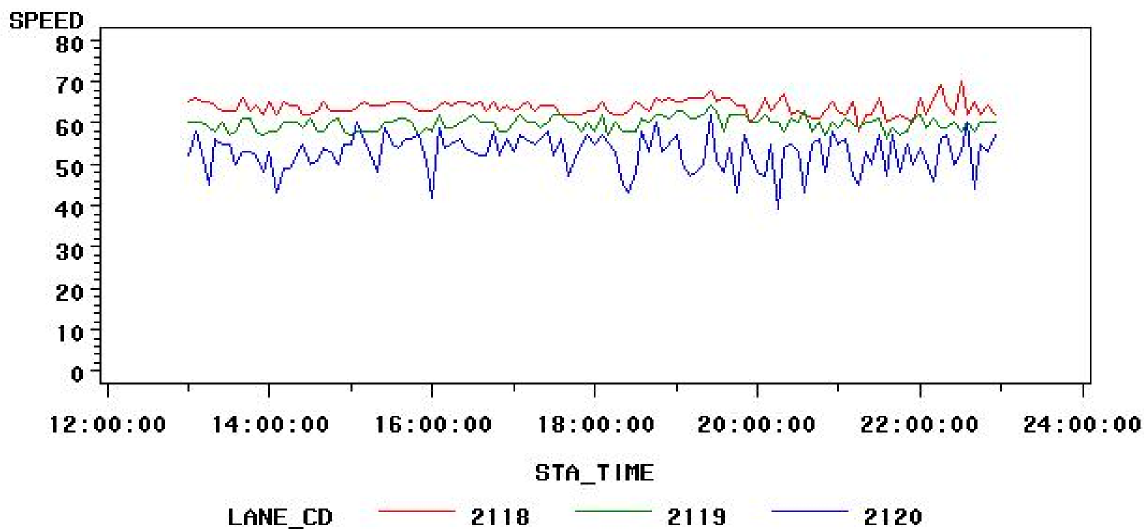

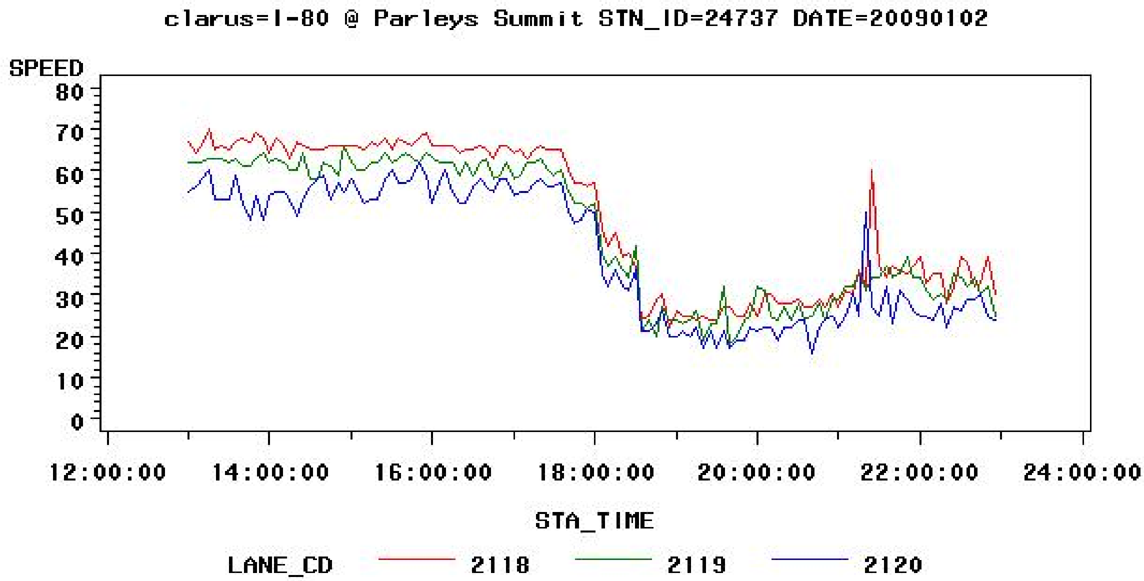
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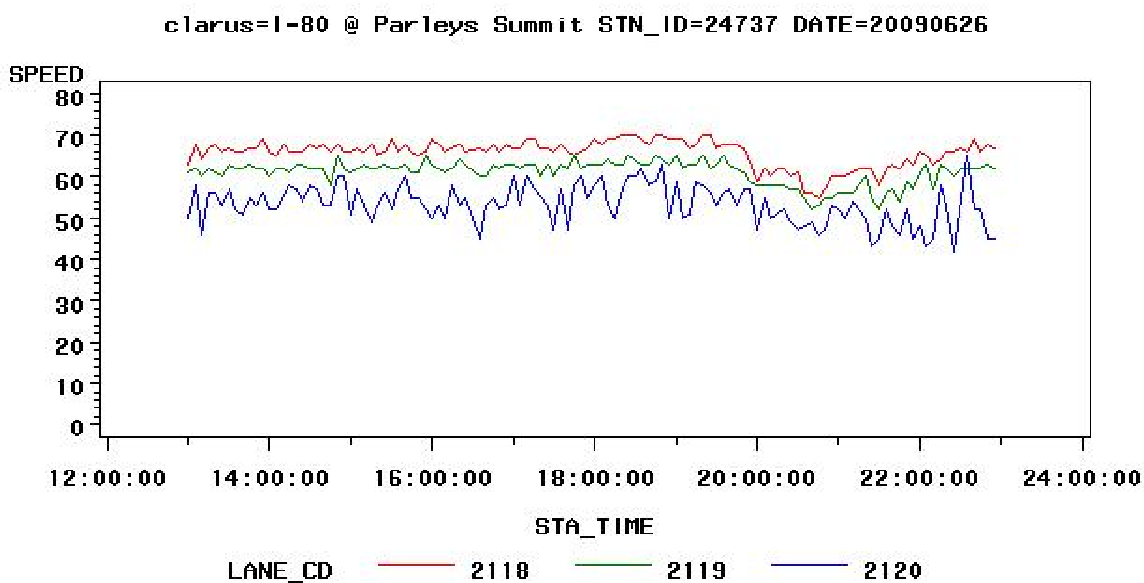
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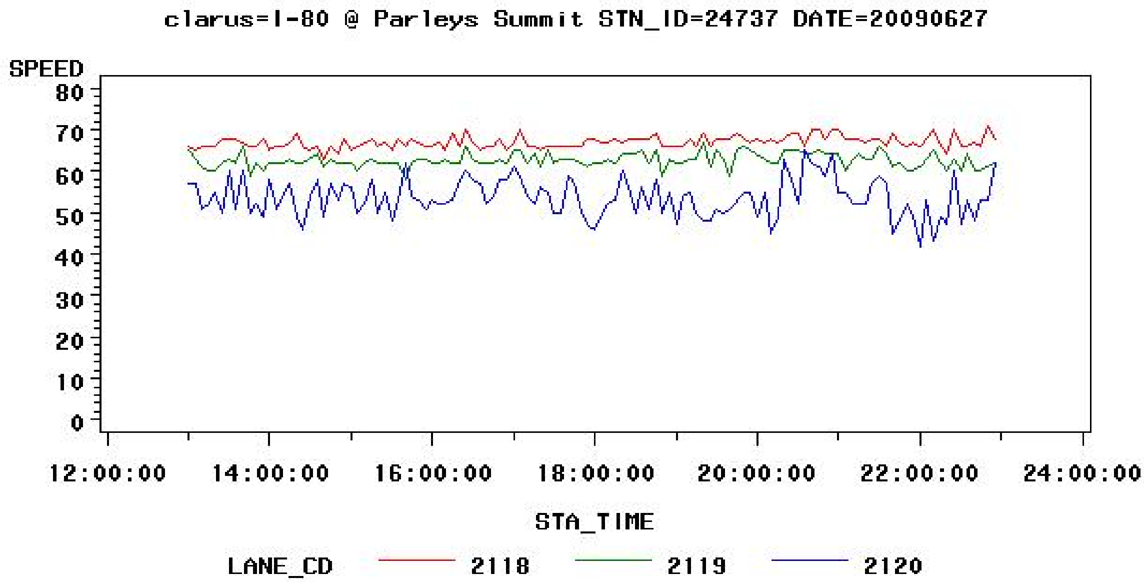
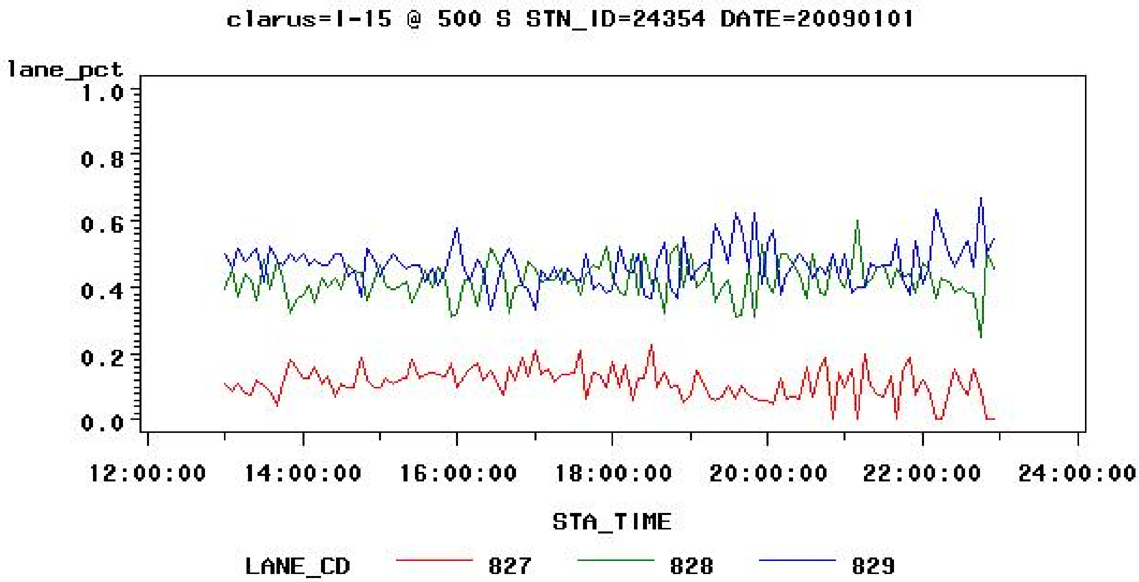


Lane Volume Distribution

The following graphs show the volumes distribution percentages at each lane during the four test days. Lane CD is numbered from leftmost lane (close to median) to the rightmost (close to shoulder) at each station.

All stations have distinct differences between snowfall periods and regular free-flowing traffic; slower lanes have higher percentages during snowfall than they have under free-flow conditions. However, the exact lane shifting patterns are inconclusive. For some stations, traffic tends to move the rightmost lane, while for other stations traffic tends to shift to both the middle and the rightmost lane.

On the other hand, rainfall impact on lane shifting is not easy to identify in these graphs.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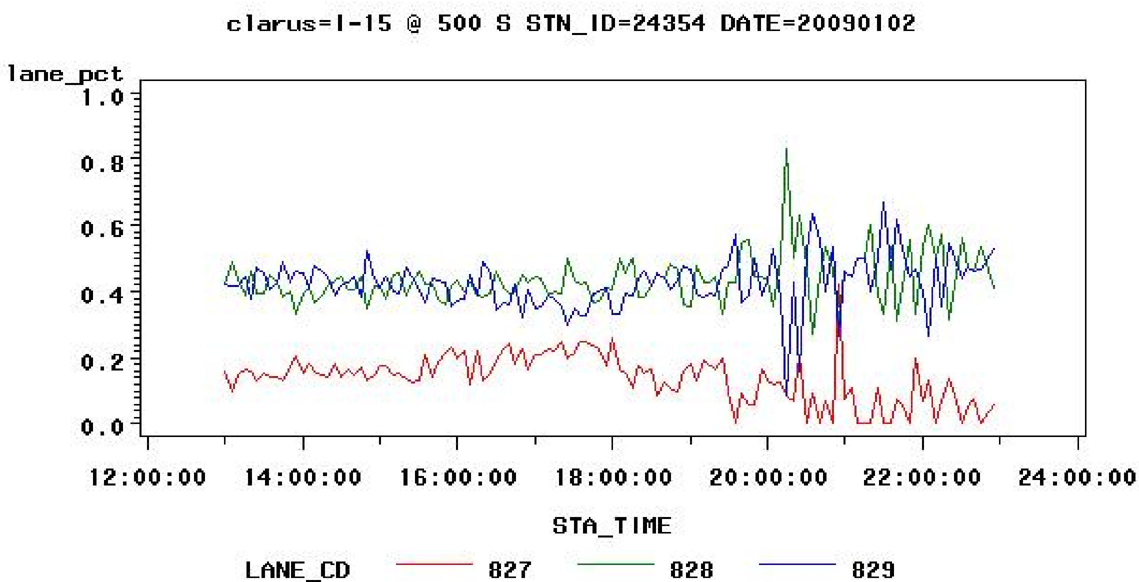
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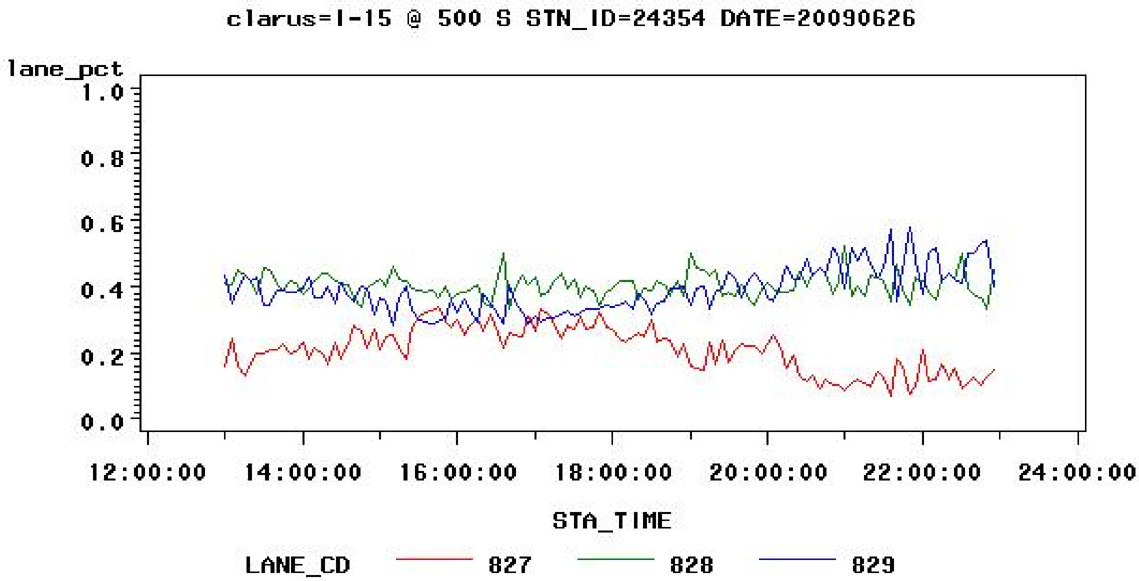
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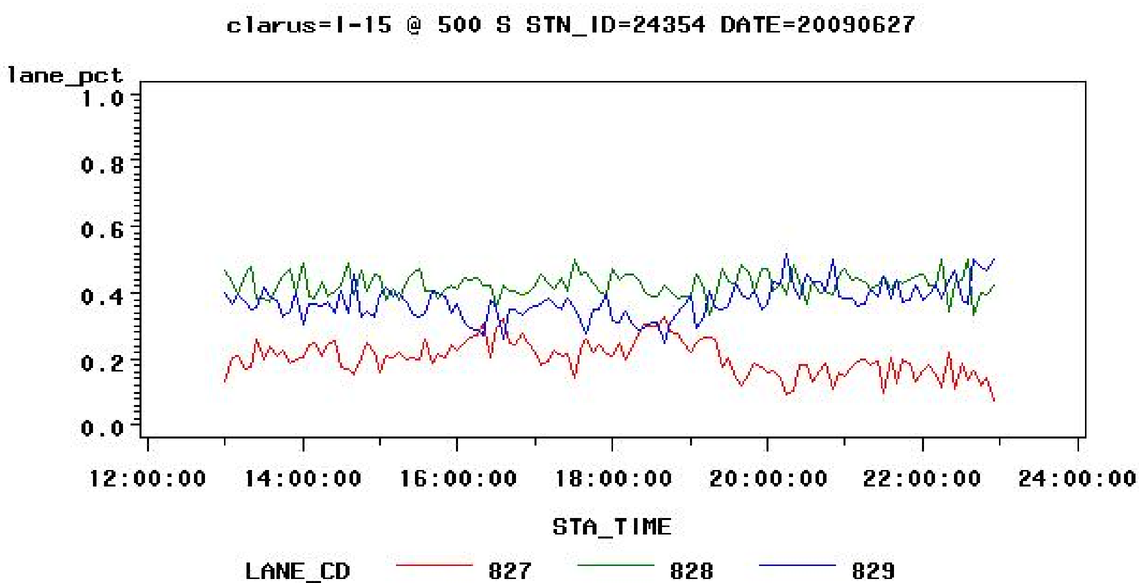
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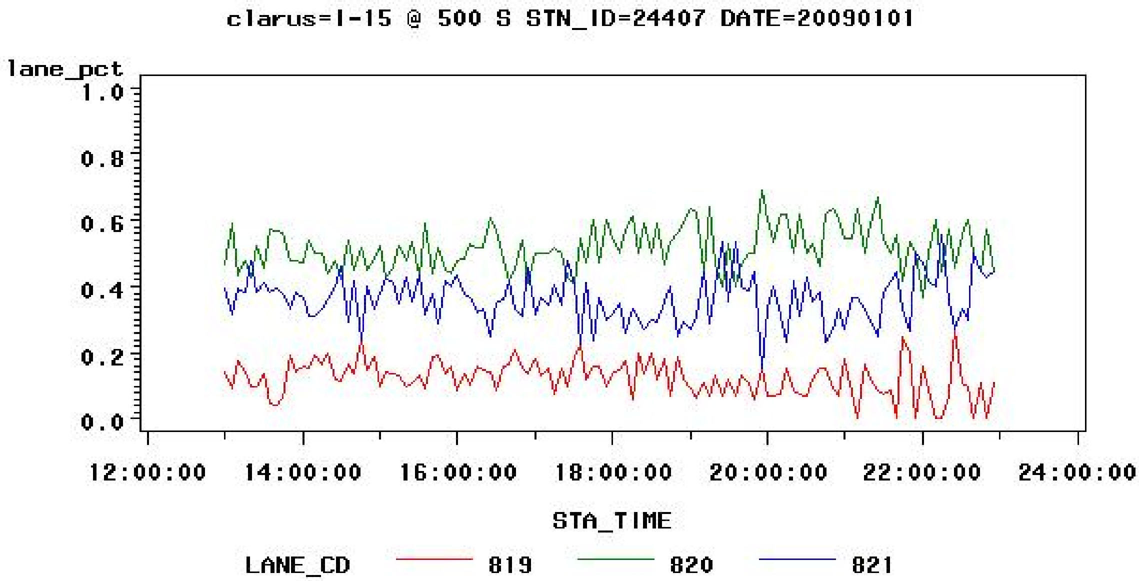
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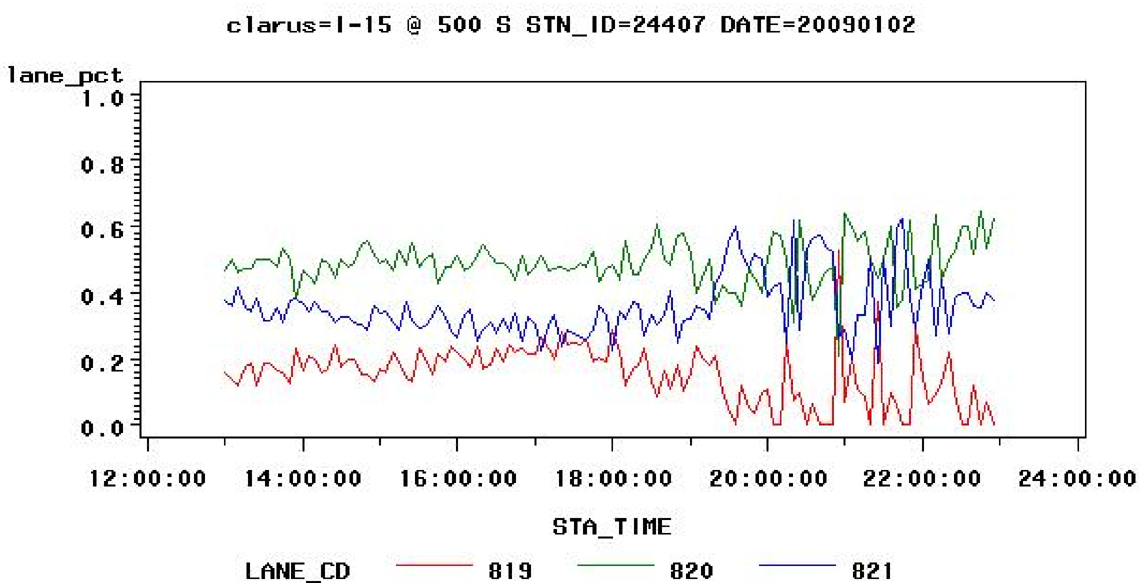
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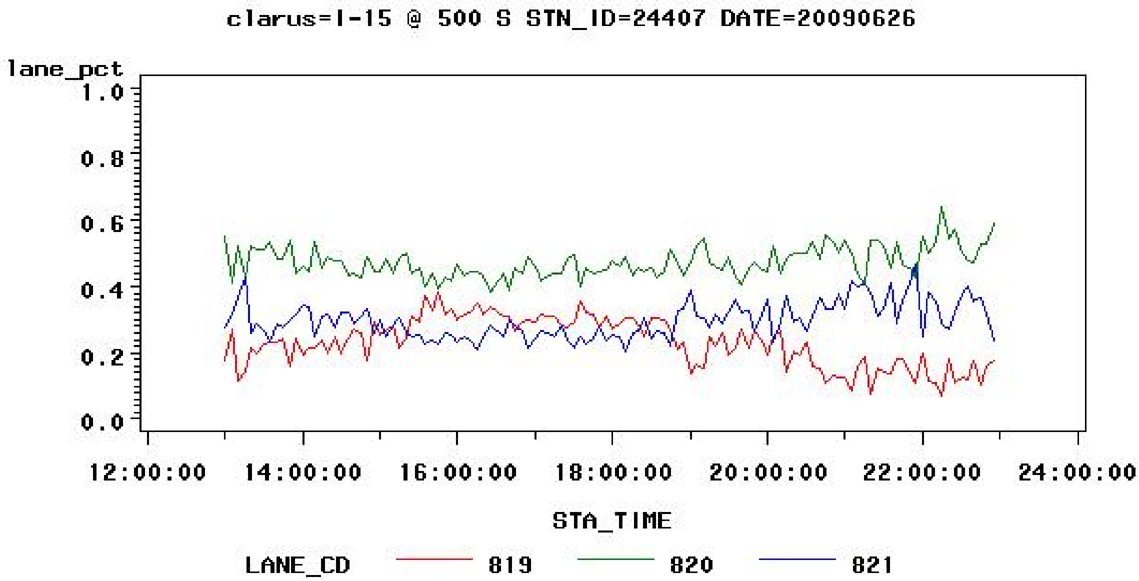
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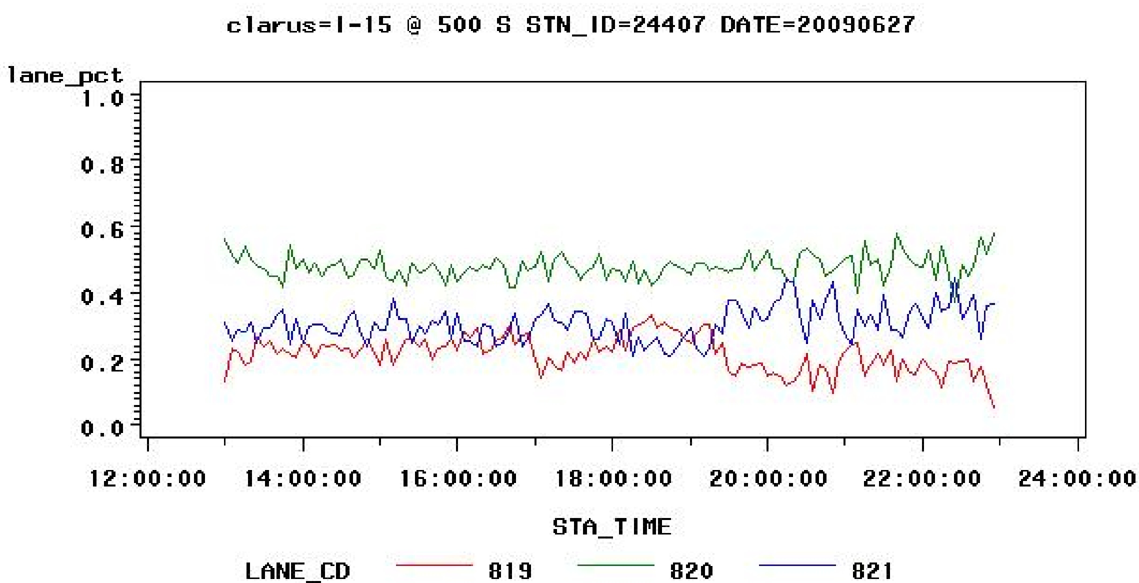
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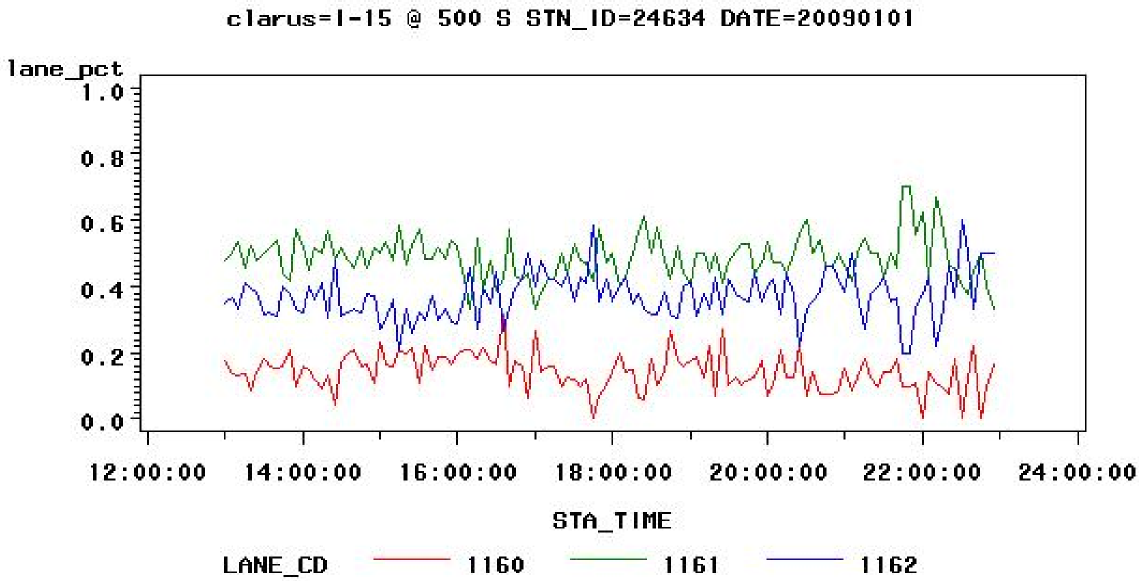
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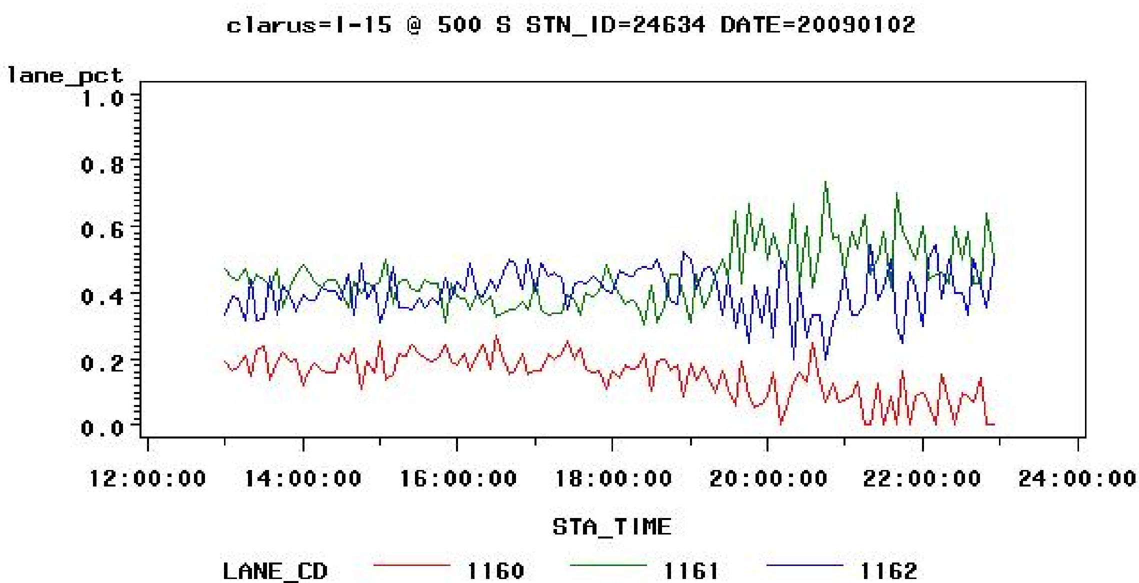
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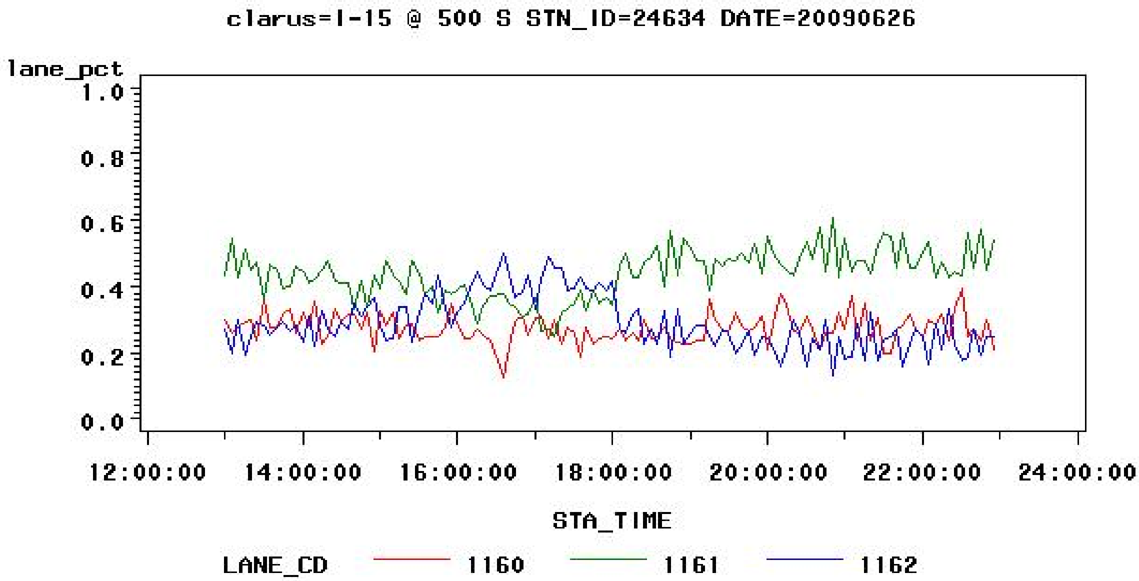
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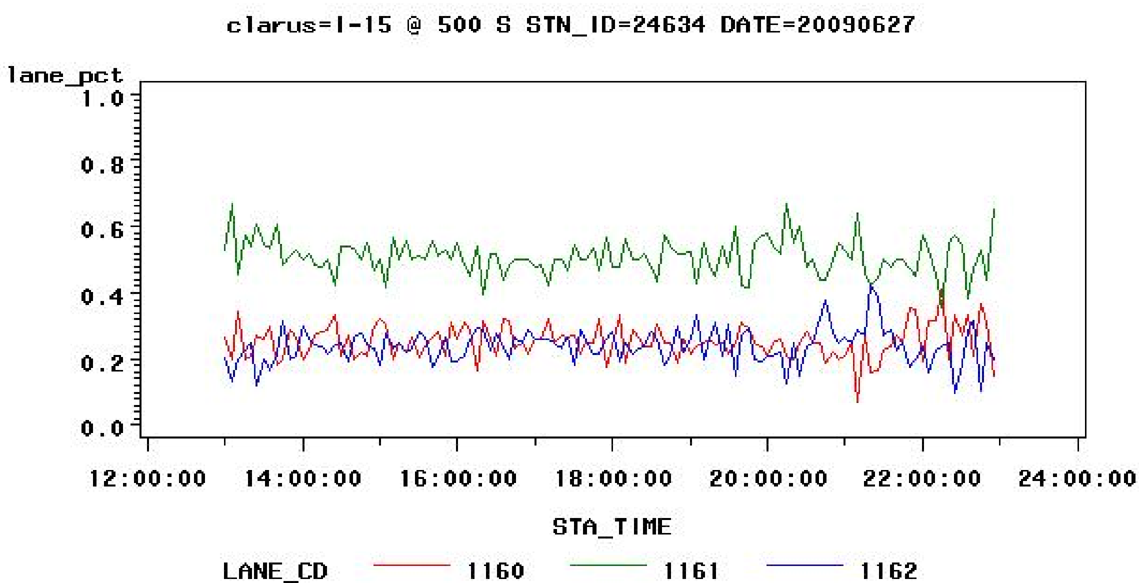
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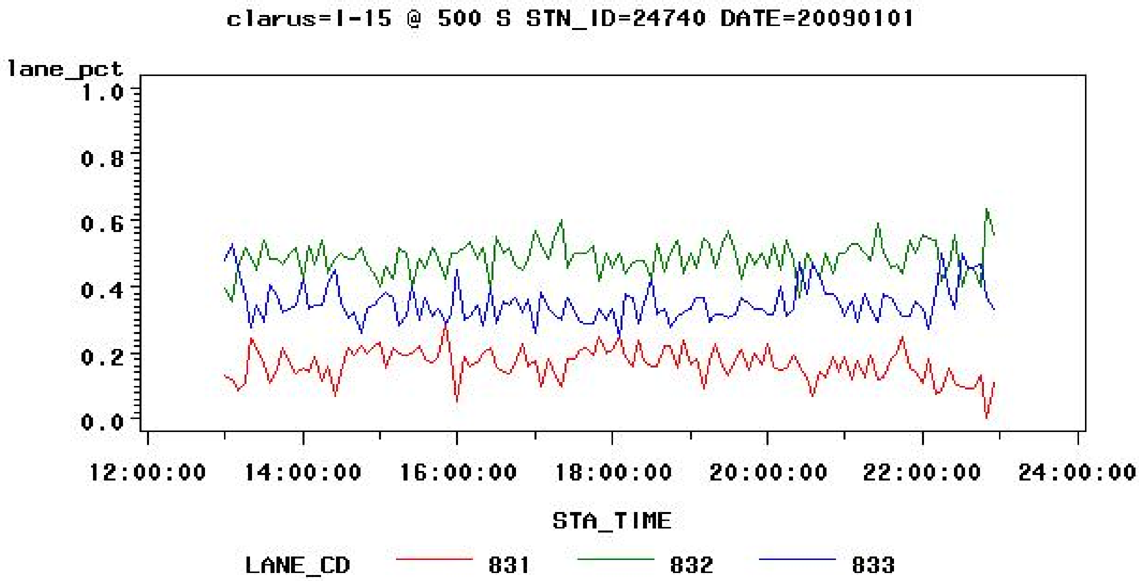
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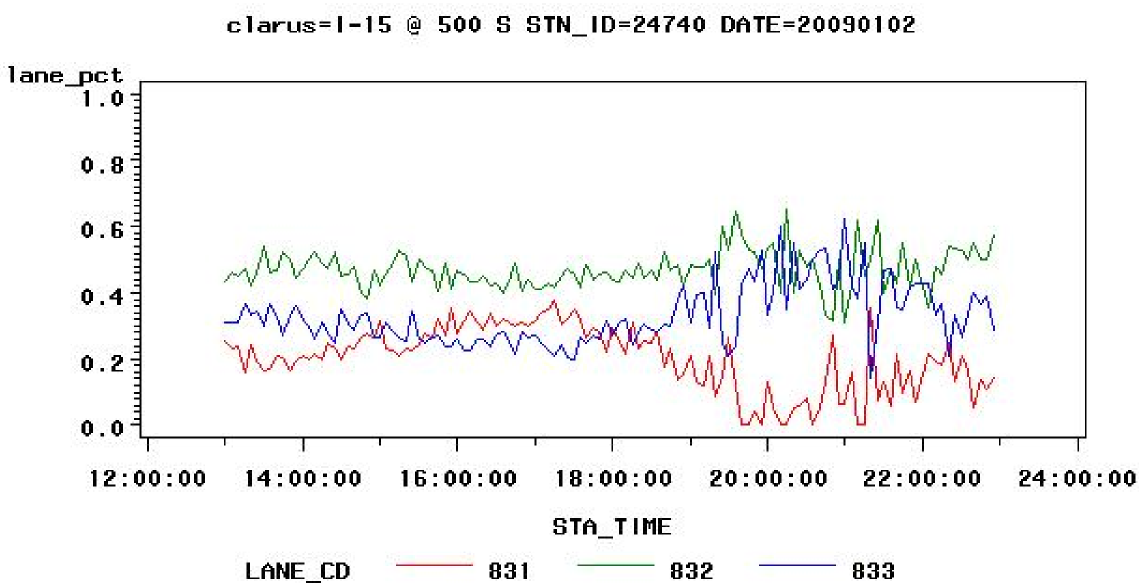
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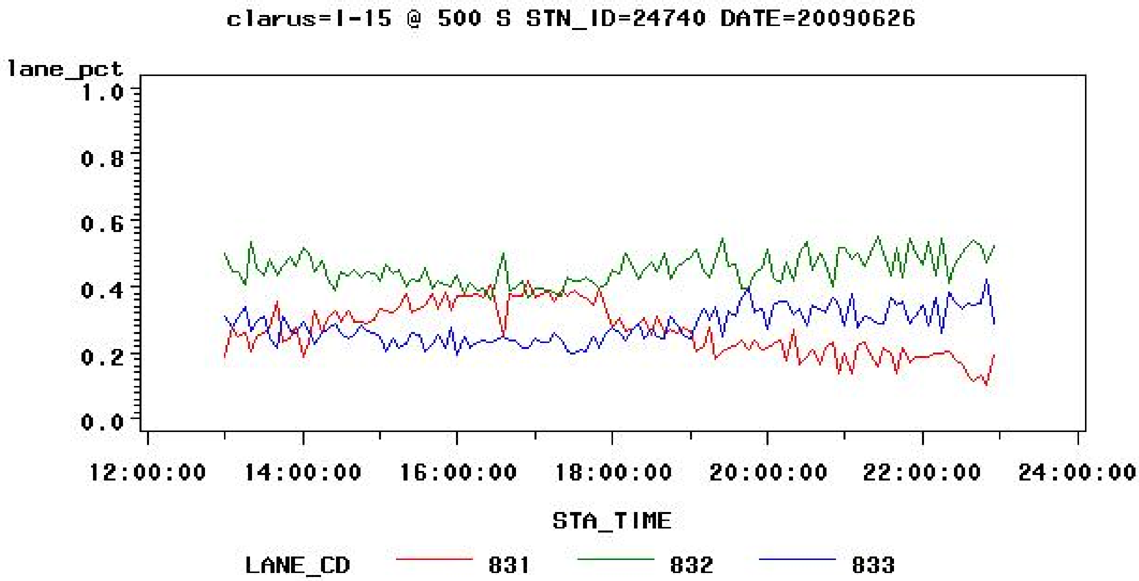
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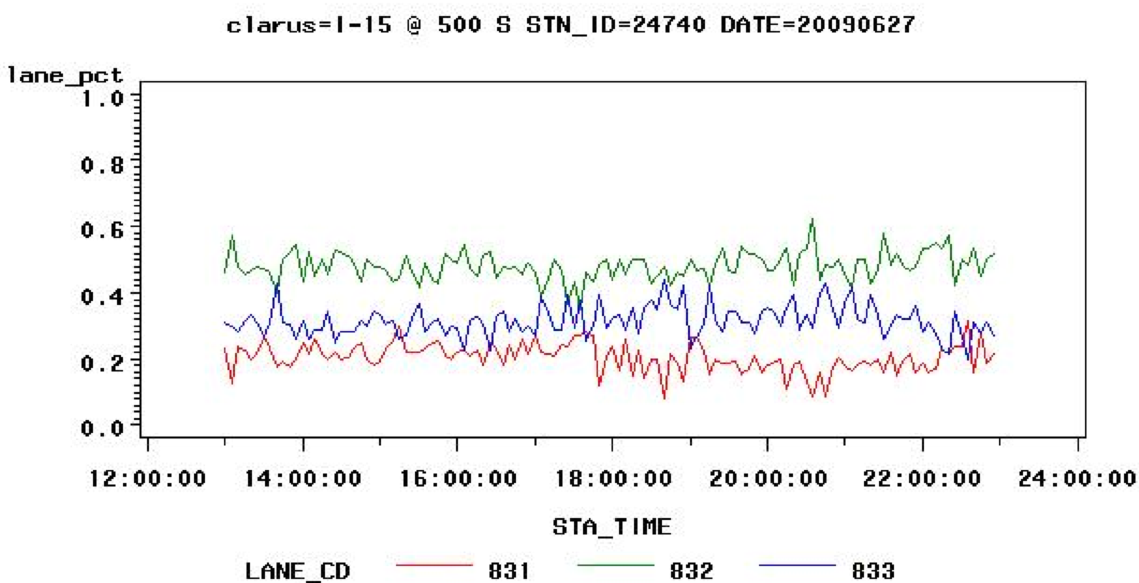
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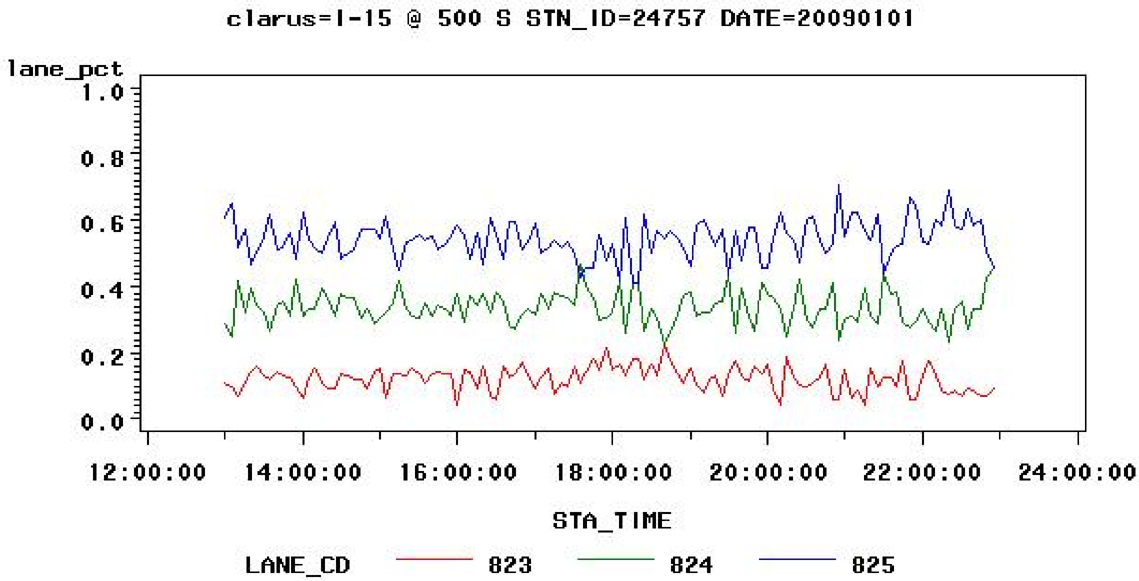
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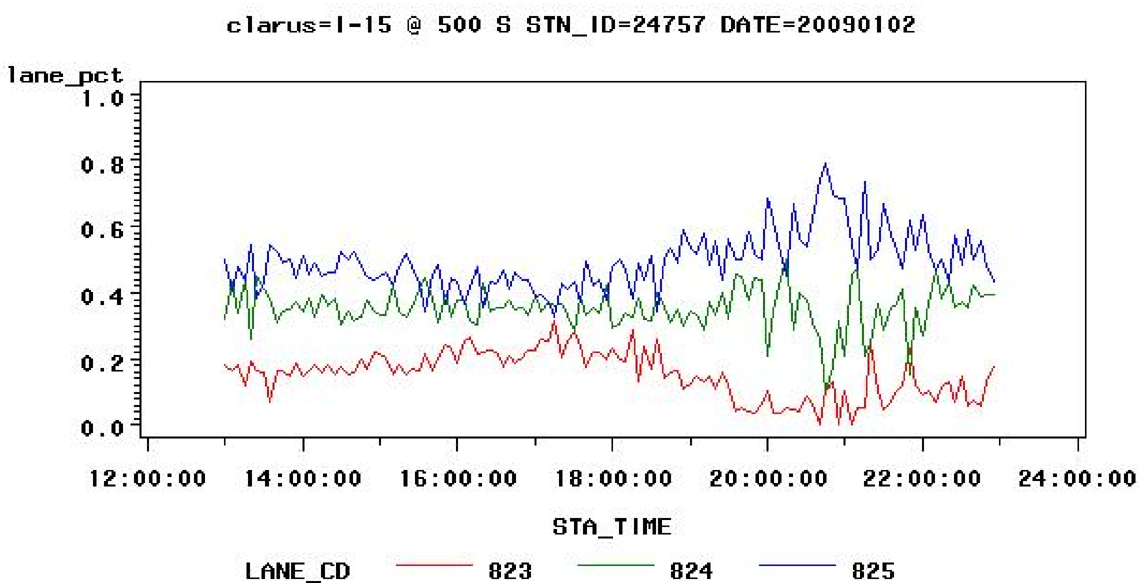
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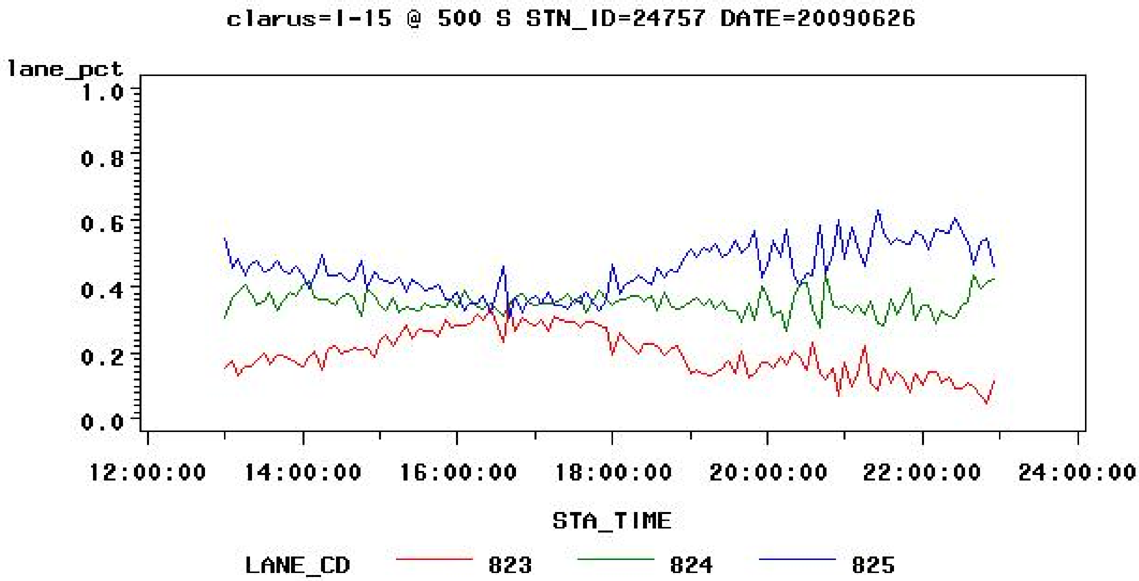
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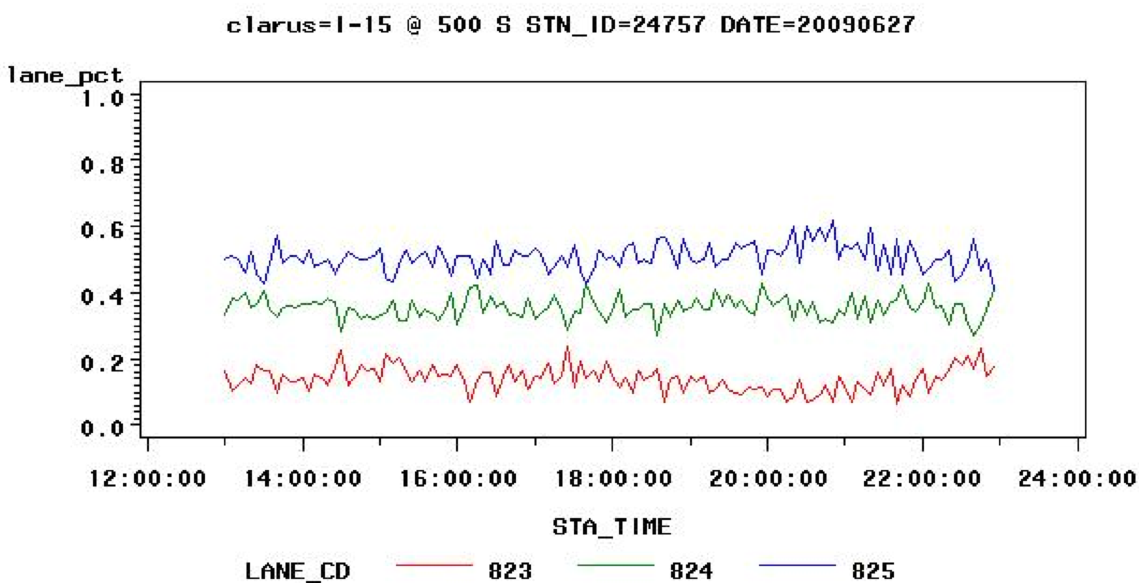
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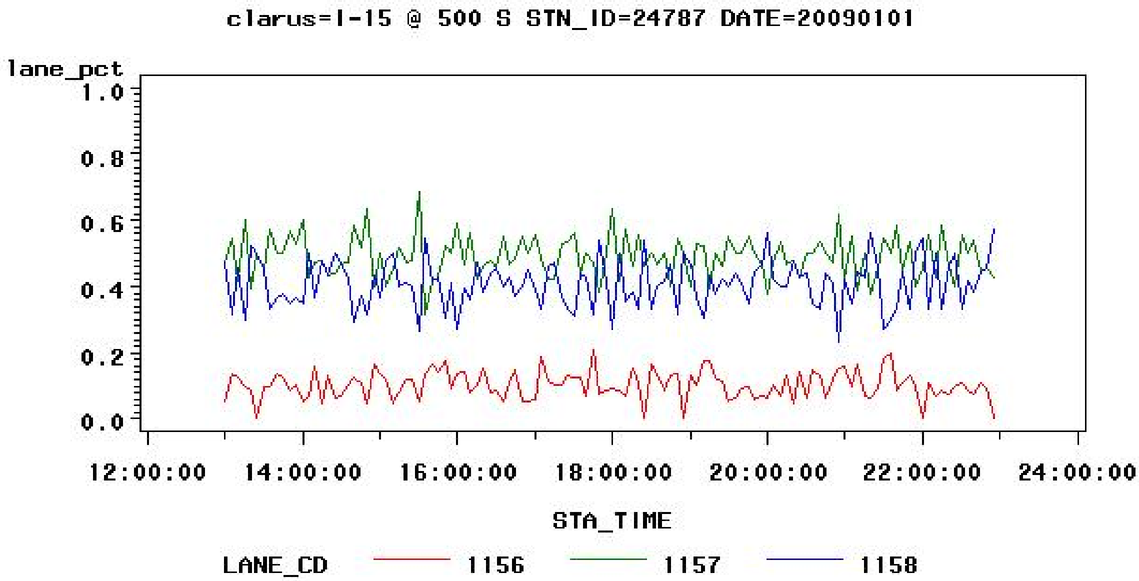
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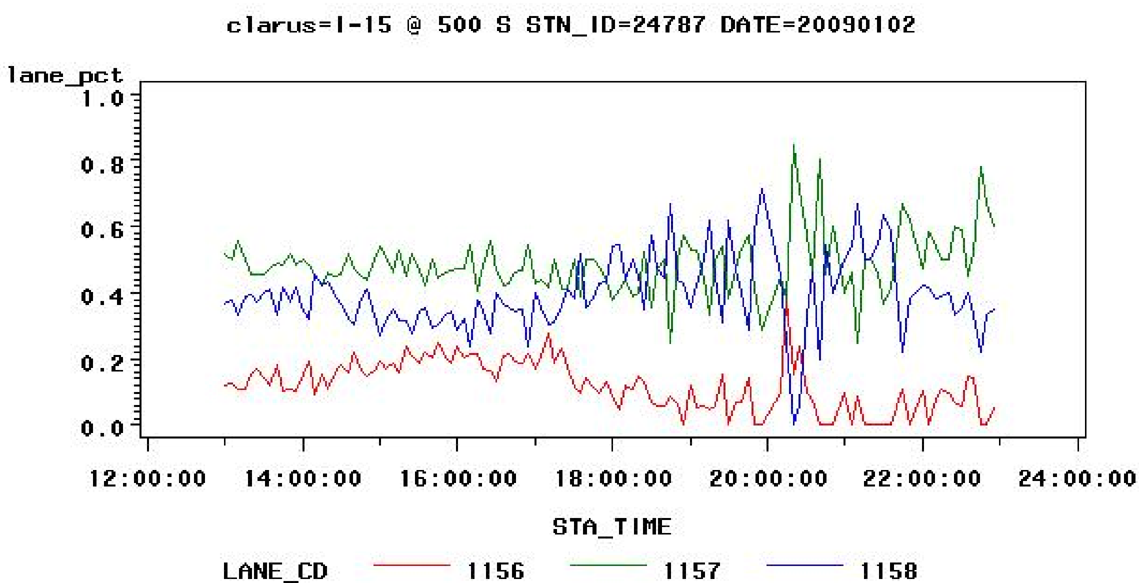
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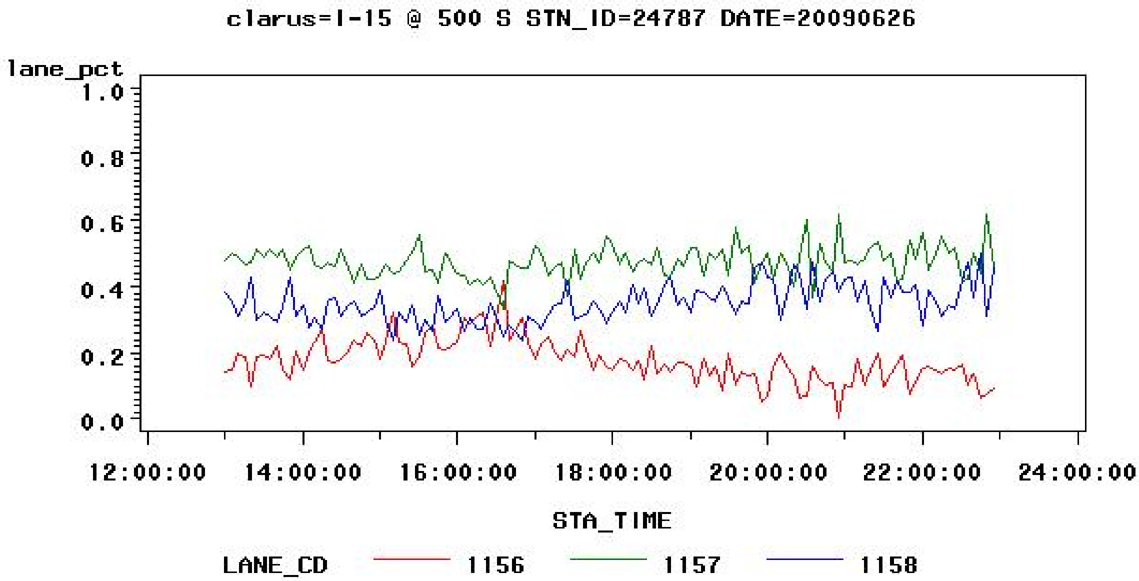
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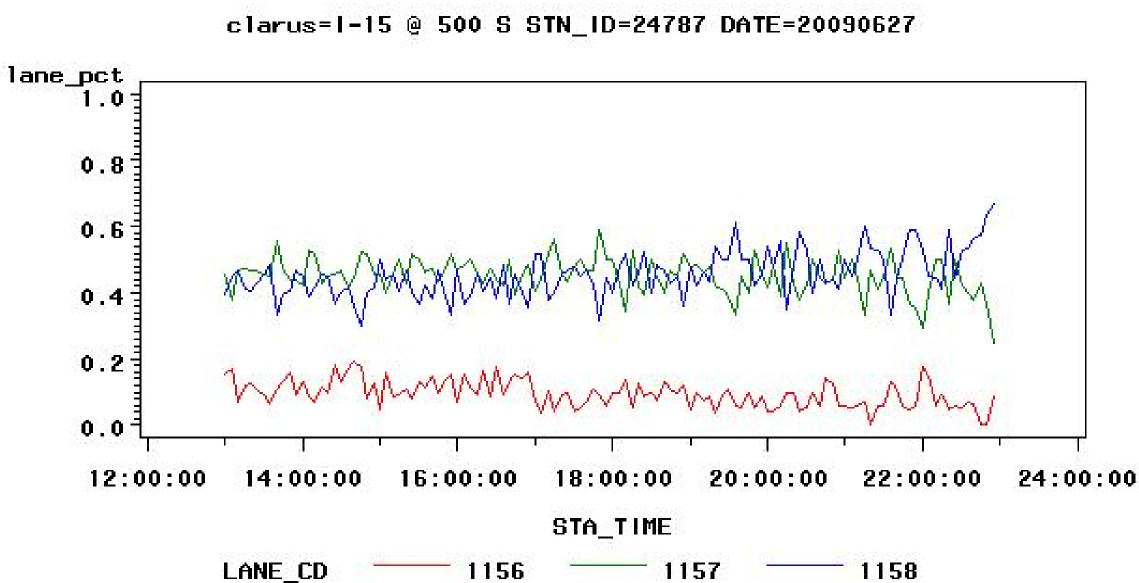
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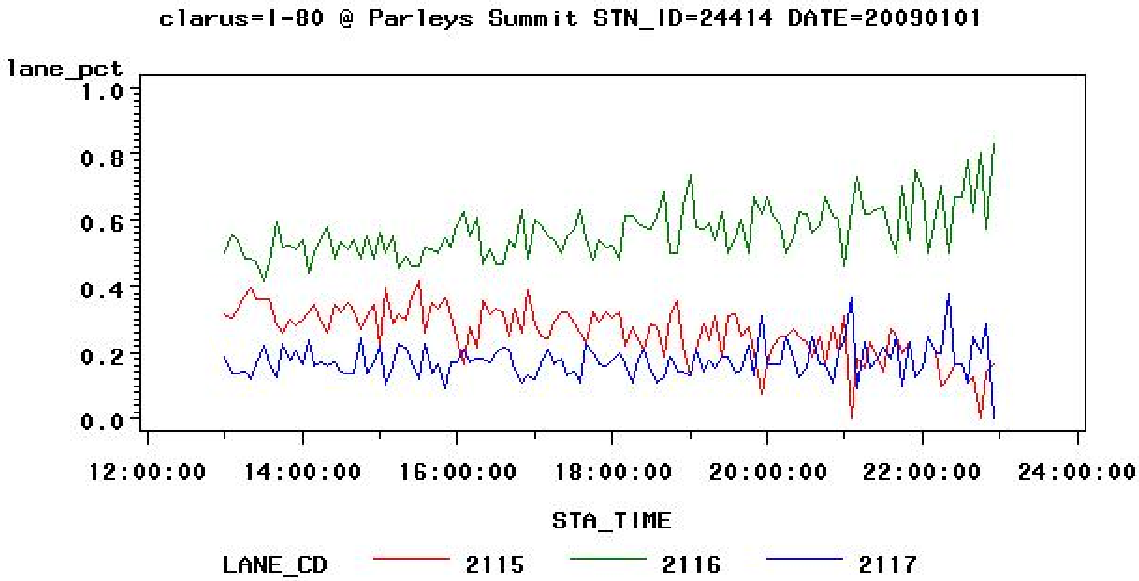
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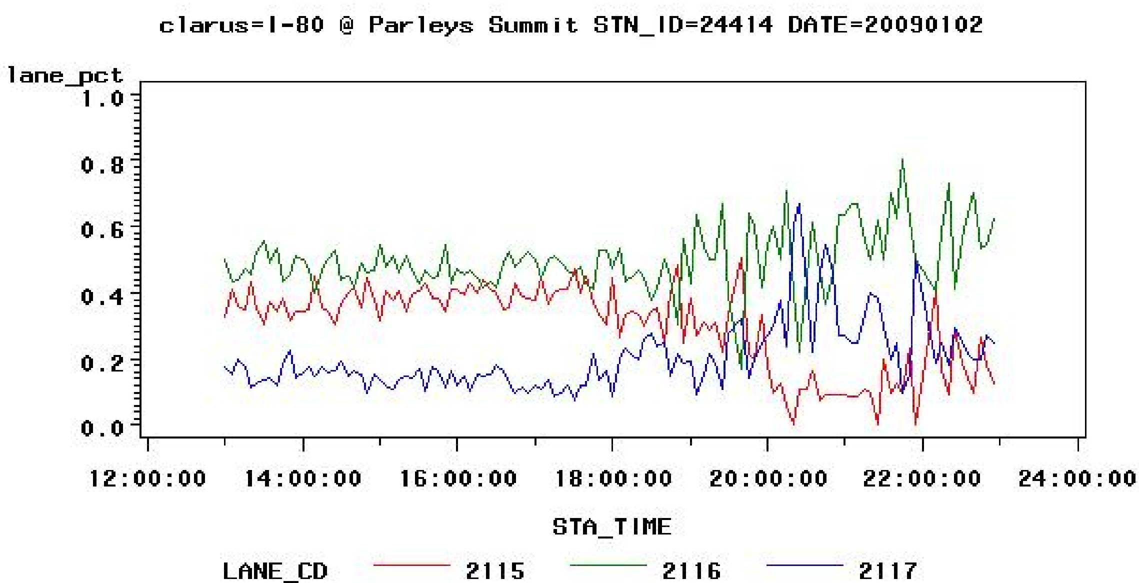
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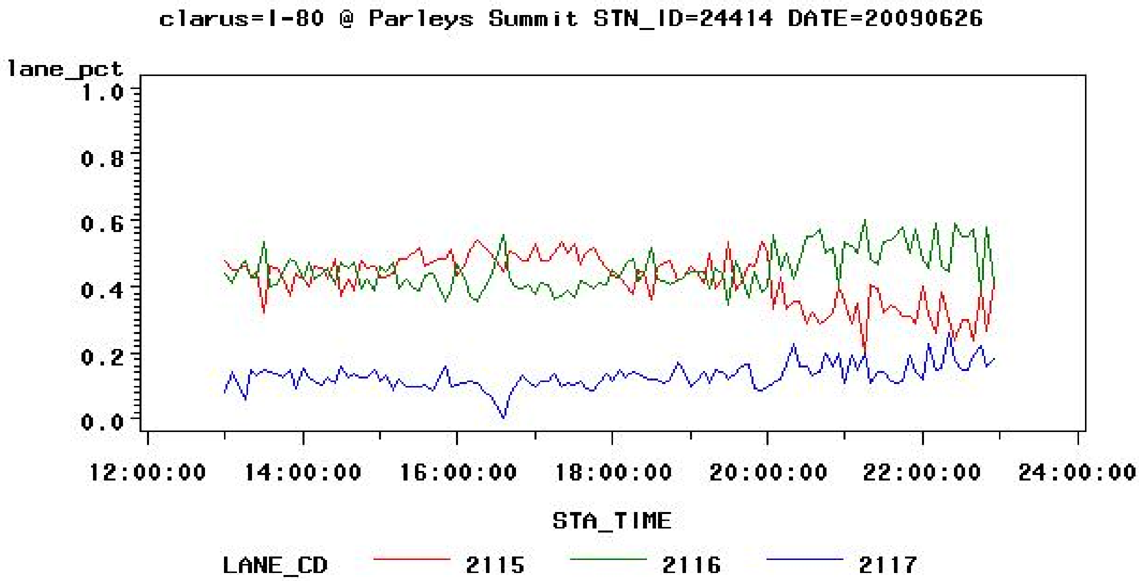
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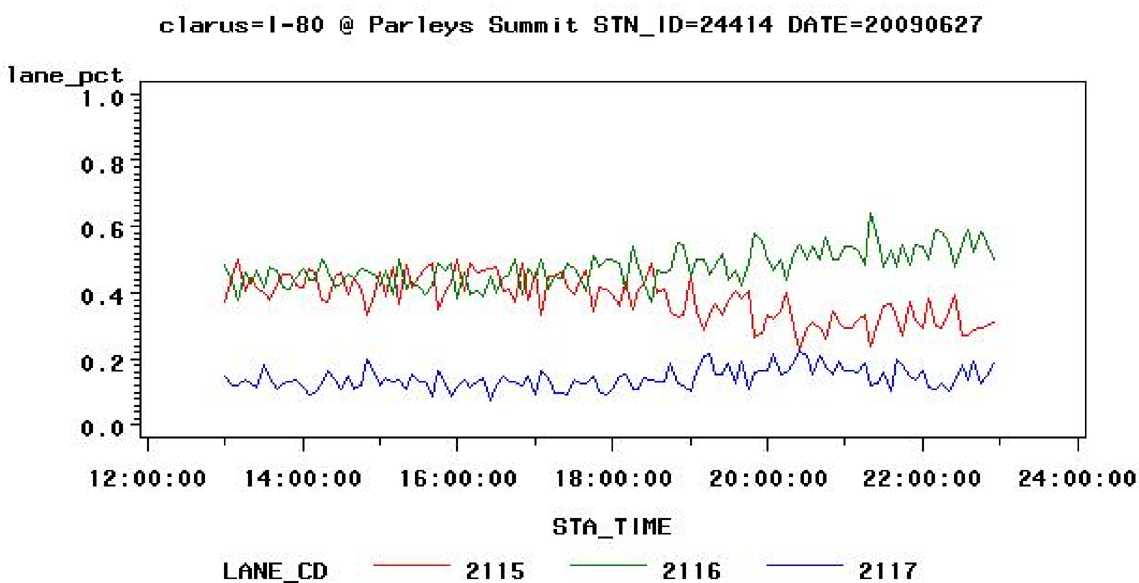
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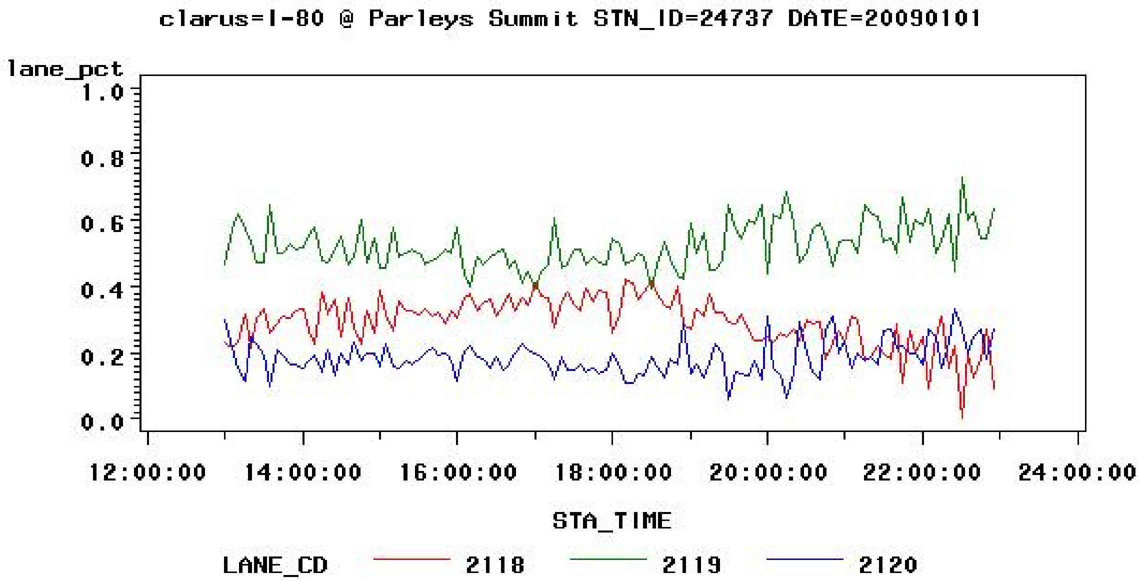
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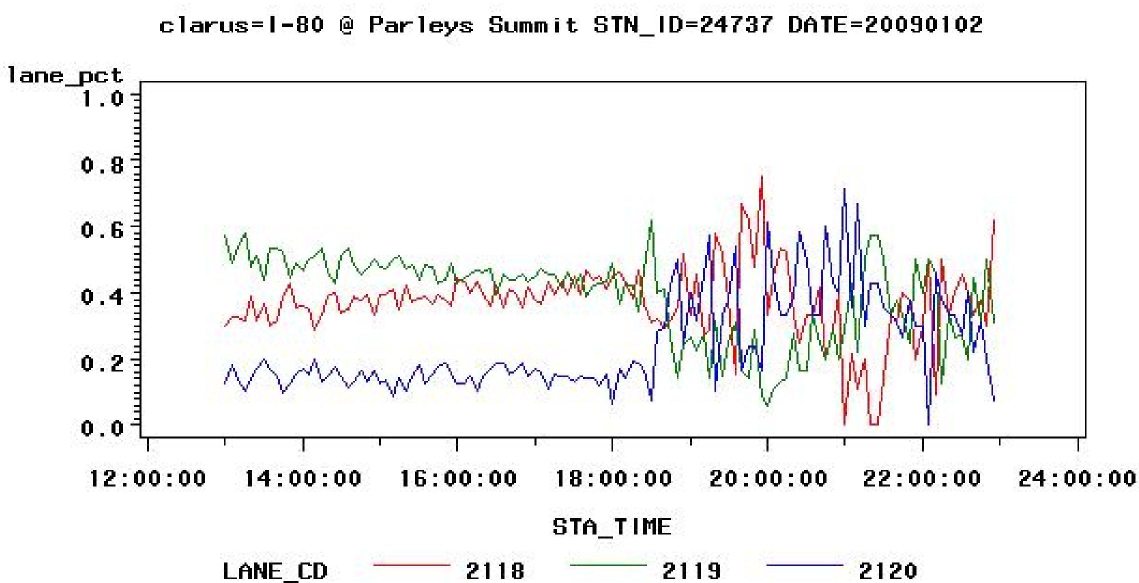
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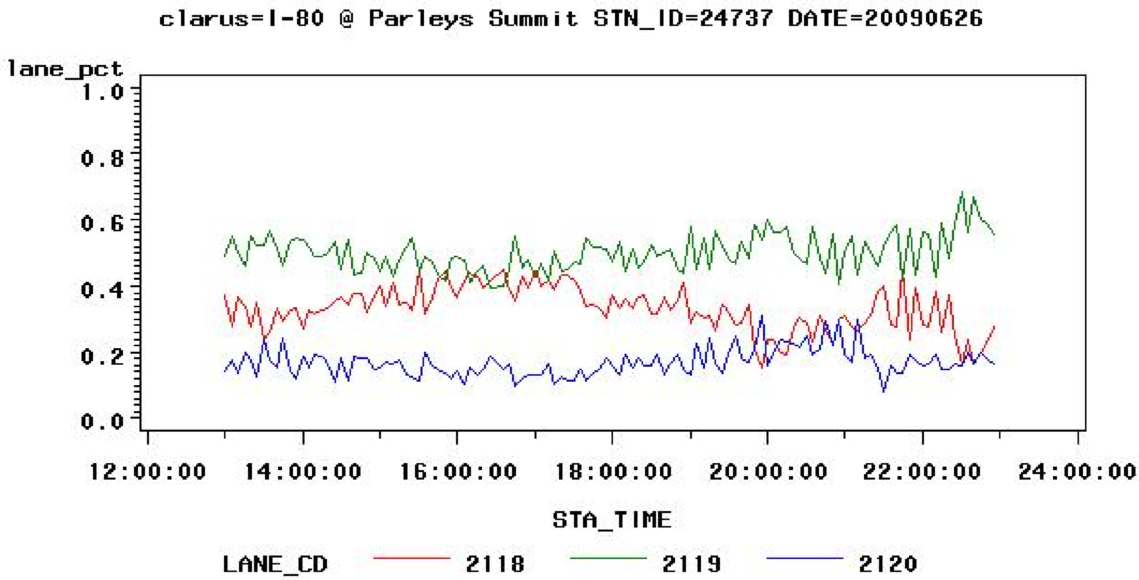
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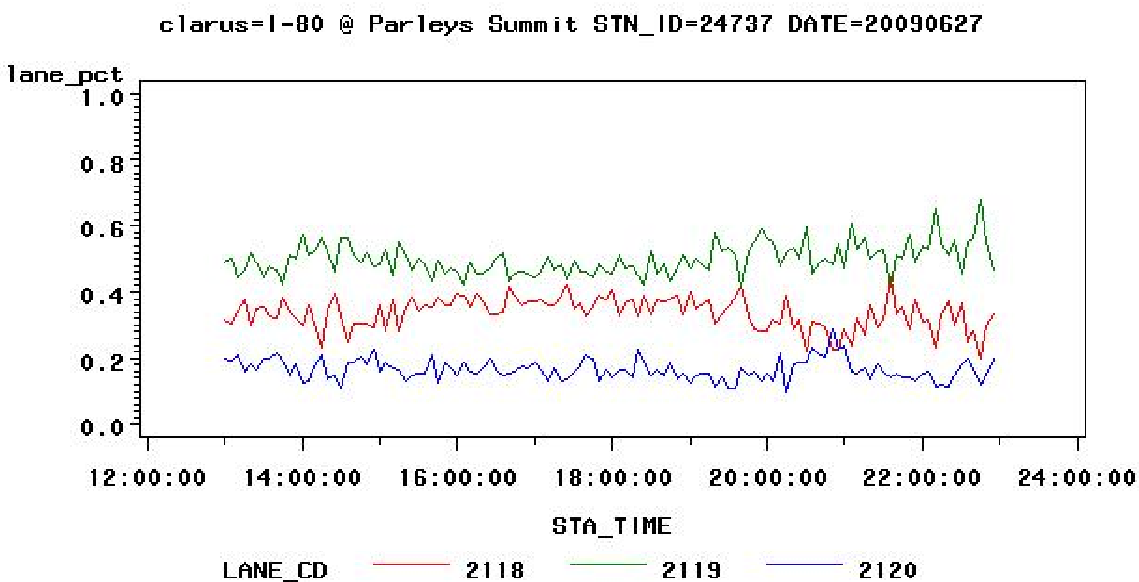
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APPENDIX B. Traffic Management Center Survey Results

The survey has **17** entries. Show details of all entries.

TMC Weather Data Questionnaire

1- Date:

17 responses view this question view all questions

2- Name of agency:

17 responses view this question view all questions

3- Name and title of the individual responding to questionnaire:

17 responses view this question view all questions

4- What types of weather data does your TMC collect and use?

Air Temperature	9	(53%)
Road Surface Temperature	5	(29%)
Road Subsurface Temperature	1	(6%)
Precipitation Status	10	(59%)
Precipitation Intensity	8	(47%)
Snow Depth	3	(18%)
Dewpoint/Relative Humidity	3	(18%)
Barometric Pressure	3	(18%)
Wind Speed and Direction	9	(53%)
Visibility	4	(24%)
Other	4	(24%)
If other, please specify	4	(24%)

5- What types of traffic data does your TMC collect and use?

Traffic Volumes	16	(94%)
Speeds	17	(100%)
Point to Point Travel Times	11	(65%)
Incident Detection and Clearance	17	(100%)
Video Data	15	(88%)
Other	3	(18%)
If other, please specify	3	(18%)

6- Please describe the primary sources of your weather data (National Weather Service, agency RWIS, Weather Channel, etc.)

17 responses view this question view all questions

7- How are these information used in the TMC?

Provide traveler information and advisories/warnings on road weather conditions (through 511, VMS/DMS, HAR, etc.).	13	(76%)
Implement weather responsive traffic control strategies (signal timing, ramp metering, and variable speed limits).	3	(18%)
Decide which weather-affected or prone areas (e.g., icy roads, flooding) to monitor with CCTVs, detectors, and other resources.	9	(53%)
Set priorities and strategies for snow removal or other maintenance activities (wind damage, flooding, etc.).	5	(29%)
Scheduling and planning of winter maintenance activity. Nonwinter maintenance activity (striping, pothole repair, etc.). (This is similar/related to 6d above, combine them.)	1	(6%)
Reposition/reallocate TMC staff or field maintenance personnel.	9	(53%)
Other.	3	(18%)
If other, please specify.	3	(18%)

8- Are there weather-responsive traffic management strategies you currently are not using, that you would like to implement? (Example, changing speed limits or ramp meter timing based on weather conditions). If “yes,” which strategies?

Provide traveler information and advisories/warnings on road weather conditions (through 511, VMS/DMS, HAR, etc.).	1	(6%)
Implement weather responsive traffic control strategies (signal timing, ramp metering, and variable speed limits).	5	(29%)
Decide which weather-affected or prone areas (e.g., icy roads, flooding, etc.) to monitor with CCTVs, detectors, and other resources.	1	(6%)
Set priorities and strategies for snow removal or other maintenance activities (wind damage, flooding, etc.).	3	(18%)
Scheduling and planning of winter maintenance activity. Nonwinter maintenance activity (striping, pothole repair, etc.). (This is similar/related to above, combine them.)	1	(6%)
Reposition/reallocate TMC staff or field maintenance personnel.	2	(12%)
Other.	0	(0%)
If other, please specify.	0	(0%)

9- Do you have any available background information on the strategies checked in Question 8, including the data that you will need?

Yes	3	(18%)
No	13	(76%)
No Answer	1	(6%)

10- If you will not be implementing any weather-responsive traffic management strategies at all, please state your reason(s).

3 responses **view this question** **view all questions**

11- Are you sponsoring any studies (theoretical or field) to examine the impact of weather on traffic? Has any university/research institution used your data for such task?

Yes	2	(12%)
No	15	(88%)
No Answer	**0**	(0%)

If "yes," is there a project description or study results available? If "no," are there plans to do so in the future?

6 responses **view this question** **view all questions**

12- Please describe any plans your agency has to expand traffic and weather data collection activities

12 responses **view this question** **view all questions**

13- If necessary, may we contact you for few follow-up questions or clarification on the responses you have provided?

Yes	14	(82%)
No	2	(12%)
No Answer	**1**	(6%)

APPENDIX C. Research Survey Results

The survey has **39** entries. **Show details of all entries**.

Researchers Questionnaire

1- Name:

38 responses view this question view all questions

2- Affiliation (University/Research center):

37 responses **view this question** **view all questions**

3- Title (Position):

36 responses **view this question** **view all questions**

4- E-mail:

37 responses **view this question** **view all questions**

5- Did you conduct any analysis using Weather data?

Yes (if "Yes," go to question 6)	25	(64%)
No (if "No," go to question 12)	13	(33%)
No Answer	1	(3%)

6- What analysis have you conducted using weather data?

Traffic flow impacts	18	(46%)
Traffic control	6	(15%)
Safety	13	(33%)
Human behavior	7	(18%)
Other	8	(21%)
If other, please specify	8	(21%)

7- How was your data analysis conducted?

Collected field data	23	(59%)
Used a driving simulator	1	(3%)
Used loop detector data	8	(21%)
Used in-vehicle data	4	(10%)
Used traffic simulation	8	(21%)
Other	8	(21%)
If other, please specify	7	(18%)

8- What sources of weather data did you use to conduct your analysis?

In-site weather stations	14	(36%)
Weather forecasting web sites	7	(18%)
Airport weather forecasting reports	3	(8%)
ASOS/AWOS automated observing systems	1	(3%)
Used Clarus weather database	1	(3%)
Used Road Weather Information System (RWIS)	6	(15%)
Other	8	(21%)
If other, please specify	7	(18%)

9- What were the weather variables that you analyzed in your analysis?

Precipitation (Rain/Snow)	24	(62%)
Visibility	9	(23%)
Ice	10	(26%)
Wind speed/direction	8	(21%)
Barometric pressure	3	(8%)
Temperature	14	(36%)
Other	7	(18%)
If other, please specify	6	(15%)

10- Did you face any restrictions and/or problems in accessing the weather data?

21 responses view this question view all questions

11- What were the limitations that you encountered with the weather data?

19 responses view this question view all questions

12- What types of data analysis would you like to conduct involving the use of weather data in the future?

Traffic flow impacts	28	(72%)
Traffic control	18	(46%)
Safety	30	(77%)
Human behavior	14	(36%)
Other	5	(13%)
If other, please specify	5	(13%)

13- What are your suggestions for future weather data collection?

21 responses **view this question** **view all questions**

14- Would you be willing to participate in follow-on survey related to weather data collection and usage?

Yes	29	(74%)
No	9	(23%)
No Answer	1	(3%)

The survey has **18** entries. Show details of all entries.

Follow-up Questionnaire

1- Name:

18 responses view this question view all questions

2- Affiliation (University/Research center):

18 responses **view this question** **view all questions**

3- Title (Position):

18 responses **view this question** **view all questions**

4- E-mail:

18 responses **view this question** **view all questions**

5- What would you use weather information for?

Study the impact of inclement weather of traffic stream behavior	16	(89%)
Study the impact of inclement weather on travel demand	7	(39%)
Study the impact of weather on driver departure time and route choice behavior	6	(33%)
Develop inclement weather traffic control strategies (signal timing, ramp metering, variable speed limits)	11	(61%)
Other	4	(22%)
If other, please specify	4	(22%)

6- For the analyses identified in (5), what level of resolution in weather data would you require?

Less than 5-minute	5	(28%)
Five-minute	4	(22%)
Between 5-minute and 15-minute	8	(44%)
Other	8	(44%)
If other, please specify	8	(44%)

7- What sources of traffic data do you need to conduct your analysis?

Aggregate loop detector data	13	(72%)
Disaggregate vehicle trajectory data (e.g., naturalistic data, GPS, etc.)	11	(61%)
Other	4	(22%)
If other, please specify	4	(22%)

8- What level of accuracy and resolution would you require in the traffic data to conduct your analysis?

16 responses **view this question** **view all questions**

9- What data would you require to integrate your weather and traffic data?

14 responses **view this question** **view all questions**

10- What are the sampling size issues that you would need to address to conduct your analysis?

14 responses **view this question** **view all questions**

11- What other data would you require?

Video data	4	(22%)
Incident data	12	(67%)
Work zone data	8	(44%)
Other	8	(44%)
If other, please specify	8	(44%)

12- What are your suggestions for future weather data collection and analysis?

11 responses **view this question** **view all questions**

APPENDIX D. Analysis of the Impact of Adverse Weather on Freeway Free-Flow Speed in Spain

D.1 General Data Overview

In this study, 15 locations from two Northwestern freeways in Spain have been studied in order to analyze the influence of adverse weather into traffic conditions. Weather stations and traffic stations were used to collect data between January 2006 and November 2008. Traffic stations collected data in a one-hour-based period, while weather stations collected data in a 15-minute period. In order to not lose precision, traffic intervals were split into four similar 15-minute intervals. Seven of those locations were from the A-6 10 freeway, covering 94.3 km; while eight stations belonged to the A-52 freeway, covering 57.4 km.

Both freeways are located in the Northern Spain, influenced by the Atlantic Climate. This region is the most cloudiest and wettest of Spain, with annual rainfall between 800 and 1,500 mm. Average temperatures are 9 ºC in winter and 18 ºC in summer.

Each one of the traffic stations was separated by an average distance of less than 100 m from its corresponding weather station. Thus, it can be considered that the weather conditions registered in the weather stations were the same than the registered on the road. Traffic data was registered in one-hour intervals, while meteorological data was registered in a 15-minute interval. In order to analyze and correlate traffic weather data, traffic data was split into 15-minute aggregation periods.

Traffic stations registered traffic volume, average speed, and truck percentage. Meteorological stations recorded a total of 16 weather variables:

- Snow layer depth (mm);
- Water layer depth (mm);
- Precipitation amount (last 24 hr), in mm;
- Wind direction (in a 360º base, North direction is 0º);
- Relative humidity (percent);
- Precipitation intensity (mm/hr), it may be rain or snow;
- Atmospheric pressure (bar);
- Global radiation;
- Salinity;
- Air temperature (ºC);
- Dew temperature (ºC);
- Freezing temperature (ºC);
- Road surface temperature (ºC);
- Road subsoil temperature (ºC);

- Wind speed (m/s); and
- Visibility index (m), from 0 (null visibility) to 2,000 (total visibility).

However, the authors only considered the following variables: truck percentage, visibility, wind speed, precipitation intensity, snow layer depth, and air temperature.

The results showed that the higher traffic volume recorded was 2,000 vph in both lanes, not reaching the capacity at any point and time. **Due to low traffic volumes reached, it was only analyzed the speed in free-flow conditions. Consequently, the traffic volume was not considered as an independent variable for the regression analysis for the speed and climate relationship.** The average speed in each site varied from 100 to almost 140 km/hr. Traffic volumes under 80 vph were taken out from the analysis. Besides that, there were used only daily data, in order to not consider an additional variable.

The paper divided the data into four main climates as follows:

Climate 1. This includes all no-rain and no-snow situations, only if air temperature is above 0 ºC. Weather variables considered in this case are heavy traffic percentage, visibility, and wind speed. It is considered as the neutral climate, in order to compare the rest of climates to it.

Climate 2. This is a similar climate to the previous one, but only considering below 0 ºC situations.

Climate 3. This includes rain situations. Weather stations used in this research did not distinguish between rain or snow precipitation, so it only considers above 0 ºC precipitation, assuming that in most cases it will be rain. Another variable considered in this analysis, besides those ones considered in Climates 1 and 2, is the precipitation intensity.

Climate 4. This includes snow situations. As mentioned before, the difference between this climate and Climate 3 is that in this case the air temperature is below 0ºC. It also gathers all cases in which there is a snow layer over the road pavement, regardless of the air temperature. Besides all variables considered in Climates 1, 2, and 3, in this case also is analyzed the depth of the snow layer as an independent variable.

Regarding the given data file, the data excel file consists of **9 sheets** divided as follows: Climate 1, Climate 2, Climate 3, Climate 4, Good Weather Conditions, High Wind Conditions, Rainy Conditions, Snowy Conditions, and Foggy Conditions, as follows:

Climates 1, 2, 3, and 4:

Hourly data for 21 columns which are:

Month, Hour, Traffic Volume (vph), Average Speed (km/hr), and Truck Percent, added to the 16 weather variables mentioned previously.

Climate 1: 24322 observations.

Climate 2: 643 observations.

Climate 3: 1,086 observations.

Climate 4: 417 observations.

Good Weather Conditions, High Wind Conditions, Rainy Conditions, Snowy Conditions, and Foggy Conditions.

Fifteen-minute data for 24 columns which are:

Year, Month, Day, Hour, Minutes, Traffic Volume, Average Speed, and Truck Percent, added to the 16 weather variables mentioned previously.

Good weather conditions (precipitation = 0): 308 observations.

High wind conditions: 256 observations.

Rainy conditions: 264 observations.

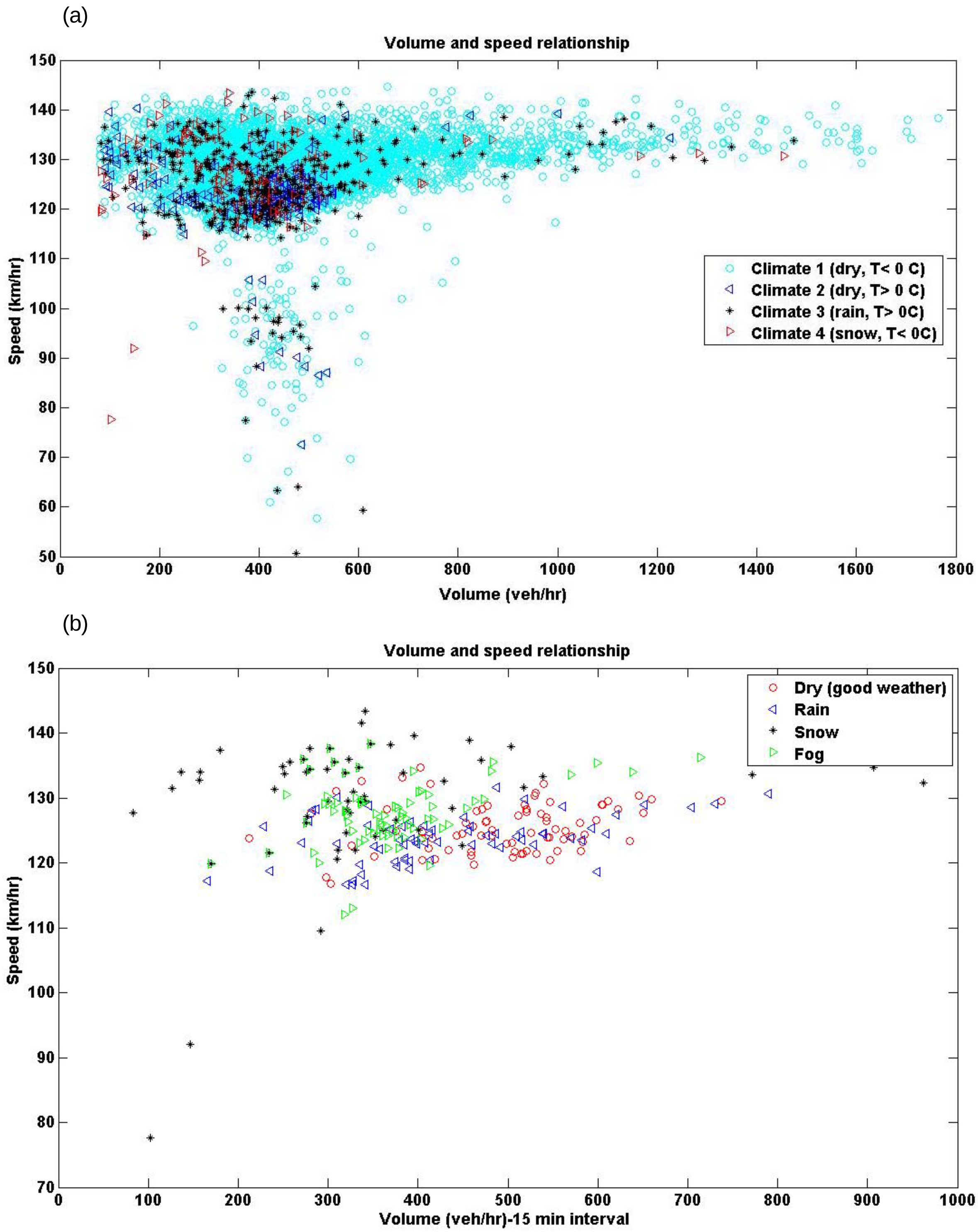
Snowy conditions: 239 observations.

Foggy conditions: 308 observations.

Using the provided data, the relationship between the speed and the corresponding volume was plotted for the different climate classifications (Climate 1, 2, 3, and 4) as shown in Figure D.1 (a). In addition, the given data was plotted using the four general climate categories (good weather, rain, snow, and fog) as presented in Figure D.1 (b).

The given volumes are for a two-lane freeway segment and it was assumed that the volumes are distributed equally between those two lanes. It is noticeable from the plotted figures that the speed range for most of the given data is between 110 km/hr and 140 km/hr. As a result, the data points are not covering the different speed ranges for both congested and uncongested traffic regime. Therefore, it could be stated that the provided data could not be used for the calibration of main traffic stream parameters (speed, volume, and density). In addition, the data is not considered valid for the microscopic analysis of traffic flow in inclement weather.

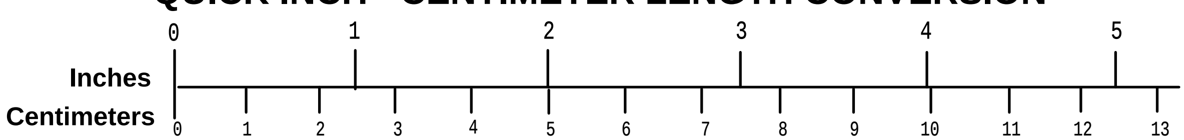
Figure D-5 Speed (km/hr) and Volume (vph/hr) Relationship for the Different Climate Classifications per Lane



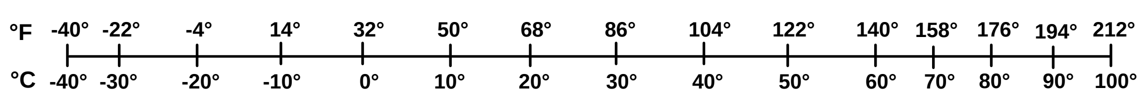
APPENDIX E. Metric/English Conversion Factors

ENGLISH TO METRIC			METRIC TO ENGLISH		
LENGTH (APPROXIMATE)			**LENGTH (APPROXIMATE)**		
1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)			**AREA (APPROXIMATE)**		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT (APPROXIMATE)**		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME (APPROXIMATE)**		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE (EXACT)**		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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