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ANALYSIS OF USING V2X DSRC-EQUIPPED SNOWPLOWS TO REQUEST SIGNAL PREEMPTION

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RESEARCH

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Keeping Utah Moving
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16. Abstract

For the 2019-2020 winter season, vehicle-to-everything (V2X) systems using dedicated short-range communications (DSRC) were placed on Utah Department of Transportation (UDOT) snowplows and state routes to test the effectiveness of snowplows requesting signal preemption from traffic controllers. This study was done to understand the impacts and benefits of using signal preemption with snowplows. There were five corridors throughout the Salt Lake metropolitan area that had roadside units (RSUs) deployed. Analysis was divided into traffic signal and snowplow and vehicle efficiency impacts. Results were analyzed for the system overall, by the different routes, and were compared to similar not-equipped routes. For the traffic signal analysis, it was found that the system is being used often, with snowplows requesting preemption over 50 percent of the time they approached a signalized intersection. Of those requests, signal controllers granted preemption over 80 percent of the time. On average, this affected the signal controller phasing and its return to coordinated status for less than 5 minutes. For vehicle performance analysis, traffic on equipped routes traveled at speeds closer to the associated posted speed limits when compared to corresponding not-equipped routes. Vehicle crash data showed that there was a greater decrease in crashes on equipped routes than not-equipped routes. Snowplows also stopped fewer times due to requesting signal preemption. Anecdotal evidence from snowplow drivers indicates a benefit to overall operations on corridors equipped with the V2X system.

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
ATSPM	Automated Traffic Signal Performance Measures
AVL	Automatic Vehicle Location
BRT	Bus Rapid Transit
BSM	Basic Safety Message
CAV	Connected and Automated Vehicle
CV	Connected Vehicle
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communication
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
LOM	Level of Maintenance
LOS	Level of Service
MAP	Map Data Message
MOE	Measures of Effectiveness
MVMT	Million Vehicle Miles Traveled
OBU	Onboard Unit
PDO	Property Damage Only
RSU	Roadside Unit
RWIS	Road Weather Information System
SAE	Society of Automotive Engineers
SII	Storm Intensity Index
SLC	Salt Lake Central
SPaT	Signal Phase and Timing
SRM	Signal Request Message
SSI	Storm Severity Index
SSM	Signal Status Message
TAC	Technical Advisory Committee
TRB	Transportation Research Board

TSP	Transit Signal Priority
TWLTL	Two-Way Left-Turn Lane
UDOT	Utah Department of Transportation
UTA	Utah Transit Authority
UVX	Utah Valley eXpress
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
WRWI	Winter Road Weather Index

EXECUTIVE SUMMARY

In 2018, a joint project between the Utah Department of Transportation (UDOT) and the Utah Transit Authority (UTA) deployed a vehicle-to-everything (V2X) system using dedicated short-range communication (DSRC) on UTA buses to request transit signal priority (TSP). Following this study, UDOT expanded the system to include snowplows capable of requesting signal preemption. This occurred in 2019, with five state routes in the Salt Lake City metropolitan area equipped with V2X technology. Comparable not-equipped corridors were selected to be used in analyzing the impacts of snowplows using V2X systems with DSRC. To communicate these signal preemption messages, UDOT snowplows in Region 2 were equipped with onboard units (OBUs), which used DSRC to send out signal preemption requests. Various intersections along the equipped routes were installed with roadside units (RSUs), V2X technology that interpreted the DSRC messages from the snowplows.

Two types of analysis were performed to understand the impacts that snowplows requesting signal preemption had on traffic signal performance and vehicle performance. Signal performance analysis was done to determine how snowplows with V2X systems using DSRC affected signals. Vehicle performance analysis was done to see if snowplow and/or background traffic efficiency and performance were improved by V2X systems using DSRC, as well as to evaluate the safety implications of signal preemption using DSRC.

To perform the signal performance analysis, V2X data were collected to understand how often signal preemption was requested by snowplows, how often it was granted by signal controllers, and how long preemption requests affected signal controller timing. V2X data included data depicting DSRC and automated traffic signal performance measures (ATSPM). Snowplows requested preemption over 50 percent of the time they approached a signalized intersection. Of messages that requested signal preemption, over 80 percent were granted. On average, signal controllers are affected by preemption processing for less than five minutes. This shows that the system works as designed, is used often, and does not have adverse effects on signal controllers.

Data for vehicle performance analysis compared snowplow and traffic performance on equipped and not-equipped routes. This included analysis of snowplow speed data from NetworkFleet, general travel speed data from ClearGuide, and crash data from AASHTOWare Safety. These were collected to analyze the effects of snowplows requesting signal preemption on vehicle performance. The analysis showed that snowplow speeds are not changed due to the signal preemption system, due to variations of types and amounts of snow and the cap in maximum speeds on the plows. However, anecdotal evidence showed the number of times snowplows stopped was reduced. General travel speeds on equipped routes were more consistently closer to the speed limits than not-equipped routes. Crash data showed a greater negative decrease on equipped routes than on not-equipped routes. These findings showed minimal changes or impacts to vehicle performance, but anecdotal evidence from snowplow drivers indicates benefits from the system overall.

There were various limitations in the analysis. Data granularity differed among datasets, making comparison between the different datasets impossible without reducing data integrity. Also, some datasets did not have much data, making statistical significance unclear. With these data limitations, conclusions were drawn, but do not fully describe all the potential benefits and impacts of snowplows with V2X systems that use DSRC to request signal preemption.

It is recommended that research continue on this project to better understand the impacts that snowplows requesting signal preemption have on different maintenance metrics, such as fuel usage and time spent plowing. It is also recommended that the data used for this analysis be explored for ways to improve the granularity.

1.0 INTRODUCTION

1.1 Problem Statement

Each year, 70 percent of all roadway networks, as well as 70 percent of the population in the United States, experiences five or more inches of snow (FHWA 2020b). These storms create poor driving conditions, including icy roads and poor visibility. This is particularly true in Utah. As the population within the state continues to grow, the Utah Department of Transportation (UDOT) has continued to place great importance on timely maintenance during these winter storms. Like most departments of transportation (DOTs), UDOT's goal each year with winter maintenance is to minimize fatalities and maintain network flow.

To provide safe conditions for drivers, UDOT has a winter maintenance budget of about $24 million, with each snowstorm costing an average of $1 million in maintenance costs (UDOT 2017). UDOT maintenance costs include fuel costs for snowplows, material placed on streets, labor costs for snowplow drivers, and other overhead costs. UDOT snowplows clear all state-owned roads, which includes interstates and state routes. To minimize such costs, states with large amounts of snowfall continue to do research to optimize winter operations.

Research studies conducted on winter maintenance operations have historically focused on snowplow blade type, snowplow route optimization, and material used on roadways. Winter maintenance research is beginning to branch into other areas within the transportation realm. A newer initiative for many DOTs is analyzing the benefits of technology within the driving experience. Along with private firms, DOTs have begun to explore the benefits of vehicle-to-infrastructure (V2I) systems. Many DOTs are looking to where V2I systems can create benefit, such as in increased efficiency in transportation systems, greater overall safety, and more timely transit schedules.

Dedicated short-range communication (DSRC) is a popular vehicle-to-everything (V2X) system that is used by DOTs in the study and application of connected and automated vehicle (CAV) technology. DSRC has proven to be an effective way for a vehicle to communicate with other vehicles or transportation infrastructure. In 2018, UDOT and the Utah Transit Authority (UTA) combined forces on a joint research project involving V2X systems which used DSRC.

The systems were used to request transit signal priority (TSP) for buses along Route 217 on Redwood Road. The use of DSRC helped increase schedule reliability of the buses. Due to the success, V2X systems using DSRC were expanded to include the bus rapid transit (BRT) route for UTA in the Provo/Orem area (Leonard 2019, Schultz et al., 2020, Sheffield et al., 2021).

In part, based on the success of V2X systems using DSRC to request TSP on buses, UDOT searched for other ways to utilize this system. As part of their efforts to create safer conditions during winter storm events, UDOT explored the usage of V2X systems using DSRC in their snowplow operations. These systems would use DSRC to request signal preemption for snowplows.

1.2 Objectives

The primary objective of this research project was to evaluate and investigate the range of benefits and expected impact using DSRC-equipped snowplows that can make use of signal preemption compared to snowplows operating on similar corridors without preemption.

1.3 Scope

The data for this study were collected during the 2019-2020 snow season. The COVID-19 pandemic did not affect data collection as there were no winter weather events past the outbreak and quarantine that began in March. Five routes in the Salt Lake City area were chosen and equipped with V2X technology for the study. These routes were compared to similar routes that were not equipped with V2X technology. The selected equipped routes for the study include:

- SR-209: West 9000 South (from 4000 West to Redwood Road)
- SR-209: East 9000 South/9400 South (from 700 East to Wasatch Boulevard)
- SR-68: Redwood Road (from 12600 South to 400 South)
- SR-71: 700 East/900 East (from 9000 South to 3300 South)
- SR-186: Foothill Drive (from I-80 to 1300 East)

1.4 Outline of Report

The body of the report is outlined as follows:

- Chapter 1 includes an introduction of the research, project objective and scope, and the organization of the report.
- Chapter 2 includes a literature review summarizing current research related to assessing effects of winter storms, costs of snowplow operations, datasets used in winter maintenance, V2X systems using DSRC, and signal preemption.
- Chapter 3 includes a discussion of methods used to assess the impacts that DSRC systems on snowplows which requested signal preemption had on signal and vehicle performance.
- Chapter 4 includes discussion on the data collection, analysis, and results used to determine signal performance. V2X data were analyzed and included DSRC and automated traffic signal performance measures (ATSPM) message record logs.
- Chapter 5 includes discussion on the data collection, analysis, and results used to determine vehicle performance. Both snowplow and general traffic performance were analyzed. Data analyzed include snowplow speed, travel speed, and safety data.
- Chapter 6 includes conclusions from the research, recommendations for future use and research, and other concluding remarks.

References and appendices follow the main chapters. Each appendix contains information which supplements portions of the report. Appendices A and B contain information about signals on equipped routes, including identification and location information. Appendices C and D analyze signal performance per segment by signal and are displayed graphically. Appendix E lists travel speed limits for equipped and not-equipped routes.

2.0 LITERATURE REVIEW

2.1 Overview

This chapter provides a review of the literature that is relevant to this research. This research analyzes V2X systems that use DSRC in requesting signal preemption for snowplow operations. The information in this review was gathered from literature published by various national organizations, such as the Transportation Research Board (TRB), the Federal Highway Administration (FHWA), the Clear Roads research consortium, and other DOT publications.

The objectives of this literature review are to identify and summarize literature involving the effects of winter storms on transportation systems, the benefits of snowplow operations, datasets used for optimization of winter maintenance programs, the components of V2X systems using DSRC, and the application of signal preemption. The findings are discussed in the following sections.

2.2 Effects of Winter Storms

The effects of winter storms are extensive. Each winter storm event causes costs derived from maintenance, travel delay, and weather-related crashes. State and local agencies often carry the weight of the cost of winter maintenance, which is more than $2.3 billion annually. For a state DOT, these costs are approximately 20 percent of their maintenance budget (FHWA 2020b). These efforts are made to provide safer driving conditions for users. The impacts on travel and safety are discussed further in the following subsections.

2.2.1 Impacts on Travel

As a winter weather event begins, there is typically a reduction in pavement friction due to ice and snow compacted on the roadway. Based on drivers' perception of roadway conditions, most users will decrease their travel speeds during winter storm events (Holik et al., 2015). The FHWA has found that average arterial speeds decline by 30 to 40 percent for snowy and slushy pavements. On freeways, speeds can be reduced by 3 to 13 percent in light snow and by 5 to 40 percent in heavy snow (FHWA 2020b).

Various studies have been conducted across the United States to determine speed reductions during winter weather. In Baltimore, Minneapolis, St. Paul, and Seattle, speeds were reduced by 5 to 16 percent on average due to snow (Hranac et al., 2006). Volume and capacity reductions have also been found, as shown in Table 2.1. The reduced visibility and traction during a winter storm not only decreases driving speeds, but also reduces acceleration and increases headway. This leads to a decrease in the effectiveness of traffic signal plans and roadway capacity (FHWA 2020a).

Table 2.1 Traffic Flow Reductions on Freeways Due to Winter Weather (FHWA 2020a)

Weather Conditions	Freeway Traffic Flow Reductions			
	Average Speed (%)	Free Flow Speed (%)	Volume (%)	Capacity (%)
Light Rain/Snow	3 – 13	2 – 13	5 – 10	4 – 11
Heavy Snow	5 – 40	5 – 64	30 – 44	12 – 27
Low Visibility	10 – 12	N/A	N/A	12

Traffic volumes are also affected during winter storms. Research conducted by Hanbali (1992) throughout the midwestern and northeastern United States showed that the greater the snowfall, the greater the traffic volume reduction. Volume is reduced at different times of day, with PM peak volumes being less impacted when compared to AM peak volumes. There is a large difference in volume during off-peak hours, suggesting drivers will alter their travel if possible. Datla et al. (2013) analyzed 15 years of traffic and weather data to better understand the variations of traffic volumes during winter storms. Over the winter weather season, drivers adapt to the weather conditions, leading to more variance in traffic volume distribution from the beginning of the season to the end. During winter storms, commuter routes have little variance in traffic volumes, whereas non-commuter routes experience larger variation in traffic volumes. On average, overall traffic volumes are lower during winter storm events than normal average volumes. The study also saw an increase in commercial vehicles on main arterials during winter storm events, due to their required schedule and being forced from minor roads that had minimal winter maintenance performed.

With the reduction of travel volumes and travel speeds during winter weather, travel delay is increased. To the user, traffic congestion can be costly, which is estimated at $190 billion in user costs per year (Schrank et al., 2021). About 15 percent of congestion is due to weather events, leading to almost $28.5 billion in user costs per year resulting from the weather (Cambridge Systematics Inc. and Texas Transportation Institute, 2004). Specific to the freight industry, delay costs from weather events are estimated to be more than $8 billion annually (Krechmer et al., 2012). Winter weather affects travel time, speed, and costs for both individuals and businesses.

2.2.2 Impacts on Safety

Safety is a great concern during winter weather conditions. The FHWA reports that each year in the United States, 24 percent of weather-related crashes happen on snowy, slushy, or icy pavement. Of those crashes, 15 percent occur during snowfall or sleet, which result in over 1,300 people that are killed and over 116,800 that are injured (FHWA 2020b). These statistics drive DOTs to spend millions of dollars on winter maintenance each year.

Poor pavement condition can increase the risk of a crash. Figure 2.1 shows different winter pavement conditions (SRF Consulting Group, 2016). These conditions also affect the level of maintenance (LOM) for the roadway (Fay et al., 2015). Similar to level-of-service (LOS) categorizations, the better the LOM, the more easily traffic can travel on the roadway. Bare pavement, or LOM A, may be wet, but has been cleared by extensive plowing and chemical use. This condition is ideal and traffic resumes at normal travel speeds. Bare wheel paths, or LOM B, may have some slush, but plowing and chemicals have removed most of the snow. There is typically no snow in the wheel path, but there may still be some on the roadway. With conditions like these, the road is almost at normal travel. Plowed and treated roads, which may or may not have a wheel path visible, but typically have some snowpack remaining, are LOM C. Plowing and chemicals have been used to remove snow, but travel speeds are reduced. Plowed-to-snowpack roads may be having maintenance performed, but the snowpack remains on the road, resulting in a poor condition and an LOM D. Traveling is diminished, and without maintenance, approaches the point when using the roadway is inadvisable. These various pavement surface conditions lead to crashes, even when snowplows are performing maintenance (Fay et al., 2015, SRF Consulting Group, 2016).

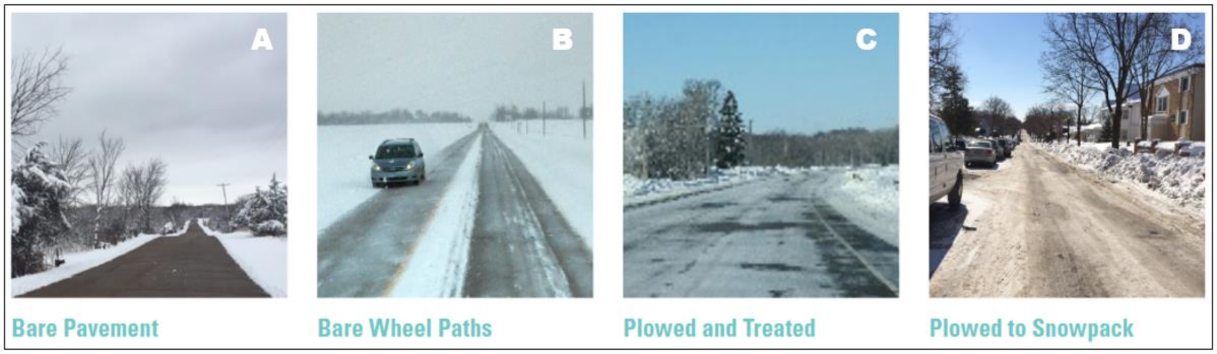


Figure 2.1 Winter level-of-maintenance (LOM) pavement conditions (SRF Consulting Group, 2016).

Using 10 years of data that resulted from weather-related conditions, the FHWA compiled annual average weather-related crash statistics. Both weather and pavement conditions were analyzed with the results shown in Table 2.2. Based on averages from the 10-year span, each year 5,891,000 vehicle crashes occurred throughout the United States. Of those crashes, 21 percent (1,235,000) were weather related. Of the weather-related crashes that occurred, 18 percent (222,300) happened in snow or sleet conditions (FHWA 2020a).

Table 2.2 Weather-Related Crash Statistics by Road Conditions for 2007-2016 Data (FHWA 2020a)

Road Weather Condition	Annual Average	Percentage of Condition	Percentage of Weather Related
Snow/Sleet	219,942 crashes	4% of vehicle crashes	18% of crashes
	54,839 persons injured	3% of crash injuries	14% of injuries
	688 persons killed	2% of crash fatalities	13% of fatalities
Snow/Slushy Pavement	186,076 crashes	4% of vehicle crashes	16% of crashes
	42,036 persons injured	2% of crash injuries	11% of injuries
	496 persons killed	2% of crash fatalities	10% of fatalities

A variety of studies have been conducted to determine when winter weather-related crashes are likely to occur. One study examined the relationship between winter weather precipitation and injury and fatality crashes for 13 cities in the United States from 1996 to 2010 by analyzing crash and weather data. The locations for the study were chosen due to the frequency and type of winter precipitation they experience. The results of the research showed that injury collision risk increased by 13 percent during winter precipitation compared to a control period. The strongest predictors for crashes were precipitation intensity, time of day, and order of the precipitation. Crashes occurred more often during intense precipitation, during the afternoon and evening time periods, and during the first three precipitation events of a winter season (Black and Mote, 2015).

Another indicator of when a crash will occur relates to the time since a snowplow has serviced an area. The longer it has been since a snowplow has passed, the more likely there will be a crash in the area. One study showed that half of the winter-related crashes on Iowa roads occurred during a winter storm, where the other half occurred outside a winter storm. The crashes that took place shortly after a winter storm were often caused by poor pavement conditions. Higher crash frequencies were shown to be related to the number of snowplow passes and storm intensity. If the storm was more intense, the snowplow passed more often but had to travel greater distances, leading to greater accumulation of snow on the roadways. Crashes were more likely to occur when the snowplows were furthest away, typically if it had been approximately 2 hours since the last snowplow had passed (Dong et al., 2019).

Another study on Iowa roads found that most crashes occurred in the snowplow pass interval of 90 minutes to 2 hours before the crash and within 30 minutes after the crash. As shown in Figure 2.2, one-third of crashes occurred 90 minutes to 2 hours after the last snowplow pass, with more than 70 percent of crashes happening during a 2-hour period after the previous snowplow pass. As snowplow frequency increases, the volume of traffic crashes per million vehicle miles decreases, showing the importance of frequent and timely winter maintenance (Hans et al., 2018).

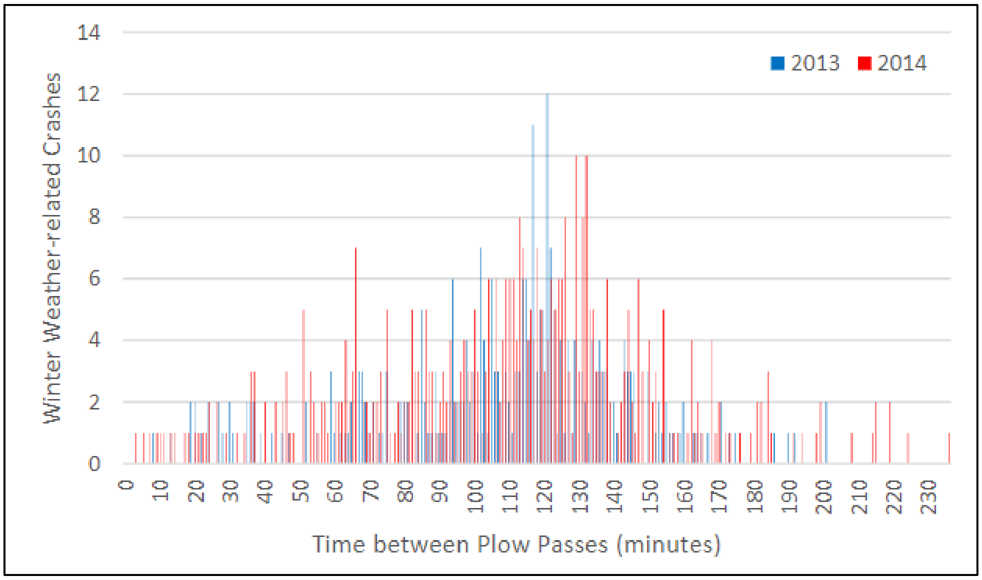


Figure 2.2 Winter weather-related crashes after snowplow pass (Hans et al., 2018).

2.3 Snowplow Operations

Due to the importance of winter maintenance, research has been conducted on how to make operations more effective. Although winter maintenance operation responsibilities fall on state and local agencies, collaborations are often formed to share the results of research. Clear Roads, a national research consortium comprised of various state DOTs, works together to fund research related to winter weather maintenance. Most research on optimizing winter maintenance revolves around material and chemical application, snowplow route optimization, blade type, and type of snowplow. This section will discuss the research available on the costs and benefits associated with plowing, and when is best to activate snowplows during a storm.

2.3.1 Cost and Benefits of Snowplowing

On average, state DOTs spend about 20 percent of their overall budget on anti-icing, deicing, and sanding practices; mechanical removal, such as snowplowing; and snow fencing (FHWA 2020a). These are necessary basic activities of winter maintenance and are the first steps taken to maintain traffic flow and safety. One study researched the cost, benefits, and impacts of snowplows. The research found that, on average, state DOTs pay an annual cost of $1,353 per lane mile in plowing costs. By solely plowing, LOM C or D can be accomplished. Snowplows are effective in removing snow and ice from the road surface, which allows for improved mobility for general traffic. When combined with the use of abrasives or chemicals, snowplows can achieve greater LOM than by plowing alone (Fay et al., 2015). The economic benefits also affect all drivers. A study from 1993 found that there is a direct road user benefit of $6.50 for every $1.00 spent on maintenance by the DOT on two-lane highways, and $3.50 in user benefit for every $1.00 spent by the DOT for maintaining freeways (Hanbali and Kuemmel, 1993).

Proper winter maintenance also helps limit economic costs related to crashes and travel time. The cost savings that occur from proper winter roadway maintenance are shown in Table 2.3. The numbers listed are the cents per vehicle mile that result from icy or de-iced roadways. On a de-iced highway, the user costs are 24.0 cents per vehicle mile driven for both crash and time costs. However, with an icy freeway, the user cost goes up to 84.7 cents per vehicle mile driven. This is due to the increased travel time and the increase in crashes that occur. As roads become clearer from snow and ice, drivers have fewer interruptions, leading to decreased travel time and associated costs of fuel.

Table 2.3 Influence of Winter Road Maintenance on Economic Costs (Hanbali, 1992)

	Two-Lane Highways		**Freeways**	
	Icy	**De-Iced**	**Icy**	**De-Iced**
Crash Costs	62.5	7.4	31.6	4.9
Time Costs	22.2	16.6	13.3	11.1
Total	84.7	24.0	44.9	16.0

*Costs are in cents per vehicle mile in 1992

When analyzing plowing being used with a salt-spreading application, for the first hour after application, there was a benefit of $172 per mile for two-lane highways and $423 per mile for freeway segments (Hanbali, 1992). A study by the consulting firm Booz Allen Hamilton showed the effects of time delay on the economy. The firm estimated that in 1999, approximately $1.4 billion would have been lost in wages alone if all the snowbelt states were immobilized for just one day due to a winter weather event. The estimated full economic impact at a federal, state, local, and individual level would accumulate to around $3.9 billion (Booz Allen Hamilton, 1999).

2.3.2 Activating Snowplows

The timely launching of snowplows to plow during a snowstorm is ideal to optimize safety benefits while keeping maintenance costs low. This can be accomplished through analysis of weather conditions. A study conducted in conjunction with the Clear Roads coalition found that agencies weigh current and forecasted conditions almost equally when deciding when to mobilize their crews (CTC & Associates, 2018). When current and forecasted temperatures are at or near freezing, agencies begin to assess other weather factors, such as dew point, humidity, and wind speed to make informed decisions on mobilizing winter weather teams.

Most DOTs work closely with a storm monitor, meteorologist, or weather manager to know when to respond with winter maintenance. Data needed to make these decisions are commonly gathered from road weather information system (RWIS) locations. This system will be discussed in depth in Section 2.4.1. Agencies use a variety of the following current and forecasted indicators for activation: pavement temperature, air temperature, dew point, wind speed, and precipitation. UDOT uses all of these, with the following thresholds for snowplow activation: 32°F for current pavement temperature, 35°F for current and forecasted air temperature, and 20 mph for current and forecasted wind speed. Other indicators of when to launch maintenance crews include plow cameras, humidity levels, pavement type, soil temperatures, frost triggers, and wind direction (CTC & Associates, 2018).

The decision to activate or deactivate crews is typically made at a regional or district level. Most activation decided within these agencies is done before the arrival of a forecasted severe storm. Deactivation indicators are the same as activation indicators, with some states informing their decisions by also using additional indicators such as travel speeds or LOM. The deactivation thresholds UDOT holds are 33°F and rising for current pavement temperature, 36°F and rising for current air temperature, and less than 20 mph and decreasing for current wind speed (CTC & Associates, 2018). Snowplow operations may last longer than the storm due to blowing snow and other factors (Dong et al., 2019).

2.4 Datasets Used in Winter Maintenance

Several datasets are used in optimizing winter maintenance. Weather, snowplow fleet, and Bluetooth traffic data can all be used in combination to evaluate the conditions and effectiveness of snowplow operations. Each of these datasets will be discussed in the following subsections.

2.4.1 Weather Data

A variety of weather data can be used by agencies to analyze incoming storms, but the most commonly used are RWIS data. RWIS are a combination of field hardware components and software that provides timely and detailed road-weather information that organizations use to support operation and maintenance decisions. The systems obtain two categories of data: atmospheric and pavement. Atmospheric data includes air temperature, humidity, visibility distance, wind speed and direction, and precipitation type and rate. Pavement data contains pavement temperature, pavement condition (e.g., dry, wet, ice, or frost), and subsurface temperatures. These data are gathered from an environmental sensor station. The data are used to determine when to send maintenance crews out into storms (SRF Consulting Group, 2016).

UDOT has an extremely successful RWIS program that has been analyzed by other DOTs across the country. Their annual budget planning process for winter maintenance has been improved by decreasing costs through a reduction in labor hours, unnecessary callouts of equipment, and limiting the material required. This has happened while increasing LOM on roadways during storms, decreasing incident response time, and decreasing construction project costs through better planning for winter storms. These forecasts provided by the UDOT Weather team are extremely detailed, as shown in Table 2.4 (Strong and Shi, 2008). Currently, UDOT works closely with the National Weather Service to create their road weather forecasts. Data are gathered through in-road sensors, roadside sensors, and traffic cameras. These reports are published on the UDOT Traffic website and mobile application. Not only does this system use current and forecasted weather conditions, but the system also factors current traffic conditions in providing recommended action for drivers (UDOT, 2020).

Table 2.4 Comparison of Traditional and UDOT Forecasts (Strong and Shi, 2008)

Example of Traditional Weather Forecast	UDOT Weather Forecast
• Mostly cloudy with a 20% chance of light snow. Lows near 8° F. North winds 15 to 25 mph.	• Quick ¾ to 1 in. snow over the next 1 hr. • Alerted for road concerns developing by 1400, sloppy onset. Up to 1 to 2 in. road snow for the commute tonight. • Snow band stalling again over your routes' areas. Big thing will be dropping temps W-E late afternoon Park Valley, I-15 areas around 1800. General Tapering trend west desert areas after temp drop, snow I-15 corridor through 0000.

UDOT began looking into applications for RWIS before the 2002 Winter Olympic Games that were held in Salt Lake City, Utah. The agency needed accurate weather data to provide for spectators traveling to and from events. Since then, UDOT has combined their RWIS program with their Weather Operations program and has found new uses, as shown in Figure 2.3. The combined program gives pre-storm, during-storm, and post-storm forecasts to various personnel, including maintenance engineers, area supervisors, and personnel at local maintenance sheds. The program has proven to be cost effective. In the winter of 2004-2005, UDOT estimated that the program saved over $2.2 million. As the program only costs $200,000, the benefit-to-cost ratio is more than 11 to 1 (Strong and Shi, 2008).

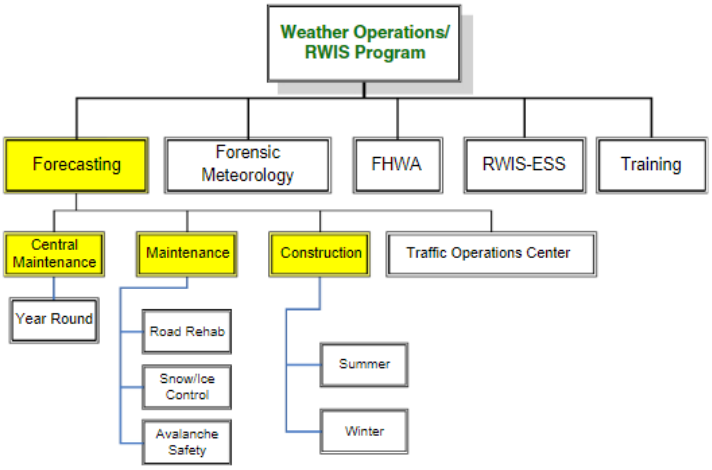


Figure 2.3 Organizational chart of UDOT weather operations/RWIS program services (Strong and Shi, 2008).

Several entities use UDOT's weather services today, including UDOT signals, traveler information, operations, and communication teams, as well as Ports of Entry, Utah Highway Patrol, and private snowplow companies. The services have evolved over time. In 2013, a Winter Road Weather Index (WRWI) project was launched, which now has transformed into winter weather performance metrics. These metrics are published in real time to a dashboard that is used by UDOT maintenance crews. The dashboard shows how effective the crews are at maintaining road conditions during the storm, as shown in Figure 2.4. The data used as metrics are gathered by RWIS sites (UDOT Communications, 2016). The metrics include condition value, snowfall value, road temperature value, wet-bulb and wind value, and freezing rain value. Each metric is given different values that are summed to determine if the road is being maintained or not. In addition to the data gathered from the RWIS, images from traffic cameras give a visual to current conditions on the roadway (Williams et al., 2014).

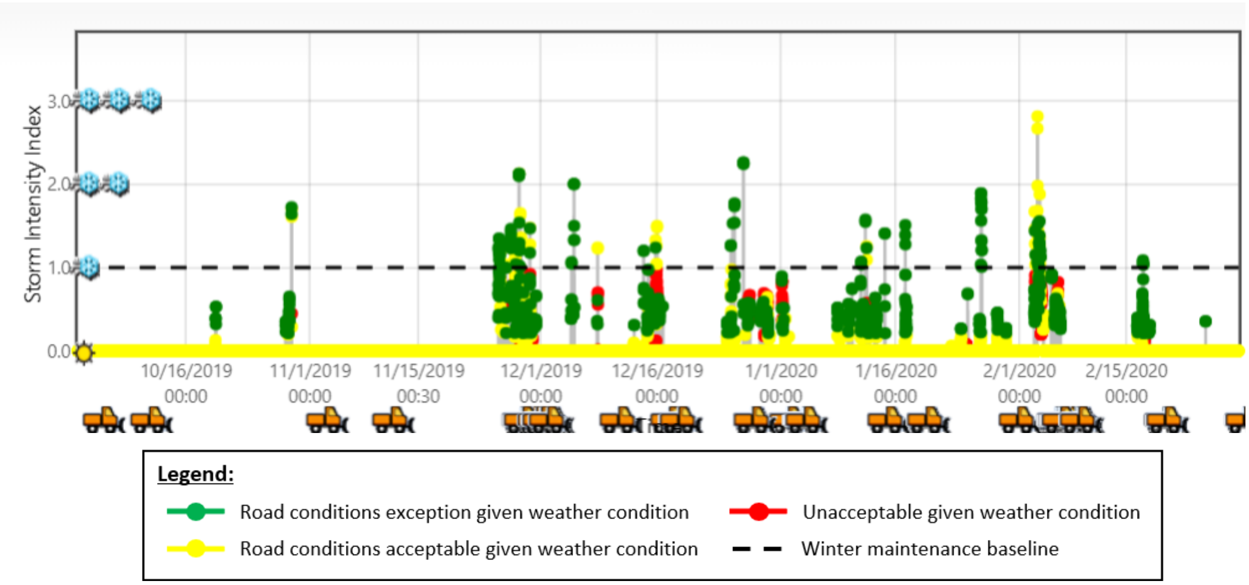


Figure 2.4 UDOT winter weather maintenance metric dashboard (UDOT Communications, 2016).

2.4.2 Snowplow Fleet Data

Snowplow fleet, or maintenance fleet data, are commonly known as automatic vehicle location (AVL) data. Various companies provide this type of data. AVL systems are used to automatically determine and transmit the location of the vehicle. They have an online dispatch center that monitors the location of all vehicles continuously in real time. There is typically an integrated Geographic Information System (GIS) mapping component to streamline functionalities. This is beneficial in managing snowplow operations to monitor progress during a weather event. The dispatcher can adjust equipment as needed to meet changes in weather conditions (SRF Consulting Group, 2016). For snowplows that do not have an AVL system, global positioning systems (GPS) can be used to find snowplows and optimize plowing routes (Elhouar et al., 2015).

AVL systems can provide a variety of data. Important attributes for analyzing snowplow use include data for plow number, location (longitude and latitude), date, time, heading, velocity, and distribution rates (solid, liquid, and pre-wet) (Hans et al., 2018). AVL systems can also generate “end-of-shift” reports that historically had to be filled out by hand from the operator. This information can include material applications rates, status of the plow, and other vehicle status indicators. This technology has helped increase productivity and quality of maintenance operations to maintain LOM on roadways (Santiago-Chaparro et al., 2012).

The benefits of AVL systems are difficult to quantify. The amount of material saved in the reduction of use can be quantified, but it is difficult to assign a value to the benefits that AVL systems bring in relation to other maintenance operations (Fay et al., 2015). The AVL systems have been useful when compared with other data to determine winter weather-related statistics, such as crash data and its relation to plow events (Dong et al., 2019). The implementation of AVL systems have also correlated to the following benefits: safety improvements due to better road conditions, optimization of maintenance routes, better driver compliance with instructions, increased accountability, and faster response to incidents (Santiago-Chapparro et al., 2012).

2.4.3 Traffic Data

There are a variety of means that can be used to collect and analyze traffic data. These methods include point, probe, and Bluetooth. Traffic data can be used in a variety of ways but can show the success of winter maintenance operations based on travel speeds and delay. Research on various types of traffic data and how they are collected was conducted by Macfarlane and Copley (2020) to analyze the best implications of each type of data for different uses.

Point data are gathered from specific locations where equipment is set up, such as radar or roadway loops. A variety of information can be gathered, such as speeds, volumes, vehicle length, and travel times. This does not need to be purchased from a third party but can only be collected at equipped locations. This type of data is typically gathered on major highways. UDOT has purchased Wavetronix sensors and other detection types to provide this type of data on their interstates, state routes, and highways (UDOT, 2019).

Probe data does not require field equipment and is gathered through vehicle navigation systems or are activated by an app. This type of data collection cannot collect volumes but collects speed and travel times and is often purchased from third-party companies (UDOT, 2019). Companies such as HERE Technologies have sold this type of data to various government agencies including, but not limited to UDOT, Virginia DOT, South Carolina DOT, Caltrans, the City of Toronto, and Transport Canada (Kehrli, 2019).

Bluetooth data are also used to analyze traffic patterns. A study by Holik et al. (2015) used Bluetooth nodes to analyze motorists' speeds and delays during winter storm events compared to different types of snowplows that were used for maintenance. The data are gathered through sensors in the field and are most often purchased through a third party. To gather data, a motorist must have their Bluetooth or Wi-Fi activated. These data are beneficial due to the high penetration rate, ease of installation (useful for specific projects), and the ability to collect travel time, speed, and origin-to-destination data. However, Bluetooth-derived data cannot determine traffic volumes.

Another method of collecting traffic data is through the use of temporary sensors. UDOT, in partnership with Blyncsy Movement Data, have placed several temporary sensors around the state for data collection purposes (UDOT, 2019).

2.5 Dedicated Short-Range Communication Systems

V2X systems using DSRC are wireless communication systems placed on different vehicles to communicate with each other or to infrastructure for a variety of reasons. According to research done at the University of Minnesota in 2013, "the USDOT currently holds the DSRC as the only wireless communication technique that provides desired qualities for vehicular communication such as fast network acquisition time,… high reliability, priority for safety applications,… security and privacy" (Ibrahim and Hayee, 2013). In early research conducted on CAV technology, the USDOT encouraged state DOTs to start implementing this technology in their transportation networks. This was due to the low-latency and high-reliability performance that can be used to reduce fatalities while supporting close-range communication requirements (Perry et al., 2017).

UDOT, as well as other DOTs, began expanding their use of V2X systems that use DSRC between 2013 and 2017. This section will discuss the components of the DSRC system, DSRC research that has been performed in Utah, and DSRC usage for winter maintenance operations at the time of this research. It should be noted, however, that recent Federal Communications Commission actions have shifted focus away from DSRC and onto Cellular-V2X technology as the way to communicate in the 5.9 GHz spectrum. Because the research was conducted using DSRC, this change will not be discussed in detail in this report.

2.5.1 DSRC System Components

DSRC systems are made up of multiple components. Each vehicle has an onboard unit (OBU) that sends signals out while the vehicle is in motion. Traffic signal controller cabinets are installed with roadside units (RSUs) to receive these signals as illustrated in Figure 2.5. Vehicles and intersections that have these DSRC radios are considered "equipped." Depending on the message that is received, the RSU can pass on information to the signal controller. The signal controller will adjust the signal phasing accordingly (WSP and SRF Consulting Group, 2018).

DSRC can be used for a variety of purposes, such as vehicle to vehicle (V2V) and V2I communication. These communications are also referred to as V2X. There are multiple messages that are distributed by the traveling vehicle, each containing different information. The Society of Automotive Engineers (SAE) created a V2X Communications Message Set Dictionary, SAE J2735, that outlines the content and format of the V2X messages (SAE, 2016). These messages include basic safety message (BSM); signal request message (SRM); signal status message (SSM); signal, phase, and timing message (SPaT); and a map message that gives information about geometry and layout of the intersection (MAP). Table 2.5 contains a list of each of the messages, how often they are sent, and the origin and destination of the message.

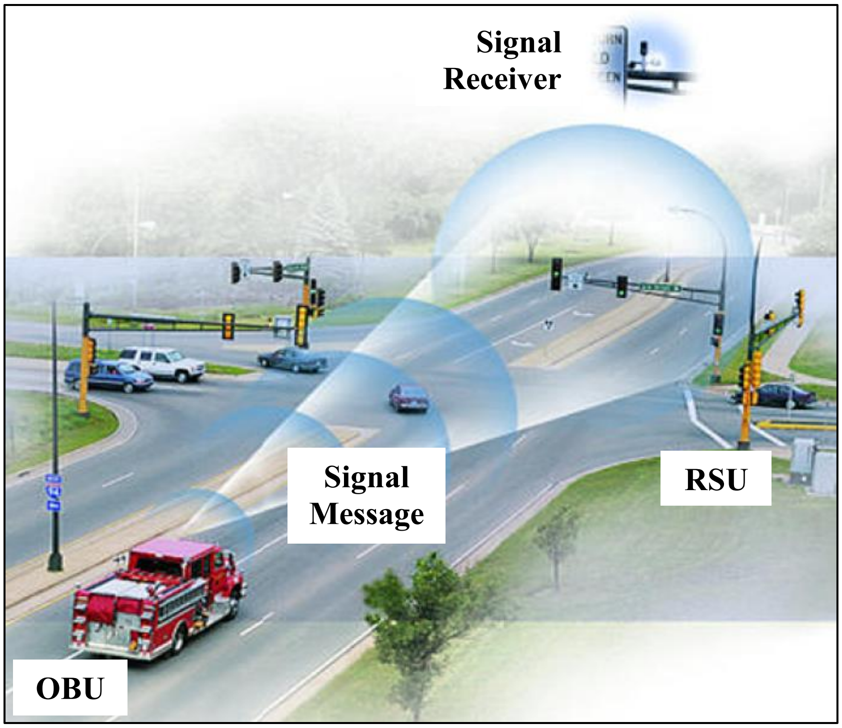


Figure 2.5 DSRC system communicating with traffic signal (FHWA, 2008).

Table 2.5 DSRC Messages (University of Arizona et al., 2016)

Message	Frequency (per second)	From	To
BSM	10	OBU	RSU, OBU
SRM	1	OBU	RSU
SSM	1	RSU	OBU
SPaT	10	RSU	OBU
MAP	1	RSU	OBU

The message sent from the vehicle is a BSM. These messages are the primary and most important message type for V2X communication. In addition to delivering safety information, the information in these messages can be used in mobility, weather, and real-time situation awareness applications (Harding et al., 2014). These messages contain a variety of information, including mandatory and optional data, as shown in Table 2.6 and Table 2.7. These messages are continually sent out at a rate of 10 per second as soon as the OBU system is started (SAE, 2016).

Table 2.6 BSM Mandatory Part I Content (SAE, 2016)

Content	Description and Data Elements
Message Count	This data element provides a sequence number used to determine if all messages are received
Temporary ID	A randomized string that periodically changes to ensure the overall anonymity of the vehicle
Timestamp	Timestamp with millisecond granularity
Location	Includes latitude, longitude, elevation, and positional accuracy
Transmission State	States whether the transmission is in neutral, park, a forward gear, or a reverse gear
Vehicle Movement	Includes vehicle speed, heading, steering wheel angle, longitudinal, lateral, and vertical acceleration, and yaw rate
Brake Status	Describes the status of the brakes, ABS brakes, traction, and stability control systems
Vehicle Size	States the length and width of the vehicle

Table 2.7 BSM Optional Part II Content (SAE, 2016)

Content	Description and Data Elements
Vehicle Event Flags	Permits specific safety-critical messages to be broadcasted, such has ABS brake activation, hard braking, airbag deployment, or loss of traction control
Travel Path	Provides a breadcrumb trail of vehicular and location data for the last 10 minutes and a prediction of future travel path
Exterior Lights	Conveys the status of the exterior lights, such as low and high-beam headlights, turn signals, hazards, or parking light
Emergency Response	For an emergency response vehicle, this indicates the status of the sirens, light bar, response type, and the direction of travel this message applies to
Trailer Data	Allows vehicles pulling a trailer to describe the trailer, including dimensions, mass, and pivot angle
Supplemental Information	Broadly provides information about the vehicle and its operating conditions, such as vehicle class, whether it is disabled, average speed of oncoming traffic, and weather-related information

SRMs are sent by vehicles that are equipped as they approach an intersection to request priority or preemption at a signal. These vehicles include transit vehicles, emergency response vehicles, and snowplows. As show in Table 2.8, the information contained in these messages is necessary to request signal priority or preemption. To send the correct information, the OBU first interprets the MAP message to determine which intersection that the SRM applies to and the lane and approach ID for the direction the vehicle is traveling (Schultz et al., 2020).

Table 2.8 SRM Content (SAE, 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
Request Package	This contains the intersection ID, request type, request ID, and lane and approach IDs for the incoming vehicle
Vehicle Information	Describes the vehicle role and type, what level of priority the request is, and if it is a transit vehicle, its route, occupancy, and schedule adherence

SSMs are sent by the RSU as the vehicle approaches an intersection to relate the current status of the signal and the collection of pending or active priority or preemption requests acknowledged by the controller (SAE, 2016). This message confirms that the SRM was received and communicates to all approaching equipped vehicles that a request has been made (Schultz et al., 2020). The content of an SSM message is described in Table 2.9.

Table 2.9 SSM Content (SAE, 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
SRM Content	Relays back much of the information received in the SRM
Priority Status	Indicates the general status of a prior request, such as requested, processing, watch for other traffic, granted, rejected, or unable to serve at this time

In addition to the OBUs sending messages, the RSUs also send messages back to vehicles. These units broadcast SPaT messages concerning the current status of signal light phases for each intersection. A MAP message is needed in conjunction with a SPaT message to understand it properly (Leonard et al., 2019). The message components for a SPaT message are shown in Table 2.10.

Table 2.10 SPaT Message Content (SAE, 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
Intersection ID	Contains the intersection ID and a reference to the entity with authority over the intersection
Controller Status	Conveys whether the controller is off, in failure, controlled manually, has fixed or actuated timing, and if preemption or priority is being granted
Enabled Lanes	Conveys which lanes are open to travel, which may change depending on the time of day without requiring a new MAP message
Intersection Movements	Describes, for each movement, the state of signal phasing for that movement, timing details (start of phase, estimated end time, and time when phase will next occur), and an advisory speed
Connection Maneuvers	Describes, for each lane or group of lanes, queue length, available storage length, and if any pedestrians or bicycles are crossing the lane or group of lanes

The needed MAP message is used to convey one or more intersection lane geometry maps within a single message (SAE, 2016). Table 2.11 shows a description of the content within a MAP message, where Figure 2.6 displays an example of a MAP message from the California Connected Vehicle (CV) Testbed.

Each message is recorded at the intersection. From analysis with offsite software, the data can be calculated to determine when the equipped vehicle was there, how many requests were made, what was happening in the signal controller, and if the signal changed due to the messages sent by the DSRC system. This analysis is necessary to determine the benefits of such a system for new uses. There is no simple key that relates the different datasets together, causing intense data consolidation. Processing data like this takes time and skills and is one part of the progress of development of connected vehicles that seems to be forgotten. After one dataset has been analyzed, it is easier to create processes to analyze the data. From this data analysis, cost savings can be interpreted, effects to other traffic can be calculated, and increase in safety and reliability can be determined (Avenue Consultants, 2018).

Table 2.11 MAP Message Contents (SAE, 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
Intersection ID	Contains the intersection ID and a reference to the entity with authority over the intersection
General Lane Information	Conveys the lane ID, the approach it belongs to, and its direction of travel
Lane Type	Describes whether the lane is a vehicle lane, bike lane, crosswalk, sidewalk, tracked lane (trains or trolleys), striping, or parking
Lane Sharing	Describes the type of traffic that may share this lane and its direction of travel, such as individual motor vehicles, buses, taxis, cyclists, trains, or pedestrians
Allowed Maneuvers	Lists allowed maneuvers from the lane, such as straight, left, or right turn, left or right turn on red, U-turn, or proceed after making a full stop
Lane Nodes	A sequence of two or more nodes are used to denote the lane centerline, among other things
Node Attributes	Conveys node-specific information, such as stop line, merge, or diverge point, curb is present, or hydrant is present
Segment Attributes	Conveys information relevant to the space between one or more nodes, such as merging abilities, presence of adjacent loading zones, parking spots, bike lanes, or transit stops, and pedestrian support attributes, such as the presence of curb intrusion, low curb, rumble strips, audible pedestrian signal, or a call request button

Figure 2.6 MAP message aerial view of Page Mill Rd. and El Camino Real in Mountain View, CA (California CV Testbed et al., 2020).

2.5.2 DSRC Research in Utah

Over the past several years, UDOT has invested in V2X systems using DSRC to assess its impacts on improving the transportation system. In 2018, UDOT, in conjunction with UTA, put OBUs in buses on Route 217, for the portion that runs on Redwood Road in Salt Lake County. These buses communicate with signals to receive signal priority. Of the 30 signalized intersections on the corridor, 25 were set up with RSUs as shown in Figure 2.7 (Avenue Consultants, 2018). A study of the success of the systems was undertaken by UDOT personnel and Avenue Consultants.

There were a variety of goals for the study on Redwood Road. One was for UDOT to experiment with DSRC technology and to see its impacts on Utah roads. The system was also deployed on one specific corridor to see if real cost savings could be produced. In addition to immediate use, UDOT wanted a corridor where they could develop and test new technologies related to autonomous vehicles (Leonard et al., 2019).

The study on Redwood Road compared V2X system-equipped buses against not-equipped buses on the same corridor and during a four-month study period. One of the measures of effectiveness (MOE) was reliability.

Figure 2.7 Reliability of DSRC-equipped buses on Redwood Road compared to non-equipped buses (Avenue Consultants, 2018).

According to UTA, a bus is reliable if it arrives within five minutes of the posted arrival time. If reliability is improved, ridership typically increases, leading to more funding for UTA. In the study, when buses were considered late and they fulfilled the occupancy requirement, they could request signal priority. During the study, other impacts on surrounding traffic were also analyzed. Using message record data from the DSRC system, as well as traffic data from high-resolution signal controller logs used with the ATSPM system, a variety of information was found. The consultants used the data to show the difference in reliability between buses equipped and not equipped with DSRC. Figure 2.7 shows the difference in reliability along the southbound direction on Redwood Road in the Salt Lake valley. The DSRC-equipped buses are more reliable than the other buses, due to being able to make signal priority requests. This occurred in both directions on the test area. The consultants also found that as the buses called for signal priority, they were not granted priority all the time. This helped limit impacts on surrounding traffic. Traffic was found to not be affected greatly, with less than 20 percent of the TSP-served occurrences resulting in a negative impact to opposing traffic (Avenue Consultants, 2018).

The study was deemed a success, as UTA buses became more reliable. Since this study has been done, the technology has been implemented in the BRT system—the Utah Valley eXpress (UVX) line—in Orem and Provo, Utah. After this installment, another study was done in 2019 to further analyze benefits of TSP for buses on both Redwood Road and the UVX line (Schultz et al., 2020; Sheffield et al., 2021). This sensitivity study included a seven-month study period to analyze the impacts that TSP-requesting thresholds had on bus performance and general traffic. Using the same DSRC system to request TSP that was used in the previous study on Redwood Road, data were gathered to assess different requesting thresholds. Bus performance was analyzed through on-time performance, schedule deviation, travel time, and dwell time. Traffic impacts were analyzed by evaluating split failure, change in green time, and the frequency which TSP was serviced.

In the analysis, a combination of observation and statistical analysis was performed. On Redwood Road, requesting thresholds were analyzed for 5, 3, 2, and 0 minutes. This was done to demonstrate different times of the bus being behind schedule. When the requesting threshold was changed to be closer to 0, on-time performance increased between 2.0 and 2.5 percent. There would be negative effects on traffic if there was an increase in split failure that was measured after TSP was serviced. However, this only occurred a maximum of once every 43 minutes.

For UVX, 5- and 2- minute thresholds were analyzed, as well as ON and OFF scenarios. ON scenarios were always requesting TSP no matter how late the bus was, and OFF scenarios had no TSP requests sent. The OFF scenarios were used as a baseline to determine how the system normally functioned. When the requesting threshold went from 5 to 2 minutes, on-time performance increased 7.6 percent, and was increased by 4.7 percent when changed from a 2-minute threshold to an always ON scenario. The study overall showed with TSP being requested by DSRC systems, that on-time performance, schedule deviation, and travel time improves as the requesting threshold approaches zero with little impacts to general traffic (Schultz et al., 2020; Sheffield et al., 2021).

2.5.3 DSRC Usage in Winter Maintenance Operations

There have been various ways that DSRC systems have been implemented into the transportation realm. They are most commonly used in the rail industry and with transit. Utah is the first known DOT to carry out a large-scale experiment of DSRC systems on snowplows. Other DOTs, such as Minnesota, have conducted studies and simulations to see if using DSRC systems on snowplows to request signal preemption would be beneficial in reducing crashes, minimizing winter maintenance costs, and optimizing winter maintenance services.

In a study performed by the Minnesota Department of Transportation that modeled the potential for DSRC equipment used on snowplows, the snowplows would request signal priority as they approached the intersection. The messages sent from OBUs and RSUs happened automatically, so the driver did not have to worry about collecting data while trying to clear snow. The process of how this occurs is shown in Table 2.12. The snowplow approaches the intersection, where the equipped vehicle communicates with the signal controller, requesting priority through BSMs, SRMs, and SSMs. The signal controller receives the request and will send a SPaT and MAP message back to the OBU in the snowplow with the decision of whether to accept it or not. The decision is made through a software called MaxView, which is the system the signal runs on. Coding and preferences can be changed within that software (WSP and SRF Consulting Group, 2018). The signal system that runs the signal preemption requests for a snowplow is the same type of system that would manage DSRC requests from transit, rail, or other vehicles.

Table 2.12 Flow of Events with DSRC System and Snowplow (WSP and SRF Consulting Group, 2018)

Source	Step	Key Action	Comments
Snowplow Operator	1	Approaches the intersection	From the primary arterial
Connected Corridor System	2	Determines Snowplow 1 is approaching the intersection, is actively engaged in plowing or spreading chemicals, and communicates a signal priority request to the Traffic Signal Controller	To request signal priority
Traffic Signal Controller	3	Determines it can accommodate the priority request and prioritizes the received request with other received requests	Prioritization could be performed locally on the roadside, or through communication with MaxView
Traffic Signal Controller	4	Responds to the CC system with the priority order and status (accepted/denied) of all received requests	

2.6 Signal Timing Modifications

In the research that relates to V2X systems using DSRC and traffic systems, there are two types of requests made to the signal controller: signal priority and signal preemption, each of which will be discussed in the following subsections.

2.6.1 Signal Priority

Signal priority is often given to transit vehicles. When a vehicle requests signal priority, it requests the signal controller to change to benefit them. However, since the request is only priority, depending on the phase the signal is on, the signal controller can choose if it will grant the priority, based on a number of factors. The signal controller is not required to always grant the request, so the request is only honored a portion of the time (Avenue Consultants, 2018).

2.6.2 Signal Preemption

Signal preemption differs from signal priority. As an equipped vehicle sends an SRM to the signal controller, the controller logic begins the safe process of adjusting the signal phasing to grant the preemption. If the traffic signal is not green as the vehicle approaches the intersection, it should change to green as quickly as is safely possible. When the traffic signal transitions into preemption, there are safety features that allow for the signal to transition in a safe manner. The yellow and all-red vehicle clearance intervals are not shortened or omitted. The pedestrian clearance interval may be shortened or omitted, depending on if there was a call from a pedestrian push button or based on average pedestrian counts (FHWA, 2008). This is the same system used by emergency vehicles.

In the setup of the system software, maps of each intersection are drawn to allow for limits on the geometric location of messages that the signal control will recognize. That way, the signal controller has adequate time to change the traffic light for the request that is made (Cross, 2014). Different messages are sent to the signal controller from the DSRC unit, requesting signal priority or preemption. As the vehicles pass through the system boundaries at an equipped intersection and exit the boundary map, and the request has not been granted, they cancel the requests for priority or preemption. This allows for the signal controller to return to normal operations. These data can be downloaded and used in analysis for various applications.

Signal preemption has been very beneficial for emergency response vehicles. It includes faster response times for emergency teams, improved safety for emergency vehicles, and cost savings to the general public, due to a reduction in property loss. One of the main concerns with a greater use of signal preemption is the potential effects on opposing traffic. As V2X systems using DSRC are installed on vehicles that request signal preemption, reductions in travel time have been shown to occur (Paruchuri, 2017).

2.7 Summary

This chapter discussed the current research performed about V2X systems using DSRC for winter maintenance operation purposes. Current impacts on traffic due to winter weather were addressed, as well as the benefits of snowplowing. Datasets used in the analysis of winter maintenance operation performance showed how impacts to traffic can be analyzed. The components of the V2X system using DSRC were covered, as well as additional research related to DSRC in Utah and within winter maintenance operations. The benefits of signal preemption were also addressed, particularly for systems that use both DSRC and signal preemption. The literature shows that DOTs have benefitted with increased safety, higher travel speeds, and lower travel times when DSRC systems are used in various applications.

3.0 EXPERIMENT METHODOLOGY

3.1 Overview

There are several datasets available to provide information on the impacts of V2X systems using DSRC to request signal preemption on UDOT snowplows. These datasets were utilized to answer questions that apply to two different areas: signal analysis and vehicle analysis. A methodology was developed to use these datasets to evaluate the impacts of snowplows requesting signal preemption, as shown in Figure 3.1. Each individual dataset was used to answer a separate question, while the combination of datasets was used to answer two major questions posed by this research; first, how does DSRC on snowplows affect traffic signals? and second, is plowing and traffic efficiency and performance improved with DSRC systems requesting signal preemption?

To analyze the impacts of V2X systems using DSRC, routes that were not equipped with V2X technology were selected as control sites. Each of the not-equipped routes selected were similar to a corresponding equipped route in annual average daily traffic (AADT), lane geometry, direction, and location. The equipped routes and not-equipped routes were compared to analyze the effectiveness and impacts of the DSRC equipment used to request signal preemption on snowplows. Table 3.1 shows the equipped routes with their associated not-equipped control route.

Table 3.1 Equipped Routes and Comparable Not-Equipped Routes

Equipped	Not Equipped
SR-209: West 9000 South/9400 South *(4000 West to Redwood Road)*	4500 South *(I-15 to I-215)*
SR-209: East 9000 South *(700 East to Wasatch Boulevard)*	Wasatch Boulevard *(I-215 to Little Cottonwood)*
SR-186: Foothill Boulevard *(I-80 to 1300 East)*	
SR-68: Redwood Road *(12600 South to 400 South)*	State Street *(9000 South to 3300 South)*
SR-71: 700 East/900 East *(9000 South to 3300 South)*	Van Winkle Blvd

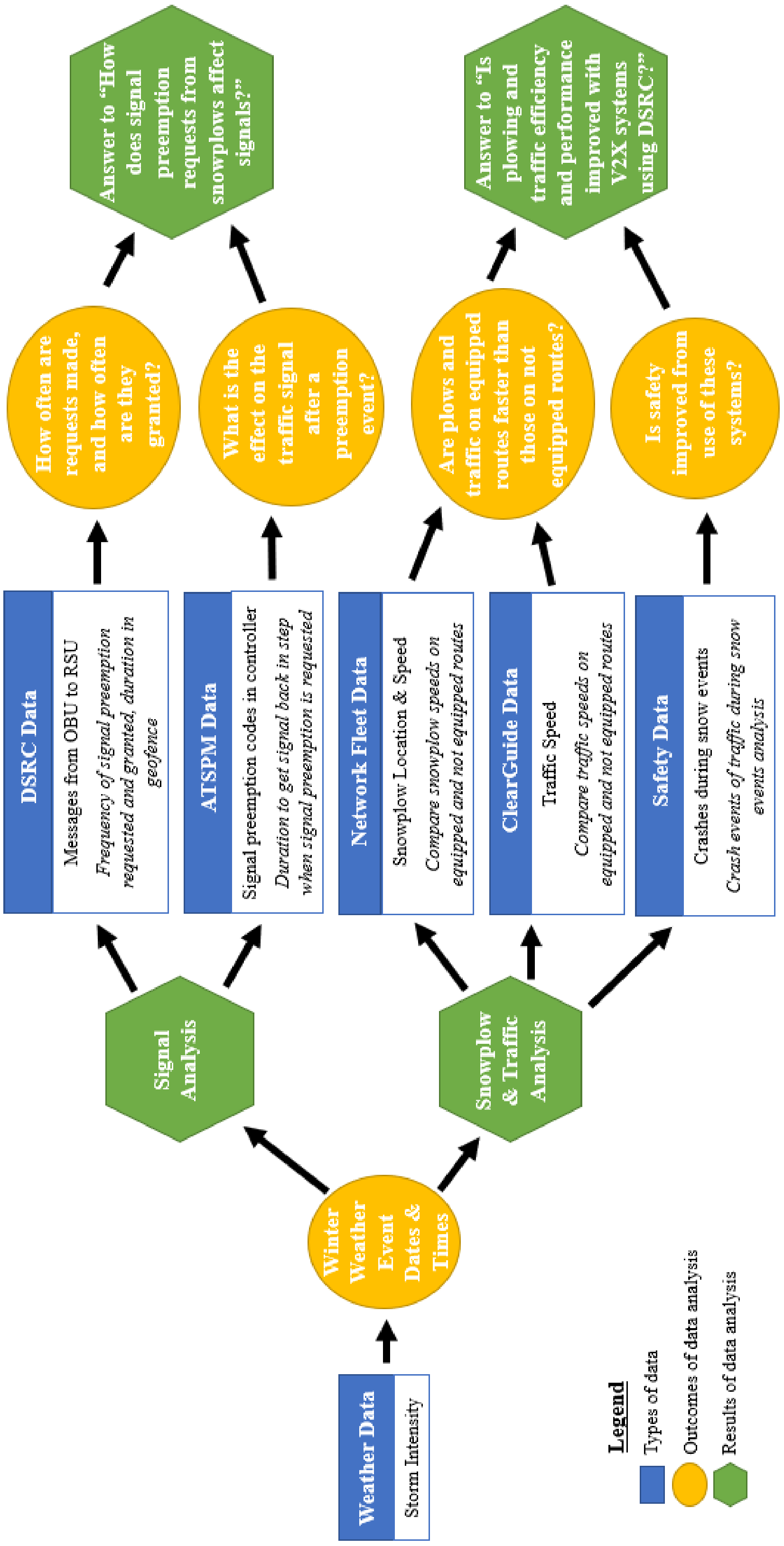


Figure 3.1 Experiment methodology flowchart.

The location of the routes is shown in Figure 3.2. Although each not-equipped route was chosen due to similarities of the equipped routes, there are differences between the routes that could not be reconciled. Both similarities and differences of the routes are expounded in Table 3.2.

Each of the equipped and not-equipped routes are plowed by UDOT snowplows. These snowplows are assigned to work in different maintenance sheds. The five UDOT maintenance sheds that were used in this project were West Jordan (Shed 231), Salt Lake Central (Shed 230), Parleys Canyon (Shed 234), Murray (Shed 232), and Cottonwood (Shed 233). The boundaries of these sheds are shown in Figure 3.2. For routes that pass through multiple sheds, the route was broken into segments by the route and shed. This was done for the Redwood Road and 700 East routes. Redwood Road was broken into the segments of Redwood Salt Lake Central (Redwood SLC), Redwood Murray, and Redwood West Jordan. The 700 East route was broken into the segments of 700 East Murray and 700 East Cottonwood. This distinction of segments was used in the analysis of the datasets, as applicable.

Winter weather data were collected to understand when there were snowstorms to analyze snowplow activity during that time. These data were used as the basis to set time filters on all datasets used in this study. A further explanation of how winter weather data was gathered and analyzed will be discussed in Section 3.2.

The evaluation of the system includes analyses at both the daily level and time of day. As traffic and signal operations vary throughout the day, it is important to understand not only the effects at a daily level, but to also determine the effects of time of day. Table 3.3 lists the hours associated with each time period. Both the AM and PM peaks are comprised of 3 hours, whereas the other periods are 6-hours long each.

To understand the impacts that V2X systems using DSRC which requested signal preemption had on both signals and vehicles, data specifically associated with the DSRC and signal controller systems, were needed as part of the evaluation. These data were analyzed to answer the questions in the experiment methodology flowchart, as shown previously in Figure 3.1. Analysis methods used included observational comparisons and statistical analysis.

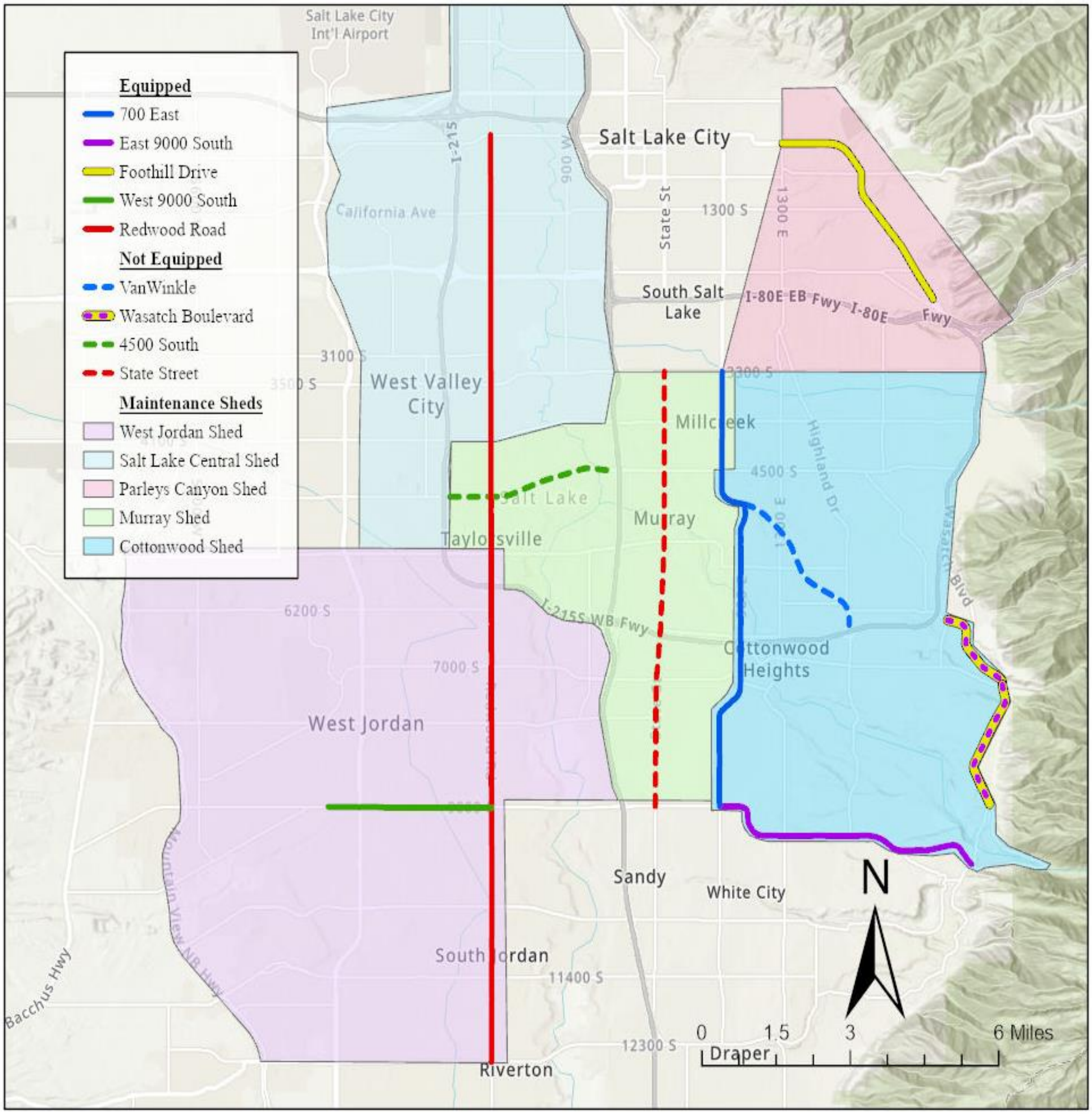


Figure 3.2 Map of equipped and not-equipped routes with UDOT maintenance sheds.

Throughout the study, acceptable values for each dataset were agreed on by the technical advisory committee (TAC). This included what were acceptable amounts of signal preemption requests being granted, how long the signal controller was affected, and snowplow speed impacts. Statistical analysis was then performed to understand the statistical significance of the comparisons. This was mainly done by performing Tukey-Kramer tests. The Tukey-Kramer test

Table 3.2 Equipped and Not-Equipped Routes Similarities and Differences

Routes	Similarities	Differences
Redwood Road	• Left and right turns at all lights • Mix of medians and two-way left-turn lanes (TWLTL) • Routes are north/south with shoulders	• Three-lane road with some railroad grade crossings • Both commercial and residential areas • Speed limits range from 40-45 mph
State Street		• Fluctuated from two to three lanes • Only commercial area • Speed limit is constant at 40 mph
700 East	• Left and right turns at all lights • Shoulders on both sides • Surrounding areas included some farmland and small commercial • Routes are in same geographical area	• Ranges from two to four lanes with bike lane • Mix of medians and TWLTL • Many driveway accesses to homes on route • Speed limit ranges from 40-45 mph
Van Winkle Boulevard		• Ranges from two to three lanes • No accesses to homes on route • Commercial buildings differ in size throughout route • Speed limit is either 40 or 50 mph
Foothill Drive	• Left and right turns at all lights • Contain traffic traveling to and from neighboring canyons	• Ranges from two to three lanes with no shoulder • Alternated from median to TWLTL • Speed limits range from 40-45 mph
Wasatch Boulevard		• Ranges from one to three lanes with shoulder • Has a TWLTL for a portion, then no median • Speed limit is constant at 50 mph
East 9000 South	• Left and right turns at all lights • No housing driveways onto roadway • Routes are in similar geographical area	• Ranges from one to two lanes with shoulder • Mostly a TWLTL but other areas have median • Speed limit is constant at 40 mph
Wasatch Boulevard		• Ranges from one to three lanes with shoulder • Has a TWLTL for a portion, then no median • Speed limit is constant at 50 mph
West 9000 South	• Left and right turns at all lights • Routes are east/west in same areas • Ranges from two to three lanes	• Roadway has TWLTL and shoulders • Had few accesses from smaller businesses and homes • Speed limit is constant at 40 mph
4500 South		• Roadway has a TWLTL or median • Route is in highly commercial area, with minimal accesses • Speed limit is either 40 or 50 mph

*Regular font is equipped route, italicized is not-equipped route makes comparisons among all types of pairs and identifies if groups in the sample differ from other groups in the data.

Table 3.3 Time Period Descriptions

Time Period	Range	Hours
Early Morning	12 AM-6 AM	6
AM Peak	6 AM-9 AM	3
Mid-Day	9 AM-3 PM	6
PM Peak	3 PM-6 PM	3
Evening	6 PM-12 AM	6

The following sections will explain the methodology for winter weather data, signal analysis, and traffic analysis. In each section, there will be discussion on what datasets were used, what each dataset entails, why it was collected, and the goal of analysis.

3.2 Winter Weather Events

The first dataset that needed to be gathered were the dates when there was snow and other winter weather for the 2019-2020 winter season. Weather data were collected to determine snow and other winter-weather-event dates and times, as well as intensities. The weather data were collected from the UDOT RWIS network. In coordination with the UDOT weather team, different RWIS sites were chosen to be associated with each equipped route, as shown in Table 3.4. A map of the locations of the RWIS sites in relation to all studied routes is shown in Figure 3.3. The primary information collected from these RWIS sites was the dates when there was snow. How weather data were collected and why it was collected will be discussed in the following subsections.

Table 3.4 Routes with Associated RWIS Site Locations

Routes	RWIS Site Location
SR-209: W 9000 South/9400 South	SR-85 at Dannon Way
SR-209: E 9000 South	I-15 at 6200 South
SR-186: Foothill Boulevard	I-80 at Mouth of Parleys
SR-68: Redwood Road	I-15 at 500 South, I-15 at 2400 South, I-15 at 6200 South
SR-71: 700 East/900 East	I-15 at 2400 South, I-15 at 6200 South

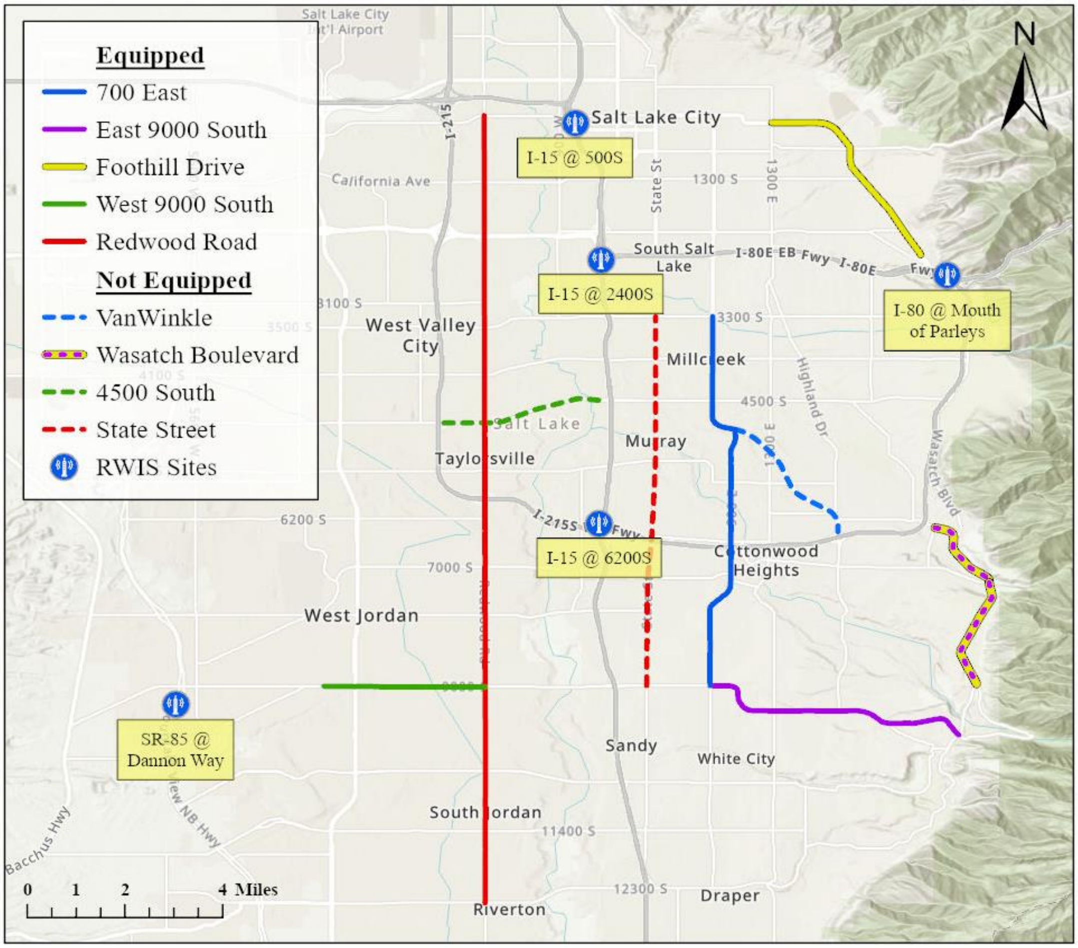


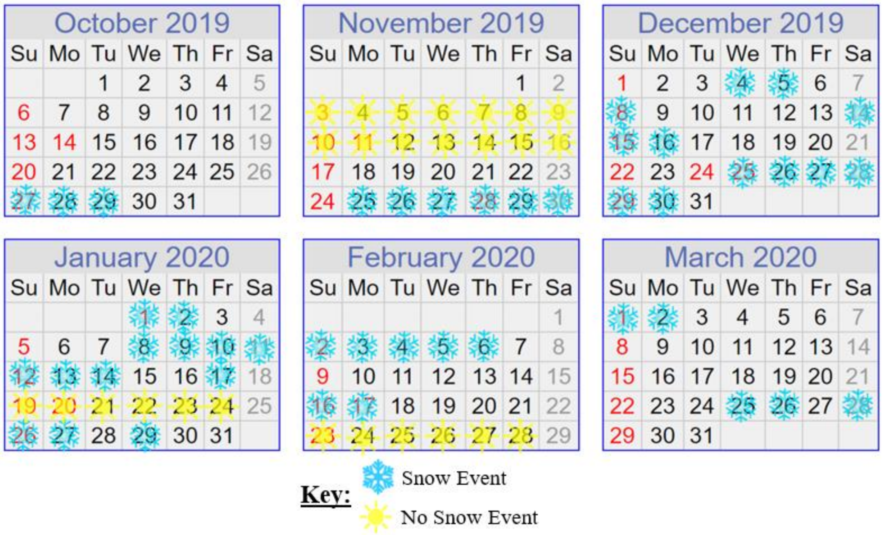
Figure 3.3 Equipped routes, not-equipped routes, and RWIS site locations.

3.2.1 Weather Collection

The RWIS network provides data on a variety of weather and road-related attributes. These include average wind speed, snowfall rate, air temperature, precipitation intensity, calculated storm intensity index, surface temperature, surface status, and surface snow depth. Anytime there was snowfall or snow accumulation at one RWIS location, data were collected for that entire calendar day at all selected RWIS locations. This was done as it was assumed that those dates would be the days where UDOT snowplows would be out clearing snow.

Gathering data for the entire day also allowed for any of the effects of signal preemption on the snowplows to be included in the analysis, especially showing effects of signal preemption that could have taken place before or after winter weather events. UDOT snowplows may be out on routes up to 12 hours prior to a storm to pretreat pavement. Some of the older snowplows request signal preemption constantly, leading to preemption requests before snow begins to fall. Also, as weather fluctuates greatly during a storm and throughout the study area, it was decided that when a snowstorm was reported at any RWIS site, data were downloaded for the entire 24-hour period of the storm day. Travel speeds and safety can also continue to be impacted after it stops snowing. For these reasons, it was determined to collect data from the entire day there was snow in all efforts of data collection to measure the lasting effects of the DSRC systems requesting signal preemption.

For the 2019 to 2020 winter weather season, it was determined that there were 46 days that had some degree of snowfall at the selected RWIS stations. This created a total of 25 storms. These storms would last from a single day to several days. UDOT’s RWIS system would report that a snowstorm had begun if there was greater than 0.25 inches of snow. After dates with snowfall were determined, a group of days without winter weather were selected to be used as a baseline control. The baseline was only used to compare traffic operation and focused on travel speeds. The days with snow, as well as the control days selected without snow, are shown in Figure 3.4. The data were downloaded from the UDOT RWIS online interface, which included a variety of associated data, such as intensity of the snowstorms (UDOT Weathernet, 2021).



October 2019

Su	Mo	Tu	We	Th	Fr	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27 ❄	28 ❄	29 ❄	30	31		

November 2019

Su	Mo	Tu	We	Th	Fr	Sa
					1	2
3 ☀	4 ☀	5 ☀	6 ☀	7 ☀	8 ☀	9 ☀
10 ☀	11 ☀	12 ☀	13 ☀	14 ☀	15 ☀	16 ☀
17	18	19	20	21	22	23
24	25 ❄	26 ❄	27 ❄	28 ❄	29 ❄	30 ❄

December 2019

Su	Mo	Tu	We	Th	Fr	Sa
1	2	3	4 ❄	5 ❄	6	7
8 ❄	9	10	11	12	13	14 ❄
15 ❄	16 ❄	17	18	19	20	21
22	23	24	25 ❄	26 ❄	27 ❄	28 ❄
29 ❄	30 ❄	31				

January 2020

Su	Mo	Tu	We	Th	Fr	Sa
			1 ❄	2 ❄	3	4
5	6	7	8 ❄	9 ❄	10 ❄	11 ❄
12 ❄	13 ❄	14 ❄	15	16	17 ❄	18
19 ☀	20 ☀	21 ☀	22 ☀	23 ☀	24 ☀	25
26 ❄	27 ❄	28	29 ❄	30	31	

February 2020

Su	Mo	Tu	We	Th	Fr	Sa
						1
2 ❄	3 ❄	4 ❄	5 ❄	6 ❄	7	8
9	10	11	12	13	14	15
16 ❄	17 ❄	18	19	20	21	22
23 ☀	24 ☀	25 ☀	26 ☀	27 ☀	28 ☀	29

March 2020

Su	Mo	Tu	We	Th	Fr	Sa
1 ❄	2 ❄	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25 ❄	26 ❄	27	28 ❄
29	30	31				

Key:
❄ Snow Event
☀ No Snow Event

Figure 3.4 Days with snow events and control days without snow.

3.2.2 Intent of Weather Data

One part of the weather data that was explored for usage was storm severity. In the UDOT RWIS system, the UDOT weather team has a formula that calculates a Storm Intensity Index (SII). The SII is an instantaneous value calculated every ten minutes from a mixture of snowfall rate, wet-bulb temperature, wind speed, and road temperature. This characterization of different times of the snowstorm relates to snowplow activity. When SII is less than 0.25, the storm intensity is light, as the snowfall rate is less than 0.25 inches per hour. There are some snowplows out during this time, but not many. When the SII is between 0.25 and 1.0, the storm intensity is moderate. The snowfall rate is less than 1 inch per hour. There is some slush on the roads, but most of it should be clear. When SII is greater than 1.0, the storm intensity is heavy, as conditions are severe enough that it is difficult to keep the roads plowed. During this time there is heavy snowfall, blowing winds, and low visibility. Examples of these conditions are shown from traffic camera screenshots in Figure 3.5. From SII, the storm severity index (SSI) is calculated by taking the SII for the storm and multiplying it by the number of hours the storm lasted.

Light (SII < 0.25) Moderate (0.25 ≤ SII ≤ 1)

Heavy (SII > 1)

Figure 3.5 Storm intensity index categories (UDOT Weathernet, 2021).

Although SII and SSI are useful metrics for weather analysis, these metrics were not determined to be useful for this project. This is due to the diversity of weather events and intensities in a single storm in not only one location, but across the entire study area. It was found that the time increments differed between the datasets, making a statistically significant comparison not plausible.

3.3 Traffic Signal Method of Analysis

Analysis of the traffic signals answers the overall question of how V2X systems using DSRC on snowplows affects signal performance. This was done by analyzing two different datasets, DSRC message records and high-resolution preemption signal controller event logs associated with the ATSPM system. This section will discuss components of each dataset and why data were collected for this project.

3.3.1 DSRC Messages Method of Analysis

As discussed in Chapter 2, DSRC uses radio frequency to converse with infrastructure or other vehicles. For this project, DSRC was used by the V2X system to communicate requests for signal preemption from the snowplow to the traffic signal controller. The data associated with DSRC include BSM, SRM, SSM, and SPaT message logs. These preemption messages can be used to distinguish individual preemption requesting events.

BSM and SPaT messages are sent every tenth of a second, while SRM and SSM messages are sent every second. The BSM and SRM messages originate from the OBU on the snowplow and communicate with the RSU located at the signal, which then logs and relays the messages to the signal controller. The messages include the necessary information for the RSU to process and send a request for signal preemption to the signal controller. A plow preemption event is defined as when a snowplow communicates to the RSU and requests preemption, regardless of whether preemption is actually granted. The number of snowplow preemption events shows how often the V2X system is sending out requests, whereas the number of granted events shows how often the signal controller goes into preemption mode.

Another measure that can be taken from individual plow preemption events is occupancy. Occupancy is how long the snowplow occupied the geofence area of the signalized intersection. This is the total time from when the snowplow entered the geofence, which is the point from which it can send a request for preemption, to when it exits the geofence, when a cancel request is sent for the signal to exit preemption mode. This is beneficial to see how often preemption is being requested and granted, as well as the duration the plow is at each intersection.

DSRC message records and signal controller logs are necessary to understand how the V2X system affects traffic signals, as this data can answer the question of how often requests are made and how often the requests are granted. The answers to these questions can be used to determine the efficacy of the system for UDOT.

3.3.2 Preemption Duration Method of Analysis

The signal controller high-resolution data provides details on how the normal operation of each signal along the study routes is affected when a preemption request is granted. There are different levels of priorities for preemption within UDOT’s signal controllers. The highest priority of preemption goes to rail (including light rail transit (TRAX)), then emergency vehicles, followed by snowplows on equipped routes. As each snowplow requests preemption, the signal controller system can then grant preemption if the parameters are correct. When preemption is granted, the signal timing is altered by stepping out of coordination from the original signal timing plan. Many traffic issues can be caused by coordination being out of step and preemption can affect the ability of the signal to get back into step if continual requests are sent. The coordination of the system can be determined through a variety of signal codes, in accordance with the Indiana Traffic Signal Hi-Resolution Data Logger Enumerations (Li et al., 2012). The codes record when preemption is requested (call input on), when the signal begins to process it (entry started), when the preemption is granted (dwell service), and when the preemption request is canceled (call input off). This data show when the signal controller goes back to its normal cycle, or when it is back in step, after a preemption event. The time this process took is affected duration, or how long preemption affected the timing of the signal and subsequent traffic.

High-resolution signal controller data were deemed necessary to analyze long-lasting effects of snowplow requests for preemption on the signal performance and cycles. Evaluating and analyzing the data can help determine the effect of a preemption event on the traffic signal. This analysis gives clarity to the overall question of determining the effect on signal controllers that snowplows requesting signal preemption by DSRC have.

3.4 Vehicle Performance Methods of Analysis

This section explains the methods of analysis for the following three datasets: snowplow speed, general travel speed, and crash data. The analysis of these three datasets provides the answers for determining if snowplow and traffic efficiency and performance are improved when snowplows use DSRC systems. This was done by focusing on general travel and snowplow speeds, where speeds from equipped routes and not-equipped routes are compared. The analysis of crash data was used to compare the safety of vehicles on both equipped and not-equipped routes. These datasets help determine if traffic and snowplow operations are being benefitted by the preemption requests, by using speed and safety analysis. In the following subsections, each dataset pertaining to snowplow and traffic analysis will be described, as well as what the dataset entails and why it was collected.

3.4.1 Snowplow Speed Data Method of Analysis

Snowplow speed was gathered using Networkfleet, which is Verizon's version of AVL data. This is used by UDOT to monitor various snowplow events. A cellular GPS device is located on each snowplow that transmits messages to the central database in intervals of 30 seconds. A variety of information, such as snowplow location and speed, is transmitted through these messages from the snowplows to the system.

Snowplow speed data were beneficial in the study as they were used to evaluate snowplow location and speeds. Data for snowplows were gathered for equipped and not-equipped routes for every day there was a winter weather event. The data were gathered using AVL data, since data from DSRC messages could not be gathered on not-equipped routes since there are no RSUs to collect the data. The snowplow speed data were analyzed to determine if snowplows on equipped routes had greater speeds during winter weather events than snowplows on not-equipped routes. This dataset, in conjunction with the general traffic travel speed data as described in the next section, answers the question of whether snowplows and traffic on equipped routes are faster than those on not-equipped routes.

3.4.2 General Traffic Travel Speed Data Method of Analysis

General traffic travel speed data were gathered using the ClearGuide platform. Previously known as iPeMs, the platform uses HERE data, which is third-party, historical, and real-time speed data, to measure the performance of transportation systems across the United States. UDOT's subscription to ClearGuide, provided as a service from Iteris, utilizes a user web interface to create specific routes or segments to determine various traffic patterns, congestion, and performance measures. In this study, average speeds and average travel times on each segment and route were gathered and analyzed.

The general travel speed data were used on both equipped and not-equipped routes to analyze the effects of snowplow requests for signal preemption on general traffic. The comparison shows if vehicle speed is affected more on routes with equipped snowplows than on not-equipped routes.

3.4.3 Crash Data Method of Analysis

Safety data are provided from UDOT as a service from AASHTOWare Safety (https://numetric.com/aashtowaresafety), managed by Numetric, a firm that specializes in traffic safety analysis. The data collected about crashes contain the location and time of the crash, severity of the crash, light condition, weather condition, and roadway surface condition. Data on crashes were gathered for both equipped and not-equipped routes to determine if snowplows requesting signal preemption through DSRC generated improvements to surrounding traffic safety. This analysis of crash data was done as an addition to the initial scope. With more investigation of the data, additional correlation may be found, but the analysis for this project focused on overall differences of safety statistics for equipped versus not-equipped routes.

3.5 Summary

Data from the 25 snowstorms during the 2019-2020 winter were gathered at each RWIS location to determine days with winter weather events. This was done for routes equipped with V2X technology, as well as similar routes that were not equipped with the technology. From the weather dates, datasets were gathered for two types of analysis: signal analysis and vehicle analysis. The question that the signal analysis answers is how snowplows requesting signal preemption affect traffic signals. This is done with the DSRC message logs and high-resolution signal controller logs datasets, which answer how often signal preemption requests were made and how often they were granted, as well as the effect of a preemption event on a signal cycle.

Vehicle analysis data are used to determine how plowing and traffic efficiency and performance are improved with snowplows requesting signal preemption through the DSRC systems. This is found through analyzing the snowplow speed and general travel speed, which help determine if snowplows and traffic on equipped routes were faster than those on not-equipped routes; as well as through crash data, which analyzed if safety is improved with snowplows using DSRC.

4.0 TRAFFIC SIGNAL PERFORMANCE ANALYSIS

4.1 Overview

A major focus of the study was to determine the impacts that snowplows requesting signal preemption through DSRC had on traffic signal operations. This was done by analyzing datasets with DSRC message record data (message records) and high-resolution signal controller log (controller logs) data. The DSRC message data were generated by the OBU located on the snowplow and logged by the RSU at the intersection on equipped corridors. The brands of OBUs and RSUs used in the study were Lear and Cohda. Each of the following sections includes information for message records and controller logs' processes for data collection, analysis, and determined results.

4.2 Preemption Status Data Analysis and Results

The preemption status data and analysis are based on two distinct datasets. The first is the DSRC message logs and the second is the signal controller logs. Message logs data depicts the frequency with which signal preemption was requested by the snowplows. It also shows occupancy, which is the time the plow is interacting with a specific signal and can be used in conjunction with affected duration, the time it takes a signal to receive, act on, and complete the signal preemption request. The high-resolution data depicts whether the request is granted as well as how long it took the signal to recover from granting preemption to the snowplow. These attributes assist in determining how the V2X system that uses DSRC is working and the direct impacts it has on overall signal performance. The following subsections contain information on data collection, analysis, and results.

4.2.1 Preemption Status Data Collection

Message data logs were downloaded from the UDOT DSRC server, which stores the DSRC message logs in separate tables based on the message types. The controller event log data were downloaded from the UDOT ATSPM server, which stores high-resolution traffic data at every one-tenth of a second from each equipped signal controller. The message logs are composed of records of BSM, SRM, and SSM messages, where the controller event log records each event that occurs within a signal controller. Records of data were gathered from each equipped signal controller for days with winter weather events during the study period.

Controller event logs were collected in accordance with the Indiana Traffic Signal Hi-Resolution Data Logger Enumerations (Li et al., 2012). Only data points containing event codes 102 to 111 and 150 were included in the study to analyze the traffic patterns at each intersection and the regarded signal preemption. Table 4.1 contains a list of the event codes, event descriptors, parameters, and descriptions used in the referenced study.

Each event code has an associated preempt code ranging from 1 to 10. Codes 1 and 2 relate to railroad preemption; codes 3 through 6 relate to emergency vehicle preemption; and codes 7 through 10 are used for snowplow preemption. The snowplow codes are directional. Code 7 corresponds to northbound snowplows, 8 to southbound snowplows, 9 to eastbound snowplows, and 10 to westbound snowplows. During data collection, calls that had preempt codes 1 to 6 were filtered out, leaving only snowplow-related preemption calls.

Basic information also contained in DSRC message logs include the date and time of when the message was received; the applicable UDOT vehicle ID; the latitude, longitude, and elevation of the geographical point from where the message was sent; and the heading and speed of the snowplow. This information was used to determine location of snowplows and the frequency with which signal preemption requests were sent.

As DSRC equipment can send and receive messages anywhere up to 2 kilometers from their source, the equipped snowplows could only send requests to the RSU of a traffic signal while within geofences. However, the BSM could be received at any RSU within range. Geofences were created using latitude and longitude points, indicating the exact location of the ingress and egress by lane for each intersection. The locations of these points were based on the dimensions UDOT used to program their signal systems to process signal preemption, as well as MAP messages. To filter out which message logs applied to what signals, ArcGIS was used to map geofence areas and filter out message logs with coordinates outside the geofence locations. Geofence locations were given as JavaScript Object Notation (or JSON) files. The maximum and minimum ingress and egress points for each equipped intersection analyzed can be found in

Table 4.1 Preemption Code Descriptions (adapted from Li et al., 2012)

Code	Preempt Call	Preempt Codes	Description
101	Preempt Advance Warning Light	Preempt # (1-10)	Set when preemption advance warning input is activated.
102	Preempt (Call) Input On	Preempt # (1-10)	Set when preemption input is activated (prior to preemption delay timing). May be set multiple times if input is intermittent during preemption service.
103	Preempt Gate Down Input Received	Preempt # (1-10)	Set when gate down input is received by controller (if available).
104	Preempt (Call) Input Off	Preempt # (1-10)	Set when preemption input is de-activated. May be set multiple times if input is intermittent preemption service.
105	Preempt Entry Started	Preempt # (1-10)	Set when preemption delay expires, and controller begins transition timing (force off) to serve preemption.
106	Preemption Begin Track Clearance	Preempt # (1-10)	Set when track clearance phase is green and track clearance timing begins.
107	Preemption Begin Dwell Service	Preempt # (1-10)	Set when preemption dwell or limited service begins, or minimum dwell timer is reset due to call drop and reapplication.
108	Preemption Link Active On	Preempt # (1-10)	Set when linked preemptor input is applied from active preemptor.
109	Preemption Link Active Off	Preempt # (1-10)	Set when linked preemptor input is dropped from active preemptor.
110	Preemption Max Presence Exceeded	Preempt # (1-10)	Set when preemption max presence timer is exceeded, and preemption input is released from service.
111	Preemption Begin Exit Interval	Preempt # (1-10)	Set when preemption exit interval phases are green and exit timing begins.
150	Coord Cycle Stated Change	Parameter (0-6) defined as: 0 = Free 1 = In Step 2 = Transition – Add 3 = Transition – Subtract 4 = Transition – Dwell 5 = Local Zero 6 = Begin Pickup	

Appendix A. These locations were placed into a spreadsheet file and then were converted to an ArcGIS shapefile.

Not every intersection along the equipped routes was equipped with the V2X equipment due to potential issues that signal preemption could cause at those intersections. The intersections not included in the study typically included intersections with ramps and/or light-rail transit (TRAX) crossings. A combined list of DSRC-equipped signals, with their associated cross streets, can be found in Appendix B.

Several issues occurred during data collection. First, multiple requests for preemption were found in the data for what should have been a single occupancy at an intersection. This occurred for various reasons but were primarily due to the snowplow placing a request and then immediately canceling the request due to leaving the geofence limits. These issues are theorized to be caused by GPS drift; uncorrected GPS coordinates; the OBU being inserted incorrectly; or snowfall, trees, and other obstructions affecting signal communication. These issues not only cause duplicates in the signal preemption requested data, but also in the occupancy data.

Second, the geography of the intersection (i.e., roadway geometry) greatly affected the quality of data received, as it would prohibit or limit data collection. Also, the directionality of preemption being requested and granted differed for some controllers, due to the skew of the intersection, and were verified with UDOT and Narwhal. On curves, the geofences at times were not wide enough for the RSU to receive the SRM calls with signal preemption requests. Being nonorthogonal, the directions that the intersections were programmed had to be confirmed, ensuring preemption detector channels in the signal controller match the directions of MAP messages. Another issue was there could be delays up to 0.5 seconds before cancellation messages were received and began to take effect. Finally, another issue was that some snowplows in the study always had their spreaders on, which means they were continuously sending out requests for signal preemption. To combat this, only dates with winter weather were included in the analysis.

4.2.2 Preemption Status Analysis

The preemption status analysis was done to determine how often signal preemption requests were made, how often requests were granted, and the time that snowplow occupied the intersection. After data were downloaded, they were processed through a Microsoft Access database that had been altered from use in a previous UDOT study (Schultz et al., 2020). This database filtered and aggregated the message logs received and controller event data to determine when a snowplow was requesting signal preemption and if the snowplow was granted signal preemption.

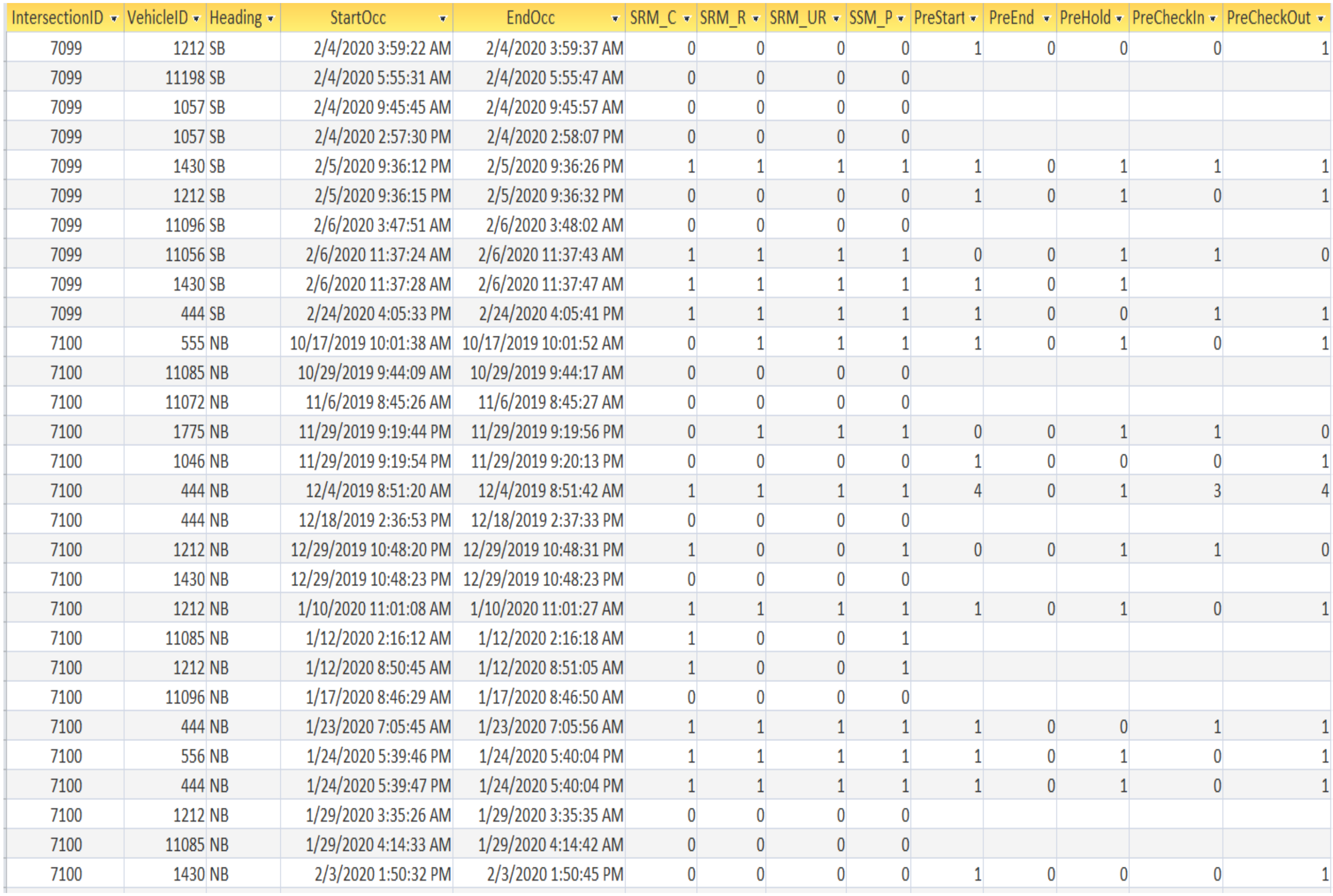
The methodology in the database to determine signal preemption analyzed SRM messages from the OBU to the RSU, SSM messages identifying communication between the RSU and signal controller, and preemption status code within the signal controller. Each SRM consists of status tags to check-in (request), hold (update request), or check-out (cancel) based on these tags' type. Each of the SRM tags generally relate to a preemption status code in the signal controller based on the parameters for each event code. When analyzed together, they can depict the various steps and status of a preemption event. If an SRM or SSM was recorded, it was determined that signal preemption was requested. This method was selected based on the assumption that follow-up messages within the DSRC system could only send once an initial request was made. If a preemption event was recorded by the signal controller, the preempt codes were analyzed to determine if the preemption status was to begin, to hold, or to be terminated. The data processor first combined the two datasets based on the timestamp occurring during a plow event, then took each of the various DSRC message tags and signal controller preemption codes and identified the applicable parts from each record to show a complete signal preemption process from a snowplow request to each step within the signal controller. The data processor also adjusted the timestamps of the DSRC message record from GMT to MST (7-hour difference) and MDT (6-hour difference) based on the day the message was sent. This was required based on message logs not being recorded at local time, while the control event logs were.

Figure 4.1 illustrates an excerpt of the DSRC message logs and high-resolution signal controller logs' compiled results pulled from the Microsoft Access database. In the data, modifications for analysis, route, segment, direction, and time period were added for easier comparison as shown in Figure 4.2. These results were used to determine how often the snowplows were requesting and being granted signal preemption; a “YES” or “NO” was recorded based on values from within the compiled dataset. The conversion to binary response for requested was based on the “SRM_Sum” value being greater than one, and for granted preemption based on the sum of “PreStart” through “PreHold” columns, as shown in Figure 4.2.

In addition to analysis being completed on how frequently DSRC messages were requested and were granted signal preemption, occupancy was also calculated. Occupancy is directly correlated with how effective preemption is working. On a well-performing signal, snowplows will not remain in the geofence for an extended time, as they will be granted preemption and pass through the intersection. Snowplow occupancy duration data were collected for each of the signals on equipped routes to determine average occupancy used in analysis.

One common challenge with big data (including data in this study) is missing records. The compiled data includes records where controller logs showed that signal preemption was granted, without the accompanying DSRC message log indicating a request for preemption. In these instances, the missing data implies there is a missing DSRC message requesting signal preemption. This was determined with message records showing a “NO” for requested but a “YES” for granted. These errors from recording data were not changed in the analysis. Out of all the DSRC messages recorded, only 7 percent of the data had messages not recorded as requesting signal preemption when it was granted. The signal IDs for the RSUs that did not record request data correctly (by route) are as follows:

- 700 East Cottonwood: 7207, 7210
- East 9000 South: 7019, 7197, 7601
- Foothill Boulevard: 7218, 7220, 7222, 7371
- Redwood Salt Lake City: 7090, 7091, 7092, 7093, 7094, 7095, 7096, 7098, 7099, 7100
- Redwood West Jordan: 7116, 7234
- West 9000 South: 7418



IntersectionID	VehicleID	Heading	StartOcc	EndOcc	SRM_C	SRM_R	SRM_UR	SSM_P	PreStart	PreEnd	PreHold	PreCheckIn	PreCheckOut
7099	1212	SB	2/4/2020 3:59:22 AM	2/4/2020 3:59:37 AM	0	0	0	0	1	0	0	0	1
7099	11198	SB	2/4/2020 5:55:31 AM	2/4/2020 5:55:47 AM	0	0	0	0					
7099	1057	SB	2/4/2020 9:45:45 AM	2/4/2020 9:45:57 AM	0	0	0	0					
7099	1057	SB	2/4/2020 2:57:30 PM	2/4/2020 2:58:07 PM	0	0	0	0					
7099	1430	SB	2/5/2020 9:36:12 PM	2/5/2020 9:36:26 PM	1	1	1	1	1	0	1	1	1
7099	1212	SB	2/5/2020 9:36:15 PM	2/5/2020 9:36:32 PM	0	0	0	0	1	0	1	0	1
7099	11096	SB	2/6/2020 3:47:51 AM	2/6/2020 3:48:02 AM	0	0	0	0					
7099	11056	SB	2/6/2020 11:37:24 AM	2/6/2020 11:37:43 AM	1	1	1	1	0	0	1	1	0
7099	1430	SB	2/6/2020 11:37:28 AM	2/6/2020 11:37:47 AM	1	1	1	1	1	0	1		
7099	444	SB	2/24/2020 4:05:33 PM	2/24/2020 4:05:41 PM	1	1	1	1	1	0	0	1	1
7100	555	NB	10/17/2019 10:01:38 AM	10/17/2019 10:01:52 AM	0	1	1	1	1	0	1	0	1
7100	11085	NB	10/29/2019 9:44:09 AM	10/29/2019 9:44:17 AM	0	0	0	0					
7100	11072	NB	11/6/2019 8:45:26 AM	11/6/2019 8:45:27 AM	0	0	0	0					
7100	1775	NB	11/29/2019 9:19:44 PM	11/29/2019 9:19:56 PM	0	1	1	1	0	0	1	1	0
7100	1046	NB	11/29/2019 9:19:54 PM	11/29/2019 9:20:13 PM	0	0	0	0	1	0	0	0	1
7100	444	NB	12/4/2019 8:51:20 AM	12/4/2019 8:51:42 AM	1	1	1	1	4	0	1	3	4
7100	444	NB	12/18/2019 2:36:53 PM	12/18/2019 2:37:33 PM	0	0	0	0					
7100	1212	NB	12/29/2019 10:48:20 PM	12/29/2019 10:48:31 PM	1	0	0	1	0	0	1	1	0
7100	1430	NB	12/29/2019 10:48:23 PM	12/29/2019 10:48:23 PM	0	0	0	0					
7100	1212	NB	1/10/2020 11:01:08 AM	1/10/2020 11:01:27 AM	1	1	1	1	1	0	1	0	1
7100	11085	NB	1/12/2020 2:16:12 AM	1/12/2020 2:16:18 AM	1	0	0	1					
7100	1212	NB	1/12/2020 8:50:45 AM	1/12/2020 8:51:05 AM	1	0	0	1					
7100	11096	NB	1/17/2020 8:46:29 AM	1/17/2020 8:46:50 AM	0	0	0	0					
7100	444	NB	1/23/2020 7:05:45 AM	1/23/2020 7:05:56 AM	1	1	1	1	1	0	0	1	1
7100	556	NB	1/24/2020 5:39:46 PM	1/24/2020 5:40:04 PM	1	1	1	1	1	0	1	0	1
7100	444	NB	1/24/2020 5:39:47 PM	1/24/2020 5:40:04 PM	1	1	1	1	1	0	1	0	1
7100	1212	NB	1/29/2020 3:35:26 AM	1/29/2020 3:35:35 AM	0	0	0	0					
7100	11085	NB	1/29/2020 4:14:33 AM	1/29/2020 4:14:42 AM	0	0	0	0					
7100	1430	NB	2/3/2020 1:50:32 PM	2/3/2020 1:50:45 PM	0	0	0	0	1	0	0	0	1

Figure 4.1 Preemption status from Access database.

Route	Segment	IntersectionID	VehicleID	Direction	Time Period	StartOcc	EndOcc	Occupancy	SRM_Sum	SSM_P	PreStart	PreEnd	PreHold	PreCheckIn	PreCheckOut
700 E	700 E Cottonwood	7194	1623	Northbound	Evening	25-Nov-19	25-Nov-19	0.51666667	1	0	1	1	0	0	1
700 E	700 E Cottonwood	7194	11044	Northbound	Early Morning	26-Nov-19	26-Nov-19	0	0	0					
700 E	700 E Cottonwood	7194	444	Northbound	AM Peak	26-Nov-19	26-Nov-19	0.4	1	1	1	0	1	0	1
700 E	700 E Cottonwood	7194	1021	Northbound	Evening	27-Nov-19	27-Nov-19	0.11666666	0	1					
700 E	700 E Cottonwood	7194	1021	Northbound	Early Morning	28-Nov-19	28-Nov-19	0.68333334	1	1	1	1	1	0	1
700 E	700 E Cottonwood	7194	1623	Northbound	Early Morning	28-Nov-19	28-Nov-19	0.5	1	0	0	0	1		
700 E	700 E Cottonwood	7194	1623	Northbound	AM Peak	28-Nov-19	28-Nov-19	0.46666666	1	0	1	1	1		
700 E	700 E Cottonwood	7194	1021	Northbound	Early Morning	29-Nov-19	29-Nov-19	0.01666666	0	0					
700 E	700 E Cottonwood	7194	1439	Northbound	Mid Day	29-Nov-19	29-Nov-19	0.71666667	1	1	1	1	0	0	1
700 E	700 E Cottonwood	7194	1439	Northbound	Evening	29-Nov-19	29-Nov-19	0.45	1	1	1	1	0	0	1
700 E	700 E Cottonwood	7194	1623	Northbound	Early Morning	30-Nov-19	30-Nov-19	1	3	1					
700 E	700 E Cottonwood	7194	1249	Northbound	Early Morning	30-Nov-19	30-Nov-19	0.03333333	0	0					
700 E	700 E Cottonwood	7194	1623	Northbound	Early Morning	30-Nov-19	30-Nov-19	0.45	1	0	1	1	0	0	1
700 E	700 E Cottonwood	7194	1249	Northbound	Early Morning	30-Nov-19	30-Nov-19	0	0	0					
700 E	700 E Cottonwood	7194	1439	Northbound	Mid Day	08-Dec-19	08-Dec-19	0	0	0					
700 E	700 E Cottonwood	7194	1439	Northbound	Mid Day	08-Dec-19	08-Dec-19	0.35	3	1	3	2	0	2	3
700 E	700 E Cottonwood	7194	1249	Northbound	Early Morning	16-Dec-19	16-Dec-19	0.46666667	1	1	1	1	0	0	1
700 E	700 E Cottonwood	7194	1439	Northbound	Early Morning	16-Dec-19	16-Dec-19	0.03333333	1	1					
700 E	700 E Cottonwood	7194	1439	Northbound	AM Peak	16-Dec-19	16-Dec-19	0.55	1	1	1	1	1	0	1
700 E	700 E Cottonwood	7194	444	Northbound	AM Peak	27-Dec-19	27-Dec-19	0.11666667	0	1					
700 E	700 E Cottonwood	7194	1439	Northbound	Mid Day	30-Dec-19	30-Dec-19	0.43333334	1	1	1	1	1	0	1
700 E	700 E Cottonwood	7194	1623	Northbound	Mid Day	30-Dec-19	30-Dec-19	0.4	3	1	4	2	1	3	4
700 E	700 E Cottonwood	7194	1623	Northbound	AM Peak	01-Jan-20	01-Jan-20	0.11666667	1	1	1	1	0	0	1
700 E	700 E Cottonwood	7194	11140	Northbound	AM Peak	01-Jan-20	01-Jan-20	0.45	3	1	9	3	2	8	9
700 E	700 E Cottonwood	7194	11140	Northbound	Mid Day	01-Jan-20	01-Jan-20	0	0	0					
700 E	700 E Cottonwood	7194	1439	Northbound	PM Peak	01-Jan-20	01-Jan-20	0.3	0	1	0	0	1		
700 E	700 E Cottonwood	7194	1021	Northbound	Early Morning	10-Jan-20	10-Jan-20	0.01666667	0	0					
700 E	700 E Cottonwood	7194	1439	Northbound	Early Morning	10-Jan-20	10-Jan-20	0.41666666	3	1	4	2	2	3	3
700 E	700 E Cottonwood	7194	1439	Northbound	Mid Day	12-Jan-20	12-Jan-20	0.61666666	3	1	2	1	0	1	2

Figure 4.2 Preemption status used in analysis.

In addition to errors in the DSRC message data, it was also determined during the analysis that the data for 11 intersections in the Redwood West Jordan segment were missing. As a result, the intersections from 8400 South and 12600 South on Redwood Road were not included in the study. Although they were not in the study, RSUs at these intersections still worked, processing and granting requests for signal preemption.

Another challenge was only analyzing DSRC calls made when snowplows were actively plowing. About half of the snowplows in the study were sending SRMs to request preemption constantly, while the other half sent SRMs to request preemption only when their spreader was active. This was due to age and configuration of the snowplow and available technology. To combat this, only dates that UDOT’s weather team determined there was snowfall and other winter weather were analyzed.

There were various challenges that were also encountered when analyzing occupancy from the DSRC message logs. The analysis included cross streets originally, but the cross streets were removed to analyze only the effects of signal preemption on equipped routes. There were also issues caused by GPS drift, or uncorrected GPS coordinates, creating data with occupancies of 0 minutes. Any calls that listed an occupancy of 0 were removed from the dataset.

The results from data filtering were analyzed for the percent of plow events requested, percent of plow events that were granted, and snowplow occupancy. Statistical analysis was also performed. These groups were analyzed by route, segment, signal ID, and by time period.

4.2.3 Preemption Status Results

Efficiency of the DSRC system in coordination with signal preemption was measured by the frequency of signal preemption requests, the frequency of those requests being granted, and how long the snowplows occupied the geofence. Findings on the frequency in which signals received requests for signal preemption and granted them will be shared, as well as average occupancy of the snowplows. The results will be provided for each equipped route, segment, and time period. Information relating to each individual signal can be found in Appendix C.

4.2.3.1 Signal Preemption Requests

During the study period, on days with winter weather, snowplows occupied signals along equipped corridors 7,349 times. Of those 7,349 events, 3,636 occurrences, or 49.5 percent of total events, did not request signal preemption. This can be a result of snowplows that are not plowing or due to other various reasons. The remaining 3,713 occurrences, or 50.5 percent of total events, requested signal preemption. The results of the request analysis showed the following percent of total events that requested preemption by route, 700 East had 56.2 percent, East 9000 South had 64.6 percent, Foothill Boulevard had 71.9 percent, Redwood Road had 38.0 percent, and West 9000 South had 43.1 percent. The percent of requested calls to total calls for each route is shown in Figure 4.3.

Result percentages were also broken down by segment, as shown in Figure 4.4. This analysis allows the reader to see how results differ between maintenance sheds on routes that pass through multiple sheds. The two routes that have multiple segments are 700 East and Redwood Road. The 700 East Cottonwood segment had 60.1 percent of all plow events request signal preemption, where 700 East Murray only had 34.9 percent of all plow events request signal preemption. On Redwood Road, only 34.4 percent of events on the Redwood Murray segment requested signal preemption. This trend follows with 36.3 percent of events requesting preemption for Redwood SLC and 41.5 percent requesting preemption for Redwood West Jordan.

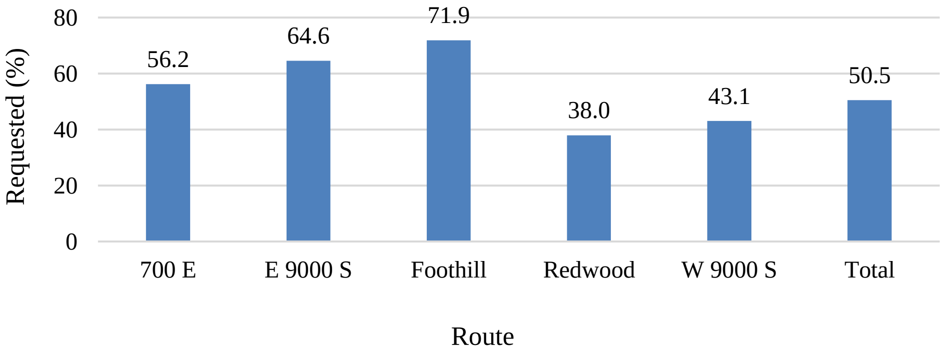


Figure 4.3 Signal preemption requests by route from all plow events.

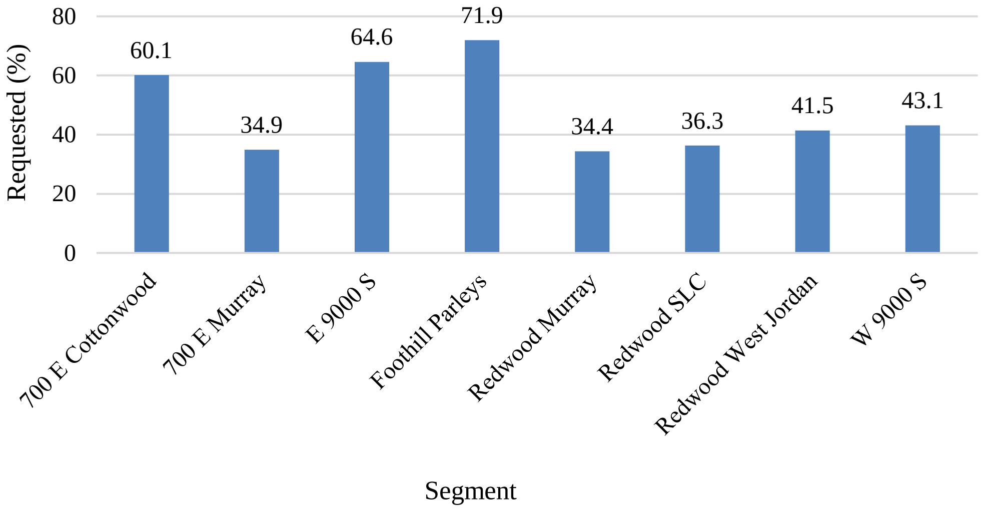


Figure 4.4 Signal preemption requests by segment for all plow events.

To find the significance of the differences between segments on the same route, statistical tests were performed. The tests showed that there was a statistically significant difference between 700 East Cottonwood and 700 East Murray. This was done by using a chi-square test which resulted with a probability of less than 0.0001. A chi-square test is used to determine if a difference in data is caused by chance or by the variables that are being studied. Similar statistically significant differences were found on Redwood Road. A chi-square test was performed between segments on Redwood Road. The results showed the differences between Redwood Murray, Redwood SLC, and Redwood West Jordan were all statistically significant, resulting in a probability of 0.0053.

Requests made for signal preemption were also analyzed by time of day. Figure 4.5 shows the percent of plow events that requested signal preemption by time period. The fewest requests occurred during the PM peak. All other time periods of the day had request percentages that were close to the request percent for the total events. Assessing system functionality was not part of the project, but the time of the calls can be influenced by snowstorm timing or signal coordination. Typically, snowstorms occur overnight, in the early morning, or in the late evening. Also, during PM peak times, signal coordination is favored to the equipped routes negating the need to request signal preemption.

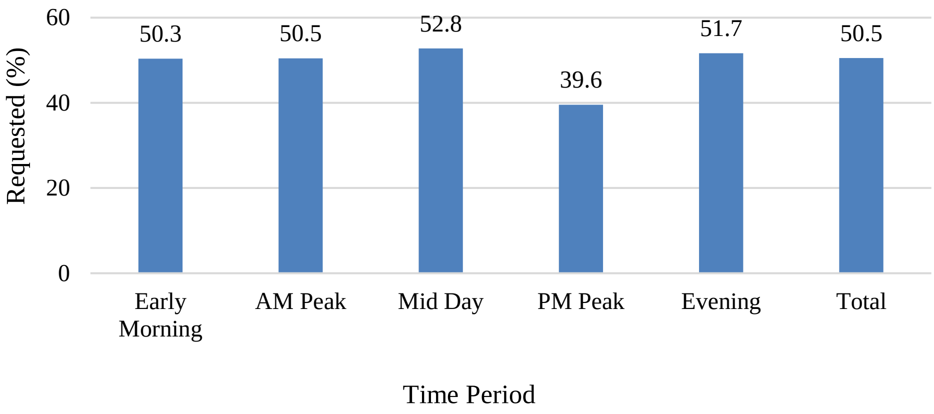


Figure 4.5 Signal preemption requests by time period for all plow events.

4.2.3.2 Granted Signal Preemption

After a request for signal preemption is made, the signal controller either grants the request or does not have time to process the preemption request. This section analyzes plow events that were granted signal preemption. These were the requests that had high-resolution codes which began shifting signal processes inside a signal controller. The duration of the preemption requests affecting the signal controller performance as determined with high-resolution data are discussed in Section 4.3.

There are a variety of reasons that a preemption request may not be granted. If the traffic signal is already green and will stay green during the time the snowplow needs to get through the intersection, the request will not be granted. It also may not be able to grant the request due to pedestrian clearance times if there is a pedestrian call and due to other safety features set up in the signal coordination phasing.

Out of all plow events received, the number of events per route granted ranged between 35.3 percent and 52.4 percent. The percent of all events granted for each individual route is listed in Figure 4.6. Out of total plow events, 42.3 percent were granted signal preemption. Analysis of how many requested calls were granted will be addressed in Section 4.2.3.3.

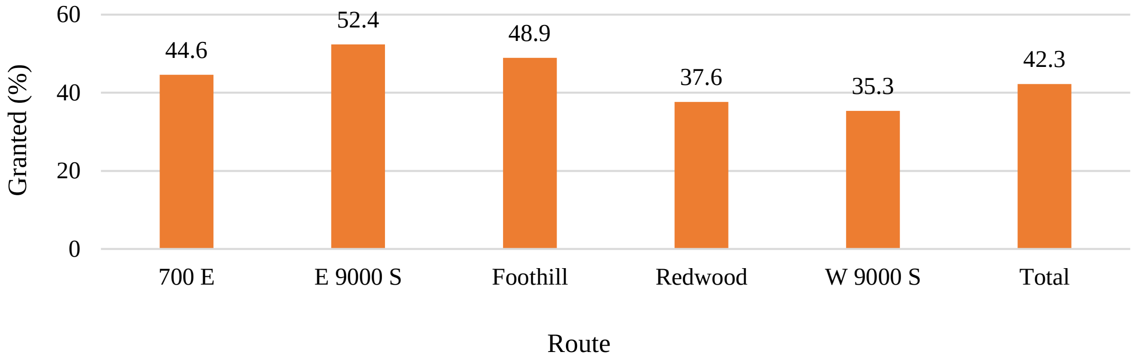


Figure 4.6 Plow events granted preemption by route.

The percent of plow events that were granted was also analyzed by segment. In Figure 4.7, the differences between segments can be seen. Both 700 East and Redwood Road, having multiple segments on each route, had statistically significant differences between segments. This was found by performing a chi-square statistical test. The results showed a statistically significant difference between the segments for both routes, with a p-value of less than 0.0001 for both 700 East and Redwood Road.

Data were gathered as well for time periods of the day when preemption requests were granted. Percentages can be found in Figure 4.8. Requests were most often granted during the evening time period, with 55.2 percent of all events during that time being granted signal preemption. The other time periods ranged between 37.3 percent and 41.5 percent of signal preemption requests being granted, which is near the total average of 42.3 percent.

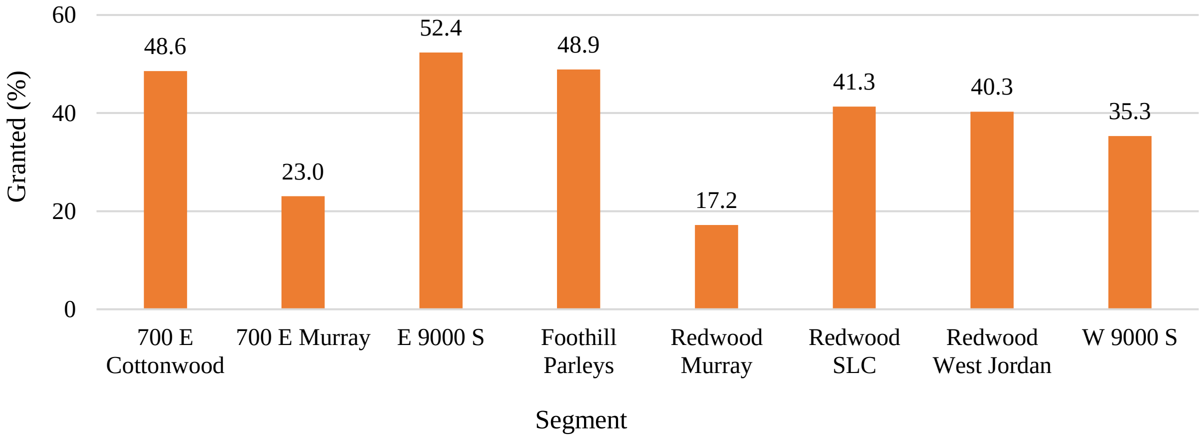


Figure 4.7 Plow events granted preemption by segment.

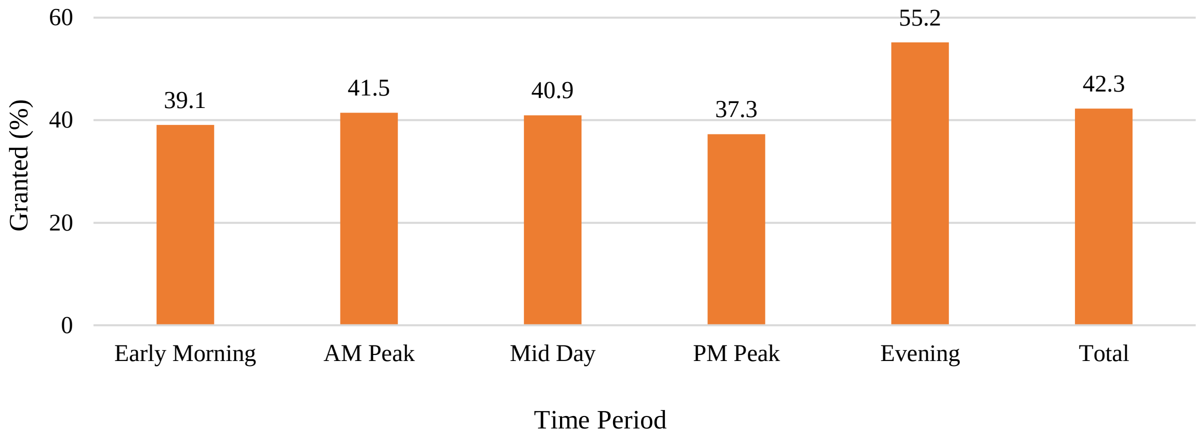


Figure 4.8 Plow events granted preemption by time period.

4.2.3.3 Requests for Signal Preemption versus Granted

To determine how often plow event requests for signal preemption were being granted, the percent of granted requests to total requests were calculated and analyzed. This was done by route, segment, time period, and by signal. The comparisons between the total percentage of plow events for each route that requested signal preemption and were granted signal preemption can be found in Figure 4.9. The analysis on the percent of the preemption requests that were granted was completed and is shown in Figure 4.10. For all routes, except Foothill Boulevard, requests for signal preemption were granted more than 79 percent of the time. Requests along Foothill Boulevard were granted 68.0 percent of the time.

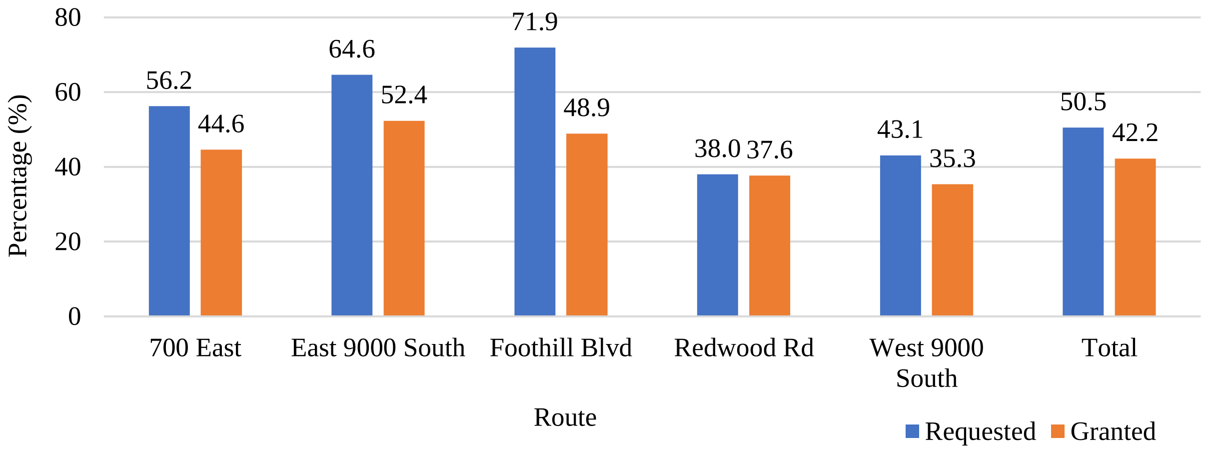


Figure 4.9 Preemption requests and granted by route of total events.

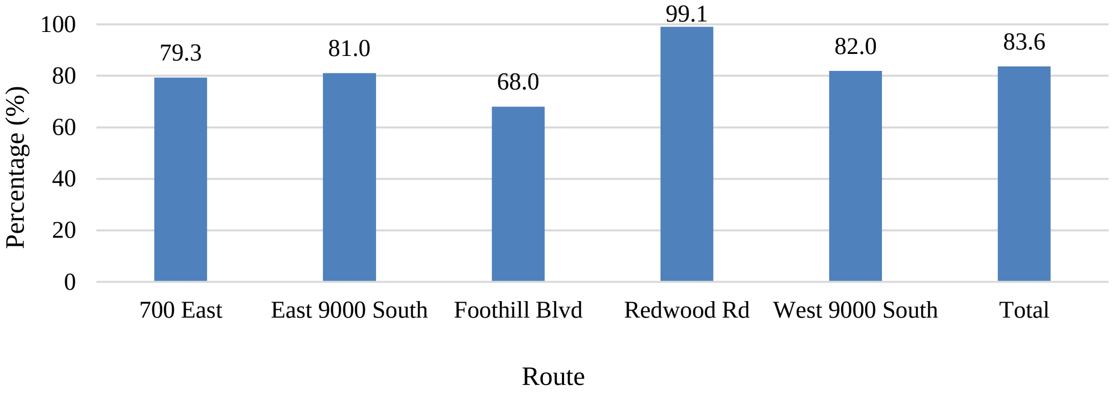


Figure 4.10 Percent of preemption requests granted by route.

This analysis of the number of requests that were granted was also done by segment. Figure 4.11 compares the percent of requests versus the percent granted by segment. The percentage of how many requests that were granted was found for each segment, as shown in Figure 4.12. All segments had granted at least 50 percent of the preemption requests, with Redwood Murray being the lowest at 50 percent and Redwood SLC being the highest segment at almost 114 percent. Occasionally, such as with the segment for Redwood SLC, there are findings that show over 100 percent of the preemption requests were granted. This can be due to data collection issues that were described in the previous sections. This occurs occasionally by individual signal, as shown in Appendix C.

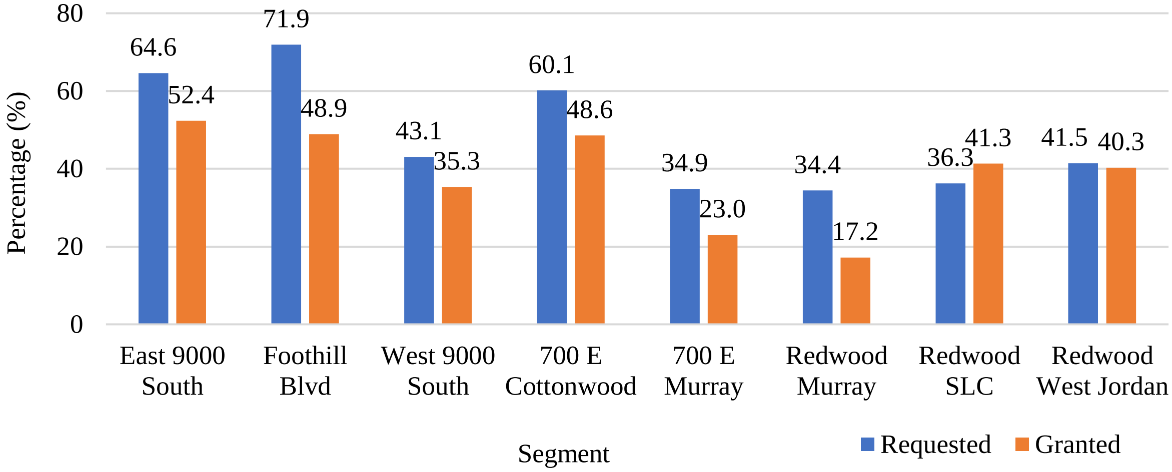


Figure 4.11 Preemption requests and granted by segment based on total.

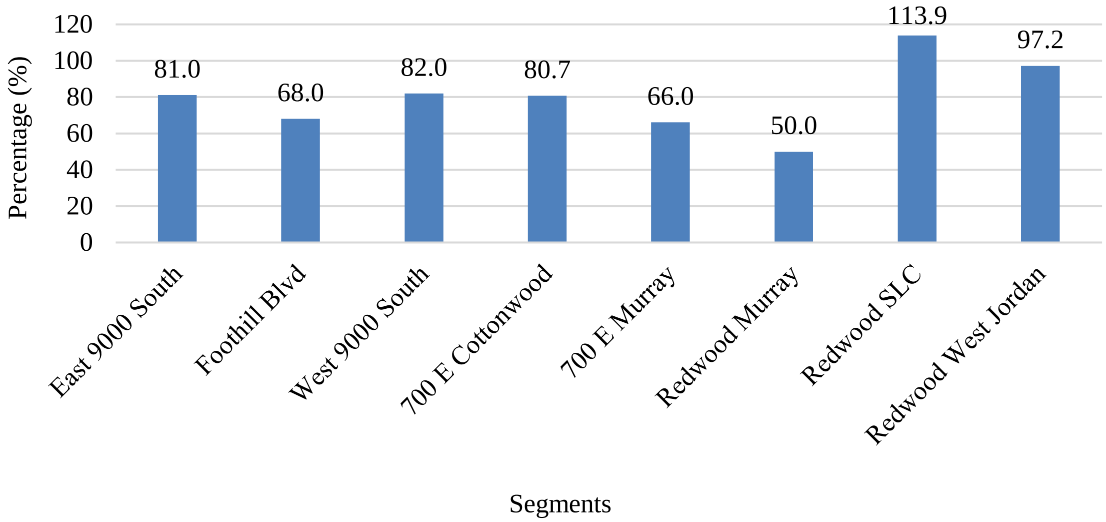


Figure 4.12 Percent of preemption requests granted by segment.

Comparisons of requested and granted events were also done by time period. A side-by-side comparison of the percent of preemption requests and granted requests is shown in Figure 4.13. The percent of how many of the requests were granted was also found, as shown in Figure 4.14. For each time period, over 75 percent of the plow events that requested signal preemption were granted. The lowest percent of requests which were granted were during the early morning and mid-day time periods. For both AM and PM peak, over 80 percent of preemption requests were granted, with values of 82.2 percent and 94.2 percent respectively. The evening time period shows that more requests were granted than requested, mirroring similar issues that were encountered on the Redwood SLC segment.

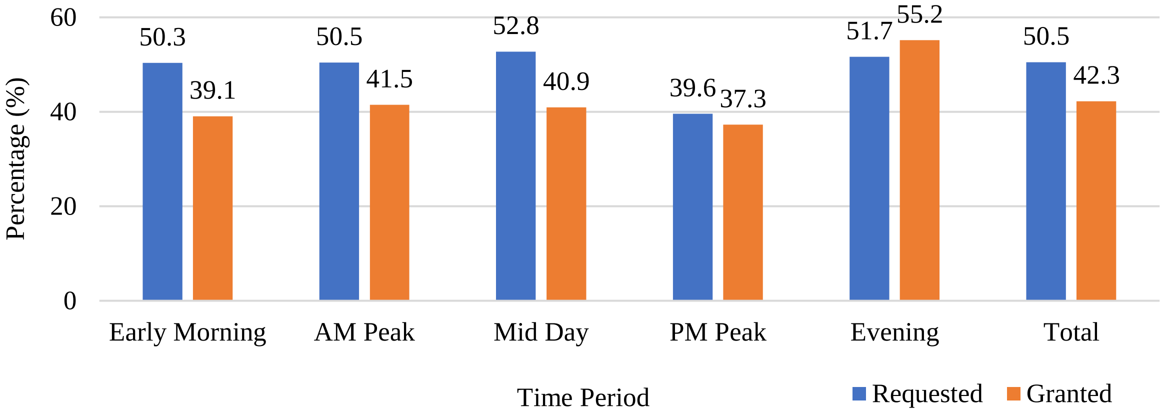


Figure 4.13 Plow events requested and granted by time period.

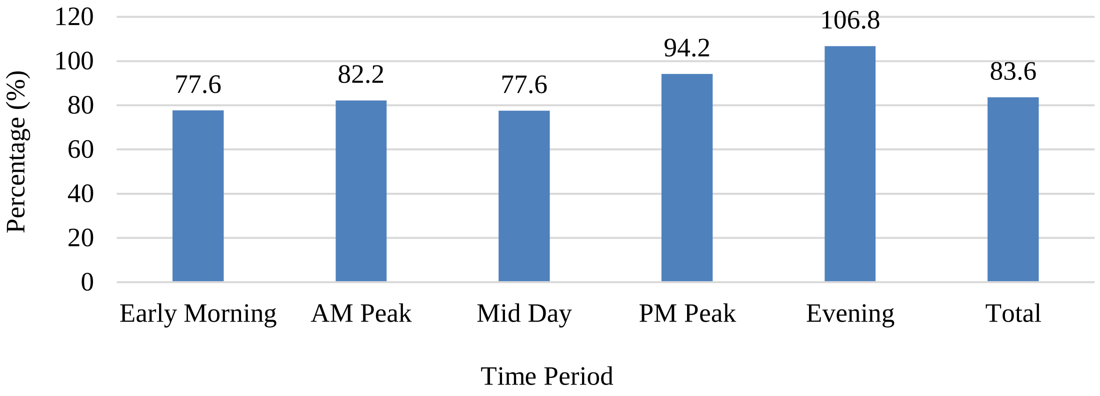


Figure 4.14 Percent of preemption requests granted by time period.

Preemption status analysis of how many of the requests were granted was also done for individual signals, grouped by segment. A list of the equipped signals can be found in Appendix B. Figure 4.15 shows the 700 East Cottonwood segment by individual signal. Each segment and associated signals are included in figures found in Appendix C. As shown with Signal 7338 on 700 East Cottonwood, there are times that a signal receives numerous requests, but none of the requests are granted. Signal IDs that had these issues are listed as follows (by route).

- 700 East Cottonwood: 7338
- East 9000 South: 7020
- Foothill Boulevard: 7216, 7217, 7221, 7224, 7274
- Redwood Road Murray: 7108

It was theorized that this was caused by the signal preemption protocols being coded incorrectly. Due to errors such as this, the percent of requested calls granted by signal range from 0 percent to 110 percent, as shown in Figure 4.16. Although this error occurs with only one signal on this segment, it greatly affects the average percent for the segment. The majority of signals on 700 East Cottonwood grant between 80 and 96 percent of all requests. However, the overall average of granted requests for 700 East Cottonwood is 80.7 percent. This error of signals being coded incorrectly occurs at other signals as well, which can be seen in Appendix C.

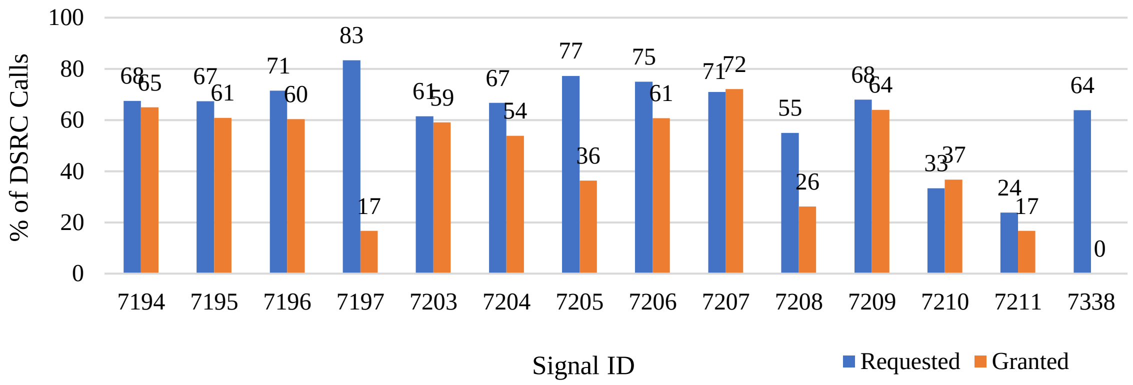


Figure 4.15 Preemption requested and granted for 700 East Cottonwood by signal.

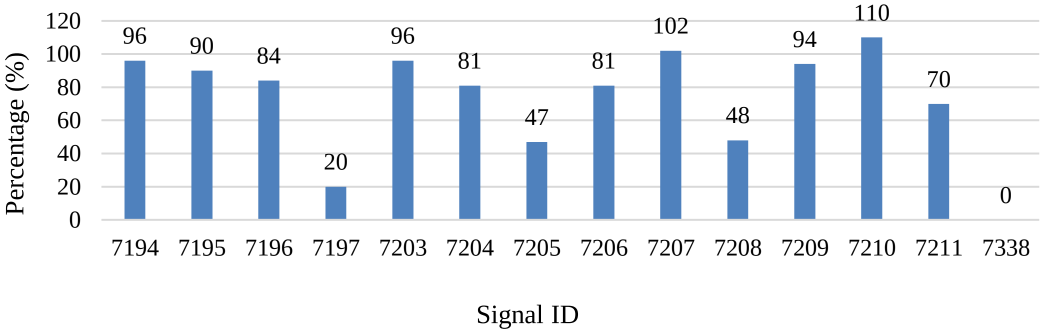


Figure 4.16 Percent of preemption requests granted for 700 East Cottonwood by signal.

4.2.3.4 Snowplow Occupancy

In addition to analyzing how often the DSRC units on snowplows requested and were granted signal preemption, the occupancy of the snowplow in the geofence of each equipped signal was also determined. Understanding the average time snowplows occupied the signals when preemption was granted depicts how well the system works. The occupancy was analyzed by routes, segments, time periods, and signals.

Occupancy was defined as the number of seconds the snowplow spent inside the geofence. For each route the average duration of occupancy was calculated for all plow events. The overall average occupancy for the entire study area was 25.7 seconds. Each of the routes reflects similar occupancies to this, ranging from 21.5 seconds to 32.4 seconds, as shown in Figure 4.17.

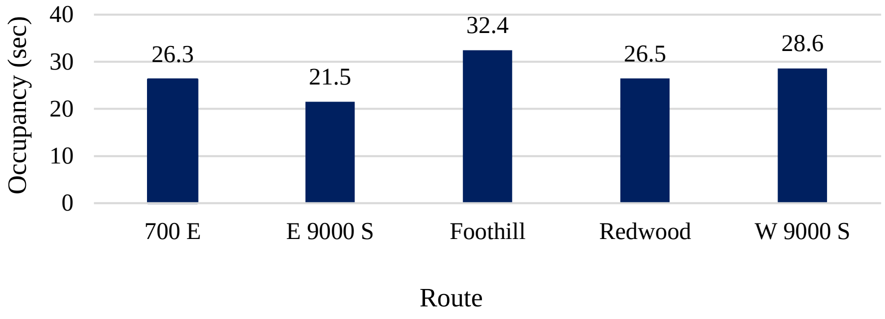


Figure 4.17 Snowplow occupancy by route.

When analyzed by segment, there is a greater range in average occupancy. As shown in Figure 4.18, the segments have occupancy values that range from 21.1 to 40.4 seconds. The higher values for occupancy are associated with long durations a plow was located at an intersection. These longer times can be related to higher wait for signal preemption to be granted or can be caused by higher traffic volumes at the intersections.

The effects of traffic on occupancy can be seen when analyzed by time period. As depicted in Figure 4.19, the time periods with the lowest occupancy are the ones where there are typically the fewest vehicles on the roads, particularly in the early morning and evening periods. The highest occupancy is during the PM peak, which has an occupancy of 37.9 seconds. This time period is typically when the highest volume occurs on snowy days, leading to snowplows being in the geofence of a signal for a longer period of time.

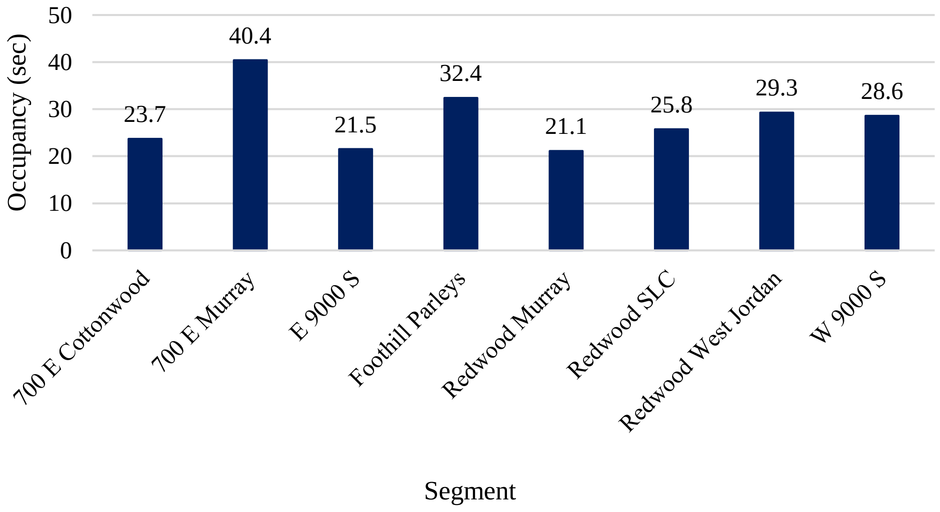


Figure 4.18 Snowplow occupancy by segment.

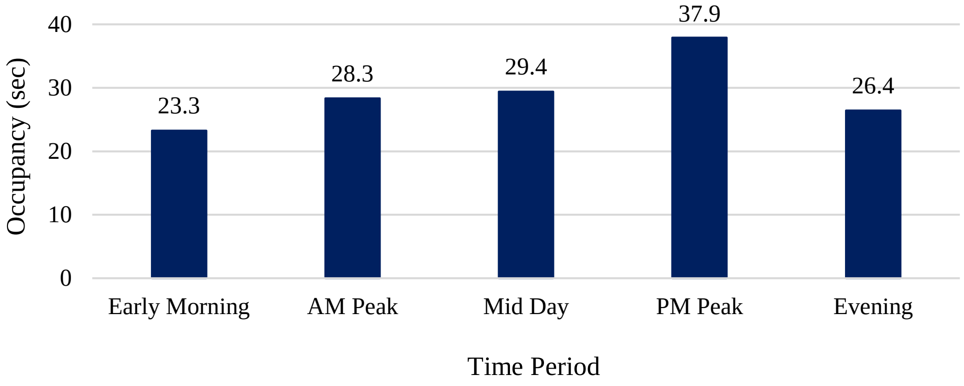


Figure 4.19 Snowplow occupancy by time period.

Each signal differs in their occupancy times, as shown in Figure 4.20, which depicts individual signals for 700 East Cottonwood. The occupancy times on this segment range from 13.5 seconds to almost 33 seconds. Data for each signal by segment can be found in Appendix C. The range of average occupancy times for each equipped traffic signal in the project was compiled and the results are shown in Figure 4.21. Although there are a few outliers, the majority of snowplows in the study occupied the geofence for fewer than 40 seconds.

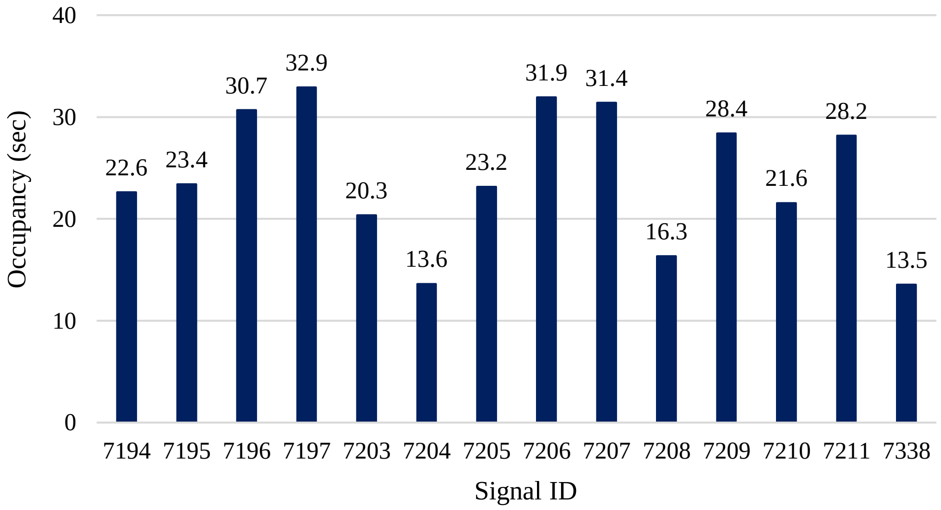


Figure 4.20 Snowplow occupancy for 700 East Cottonwood by signal.

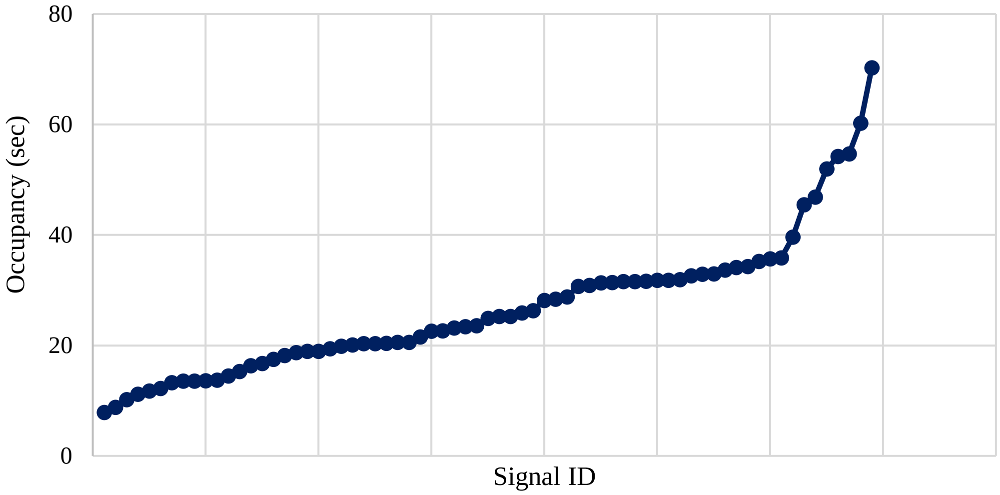


Figure 4.21 Distribution of occupancy in study.

Understanding the percentage of equipped snowplows that requested and were granted signal preemption, as well as the length of time the snowplow was in the geofence, helps determine how well the DSRC system was working during the study period. For a signal preemption program, the percentages for both requested and granted are high and satisfactory for their intended use.

4.3 Preemption Duration Data and Results

In conjunction with the data used for the status and occupancy analysis, the high-resolution signal controller log data, also known as ATSPM data, were used to determine how requesting signal preemption affected signal controller operations. Controller log data contain coordination state event codes that can be used to show affected duration. Affected duration is the time the operation of a signal is affected, or in other words, the time it took the signal to get back into step or return to previous coordinated signal timing. The findings from analyzing the controller log data can determine the effect individual preemption events have on signal controller operations. Data are gathered from signal controller logs and are found in the MOE database. Only data from equipped routes were collected and analyzed. Data were analyzed by route, segment, and time period. Each of the following sections includes information on data collection, analysis, and determined results.

4.3.1 Preemption Duration Data Collection

As with status analysis, the same controller preemption event codes of 102 to 111, as well as the coordination state event code 150, from the Indiana Traffic Signal Hi-Resolution Data Logger Enumerations were used to understand the lasting effects that servicing preemption had on signal controllers. These data contain information from the signal, such as: the time the preemption process began in the signal controller, the associated preemption event codes that were used, and when the signal returned to normal coordination (in step). Controller log data were collected for equipped routes on days with winter weather. Data were processed through the same Microsoft Access database as with the preemption status analysis data (Schultz et al., 2020).

The codes used in analyzing the effects of signal preemption can be referenced in Table 4.1 and various preempt codes were defined previously in Section 4.2.1. The 102 code, “Preempt (Call) Input On,” indicates the beginning of when the signal controller attempts to grant preemption. This code occurs when the RSU forwards a preemption request to the signal controller from the OBU. The 104-code, “Preempt (Call) Input Off,” occurs when the preemption process is canceled. A preemption request can be canceled by completing the preemption cycle or by the plow leaving the geofence.

It was verified that the 104 events occurred after the 102 events, ensuring that the signal controller was done servicing signal preemption. Between the 102 to 104 events, the snowplow continued to send updates requesting preemption at regular intervals. After the request is cancelled, the signal controller starts to transition back to its original signal coordination. However, it takes time for the signal to return to coordination, or to be back in-step. Once the signal controller logs an event code 150, or “Coordinated Cycle State Change,” with a parameter of 1, “In Step,” it is an indication that the signal has reentered coordination after being out of step. Affected duration of a signal preemption event occurs between the first 102 event code to when the next 150 event code with parameter 1 is received.

There are built-in safety protocols that must occur prior to granting signal preemption that affects signal timing. The signal controller can terminate walk time but must allow for the minimum clearance time to occur. Additionally, prior to granting signal preemption in the requested direction, all directions must have an all-red clearance time. Affected duration times include the time it takes for these safety measures to occur.

Similar to DSRC system logs, the data faced inconsistencies and was cleaned prior to analysis. Outliers were removed, including affected durations for cross streets and events with a duration of 0. Affected durations of 0 can be caused by factors such as GPS inaccuracies. When comparing DSRC message logs and controller preemption event codes together, there were issues with signal direction matching up, but this was corrected after clarification was received on what was the coded signal direction for the even parameters.

4.3.2 Preemption Duration Data Analysis

Analysis of the ATSPM data was conducted to determine how long signal preemption affected traffic signal performance. Between the time that the first verified 102 event code and the time that the first 150 event code, with a parameter of 1 was received, the pre-programmed signal coordination was out of step. After the signal controller started to grant preemption, direct impacts from the DSRC-equipped snowplows on traffic signals could be measured. Figure 4.22 is a sample of the data that were used in the analysis. Only codes with preemption parameters pertaining to snowplows were included in the analysis, removing other forms of transportation that also request signal preemption.

To better understand the effects of signal preemption on signal controller operations, affected duration was analyzed by route, segment, time period, and signal. A threshold of 15-minute affected duration was used to remove outliers from the data. It was determined that events greater than 15 minutes contained errors of not receiving cancel requests or may have other issues.

Route	Segment	SignalID	Direction	Hour	Time Period	WeatherDay	PreCode	PreStrt	Last150	Duration
E 9000 S	E 9000 S	7009	EB	20	Evening	25-Nov-19	8	25-Nov-19	25-Nov-19	0.735
E 9000 S	E 9000 S	7009	EB	8	AM Peak	8-Dec-19	8	8-Dec-19	8-Dec-19	0.571667
E 9000 S	E 9000 S	7009	EB	9	Mid Day	8-Dec-19	8	8-Dec-19	8-Dec-19	1.84
E 9000 S	E 9000 S	7009	EB	8	AM Peak	1-Jan-20	8	1-Jan-20	1-Jan-20	2.728333
E 9000 S	E 9000 S	7009	EB	8	AM Peak	1-Jan-20	8	1-Jan-20	1-Jan-20	2.025
E 9000 S	E 9000 S	7009	EB	9	Mid Day	6-Feb-20	8	6-Feb-20	6-Feb-20	1.028333
E 9000 S	E 9000 S	7009	WB	14	Mid Day	25-Nov-19	7	25-Nov-19	25-Nov-19	0.681667
E 9000 S	E 9000 S	7009	WB	16	PM Peak	25-Nov-19	7	25-Nov-19	25-Nov-19	0.89
E 9000 S	E 9000 S	7009	WB	20	Evening	25-Nov-19	7	25-Nov-19	25-Nov-19	1.536667
E 9000 S	E 9000 S	7009	WB	7	AM Peak	26-Nov-19	7	26-Nov-19	26-Nov-19	2.423333
E 9000 S	E 9000 S	7009	WB	7	AM Peak	28-Nov-19	7	28-Nov-19	28-Nov-19	0.985
E 9000 S	E 9000 S	7009	WB	13	Mid Day	29-Nov-19	7	29-Nov-19	29-Nov-19	3.49
E 9000 S	E 9000 S	7009	WB	19	Evening	29-Nov-19	7	29-Nov-19	29-Nov-19	2.323333
E 9000 S	E 9000 S	7009	WB	9	Mid Day	8-Dec-19	7	8-Dec-19	8-Dec-19	1.116667
E 9000 S	E 9000 S	7009	WB	10	Mid Day	8-Dec-19	7	8-Dec-19	8-Dec-19	1.636667
E 9000 S	E 9000 S	7009	WB	8	AM Peak	16-Dec-19	7	16-Dec-19	16-Dec-19	2.213333
E 9000 S	E 9000 S	7009	WB	9	Mid Day	30-Dec-19	7	30-Dec-19	30-Dec-19	0.991667
E 9000 S	E 9000 S	7009	WB	10	Mid Day	30-Dec-19	7	30-Dec-19	30-Dec-19	0.908333
E 9000 S	E 9000 S	7009	WB	8	AM Peak	1-Jan-20	7	1-Jan-20	1-Jan-20	3.45
E 9000 S	E 9000 S	7009	WB	9	Mid Day	1-Jan-20	7	1-Jan-20	1-Jan-20	4.76
E 9000 S	E 9000 S	7009	WB	17	PM Peak	1-Jan-20	7	1-Jan-20	1-Jan-20	2.25
E 9000 S	E 9000 S	7009	WB	21	Evening	9-Jan-20	7	9-Jan-20	9-Jan-20	2.003333
E 9000 S	E 9000 S	7009	WB	9	Mid Day	6-Feb-20	7	6-Feb-20	6-Feb-20	1.54
E 9000 S	E 9000 S	7017	EB	12	Mid Day	25-Nov-19	9	25-Nov-19	25-Nov-19	5.691667
E 9000 S	E 9000 S	7017	EB	14	Mid Day	25-Nov-19	9	25-Nov-19	25-Nov-19	1.385

Figure 4.22 Processed signal controller log data sample.

An original goal of the analysis was to also determine how many signal cycles were affected by preemption requests. However, this was determined improbable to do, as signal cycle times are not constant and fluctuate throughout the day, as well as switch to free mode during the late evening and early morning hours. Due to this, the affected duration was chosen as the sole data metric which was used to determine lasting effects of signal preemption on signal controllers. Results were calculated and displayed in minutes.

4.3.3 Preemption Duration Results

The total average affected duration for a signal controller impacted by a signal preemption request for the study was 2.9 minutes, or about 2 minutes and 56 seconds. As a standard for comparison, after being in free mode, it takes a controller about 6 minutes to transition to a coordinated state. Thus, the value of 6 minutes became a standard in analyzing whether affected duration averages were acceptable. The results of analysis for affected duration are displayed by route, segment, time period, and individual signal.

Affected duration by route ranged from an average of 2.8 to 3.3 minutes. As shown in Figure 4.23, Redwood Road had the lowest average affected duration per route at 2.8 minutes and West 9000 South had the highest affected duration at 3.3 minutes. All routes have average affected durations within 30 seconds of each other, demonstrating the consistency in the affected duration for each route.

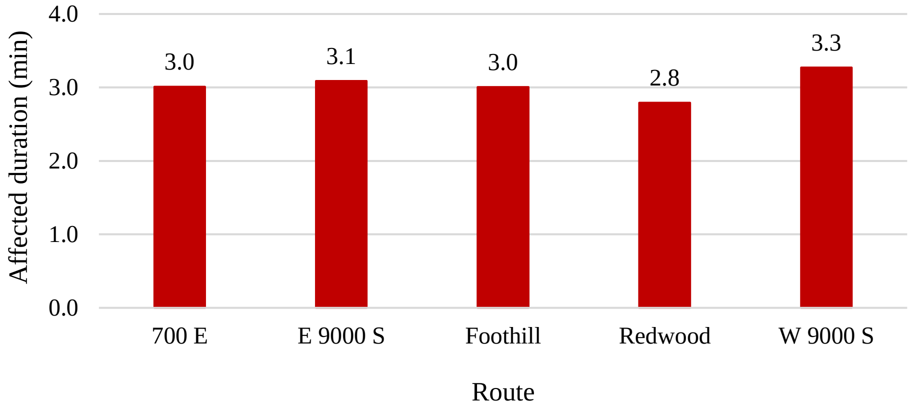


Figure 4.23 Affected duration by route.

There is more variance in average affected duration when analyzed by segment. Affected durations per segment range from an average of 2.4 minutes to 4.0 minutes, as shown in Figure 4.24. This is a variance of over 90 seconds between all segments. The variances that are important to note are segments that share the same route. For example, 700 East Cottonwood and 700 East Murray have a difference of 66 seconds in affected duration. In a Tukey-Kramer test, the difference between affected durations for the two routes was found to be statistically significant, with a p-value of 0.0207. The same analysis was performed on the segments on

Redwood Road. The three segments on Redwood Road have a difference of 42 seconds in affected duration. A Tukey-Kramer test was performed and the only pair of segments along Redwood Road that had a statistically significant difference was Redwood SLC and Redwood West Jordan, with a p-value of 0.0001. When Redwood Murray was compared to both Redwood SLC and Redwood West Jordan, the differences were not statistically significant with p-values of 0.2421 and 0.7152, respectively.

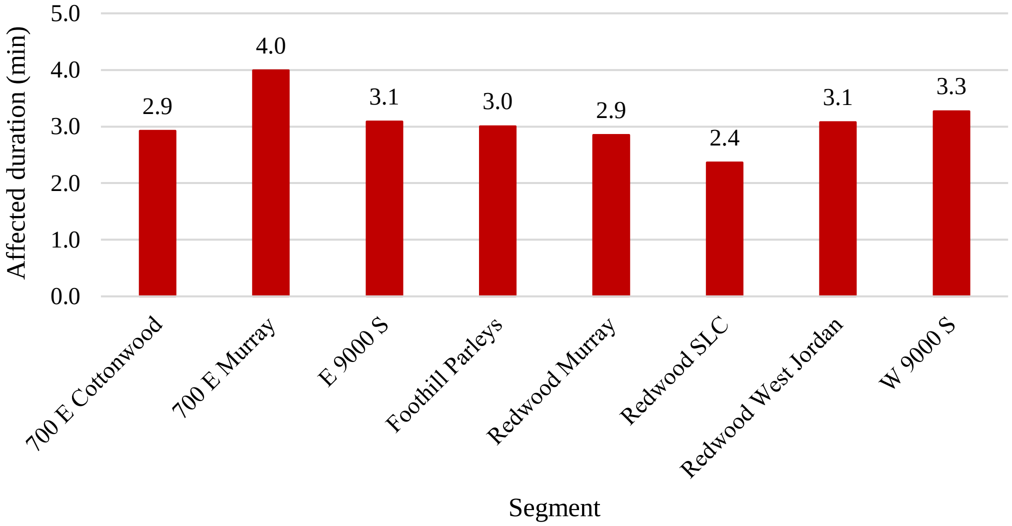


Figure 4.24 Affected duration by segment.

Affected duration was also analyzed by time period. The AM peak and PM peak were the time periods where signal controllers were most affected, with an affected duration of an average of 3.3 and 3.2 minutes. Affected duration for each time period is shown in Figure 4.25. The least affected time period was early morning, due in part to many signals being in a free coordination state during this time, leading to a lower affected duration time.

To see how signal preemption affected individual signals, the affected duration for each signal was determined. These individual signals were then grouped by segment. Figure 4.26 depicts the range of affected durations within the 700 East Cottonwood segment. The average signal-affected duration for this segment ranges from 1.3 minutes to 6.3 minutes, a difference of 5 minutes. Affected duration for individual signals can greatly vary within a segment, as shown graphically in Appendix D.

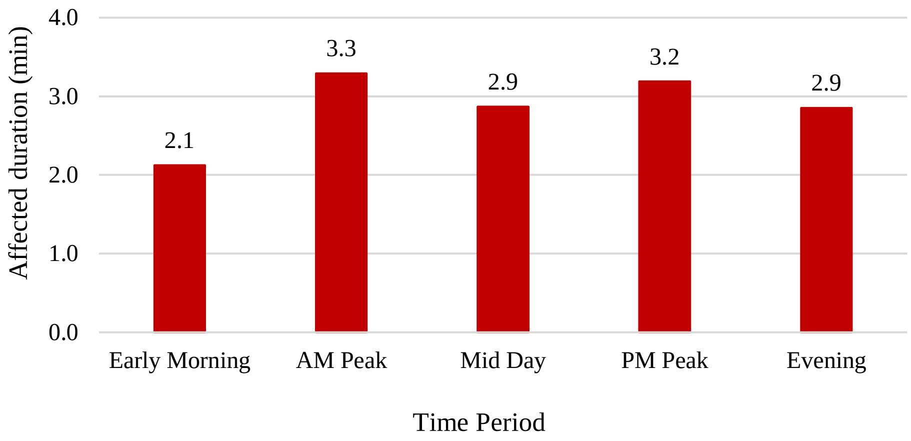


Figure 4.25 Affected duration by time period.

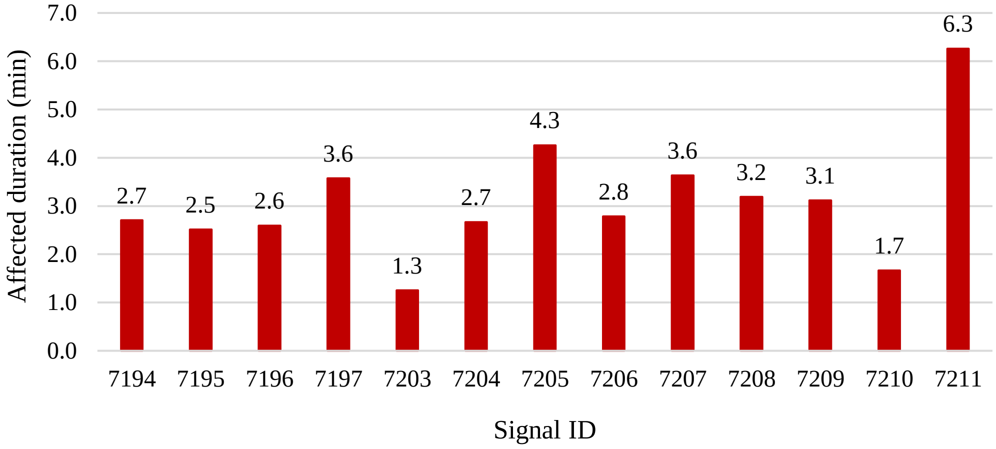


Figure 4.26 Affected duration by signal for 700 East Cottonwood.

As shown, individual signals can greatly vary in duration as they are affected by signal preemption. It is interesting to note that signals with IDs of 7203 and 7210 are T-intersections, thus the smaller average affected duration. A graphical representation of the range of average affected duration for all signals in the study is shown in Figure 4.27. Typically, plow events that granted preemption impact a signal for less than 5 five minutes. There are two outliers that have an average affected duration of greater than six minutes, signals with IDs of 7101 and 7211. It is suggested that UDOT verifies that the DSRC systems at those signals are working properly.

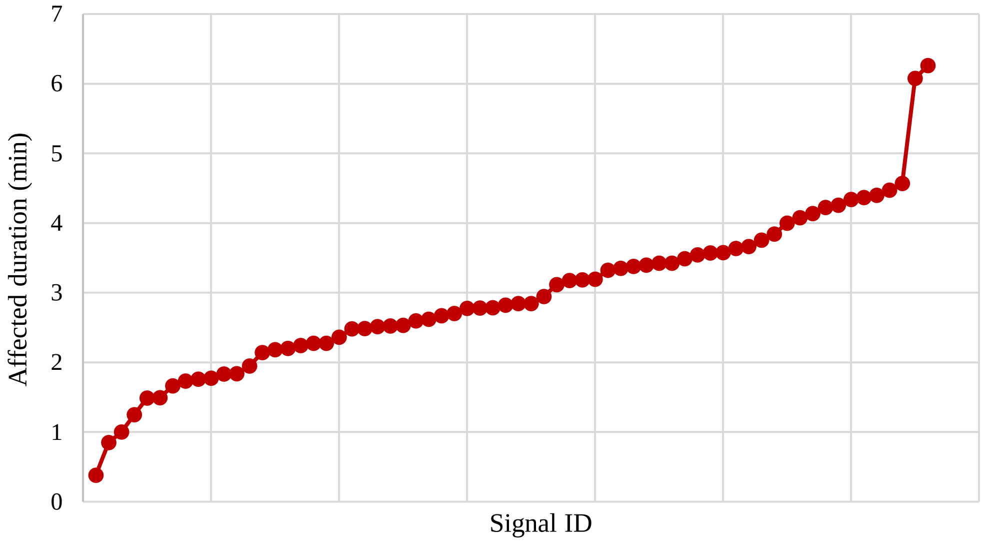


Figure 4.27 Distribution of average affected durations.

4.4 Summary

The data collection and analysis of DSRC message logs and signal controller log data were used to determine the impacts on signal controllers caused by snowplows requesting signal preemption through DSRC systems. From the analysis, both systems seem to work as designed. There were some errors and challenges encountered in the analysis; this was primarily due to the DSRC systems on snowplows that request signal preemption being a pilot program.

The analysis shows that over 50 percent of all plow events requested signal preemption, depicting high usage of the system. Of total requests for signal preemption, over 83 percent were granted. Despite some signals having issues with granting signal preemption, the data show that the system is working effectively and is being used frequently.

Of the requests that were granted signal preemption, signal controller log data were used to determine impacts on signal controller operations. The maximum acceptable duration that a signal could be affected by preemption was established to be six minutes. On average, signals were affected by preemption requests for less than three minutes and 97 percent of signals were affected for less than five minutes. This shows that on average, nearly all signals were affected by signal preemption requests for an acceptable amount of time.

Overall, it was determined that the DSRC system that requests signal preemption for snowplows has minimal impact on the functionality of signals. Snowplows request signal preemption about half the time, are granted the requested preemption at a rate of over 80 percent, and cause the signal controller to be out of coordination for a minimal, acceptable time. The overall determined impact to traffic signals is minimal. However, snowplows requesting signal preemption through DSRC systems not only impact signals, but also other vehicles. This analysis will be discussed in Chapter 5.

5.0 VEHICLE PERFORMANCE ANALYSIS

5.1 Overview

Analysis for this research focused on two parts: understanding the effects signal preemption had on signal controllers and understanding the effects of signal preemption on the surrounding vehicles. To fully understand the impacts that DSRC-equipped snowplows requesting signal preemption have, analyzing vehicle performance is vital to understand the effects on the overall system. In this chapter, equipped routes were compared to similar routes that were not equipped. These pairs, as discussed in Chapter 3, were used as a control to understand the effects of the DSRC systems requesting signal preemption. Although the not-equipped routes were selected based on similarities, the paired equipped and not-equipped routes have differences that could not be reconciled, influencing results. Analysis and findings in this chapter incorporate these comparisons.

Various data sources were used to understand the impacts DSRC-equipped snowplows requesting signal preemption had on the surrounding vehicles. This included snowplow speeds from Networkfleet data, travel speeds from ClearGuide data, and safety data. These data were gathered and analyzed for the study period and are summarized in the following subsections.

5.2 Snowplow Speed Data Analysis and Results

To understand part of how signal preemption affected overall vehicle performance, snowplow performance was analyzed. Data were collected from the fleet GPS tracking service from Verizon, called Networkfleet. Although UDOT uses other fleet tracking systems within their maintenance program, Verizon was the only fleet tracking system used in this study. Networkfleet data are collected through GPS tracking, gathering location and performance data. The objective of analysis for Networkfleet data was to determine if snowplows had higher speeds on equipped routes than on not-equipped routes, leading to potential maintenance benefits. The following sections include information on data collection, analysis, and results for the snowplow speed data.

5.2.1 Snowplow Speed Data Collection

GPS data are transmitted from snowplows every 30 seconds and stored in a database, known as Networkfleet. Data fields that were collected with an associated description are shown in Table 5.1. The data fields that proved most useful in the study included location data, speed data, and sensor activity. Regarding speed data, although the stated speed limit for roadway is recorded in the data set, UDOT maintenance guidelines do not allow the snowplows to exceed 35 mph when clearing snow. An additional data field that was added for this study was "Sensor

Table 5.1 Elements of Networkfleet Data

Data Element	Description
Label	UDOT's vehicle ID for the snowplow
VIN	Snowplow vehicle ID number from manufacturer
Date	Date and time of snowplow event
Ignition/Status	Indicates whether the ignition is ON/OFF
Address	Street address of snowplow event
City	City of snowplow event
State	State of snowplow event
Zip	Zip code of snowplow event
County	County of snowplow event
Latitude	Latitude of snowplow event
Longitude	Longitude of snowplow event
Odometer	Odometer mileage count of each snowplow
Heading	Direction of snowplow movement of event
Average Speed	Average snowplow speed within the 30-sec interval
Instantaneous Speed	Exact snowplow speed at time event was recorded
Max Speed	Maximum snowplow speed within the 30-sec interval
Posted Speed	Posted speed limit within the physical area of the event
Sensor Activity	Plow up-and-down movement status
Groups	UDOT snowplow shed ID name
Movement Status	Plow moving, idle, or stopped
Route	UDOT route name, highway name

Activity.” As discussed previously, some snowplows continually had their spreaders on, resulting in DSRC requests being sent out anytime the plow was on equipped routes. Understanding when these snowplows were actually plowing allowed for more accurate data collection, and to provide clarification as to when snowplows were plowing rather than pretreating roads.

The dataset includes the categories of “Groups” and “Label,” which identify the specific snowplow shed and route that the snowplow was servicing, respectively. “Groups” was changed to “Shed” and “Label” was changed to “Route,” to normalize labeling. An additional field was created to determine the segment where the snowplow event occurred. The segment category is needed for analysis based on maintenance shed. UDOT divides maintenance responsibilities into sheds, and snowplows in each shed do not generally cross shed boundaries. Additionally, the field “Time Period” was added to the data to determine how preemption requests affected snowplow performance at different time periods.

Snowplow speed data collected from Networkfleet included information for both equipped and not-equipped routes for days with snow as identified from the RWIS data. Compiled data were downloaded in reports called Activity Details, containing snowplow data for all of UDOT Region 2. Due to the size of the datasets, each date associated with a snowstorm was downloaded separately from the database into Activity Detail Reports.

5.2.2 Snowplow Speed Data Analysis

Snowplow speed data were used to evaluate if snowplows on equipped routes had higher speeds than those on not-equipped routes, potentially leading to benefits in maintenance performance measures. To do this, quantitative and qualitative analysis was conducted. After several steps of aggregation and processing, data were gathered and analyzed by travel speed. Average speed for a snowplow to go from one end of the route to the other was analyzed to determine if, on average, snowplows were able to go faster on equipped routes than on not-equipped routes. UDOT maintenance shed foremen were also interviewed about their experiences plowing streets equipped with the DSRC system to request signal preemption.

The original data downloaded provided location information. To collect data from just the equipped and not-equipped routes, ArcGIS was used to filter the snowplow speed data by latitude and longitude points. In ArcGIS, a buffer was created for each equipped route and not-equipped route in the study, which covered the length and width of each route. From this, the data were imported. The snowplow speed data located inside the buffers was kept while outliers were removed. This allowed for data within the designated routes of study and within the dates with snow events to remain.

Individual snowplow runs were identified as the time it took the snowplow to clear a corridor in one direction. Further aggregation was used to determine individual snowplow runs along each corridor. Using segments, a unique run ID, vehicle ID, and direction, each plow run was given a start and end time. The plow run was analyzed to determine the travel time and average speed of the snowplow for each segment. A method of sorting data points by segment, VIN number, and date in chronological order was used to identify when a snowplow started and stopped a run. This sorting method ensured data points were in separate segments, were different snowplow trucks, and were in the correct order by timestamp.

To determine that the snowplow was on an individual run, the calculation used verified that data had to have the same segment, VIN number, direction, and be within a 70-second threshold of the previous data point. A higher threshold of five minutes was initially used but proved to be ineffective. Using this methodology, any data point that was outside the parameters would be classified as a different snowplow run and would have separate average speed and travel time. A 70-second threshold was used to accommodate when there were errors in the Networkfleet log, particularly when there was a missing recording between data calls. This was done as a precaution due to data aggregation issues with big data.

There were other missing data found during the analysis process. Out of the 75,378 records, 18.8 percent of the total number of records, or 14,178 records, were missing information for the “Heading” category. There were many data points that also had incorrect headings or varied frequently from each point along a run, due to the jogging of the snowplow or switching lanes. This causes the sensor to log the slight change as a different heading in the data. Granularity was also lost with data being gathered every 30 seconds. To combat these issues, for every snowplow run ID, each direction in a run, or “Heading,” was counted, and the heading with the majority of records was assigned as the heading for the entire run.

Snowplow speed data provides headings in the four cardinal and four intermediate directions. However, the analysis of the snowplow study identifies only NB/SB or EB/WB directions for each route. Each route is different and does not traverse in a perfect cardinal direction. Different thresholds were used for each route to determine the actual direction of travel for that specific run, as shown in Table 5.2.

Table 5.2 Heading Thresholds for Direction

Route	Final Direction	Heading Thresholds
Redwood Road	Northbound	N, NW, NE
Redwood Road	Southbound	S, SW, SE
Foothill Drive	Northbound	N, NW, W
Foothill Drive	Southbound	S, SE, E
700 East	Northbound	N, NW, NE
700 East	Southbound	S, SW, SE
West 9000 South	Eastbound	E, NE, SE
West 9000 South	Westbound	W, NW, SW
East 9000 South	Eastbound	E, NE, SE
East 9000 South	Westbound	W, NW, SW
State Street	Northbound	N, NW, NE
State Street	Southbound	S, SW, SE
4500 South	Eastbound	E, NE, SE
4500 South	Westbound	W, NW, SW
Wasatch Boulevard	Northbound	N, NW, NE, W
Wasatch Boulevard	Southbound	S, SW, SE, E
Van Winkle	Northbound	N, NW, NE, W
Van Winkle	Southbound	S, SW, SE, E

To further verify and aggregate the snowplow speed data, the distance traveled for each snowplow run was calculated to determine full or partial runs on each segment. To calculate the distanced traveled, the start odometer value and end odometer value for each plow run were used to find how many miles the snowplow traveled within each run. Travel time was then calculated by subtracting the end timestamp from the start timestamp for each snowplow run. An overall average travel speed for each snowplow run was also calculated.

There were also other errors that affected the integrity of the dataset. During the 2019-2020 winter season, some snowplows were assigned to different maintenance sheds or were replaced. UDOT replaced about one snowplow each week with a new truck, leading to new VIN numbers on routes. Most of these changes were updated in the data, but there were some outliers that were not updated. This led to inconsistent snowplow readings throughout the winter. In addition, GPS accuracy is not perfect and can have effects on data integrity.

Another form of analysis that was attempted was to determine how often snowplows stopped, or when the average speed was 0 mph. This analysis proved difficult as data came in 30 second bins. A snowplow could have stopped and started moving again during that timeframe. Hence, it was determined this analysis would not be included.

Quantitative comparisons and statistical analysis were performed to quantify the speed changes and to determine if the measured effects from DSRC-equipped snowplow operations requesting signal preemption had any statistical significance. Qualitative analysis was also performed by interviewing shed foremen about their experience operating the snowplows using DSRC-equipped systems to request signal preemption. Results from both types of analysis will be described in the next section.

5.2.3 Snowplow Speed Data Results

The results for the quantitative research will be presented first, followed by the qualitative results. On average, it was determined that snowplow speeds on equipped routes were 3.2 mph slower than not-equipped routes. The average speed on equipped routes was 15.5 mph and on not-equipped routes the average speed was 18.7 mph. Each equipped route was paired up with a similar not-equipped route, and the average snowplow speed for each of these is shown in Figure 5.1. For 700 East, East 9000 South, and Foothill Drive, the equipped routes had slower average snowplow speeds than their comparative not-equipped routes. West 9000 South and Redwood Road had average snowplow speeds greater than their comparative not-equipped route.

The overall differences for the paired routes are shown in Table 5.3. The differences in the data gathered for each route was compared in a Tukey-Kramer statistical test, with the results also shown in Table 5.3. Out of the five pairs, only three showed that the differences in average snowplow speed were statistically significant. Those routes were East 9000 South (paired with Wasatch Boulevard), Foothill Drive (also paired with Wasatch Boulevard), and Redwood Road (paired with State Street).

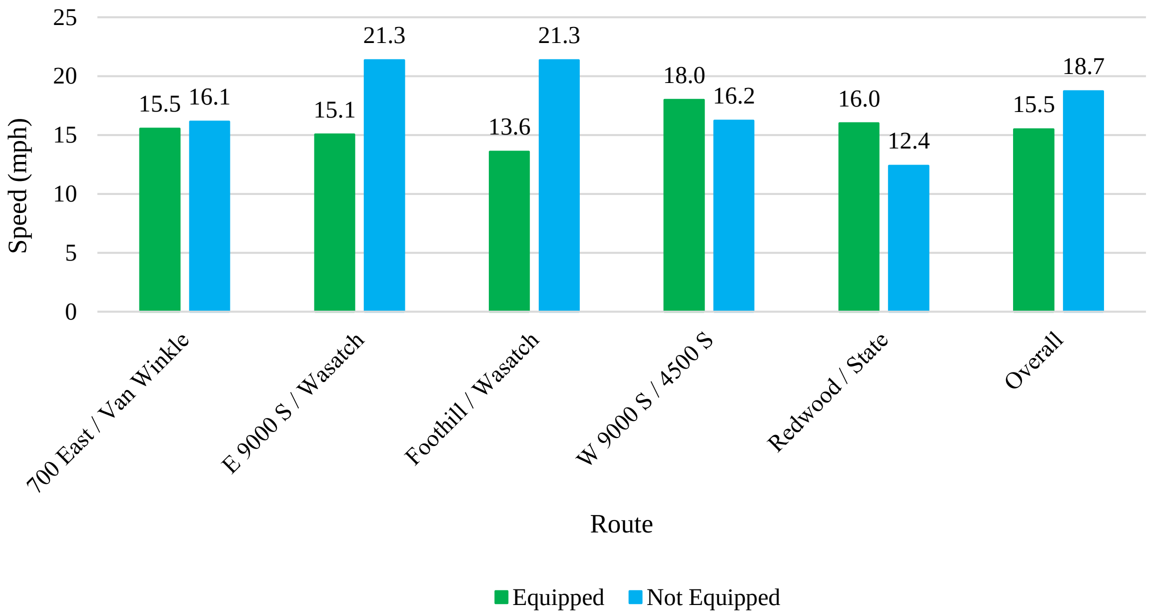


Figure 5.1 Snowplow speed during snow events for equipped versus not-equipped routes.

Table 5.3 Differences in Snowplow Speed for Equipped and Not-Equipped Routes

Equipped Route	Not-Equipped Route	Difference in Average Speed (mph)	P-Value
700 East	Van Winkle	-0.6	0.4996
East 9000 South	Wasatch Boulevard	-6.3	<.0001
Foothill Drive	Wasatch Boulevard	-7.8	<.0001
West 9000 South	4500 South	1.8	0.0619
Redwood Road	State Street	3.6	<.0001

Analysis was completed to evaluate the variance in snowplow speed by time period for the paired equipped and not-equipped segments. The results are shown in Table 5.4. The differences in speed are listed, with positive numbers in green showing a higher average snowplow speed on the equipped route and the numbers in red showing a higher average snowplow speed on the not-equipped route. The results in bold are the ones that are statistically significant, with p-values of less than 0.05, as determined by using a Tukey-Kramer test. For East 9000 South and Wasatch Boulevard, the difference for each time period proved to be statistically significant except during the evening. For Foothill Drive and Wasatch Boulevard, the difference for each time period was statistically significant except for the PM peak. The only other route with a statistically significant time period was Redwood Road and State Street, with only the difference in the evening time period being statistically significant.

Table 5.4 Differences in Snowplow Speed by Time Period by Route

Equipped Route	**Not-Equipped Route**	**Difference between Equipped Route and Not-Equipped Route (mph)**				
		Early Morning	*AM Peak*	*Mid-Day*	*PM Peak*	*Evening*
700 East	Van Winkle	-1.0	-0.3	0.5	2.1	-2.8
East 9000 South	Wasatch Boulevard	**-5.2**	**-5.4**	**-9.2**	**-8.4**	-4.0
Foothill Drive	Wasatch Boulevard	**-9.1**	**-6.7**	**-10.0**	-5.7	**-5.2**
West 9000 South	4500 South	-0.1	3.9	1.0	4.8	2.1
Redwood Road	State Street	1.9	5.1	1.8	5.8	**7.6**

Key: Red = higher average snowplow speed on the comparable not-equipped route
Green = higher average snowplow speed on the equipped route
Bold = the difference between speeds on routes was statistically significant

In addition to comparing snowplow speed on equipped and not-equipped routes, speed comparisons were done for segments on the same route. Figure 5.2 shows the average snowplow speed difference between 700 East Murray and 700 East Cottonwood. For all time periods, except for the evening, 700 East Murray had faster average snowplow speeds. A similar phenomenon occurred on Redwood Road. The differences by segment are shown in Figure 5.3. The Redwood West Jordan segment had average speeds that differed greatly compared to the other two Redwood Road segments. Both Redwood SLC and Redwood Murray had similar average snowplow speeds. The analysis of the segments on the same route shows how different maintenance sheds can affect snowplow speed. As these speeds vary greatly, it is difficult to formulate specific conclusions from this analysis.

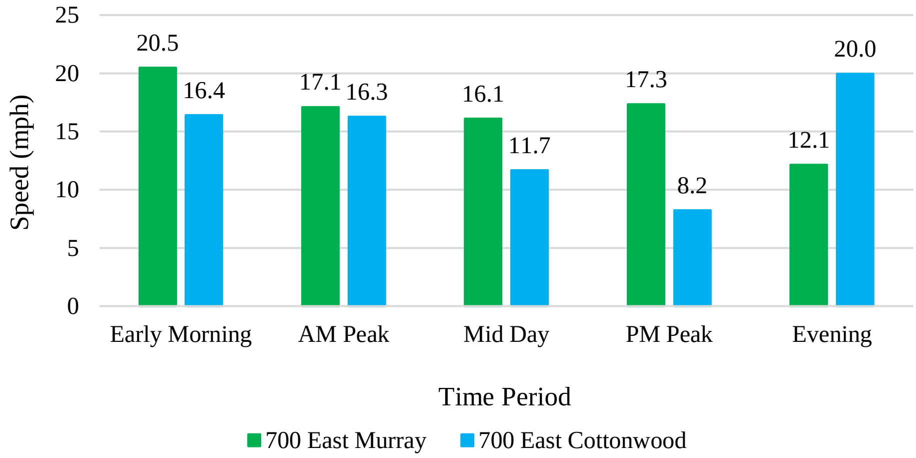


Figure 5.2 Snowplow speeds during snow events for 700 East segments by time period.

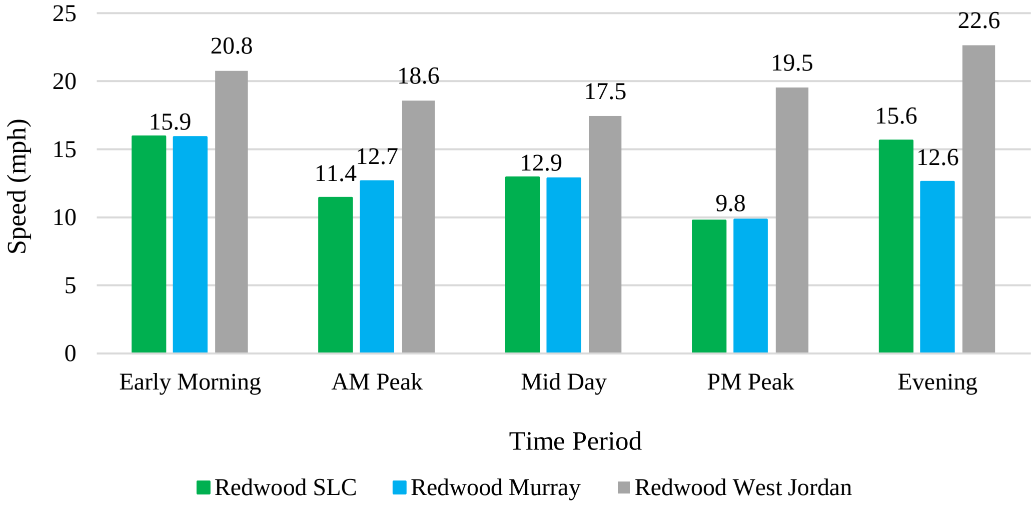


Figure 5.3 Snowplow speeds during snow events for Redwood Road segments by time period.

Due to the inconsistent and therefore inconclusive nature of the quantitative results, qualitative results were used to understand the experience of driving snowplows that requested signal preemption. Upon interviewing the shed foremen of the various sheds in the study area, some nuances were found when it comes to snowplow operations. While plowing, snowplow operators are not allowed to go more than 35 mph. Snowplow speed also heavily depends on the amount of snowfall, the density of the snow, the street geometry, and traffic. When snow is denser, or heavier, the snowplow operators cannot throw it as far and have to go slower. These factors greatly affect the inconsistency in the quantitative results with regard to snowplow speeds.

The shed foremen also explained the order of how streets are plowed in their maintenance sheds. In the quantitative analysis, it was assumed that snowplows follow a similar route each time, plowing an entire corridor at one time. However, the shed foremen shared that the path and the order of where the snowplows service depends on the storm and where the greatest needs are. The map in Figure 5.4 demonstrates the order of importance for roads in the Murray maintenance shed. Typically, the shed foreman directs snowplow operators to prioritize and clear roads in the following order: I-215, I-15, Redwood Road, 700 East, and 4500 South. This order can change based on the snowstorm and need within the maintenance shed.

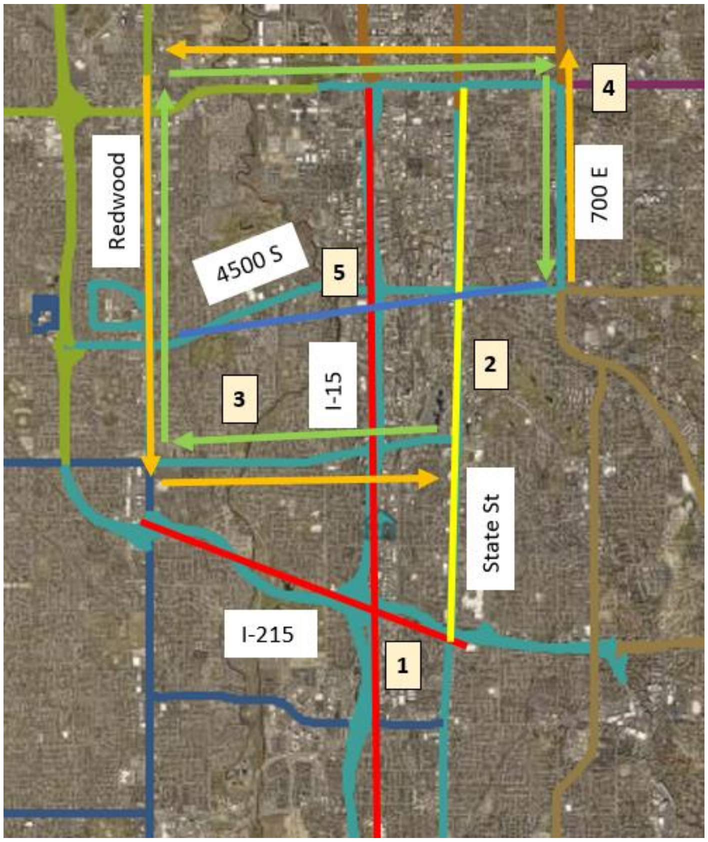


Figure 5.4 Route map for Murray shed snowplows when plowing.

The interviews with foremen recounted at great lengths the benefits of having the DSRC systems on snowplows to request signal preemption. The operators themselves noticed and perceived that they are required to make fewer stops while plowing equipped corridors which can help them clear these routes faster. When asked about their experiences plowing equipped versus not-equipped routes, many asked for the not-equipped routes to become equipped, as they noticed benefit from the systems.

Due to the inconsistency of set routes taken by the snowplow, as well as the complexity of determining what a snowplow run is and if it was a partial or full run, the conclusions on the affects to snowplow operations are based more on the interviews with the shed foremen than the travel speeds. The quantitative results can be informative, but overall results are heavily supplemented by the results from the qualitative analysis.

5.3 General Travel Speed Data and Results

To analyze additional effects that DSRC-equipped snowplows requesting signal preemption had on overall vehicle performance, general traffic operations were assessed. It was determined that analyzing general travel speeds would be an efficient way to analyze the effects from snowplows requesting signal preemption. The dataset that was used was from the ClearGuide web interface (https://udot.iteris-clearguide.com), previously known as iPeMs. This dataset was chosen over other services that collect travel speeds, such as Blynscy and Wavetronix, due to study area coverage and shed reliability. The objective of this analysis was to determine if general traffic had higher travel speeds on equipped routes versus not-equipped routes when snowplows were requesting and being granted signal preemption. The following sections include information on data collection, analysis, and results for ClearGuide data.

5.3.1 General Travel Speed Data Collection

ClearGuide web interface provides access to third-party probe data purchased by UDOT. HERE provides data for the web interface that processed the data to provide travel speeds throughout the study area. Speeds were gathered for both equipped and not-equipped routes. Routes were generated in the ClearGuide web interface, being separated into sections by segments and speed limits. This was done as speed limits vary throughout the study area. Speed limits for each part of the equipped and not-equipped routes can be found in Appendix E.

Each area with a differing speed limit was downloaded individually and compiled into a single spreadsheet for ease, including both travel directions for each segment. A control set of days without snow events were also downloaded, creating a base average speed and travel time for each segment to better assess the effects of snowstorms. Each day downloaded included data from the entire 24-hour period.

At the time of data collection, travel speeds and travel time could be downloaded by bin sizes with a granularity of 15 minutes. The data did not include AADT. Data were collected for both equipped and not-equipped routes in each travel direction and for days with and without snow. This real-time data from third-party sources shows general trends in traffic operations throughout the study area on any given day and during snowstorms.

As speed limits vary throughout each route, travel speeds downloaded were processed to provide the percentage of the speed limit for that area. It was determined that only travel speeds would be used in the analysis, rather than also including travel time, as routes could be broken up into many small areas. The final data collected included the date, time, time of day, segment, direction, weather status (snow or no snow), average travel speed for that area, corresponding speed limit, and percent of the segment’s speed limit.

5.3.2 General Travel Speed Data Analysis

The goal of analyzing travel speeds was to determine if vehicles on equipped routes traveled faster than traffic on not-equipped routes. Statistical analysis was performed on the data, which showed travel speeds as a percentage of the speed limit. The data were analyzed in various groupings, including by route, segment, time period, direction, weekdays, weekends, and overall. There were four main comparisons in the statistical analysis: days without snow events versus days with snow, equipped routes versus not-equipped routes when there was snow, equipped routes on days with and without snow, and not-equipped routes on days with and without snow.

There were challenges encountered when analyzing the data. Outliers and incorrect records were found in the data, including negative speeds and very low speeds. Any speed that was less than 50 percent of the speed limit was removed from the data, removing about 3 percent of the data.

Through the analysis, the researchers also attempted to determine the immediate effect of a snowplow plowing a route. However, with data irregularities and data granularity differences from both ClearGuide and Networkfleet, it was determined that these results would be difficult to interpret and they were, therefore, not included in the analysis.

5.3.3 General Travel Speed Results

Travel speeds from ClearGuide were analyzed by route, segment, and time period, as well as by days with snow events and days without snow. Results are shown in percent of speed limit, as to normalize the different speed limits.

Overall, equipped routes were 0.23 percent faster on days with snow events and not-equipped routes were 0.02 percent faster on days without snow. Similar differences are shown in comparison by routes, as seen in Figure 5.5. Of the route comparisons, East 9000 South/Wasatch Boulevard, Foothill Drive/Wasatch Boulevard, and West 9000 South/4500 South are the pairings where the equipped route is closer to the posted speed limit during snow events. In the other pairings, 700 East/Van Winkle and Redwood Road/State Street, the not-equipped routes have speeds closer to the posted speed limit during snow events.

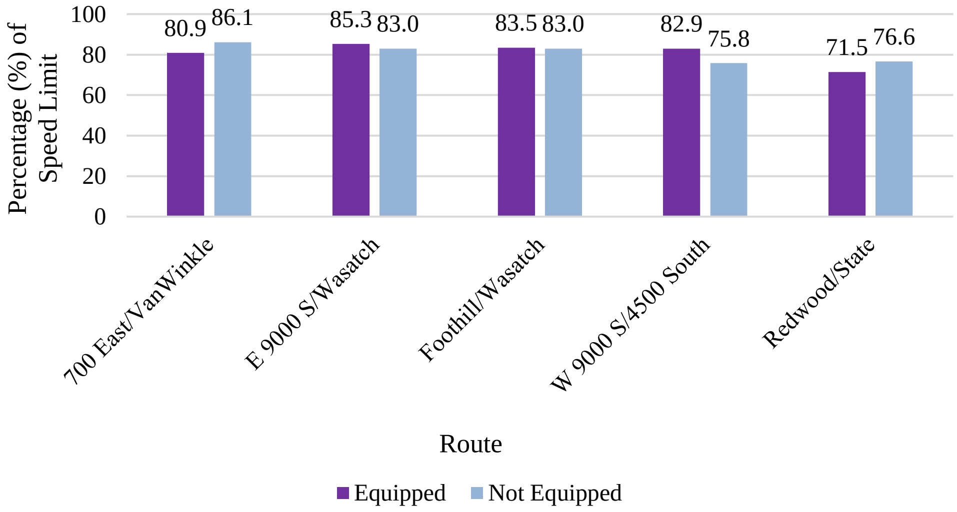


Figure 5.5 Percent of speed limit during snow events for all routes.

Due to travel speeds varying between routes based on whether there was snow or not, differences in percent of speed limit from days with snow events and days without snow events were evaluated. These can be found in Figure 5.6. The positive changes in percentile mean that the speed on that route is higher during days with snow. This shows that traffic on days with snow is actually faster and closer to the speed limit than on days without snow. The values that are negative show the percentage of the speed limit that are slower on days with snow. These routes have speeds that are slower when there is snow.

For all route pairings except for Redwood Road/State Street, the changes in speed limit percent were less extreme on the equipped route than on the not-equipped route. For the equipped 700 East, Foothill Drive, and West 9000 South routes, the difference in percent of the speed limit was greater than its not-equipped counterpart. For East 9000 South, speeds slowed during storms, but the change in percent of the speed limit was smaller than its not-equipped counterpart. Redwood Road and State Street are the only pairing that does not follow this trend, with speeds being slower on Redwood Road and higher on State Street when there is snow.

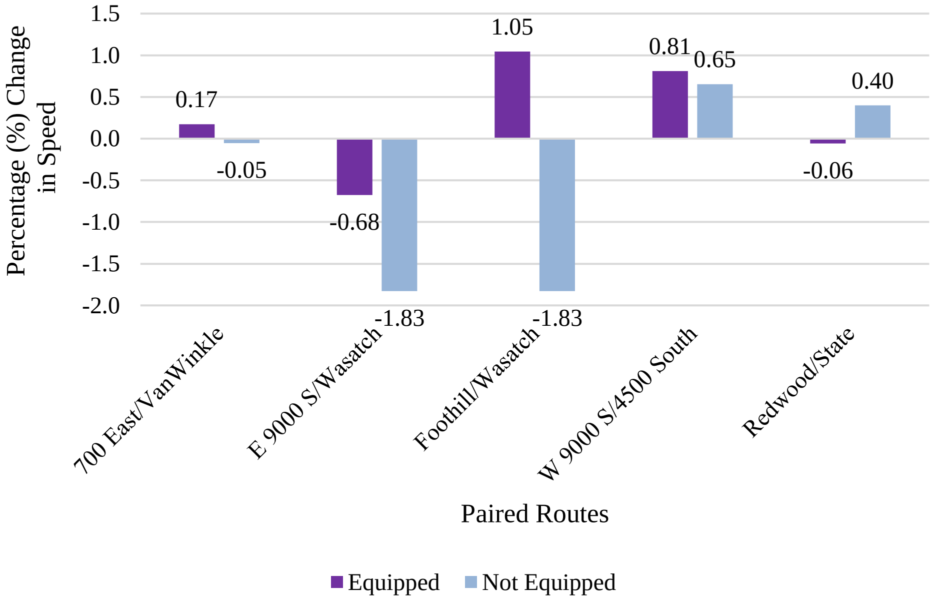


Figure 5.6 Changes in speed limit percent after comparison of snow events and normal days for all routes.

Analysis was also done to see changes in speed limit percent on the routes that contain multiple segments. These changes are shown graphically in Figure 5.7. On Redwood Road, both

Redwood SLC and Redwood West Jordan increased in speed limit percent when there was snow. Redwood Murray saw minimal decreases in speed limit percent during snow. Both segments for the 700 East route saw decreases in speed limit percent when there was snow.

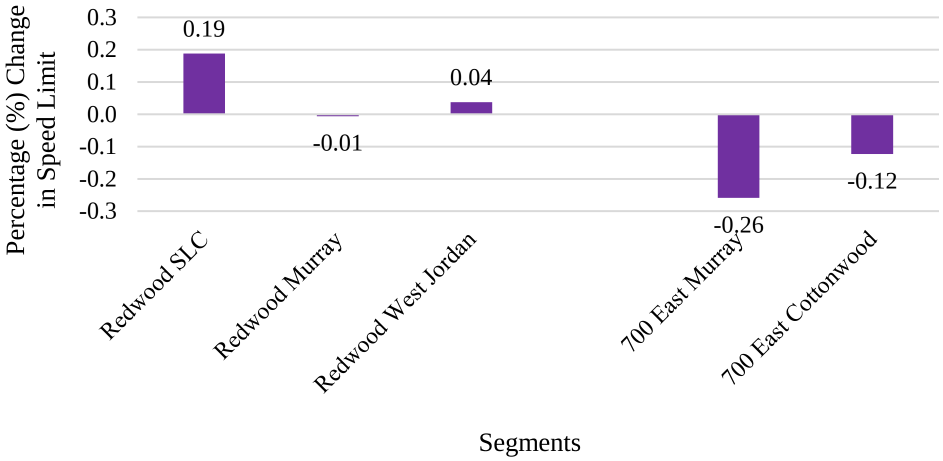


Figure 5.7 Changes in speed limit percent during snow events for Redwood Road and 700 East segments.

The differences in speed limit percentage were analyzed by time period for each equipped and not-equipped route pairing. Figure 5.8 depicts the differences for 700 East and Van Winkle. In general, there is a slightly lower speed limit percent for 700 East than for Van Winkle. The differences between East 9000 South and Foothill Drive, both being paired with Wasatch Boulevard, are shown in Figure 5.9. East 9000 South always has a higher speed limit percentage when compared to Wasatch Boulevard, but Foothill Drive only has a higher speed limit percentage for three of the time periods. The comparisons between West 9000 South and 4500 South are shown in Figure 5.10, with West 9000 South continually having a higher speed limit percentage. As stated previously, when comparing Redwood Road and State Street, State Street has the higher speed limit percentage, as shown in Figure 5.11.

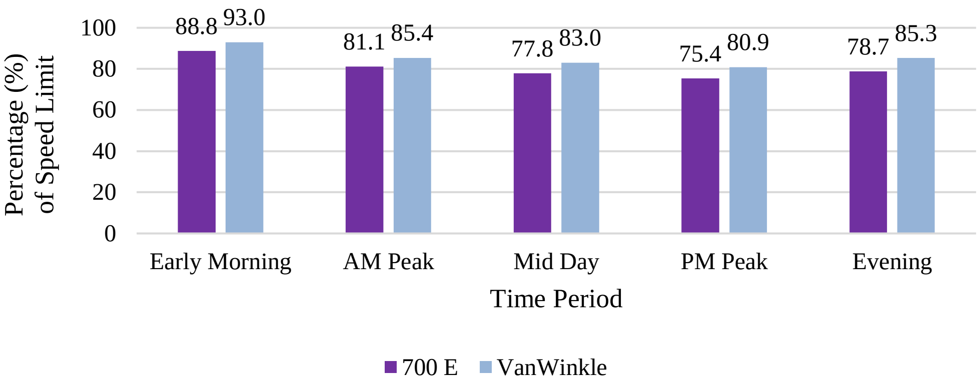


Figure 5.8 Speed limit percent during snow events for 700 East/Van Winkle by time period.

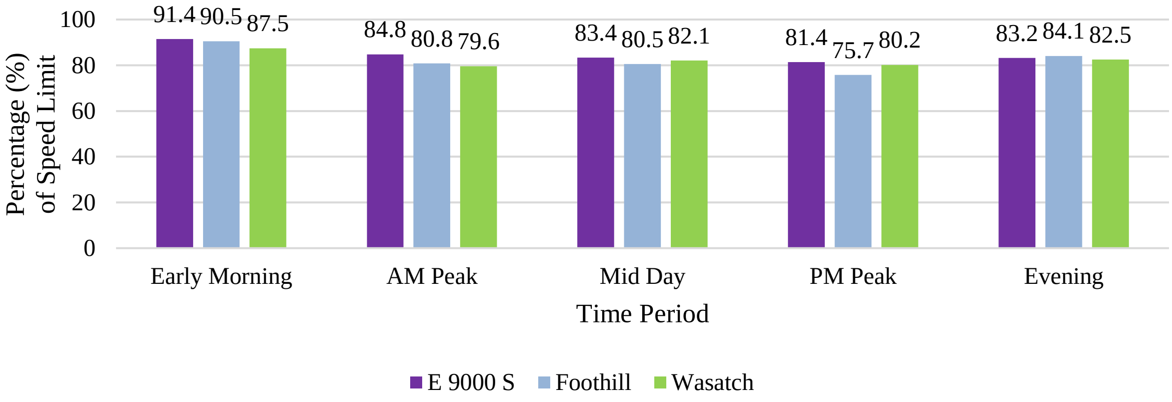


Figure 5.9 Speed limit percent during snow events for East 9000 South and Foothill Drive/Wasatch Boulevard by time period.

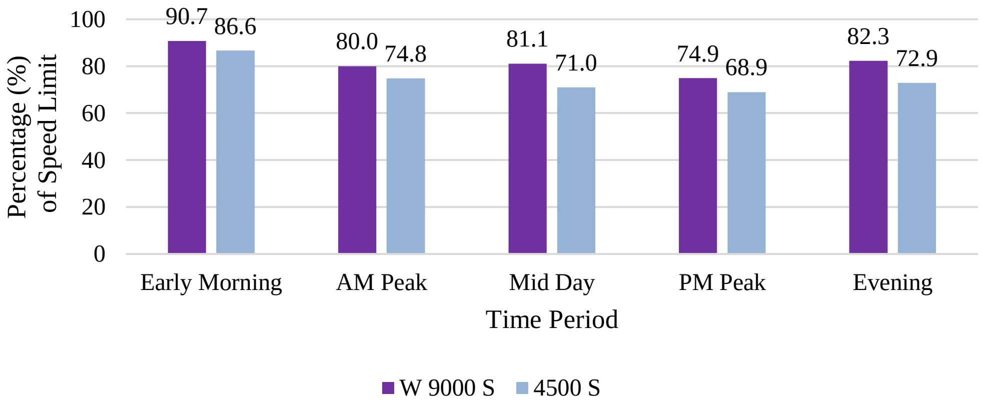


Figure 5.10 Speed limit percent during snow events for West 9000 South/4500 South by time period.

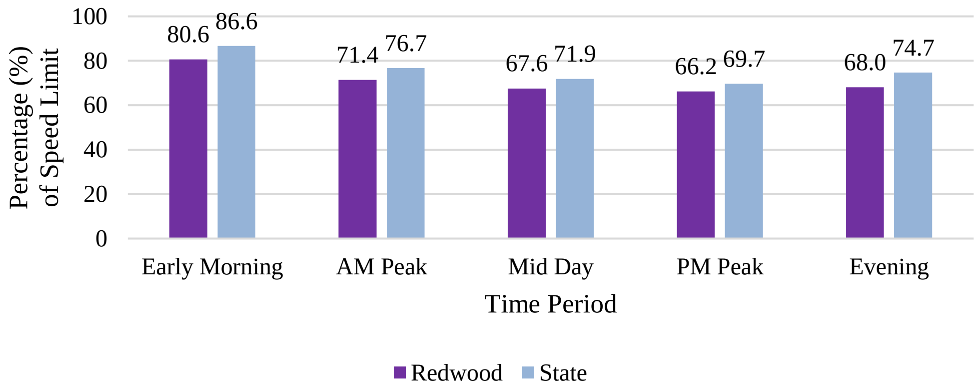


Figure 5.11 Speed limit percent during snow events for Redwood Road/State Street by time period.

Although speed limits varied on different routes and segments, the effects of snowplows using DSRC systems to request signal preemption could be seen on travel speeds. Overall, on days when there were snow events and snowplows were out on equipped and not-equipped routes, travel speeds on equipped routes were less negatively impacted than not-equipped routes. When comparing the differences in speed limit percentages between days without snow events and days with snow events, the equipped routes were less impacted and had higher percentages of their speed limits. Although the differences are minimal, the results show having DSRC-equipped snowplows clearing snow does positively impact traffic operations.

5.4 Safety Data and Results

The final analysis in understanding how signal preemption on snowplows affected overall vehicle performance was to analyze safety data. Data for days with snow events were gathered and compared for both equipped and not-equipped routes. These data are collected through a compilation of police reports after crashes. The objective of this analysis was to determine if traffic safety during snowstorms was improved on equipped routes versus not-equipped routes. The following sections include information on data collection, analysis, and results for safety data.

5.4.1 Safety Data Collection

Crash data were collected from UDOT's crash database and through the AASHTOSafetyware user interface powered by Numetric. Various attributes could be found about each crash, including the crash date, time, mile point, severity, manner of collision, roadway junction type, light condition, weather condition, roadway surface condition, and the number of vehicles involved. Historical crash data were collected based on queries and programmed routes, with the ability to narrow down searches through customizable filters. To only retrieve the needed equipped and not-equipped routes within the study areas, queries were built based off mileposts and route ID to create programmed routes. Table 5.5 shows the corresponding route ID and milepost start and end points used in gathering data. This was done to include only crashes within the study area of the research. Of the data gathered, the number of crashes, severity, and location were the main factors considered. Crash data were downloaded for both equipped and not-equipped routes on days with snow.

Table 5.5 Routes Used for Safety Analysis

Route Name	Route ID	Milepost Start	Milepost End
Redwood Road	0068P	4.375	58.825
700 East	0071P	10.25	18.3
East 9000 South	0209P	13.25	18.828
West 9000 South	0209P	7.225	9.725
Foothill Drive	0186P	4.625	8.55
State Street	0089P	367.3	373.35
Van Winkle	0152P	0	2.9
Wasatch Boulevard	0190P / 0210P	0	1.85 / 3.85
4500 South	0266P	0	2.85

The data were queried and downloaded from 2016-2020 for each route. This provided four different snow seasons to compare crash rates to see if DSRC-equipped snowplows affected crashes during the 2019-2020 storm season. As done for the 2019-2020 study season, dates with snow events were determined for the previous three seasons from the UDOT RWIS sites. The days with snow events from each of the four snow seasons were used to filter the crash data to identify each crash that occurred on the equipped and not-equipped routes on days with snow.

5.4.2 Safety Data Analysis

The goal in analyzing safety data was to determine if there was a significant improvement in safety from these systems. It was theorized that if snowplows could plow faster on state routes, that fewer crashes would occur since snow would be cleared in less time than historically. To compare each season to another, crashes, and the average number of crashes per snow day were analyzed.

In addition, a roadway crash rate equation was created to analyze the storms per season. It was altered based on a typical roadway crash rate equation. The roadway crash rate equation factors in AADT, length of segment, crashes per snow season, and number of storms in the snow season. This was done to normalize various influencers that create differences between route and segment results. These include the number of crashes per snow season, the number of days with snow per storm season, the AADT per section, and the length of the section. This is important as each year had a different number of days with snow. The 2016-2017 snow season had 30 days with snow, the 2017-2018 snow season had 24 days with snow, the 2018-2019 snow season had 35 days with snow, and the 2019-2020 snow season had 47 days with snow. The adjusted crash rate equation, shown in Equation 1, was essential to normalize these differences.

$$Roadway\ Crash\ Rate\text{:}\ \frac{1{,}000{,}000\ \times Crashes/Snow\ Season}{\#\ of\ Storm\ Days/Snow\ Season \times\ AADT\ \times\ Length\ (miles)} \quad (1)$$

The results from this equation for each roadway crash rate are shown as crashes per million vehicle miles traveled (MVMT). This adjusted equation was used to analyze the roadway crash rate for routes and segments for both equipped and not-equipped routes. Analysis was conducted comparing each roadway crash rate to the average of that specific segment. Crash severity was also noted to determine various changes in severities throughout the storm seasons. One issue that was faced during the safety analysis was limited data from this dataset (i.e., not a lot of crashes). Due to this, a statistical comparison could not be made due to the small sample size.

5.4.3 Safety Results

Due to minimal available data entries, the results from the analysis are solely observational. Results are reported as shown, however, there could be various other influences on these safety results. Snowplows using DSRC systems to request signal preemption may have affected the results, but it is inconclusive to say they were the sole factor in the reflecting results.

The number of crashes that occurred for each studied snow season are found in Appendix F as well as the average number of crashes per day with snow. To show the variation of crashes per season and per route, these data were displayed graphically. For equipped routes, Figure 5.12 shows the average number of crashes per day with snow for each of the snow seasons. Average crashes per day with snow were the lowest during the 2019-2020 season, which was the first season with plow preemption capabilities, for all routes except for West 9000 South. This trend continued with equipped segments, as shown in Figure 5.13. All segments, except for West 9000 South, had the lowest average crashes per day with snow during the 2019-2020 season when compared with the past three snow seasons. Similar results were found in not-equipped routes. As shown in Figure 5.14, not-equipped routes also saw their lowest number of average crashes per days with snow in the 2019-2020 season, except for State Street.

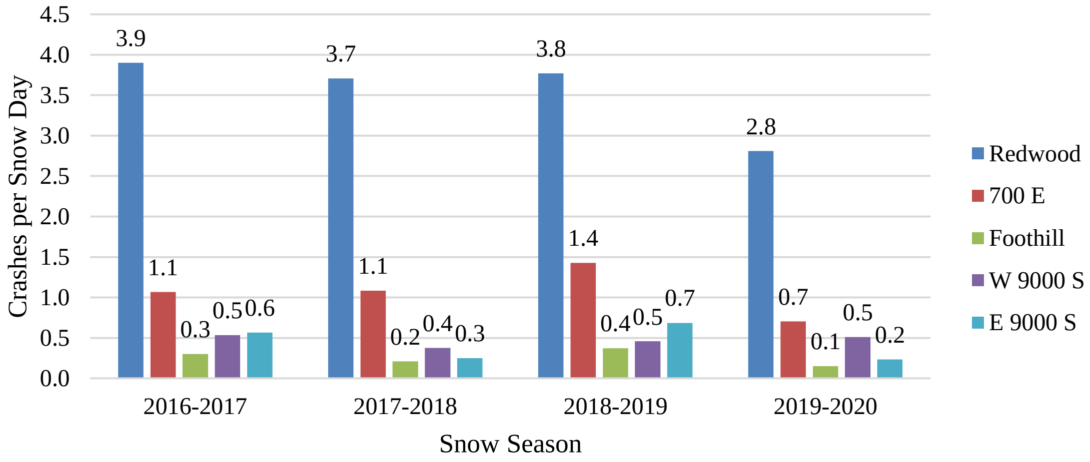


Figure 5.12 Crashes per day with snow for equipped routes by snow season.

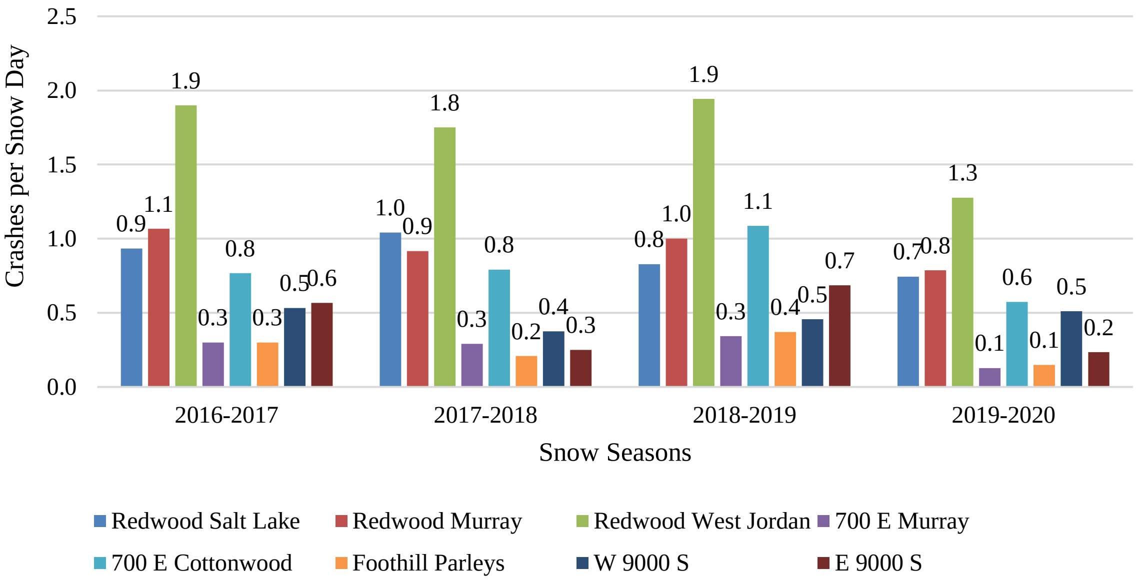


Figure 5.13 Crashes per day with snow for segments by snow season.

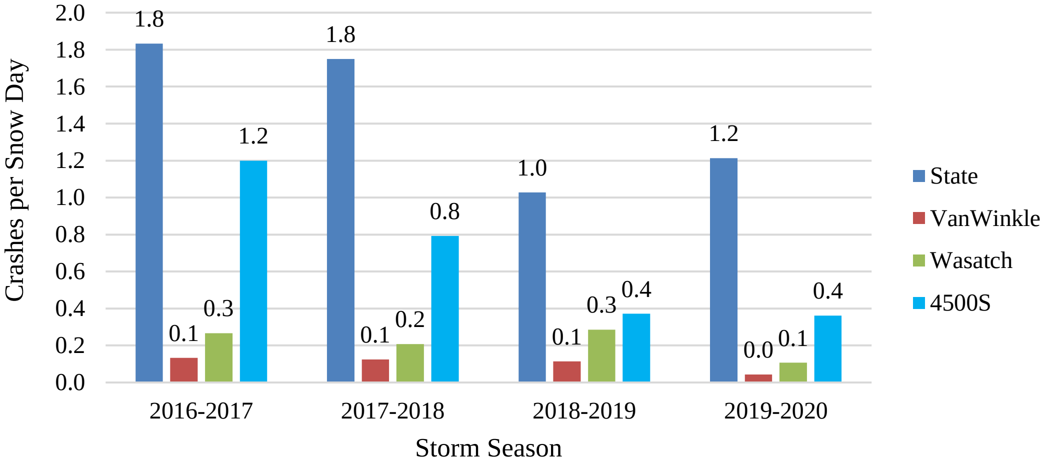


Figure 5.14 Crashes per day with snow for not-equipped routes by snow season.

The adjusted roadway crash rate was used to normalize the data for more of a side-by-side comparison. The associated adjusted roadway crash rates for both equipped and not-equipped routes for the 2019-2020 snow season are shown in Table 5.6. When comparing equipped routes to their associated not-equipped routes, only Foothill Boulevard and Redwood Road had lower adjusted roadway crash rates than their analogous not-equipped route, as shown in Table 5.6, in bold.

Table 5.6 Adjusted Roadway Crash Rate for Equipped and Not-Equipped Routes for 2019-2020 Snow Season

Equipped	Not Equipped	Difference
W 9000 S 6.70	*4500 S* 3.23	3.47
E 9000 S 2.01	*Wasatch Blvd* 1.08	0.92
Foothill Blvd 1.00	*Wasatch Blvd* 1.08	**-0.08**
Redwood Rd 4.37	*State St* 6.36	**-1.98**
700 E 2.80	*Van Winkle Blvd* 0.53	2.27

Adjusted roadway crash rates vary for each pairing of equipped and not-equipped routes. The adjusted roadway crash rates for each pairing are shown; with the 700 East/Van Winkle pairing in Figure 5.15, the East 9000 South/Foothill Drive and Wasatch Boulevard pairing in Figure 5.16, the West 9000 South and 4500 South pairing in Figure 5.17, and the Redwood Road and State Street pairing in Figure 5.18.

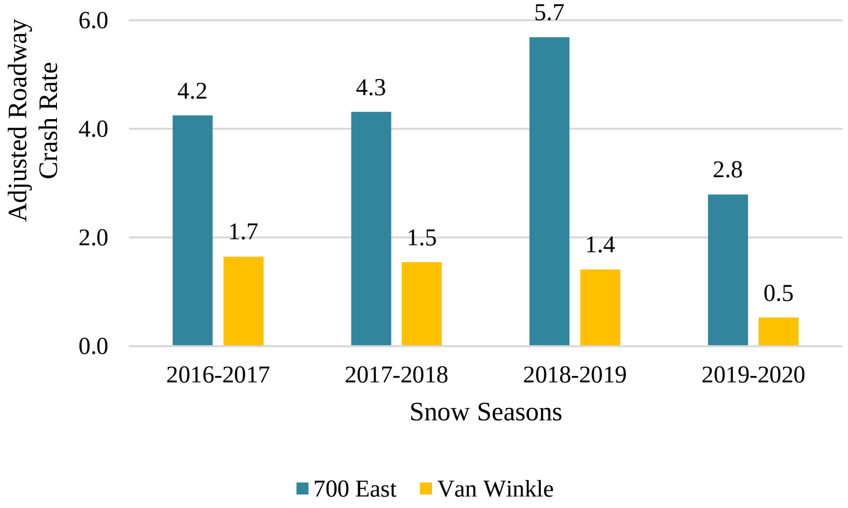


Figure 5.15 Adjusted roadway crash rate for 700 East/Van Winkle by snow season.

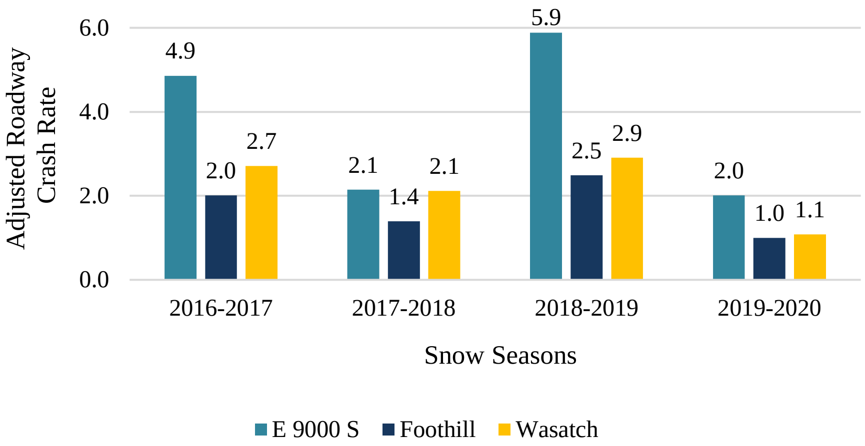


Figure 5.16 Adjusted roadway crash rate for East 9000 South/Foothill Drive and Wasatch Blvd by snow season.

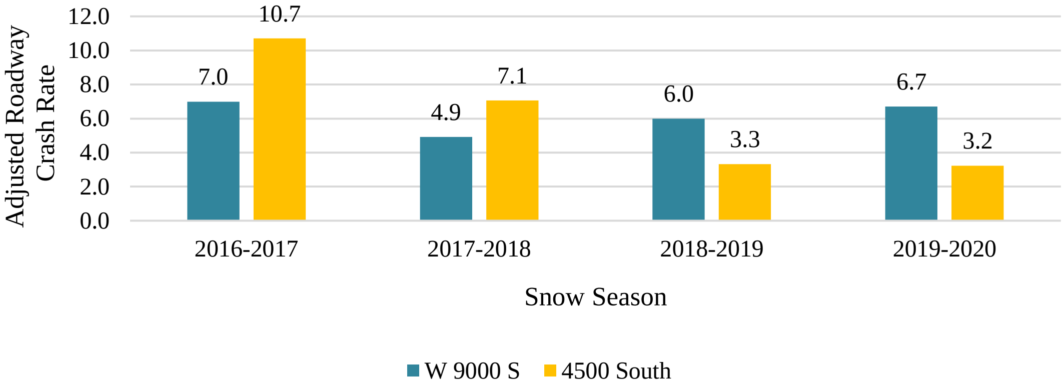


Figure 5.17 Adjusted roadway crash rate for West 9000 South/4500 South by snow season.

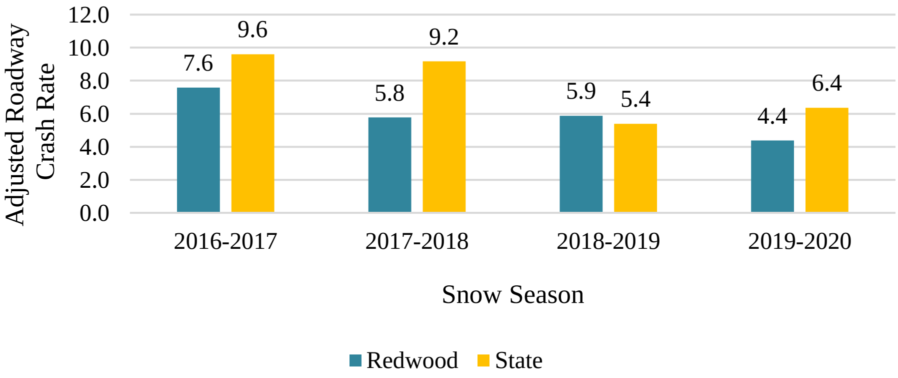


Figure 5.18 Adjusted roadway crash rates for Redwood Road/State Street by snow season.

Evaluating each equipped and not-equipped route pairing, the changes in adjusted roadway crash rate are another important factor to consider. The changes between each snow season for each equipped and not-equipped route can be found in Table 5.7. Between the snow season of 2018-2019 and 2019-2020, each equipped route had a lower change in adjusted roadway crash rate than its not-equipped counterparts, except for West 9000 South.

Table 5.7 Changes in Adjusted Roadway Crash Rate for All Routes

Routes (Equipped Route) *(Not Equipped Route)*	**2016-2017 to 2017-2018**	**2017-2018 to 2018-2019**	**2018-2019 to 2019-2020**
700 East	0.07	1.37	-2.89
Van Winkle	-0.10	-0.13	-0.89
E 9000 S	-2.72	3.74	-3.87
Foothill	-0.61	1.09	-1.49
Wasatch	-0.59	0.79	-1.82
W 9000 S	-2.08	1.08	0.70
4500 South	-3.64	-3.75	-0.09
Redwood	-1.82	0.10	-1.50
State	-0.44	-3.78	0.97

The changes in adjusted roadway crash rate were analyzed by segment for Redwood Road and 700 East. These rates for the four snow seasons considered in this analysis are shown in Figure 5.19. The adjusted roadway crash rate for each segment was lower during the 2019-2020 snow season than in previous seasons. The change in the adjusted crash rates between snow seasons are displayed graphically, with Figure 5.20 representing the segments for 700 East and Figure 5.21 representing the segments for Redwood Road. All segments followed a similar pattern of dropping in adjusted roadway crash rates for the 2019-2020 season except for the Redwood SLC segment.

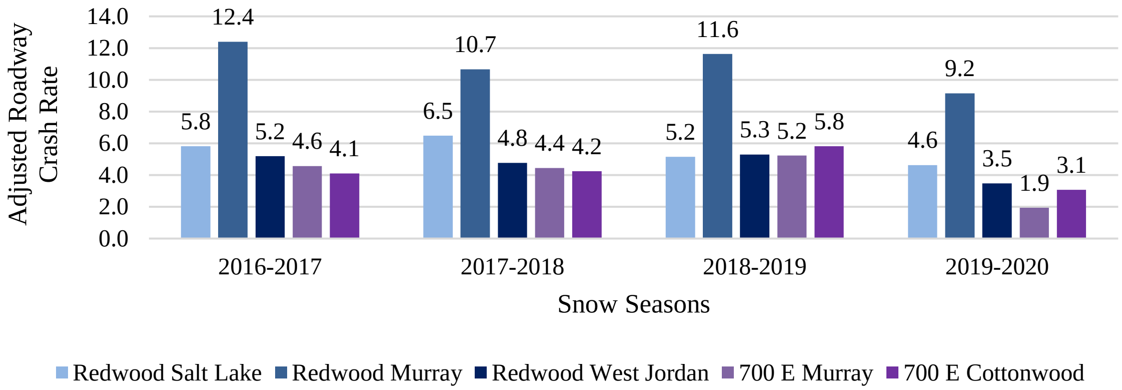


Figure 5.19 Adjusted roadway crash rates for Redwood Road and 700 East segments by snow season.

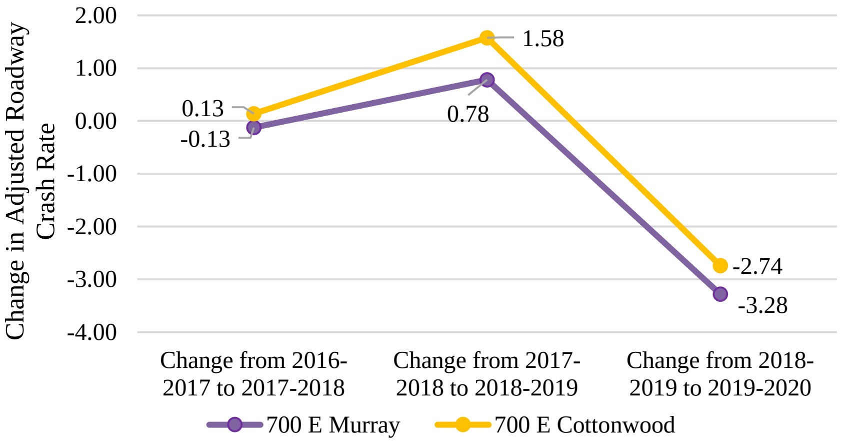


Figure 5.20 Changes in adjusted roadway crash rates for 700 East segments.

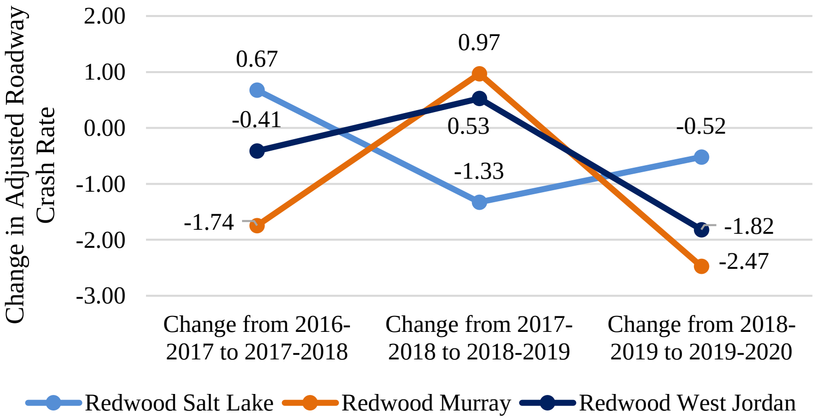


Figure 5.21 Changes in adjusted roadway crash rate for Redwood Road segments.

Crash severity was also analyzed for both equipped and not equipped routes. The different categories for crash severity are no injury/property damage only (PDO), possible injury, suspected minor injury, suspected serious injury, and fatal injury. The crash severity for crashes on equipped routes is shown in Figure 5.22 and for not-equipped routes in Figure 5.23. When comparing the change from the 2018-2019 snow season and the 2019-2020 snow season, the equipped routes had a lowering of all type of total number of crashes, particularly in no injury/PDO, suspected minor injury, and fatal injury. All crash severity categories rose for not-equipped routes, except for suspected serious injury and fatal injury.

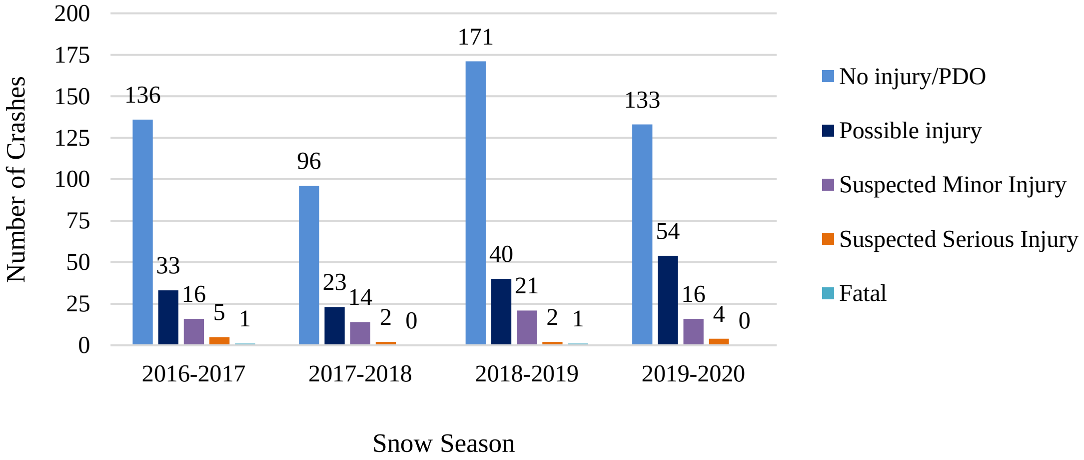


Figure 5.22 Crash severity for equipped routes by snow season.

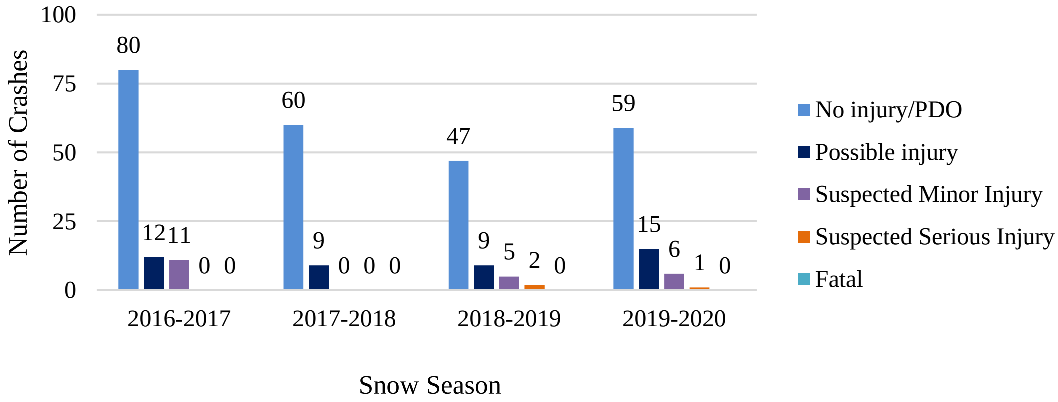


Figure 5.23 Crash severity for not-equipped routes by snow season.

Anecdotally, snowplow drivers noticed increases in safety. From qualitative data gathered for snowplow speed analysis, there is anecdotal evidence that the snowplows using DSRC systems to request signal preemption have improved safety—at least from the snowplow driver’s perspective. One main issue these drivers encounter with safety when plowing is vehicles attempting to go around them. With the implementation of the DSRC systems on snowplows that are used to request signal preemption, the drivers have noticed that vehicles do not try to go around them as often as in the past. These drivers related how they feel safer due to these changes.

5.5 Summary

The goal of doing an analysis on vehicle performance was to see if plowing and traffic operations and overall performance was improved with snowplows using DSRC systems to request signal preemption. It was found that overall, these systems do not influence average snowplow speed. The V2X DSRC system requesting preemption, however, does affect the number of times a snowplow has to stop. UDOT maintenance shed foreman noticed the benefits of the system as they have been out plowing the different equipped routes. Travel speeds show that equipped routes have a higher speed limit percentage overall, with equipped routes being affected less by snowstorms than not-equipped routes (except for Redwood Road and State Street). There was also a decrease in adjusted roadway crash rates and crash severity on equipped routes than on not-equipped routes. Within the datasets used in the vehicle performance analysis, there were other factors that could not be quantified in this study. Overall, it appears that snowplows equipped with DSRC to request signal preemption had minimal impacts on vehicle performance from the data, but according to qualitative data, had large improvements for snowplow operations and other vehicle performance.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Utah is known for the greatest snow on earth. Due to the copious amounts of snow received, UDOT evaluated ways to improve their winter maintenance by using new technology, including DSRC systems requesting signal preemption. The objective of this research was to evaluate and investigate the range of benefits and expected impacts of using DSRC-equipped snowplows to request signal preemption compared to snowplows operating on similar corridors without preemption.

There were three types of analysis performed: weather data analysis, signal performance analysis, and vehicle performance analysis. Weather data were gathered from UDOT RWIS sites and were analyzed for dates with snow. Signal performance data included DSRC message logs and signal controller event log data. DSRC message data were used to determine the number of signal preemption requests that were made, while the signal controller event log data determined if the request was granted. Signal controller event log data were used to analyze the impacts these signal preemption requests had on signal controller operations. Vehicle performance data were used to analyze impacts that snowplows equipped with DSRC to request signal preemption had on the surrounding transportation system and applicable improvement on equipped routes. Data used included records from Networkfleet AVL systems, ClearGuide web interface, and AASHTOSafetyware data. Networkfleet AVL data were used to assess snowplow speeds. Vehicle probe data from ClearGuide were used to assess travel speeds of vehicles on the roadways, and crash data were used to calculate roadway crash rates and analyze crash severity. Data from the project were analyzed in various observational comparisons, while some also had statistical analysis performed. This chapter will discuss the findings, limitations and challenges, recommendations, and suggested implementation plan.

6.2 Findings

The research found that there were 46 days with snow during the 2019-2020 winter season. During this time, DSRC-equipped snowplows requested signal preemption along five equipped routes. Analyses were made comparing equipped routes to not-equipped routes. The types of analysis performed included signal performance and vehicle performance. The findings from each type of analysis will be explained in the following subsections.

6.2.1 Signal Performance Analysis

Signal performance analysis was done to determine how DSRC systems requesting signal preemption affected signals. It was determined that snowplows equipped with DSRC systems to request signal preemption worked as intended and had minimal effects on signal controller performance. Out of all messages received by RSUs, 50 percent of the messages requested signal preemption. Of the messages that requested preemption, over 83 percent were granted signal preemption. It was found, on average, that signal controllers that granted signal preemption were affected for less than five minutes, which is below the maximum acceptable threshold of six minutes held by UDOT for being an acceptable time for a signal to be out of coordination. Although difficult to measure all impacts on signals, it was found that the system had minimal impacts on signal performance.

6.2.2 Vehicle Performance Analysis

Vehicle performance analysis was done to determine if plowing and traffic operations and performance were improved with V2X systems using DSRC. From the analysis done on snowplow speeds, it was determined that snowplow speeds were not an effective way to measure impacts to snowplow operations due to the numerous inconsistencies in overall snowplow management and operations. When surveying UDOT shed foremen, it was reported that the systems were highly beneficial to drivers, as the operators have reported snowplows stop less often and fewer passenger vehicles try to pass the snowplows. Travel speeds were also analyzed; it was found that on days with snow, equipped routes have speeds impacted less than routes that are not equipped. Crash data contained information on crashes and crash severity. Although not statistically proven, it appears that from the 2018-2019 snow season to the 2019-2020 snow season, crashes were reduced more on equipped routes than not-equipped routes. This finding, with all other findings in the vehicle performance analysis, could be influenced by various other factors that were outside the scope of this study.

6.3 Limitations and Challenges

Various limitations and challenges were encountered during this research. These included challenges with comparisons due to time intervals, weather conditions changing frequently, the differences in routes, and other influencing factors. First, assessing when there would be impacts from snowy weather proved difficult due to the different data frequency. Although it was attempted to aggregate different data into the same time period, data granularity was lost. The frequency at which data was collected varied. Overall, weather data were collected every ten minutes. Signal performance data recorded DSRC message log data occurring when a request for signal preemption was made and signal controller event log data occurring when a request was granted until the signal timing returned to normal. This was all recorded at the tenth of a second. For vehicle performance data, snowplows recorded snowplow speed data every 30 seconds the plow was out, general travel speed data were gathered in 15-minute increments, and crash data were gathered anytime a crash occurred. Due to these differing time increments, it was difficult to determine a window of time that could be used as a way to analyze how one dataset affected another.

Another challenge that was encountered was the frequency at which weather conditions change. Due to the size of the study area, it was determined that if there was snow during any part of a day on any route, data would be downloaded for the entire day. Due to this, data were collected and analyzed for times when there was no snow on individual routes. Also, depending on the intensity of the snowstorm, effectiveness of communication devices could be affected.

A third challenge that was encountered was with the equipped and not-equipped route pairings. Although each not-equipped route was chosen based on similarities it had to the equipped route, the routes were inheritably different. In the analysis process, differences were normalized when possible, but it was difficult to make comparisons with routes that were different and in different locations than the equipped routes.

Finally, although statistical analysis was possible for some of the data, it was not possible for all datasets due to small sample size and other compounding factors. Comparisons of datasets were investigated, but due to the differences in data periods and reliability, it was decided that results would be difficult to determine and would not be statistically significant. As data reliability increases for these datasets, these comparisons can be explored. For this research study, only results from each dataset studied were found to assess separate impacts of snowplows requesting signal preemption with DSRC systems. Other influencing factors could be thought to impact results, but this was out of the scope of the research. These other factors include topics covered in the literature review, such as economic benefits.

6.4 Recommendations

As stated throughout the report, there were some signals that never granted signal preemption requests. System maintenance is an ongoing concern for UDOT, and these issues were referred to UDOT for investigation. As the program continues to be used and expanded, it is recommended that more resources be added to study and maintain the system. As resources continue to be added, it will keep the system not only useful, but beneficial to winter operations.

It is also recommended that UDOT expand the program to other state routes, such as State Street and Wasatch Boulevard. This is due to the low impacts and various benefits that were found. The systems are used frequently and often grant signal preemption to snowplows. There appears to be no negative impacts to signal controller function. Vehicles on equipped routes typically experience less change in speed during a snowstorm than not-equipped routes. Snowplow drivers report that they stop less while plowing, as well as feel safer. These benefits have been seen on the equipped routes selected for this study and could be seen on other routes, if implemented.

6.5 Implementation Plan

As the program is expanded to other state routes, it would be beneficial for UDOT to add further resources to continue to study and maintain the system. These systems will need to be maintained over time as more OBUs and RSUs are added to various new routes. Routine and reactive maintenance will be required.

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APPENDIX A. EQUIPPED SIGNAL INFORMATION

This appendix contains the geofence limits used in the study. They are separated by equipped route, with each signal used in the study listing the associated UDOT ID, as well as maximum and minimum latitude and longitude.

Table A.1 West 9000 South Geofence Limits

Intersection	UDOT ID	Max Latitude	Min Latitude	Max Longitude	Min Longitude
9000 South Redwood Rd	7117	40.587800	40.587572	-111.934462	-111.945015
2200 West 9000 South	7417	40.587809	40.587680	-111.944332	-111.953976
2700 West 9000 South	7418	40.587810	40.587691	-111.952523	-111.961995
3200 West 9000 South	7419	40.587826	40.587715	-111.961718	-111.971466
3400 West 9000 South	7420	40.587932	40.587795	-111.967795	-111.976484
4000 West 9000 South	7421	40.587914	40.587817	-111.980912	-111.991191

Table A.2 East 9000 South Geofence Limits

Intersection	UDOT ID	Max Latitude	Min Latitude	Max Longitude	Min Longitude
700 East 9000 South	7197	40.588178	40.588021	-111.868420	-111.874346
1000 East 9100 South	7009	40.587259	40.585421	-111.863664	-111.864341
1100 East 9400 South	7017	40.582088	40.580695	-111.860068	-111.862678
1300 East 9400 South	7018	40.580536	40.580355	-111.849705	-111.856477
1700 East 9400 South	7601	40.580486	40.580348	-111.840569	-111.846987
2000 East 9400 South	7019	40.580534	40.580330	-111.830340	-111.838315
2100 East 9400 South	7602	40.580534	40.580352	-111.827271	-111.832299
2300 East 9400 South	7020	40.579828	40.577887	-111.822177	-111.825609
SR-209 Wasatch Blvd	7826	40.573552	40.572238	-111.797525	-111.799015

Table A.3 Foothill Drive Geofence Limits

Intersection	UDOT ID	Max Latitude	Min Latitude	Max Longitude	Min Longitude
500 South 1300 East	7224	40.758602	40.758334	-111.848174	-111.858986
500 South Guardsman Way	7216	40.758604	40.758382	-111.842437	-111.848980
500 South VA Hospital Ped Crossing	7274	40.758573	40.758407	-111.839502	-111.844503
Foothill Blvd Mario Capecchi Dr	7217	40.758020	40.756489	-111.834772	-111.837746
Foothill Blvd Wakara Way	7218	40.756418	40.752220	-111.831365	-111.835070
Foothill Blvd Sunnyside Ave	7219	40.753498	40.746738	-111.830455	-111.832544
Foothill Dr 2100 East	7503	40.746621	40.744571	-111.829644	-111.830729
Foothill Dr 1300 South	7220	40.744667	40.739636	-111.825404	-111.830012
Foothill Dr 2300 East	7221	40.741253	40.737033	-111.823253	-111.827090
Foothill Dr 1700 South	7222	40.737446	40.729847	-111.817442	-111.823780
Foothill Dr 2100 South	7223	40.727300	40.724777	-111.814063	-111.815957
Foothill Dr Thunderbird Dr	7371	40.723256	40.719682	-111.810365	-111.815957

Table A.4 700/900 East Geofence Limits

Intersection	Segment	UDOT ID	Max Latitude	Min Latitude	Max Longitude	Min Longitude
3300 South 700 East	700 E Murray	7191	40.705601	40.694586	-111.871190	-111.871475
3900 South 700 East	700 E Murray	7192	40.692990	40.681265	-111.871258	-111.871542
4500 South 700 East	700 E Murray	7193	40.678707	40.670270	-111.871330	-111.871607
4800 South Van Winkle	700 E Cottonwood	7210	40.666303	40.665538	-111.864590	-111.868496
Van Winkle 900 East	700 E Cottonwood	7211	40.665909	40.663773	-111.864552	-111.865887
5110 South 900 East	700 E Cottonwood	7203	40.661325	40.657744	-111.865155	-111.866014
5600 South 900 East	700 E Cottonwood	7204	40.652870	40.646457	-111.865886	-111.866019
5900 South 900 East	700 E Cottonwood	7205	40.645307	40.639405	-111.865859	-111.866049
6600 South 900 East	700 E Cottonwood	7206	40.636178	40.627141	-111.865887	-111.866034
Fort Union Blvd 900 East	700 E Cottonwood	7207	40.626142	40.620371	-111.865860	-111.866114
7220 South 900 East	700 E Cottonwood	7208	40.621780	40.618006	-111.865936	-111.866089
7500 South 900 East	700 E Cottonwood	7209	40.616298	40.612797	-111.867071	-111.871183
7800 South 700 East	700 E Cottonwood	7194	40.611542	40.606917	-111.872111	-111.872288
8000 South 700 East	700 E Cottonwood	7195	40.609159	40.603373	-111.872108	-111.872288
8600 South 700 East	700 E Cottonwood	7196	40.598365	40.591840	-111.872091	-111.872287
700 East 9000 South	700 E Cottonwood	7197	40.591306	40.585506	-111.872083	-111.872256

Table A.5 Redwood Road Geofence Limits

Intersection	Segment	UDOT ID	Max Latitude	Min Latitude	Max Longitude	Min Longitude
400 South Redwood Rd	Redwood SLC	7090	40.762191	40.759560	-111.938902	-111.939161
500 South Redwood Rd	Redwood SLC	7091	40.759513	40.756298	-111.938901	-111.939117
Indiana Ave Redwood Rd	Redwood SLC	7092	40.752359	40.750309	-111.938923	-111.939096
California Ave Redwood Rd	Redwood SLC	7093	40.741726	40.739097	-111.938951	-111.939176
1500 South Redwood Rd	Redwood SLC	7094	40.738723	40.735808	-111.938958	-111.939187
1700 South Redwood Rd	Redwood SLC	7095	40.735681	40.729497	-111.938892	-111.939185
2100 South Redwood Rd	Redwood SLC	7096	40.727454	40.724843	-111.938797	-111.939197
2200 South Redwood Rd	Redwood SLC	7098	40.723294	40.721799	-111.938839	-111.939147
2320 South Redwood Rd	Redwood SLC	7099	40.721750	40.719422	-111.938843	-111.939106
2495 South Redwood Rd	Redwood SLC	7100	40.718789	40.715561	-111.938843	-111.939097
3100 South Redwood Rd	Redwood SLC	7101	40.706752	40.701085	-111.938819	-111.939076
3500 South Redwood Rd	Redwood SLC	7102	40.699758	40.693351	-111.938783	-111.939062
3800 South Redwood Rd	Redwood Murray	7103	40.692015	40.686755	-111.938780	-111.939034
4100 South Redwood Rd	Redwood Murray	7104	40.684055	40.680768	-111.938760	-111.939019
4200 South Redwood Rd	Redwood Murray	7105	40.680653	40.677002	-111.938761	-111.939019
4450 South Redwood Rd	Redwood Murray	7106	40.674426	40.671814	-111.938750	-111.939009
4610 South Redwood Rd	Redwood Murray	7605	40.671567	40.668817	-111.938696	-111.939004
4700 South Redwood Rd	Redwood Murray	7107	40.668564	40.666909	-111.938621	-111.939006
4800 South Redwood Rd	Redwood Murray	7108	40.665771	40.661447	-111.938728	-111.938984
5225 South Redwood Rd	Redwood Murray	7109	40.656533	40.654933	-111.938713	-111.938972
5600 South Redwood Rd	Redwood WJ	7111	40.651245	40.648101	-111.938702	-111.938989
7000 South Redwood Rd	Redwood WJ	7115	40.626735	40.621419	-111.938631	-111.938956
7800 South Redwood Rd	Redwood WJ	7116	40.612215	40.606037	-111.938629	-111.938935
8020 South Redwood Rd	Redwood WJ	7229	40.609077	40.604355	-111.938624	-111.938934
8200 South Redwood Rd	Redwood WJ	7234	40.604105	40.599064	-111.938582	-111.938875
8400 South Redwood Rd	Redwood WJ	7232	40.601603	40.595803	-111.938600	-111.938864
9000 South Redwood Rd	Redwood WJ	7117	40.590794	40.585114	-111.938536	-111.938840

Table A.5 Continued

Intersection	Segment	UDOT ID	Max Latitude	Min Latitude	Max Longitude	Min Longitude
9800 South Redwood Rd	Redwood WJ	7404	40.577862	40.568767	-111.938598	-111.938769
10200 South Redwood Rd	Redwood WJ	7402	40.571673	40.562764	-111.938549	-111.938769
10400 South Redwood Rd	Redwood WJ	7118	40.565536	40.558951	-111.938584	-111.938759
10610 South Redwood Rd	Redwood WJ	7407	40.561491	40.554802	-111.938594	-111.938783
11010 South Redwood Rd	Redwood WJ	7408	40.555722	40.546934	-111.938596	-111.938767
11400 South Redwood Rd	Redwood WJ	7622	40.548050	40.540776	-111.938604	-111.938855
11800 South Redwood Rd	Redwood WJ	7405	40.540702	40.532861	-111.938623	-111.938784
12300 South Redwood Rd	Redwood WJ	7406	40.531519	40.525382	-111.938632	-111.938806
12600 South Redwood Rd	Redwood WJ	7119	40.525734	40.519185	-111.938679	-111.938823

APPENDIX B. DSRC-Equipped Snowplow Intersections and Cross Streets

This appendix includes a list of equipped signals with UDOT's intersection ID and applicable route, segment, state road name, and cross street.

Table B.1 DSRC-Equipped Signals

UDOT ID	Route	Segment	State Road	Cross Street
7194	700 E	700 E Cottonwood	700 E (SR-71)	7800 S
7195	700 E	700 E Cottonwood	700 E (SR-71)	8000 S
7196	700 E	700 E Cottonwood	700 E (SR-71)	8600 S
7203	700 E	700 E Cottonwood	900 E (SR-71)	5110 S (Arrowhead Ln)
7204	700 E	700 E Cottonwood	900 E (SR-71)	5600 S
7205	700 E	700 E Cottonwood	900 E (SR-71)	5900 S (Vine St)
7206	700 E	700 E Cottonwood	900 E (SR-71)	6600 S (Winchester St)
7207	700 E	700 E Cottonwood	900 E (SR-71)	Fort Union Blvd (~7100 S)
7208	700 E	700 E Cottonwood	900 E (SR-71)	7220 S (S Union Ave)
7209	700 E	700 E Cottonwood	900 E (SR-71)	Hillcrest High Dr (7400 S)
7210	700 E	700 E Cottonwood	Van Winkle (SR-71)	4800 S
7211	700 E	700 E Cottonwood	900 E (SR-71)	Van Winkle (SR-71 / SR-152)
7338	700 E	700 E Cottonwood	900 E (SR-71)	5400 S (Wood Oak)
7191	700 E	700 E Murray	700 E (SR-71)	3300 S (SR-171)
7192	700 E	700 E Murray	700 E (SR-71)	3900 S
7193	700 E	700 E Murray	700 E (SR-71)	4500 S (SR-266)
7009	E 9000 S	E 9000 S	9100 S (SR-209)	SR-209 (1000 E)/Quarry Bend
7017	E 9000 S	E 9000 S	9400 S (SR-209)	1100 E
7018	E 9000 S	E 9000 S	9400 S (SR-209)	1300 E
7019	E 9000 S	E 9000 S	9400 S (SR-209)	2000 E
7020	E 9000 S	E 9000 S	9400 S (SR-209)	2300 E
7197	E 9000 S	E 9000 S	700 E (SR-71)	9000 S (SR-209)
7601	E 9000 S	E 9000 S	9400 S (SR-209)	1700 E
7602	E 9000 S	E 9000 S	9400 S (SR-209)	2100 E (Rain Tree)
7826	E 9000 S	E 9000 S	SR-209	Wasatch Blvd
7216	Foothill	Foothill Parleys	500 S (SR-186)	Guardsman Wy/1580 E (SR-282)
7217	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	Mario Capecchi Dr (SR-282)
7218	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	Wakara Wy
7219	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	Sunnyside Ave (850 S)
7220	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	1300 S
7221	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	2300 E
7222	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	1700 S
7223	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	2100 S
7224	Foothill	Foothill Parleys	500 S (SR-186)	1300 E
7274	Foothill	Foothill Parleys	500 S (SR-186)	VA Hospital Ped Crossing
7371	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	Thunderbird Dr
7503	Foothill	Foothill Parleys	Foothill Blvd (SR-186)	2100 E

Table B.1 Continued

UDOT ID	Route	Segment	State Road	Cross Street
7103	Redwood	Redwood Murray	Redwood Rd (SR-68)	3800 South
7104	Redwood	Redwood Murray	Redwood Rd (SR-68)	4100 South
7105	Redwood	Redwood Murray	Redwood Rd (SR-68)	4200 South
7106	Redwood	Redwood Murray	Redwood Rd (SR-68)	4450 South
7107	Redwood	Redwood Murray	Redwood Rd (SR-68)	4700 South
7108	Redwood	Redwood Murray	Redwood Rd (SR-68)	4800 South
7109	Redwood	Redwood Murray	Redwood Rd (SR-68)	5225 South
7605	Redwood	Redwood Murray	Redwood Rd (SR-68)	4610 South
7090	Redwood	Redwood SLC	Redwood Rd (SR-68)	400 South
7091	Redwood	Redwood SLC	Redwood Rd (SR-68)	500 South
7092	Redwood	Redwood SLC	Redwood Rd (SR-68)	Indiana
7093	Redwood	Redwood SLC	Redwood Rd (SR-68)	California
7094	Redwood	Redwood SLC	Redwood Rd (SR-68)	1500 South
7095	Redwood	Redwood SLC	Redwood Rd (SR-68)	1700 South
7096	Redwood	Redwood SLC	Redwood Rd (SR-68)	2100 South
7098	Redwood	Redwood SLC	Redwood Rd (SR-68)	2200 South
7099	Redwood	Redwood SLC	Redwood Rd (SR-68)	2320 South
7100	Redwood	Redwood SLC	Redwood Rd (SR-68)	2495 South
7101	Redwood	Redwood SLC	Redwood Rd (SR-68)	3100 South
7102	Redwood	Redwood SLC	Redwood Rd (SR-68)	3500 South
7111	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	5600 South
7115	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	7000 South
7116	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	7800 South
7117	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	9000 S (SR-209)
7118	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	10400 S (SR-151)
7119	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	12600 S (SR-71)
7229	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	8020 South
7232	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	8400 S (Ped Crossing)
7234	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	8200 South
7402	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	10200 S (Temple Ln)
7404	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	9800 S
7405	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	11800 S
7406	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	12300 S
7407	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	10610 S
7408	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	11010 S
7622	Redwood	Redwood West Jordan	Redwood Rd (SR-68)	11400 S (SR-175)
7067	W 9000 S	W 9000 S	9000 S (SR-209)	Bangerter Hwy (SR-154)
7417	W 9000 S	W 9000 S	9000 S (SR-209)	2200 W
7418	W 9000 S	W 9000 S	9000 S (SR-209)	2700 W
7419	W 9000 S	W 9000 S	9000 S (SR-209)	3200 W
7420	W 9000 S	W 9000 S	9000 S (SR-209)	3400 W
7421	W 9000 S	W 9000 S	9000 S (SR-209)	4000 W

APPENDIX C. Requested versus Granted Results for DSRC

This appendix shows the percent of DSRC calls made that requested signal preemption and the percent that were granted signal preemption. Where there are many requests for signal preemption, but no granting of the signal preemption, it was determined that the signal was coded incorrectly for snowplow preemption requests. It is recommended that UDOT review these signals to determine the coding is now correct.

For each segment, there are also graphs that show the percentage of the requested calls that were granted for each signal ID. At times when these percentages are over 100 percent it was determined that there were errors from data collection, due to the nature of big data. It is suggested that the data be verified more in the future for more accurate data. In addition, there are graphs with the average occupancy for each signal during the request phase.

C.1 700 East Cottonwood Requested, Granted, and Occupancy by Signal

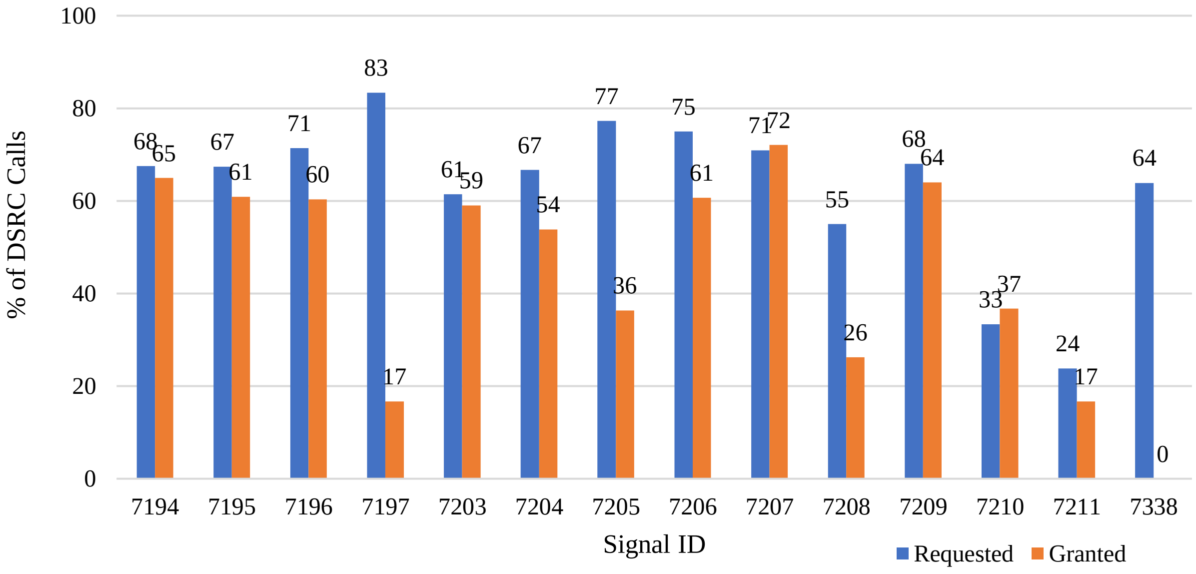

Figure C.1 700 East Cottonwood requested and granted by signal.

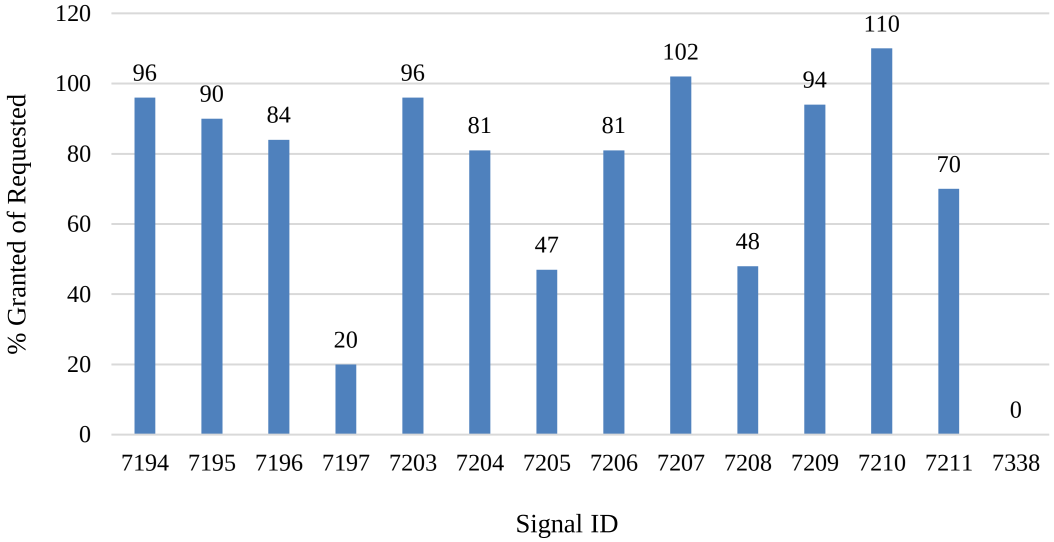

Figure C.2 700 East Cottonwood percentage of requested granted by signal.

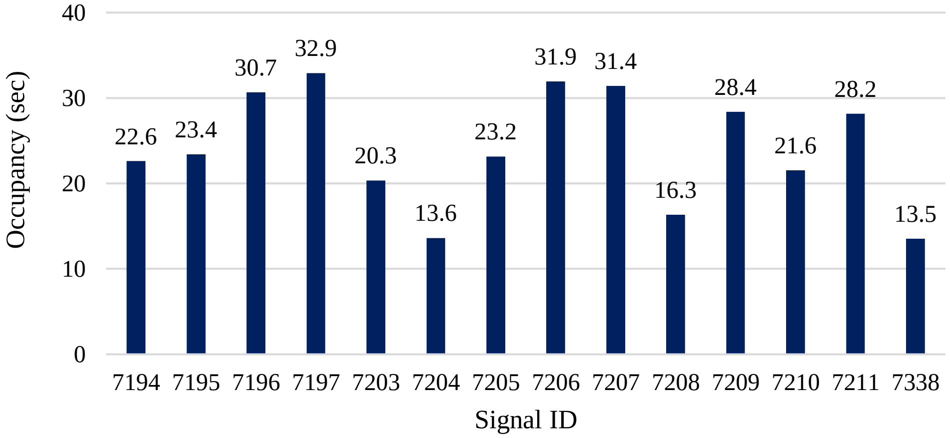

Figure C.3 700 East Cottonwood occupancy by signal.

C.2 700 East Murray Requested, Granted, and Occupancy by Signal

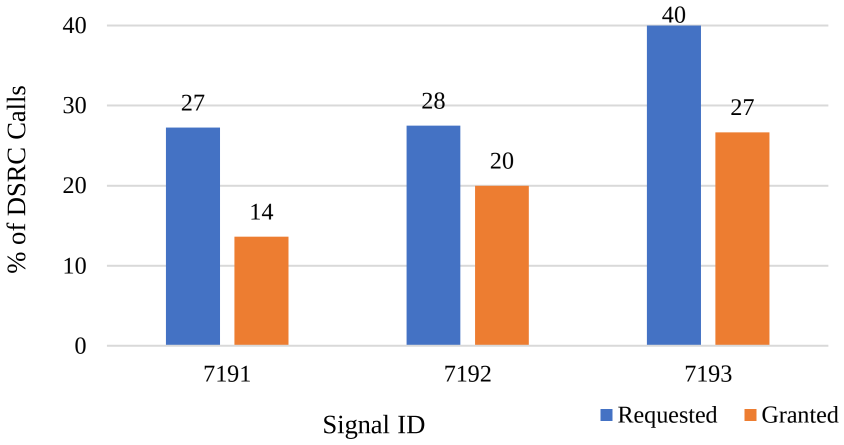

Figure C.4 700 East Murray requested and granted by signal.

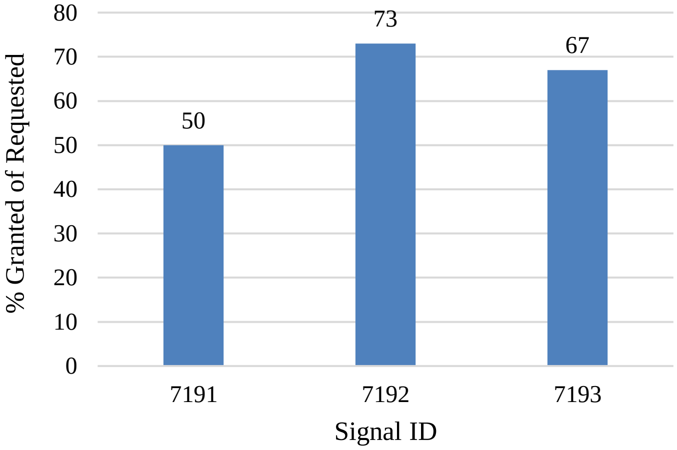

Figure C.5 700 East Murray percentage of requested granted by signal.

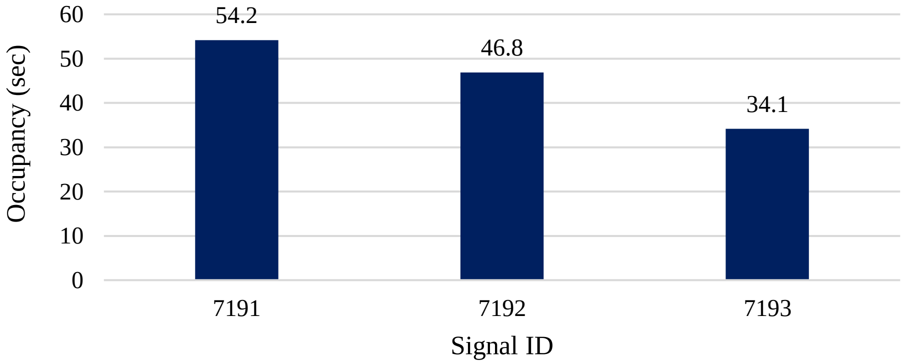

Figure C.6 700 East Murray occupancy by signal.

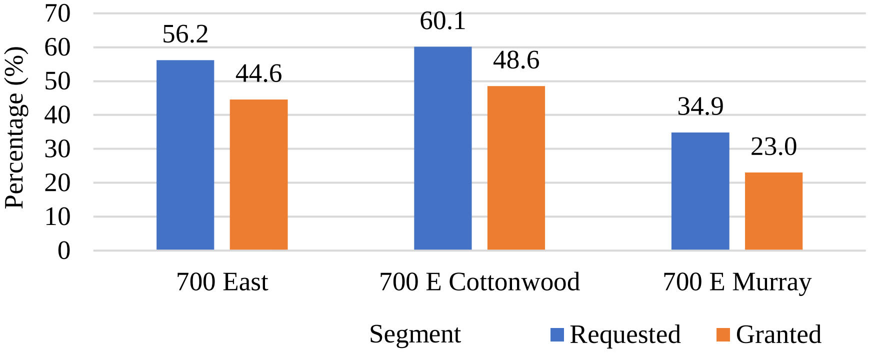

Figure C.7 700 East route and segments requested and granted.

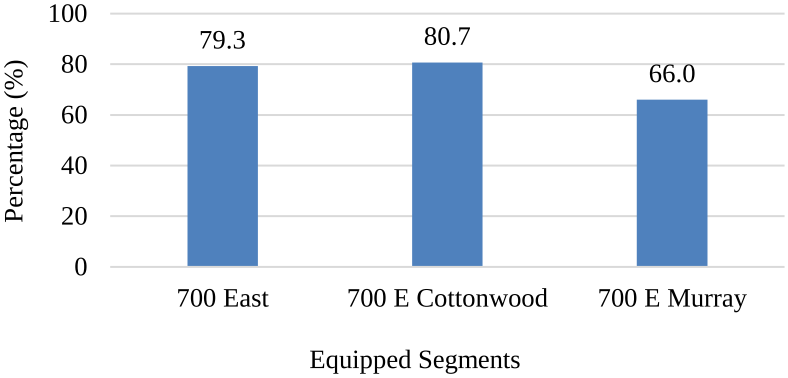

Figure C.8 Percentage of requested granted by 700 East route and segments.

C.3 East 9000 South Requested, Granted, and Occupancy by Signal

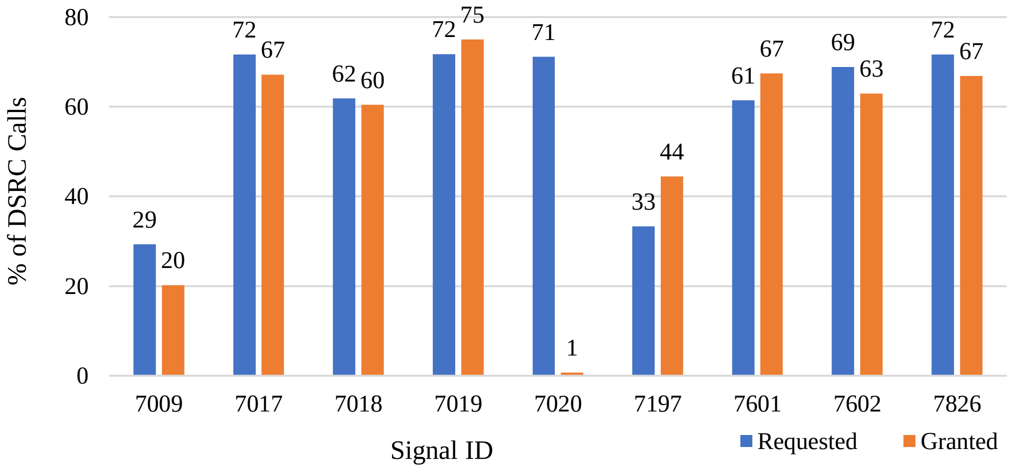

Figure C.9 East 9000 South requested and granted by signal.

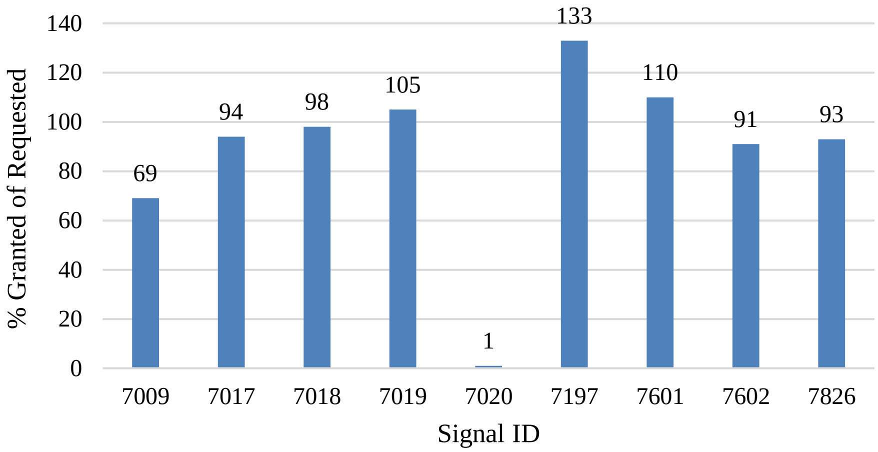

Figure C.10 Percentage granted of requested for East 9000 South by signal.

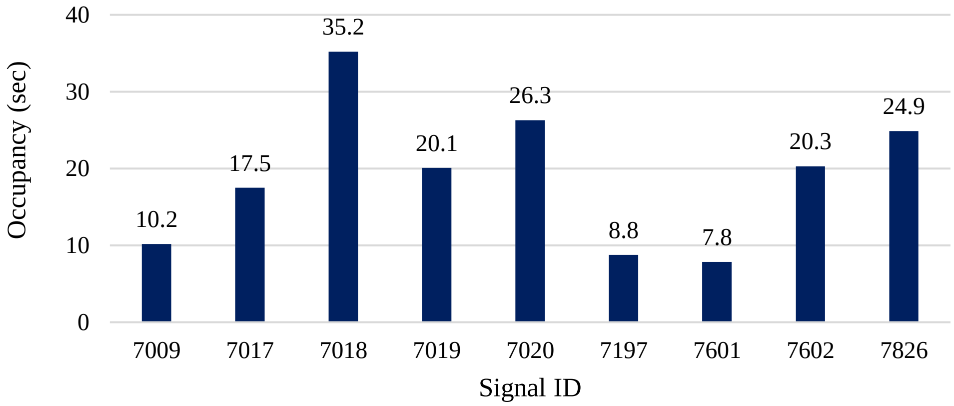

Figure C.11 East 9000 South occupancy by signal.

C.4 Foothill Boulevard Requested, Granted, and Occupancy by Signal

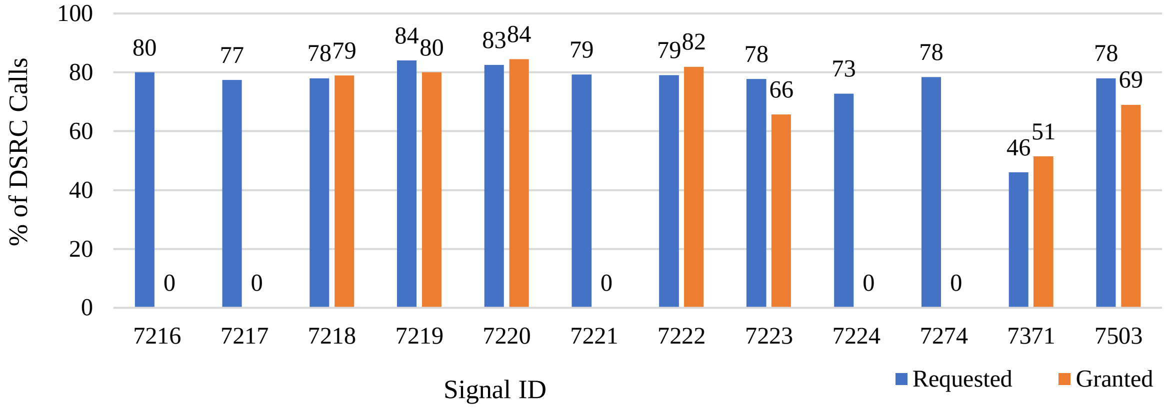

Figure C.12 Foothill Boulevard requested and granted by signal.

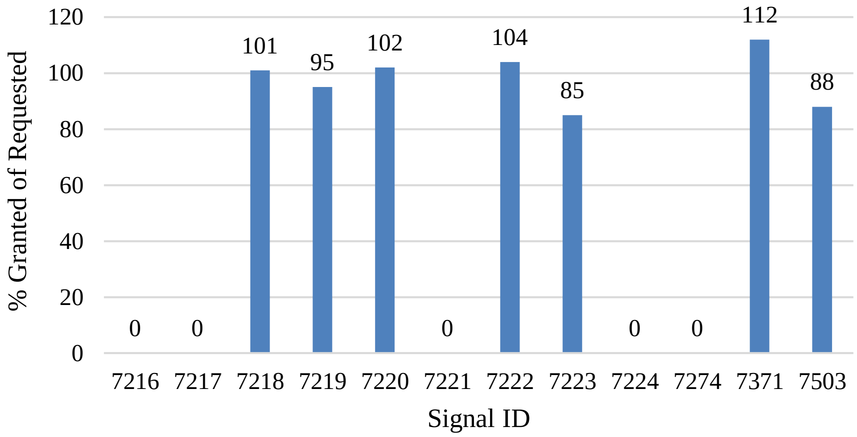

Figure C.13 Percent granted of requested for Foothill Boulevard by signal.

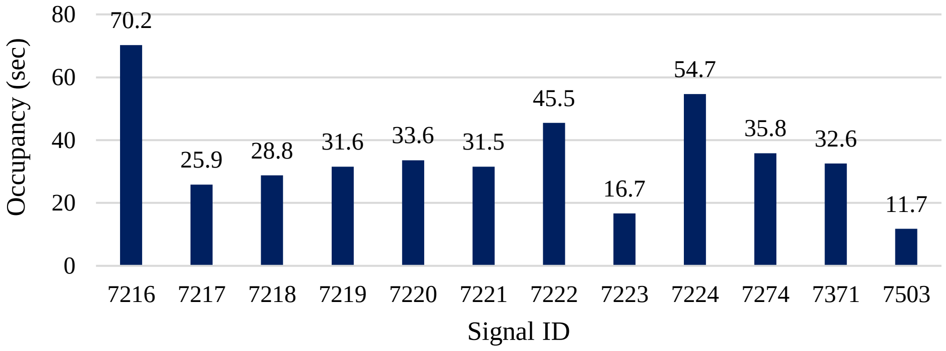

Figure C.14 Foothill Boulevard occupancy by signal.

C.5 Redwood Murray Requested, Granted, and Occupancy by Signal

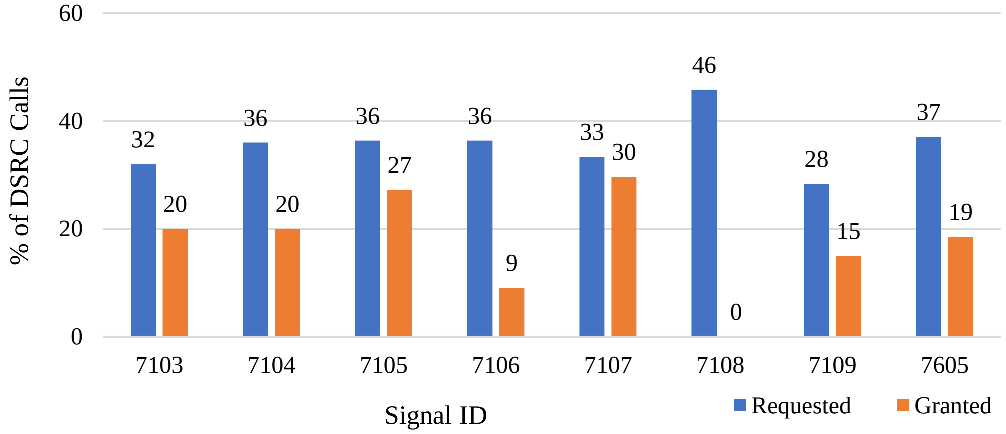

Figure C.15 Redwood Murray requested and granted by signal.

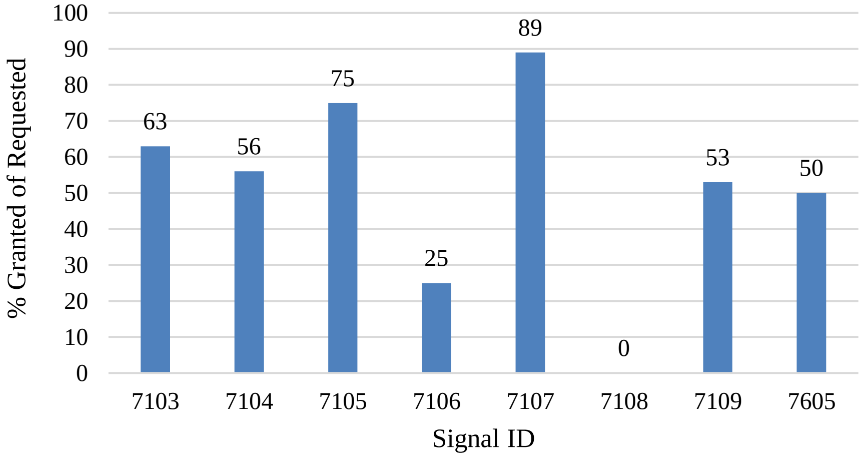

Figure C.16 Redwood Murray percent granted of requested by signal.

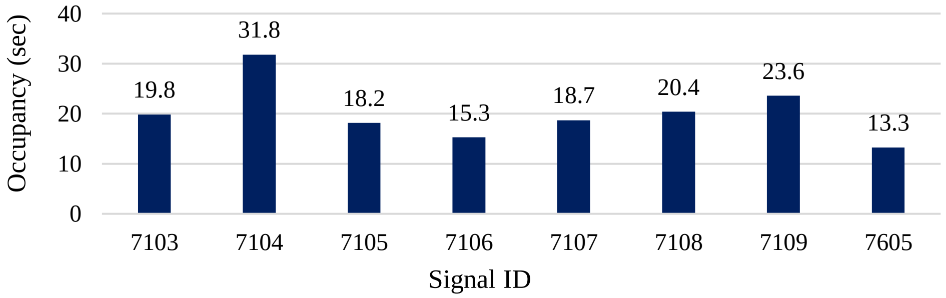

Figure C.17 Redwood Murray occupancy by signal.

C.6 Redwood SLC Requested, Granted, and Occupancy by Signal

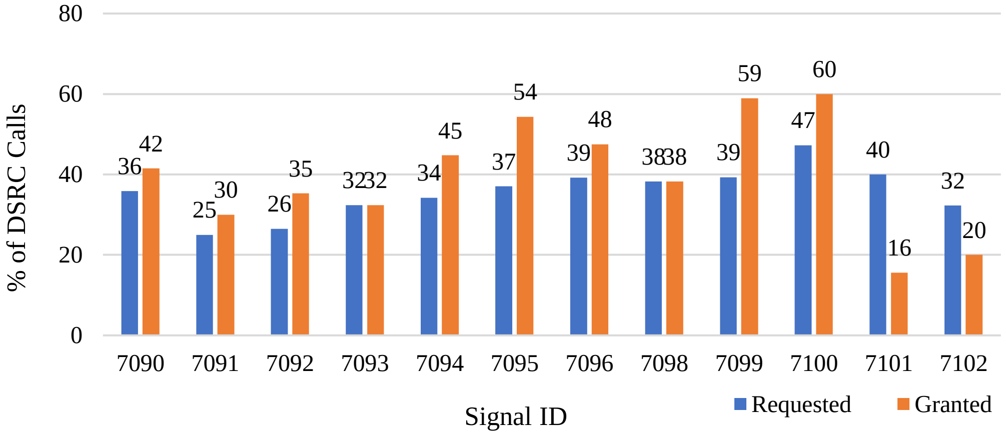

Figure C.18 Redwood SLC requested and granted by signal.

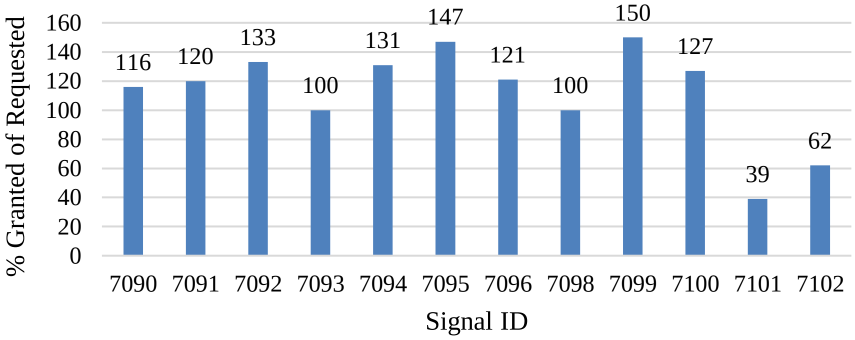

Figure C.19 Redwood SLC percent granted of requested by signal.

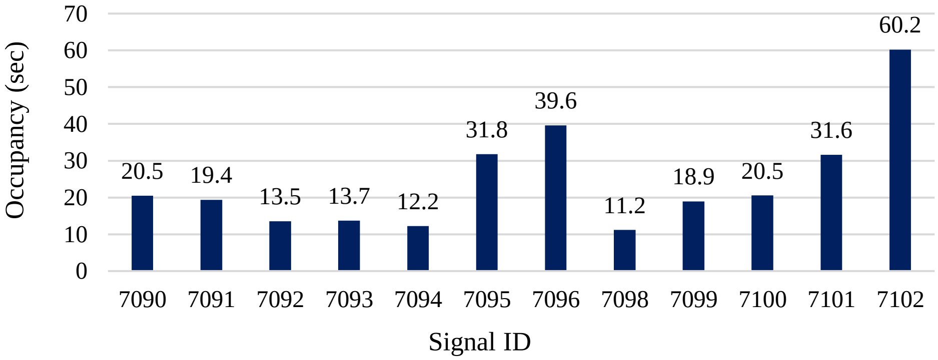

Figure C.20 Redwood SLC occupancy by signal.

C.7 Redwood West Jordan Requested, Granted, and Occupancy by Signal

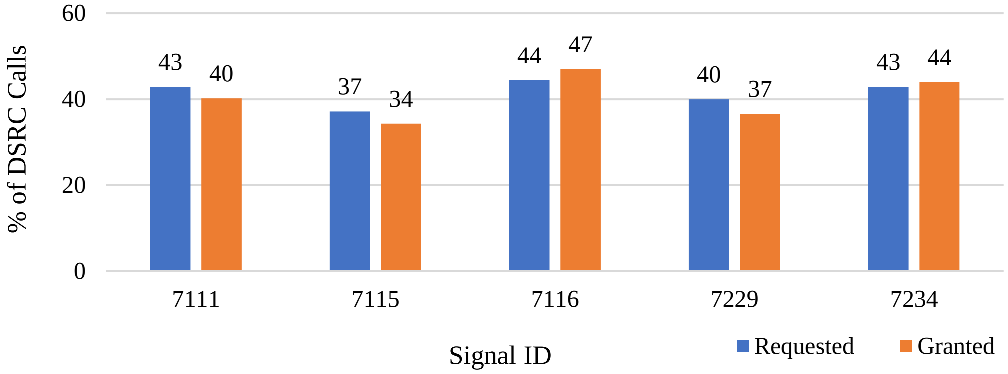

Figure C.21 Redwood West Jordan requested and granted by signal.

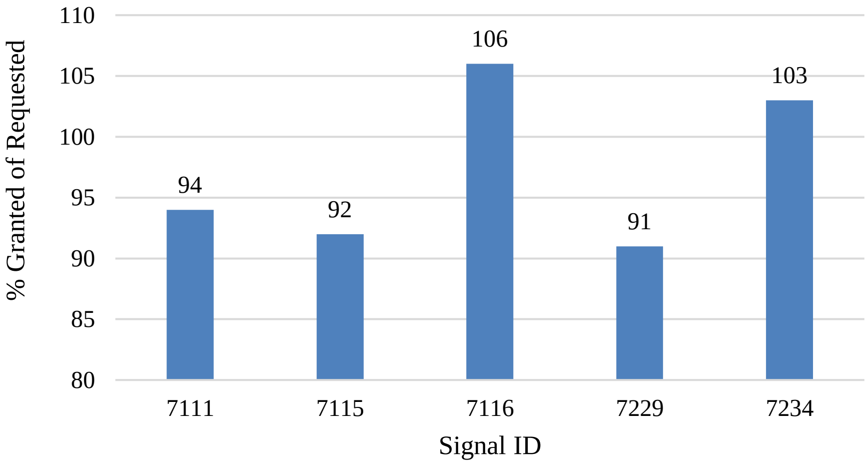

Figure C.22 Redwood West Jordan percent granted of requested by signal.

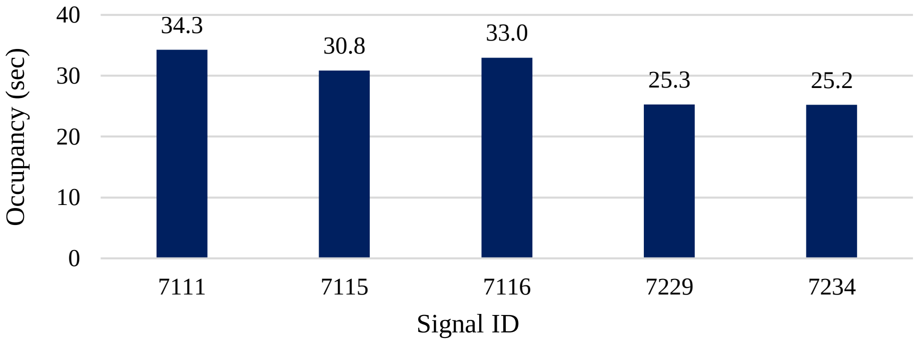

Figure C.23 Redwood West Jordan occupancy by signal.

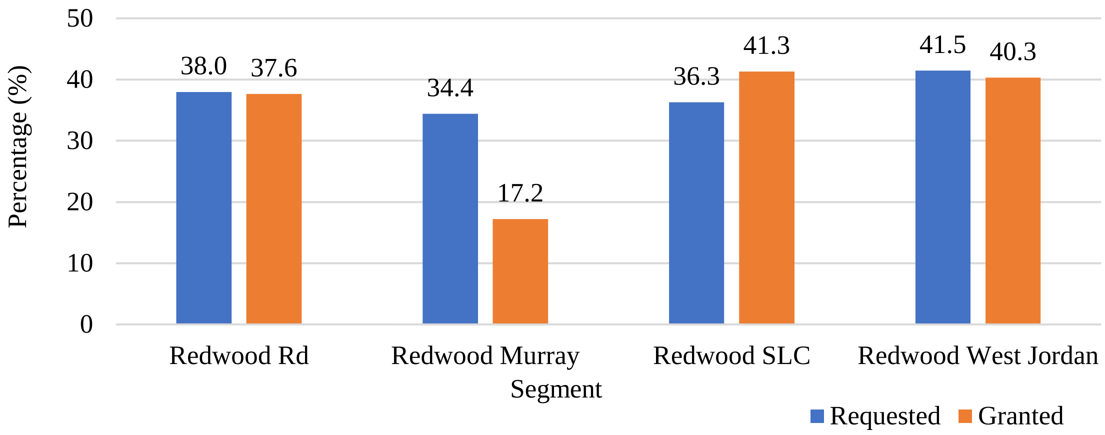

Figure C.24 Redwood Segments granted and requested.

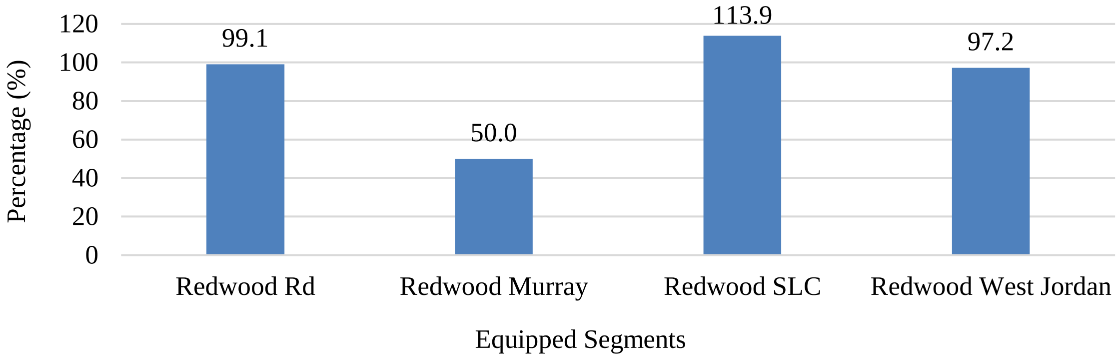

Figure C.25 Redwood Segments percent granted of requested.

C.8 West 9000 South Requested, Granted, and Occupancy by Signal

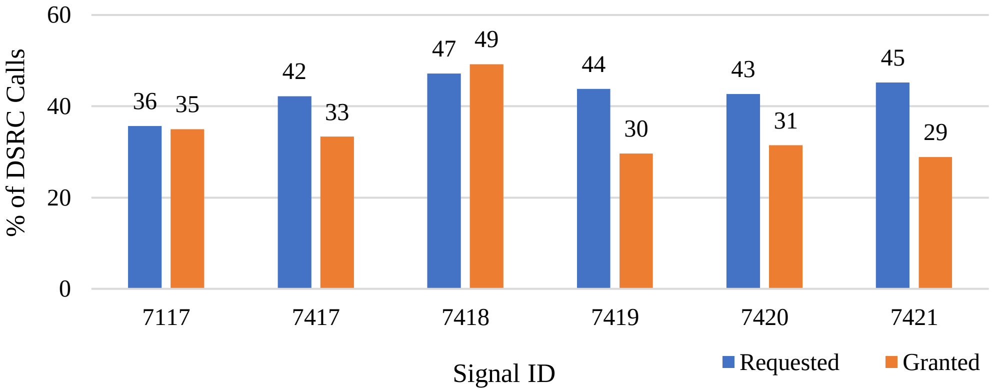

Figure C.26 West 9000 South requested and granted by signal.

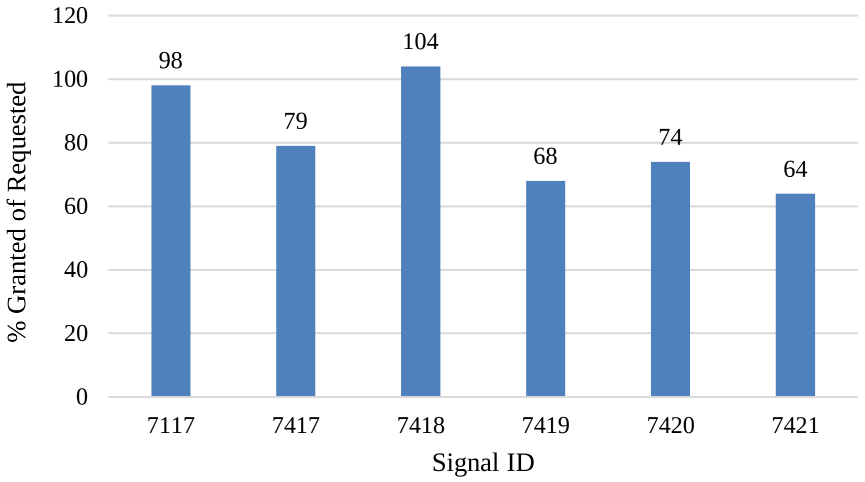

Figure C.27 West 9000 South percent granted of requested by signal.

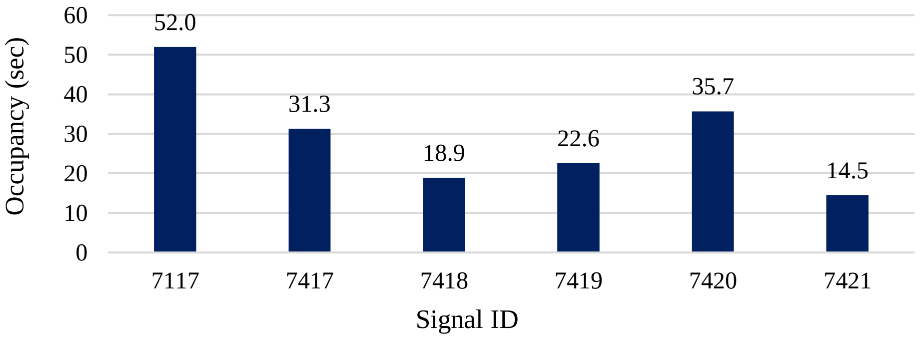

Figure C.28 West 9000 South occupancy by signal.

APPENDIX D. Affected Duration by Signal

This appendix shows the average affected duration of how long a signal controller was out of step for each signal in an equipped segment. Each segment's affected duration by signal is shown in this appendix. An affected duration of six minutes was agreed to be an acceptable value by UDOT. It is recommended that UDOT review these results to ensure signal controller performance.

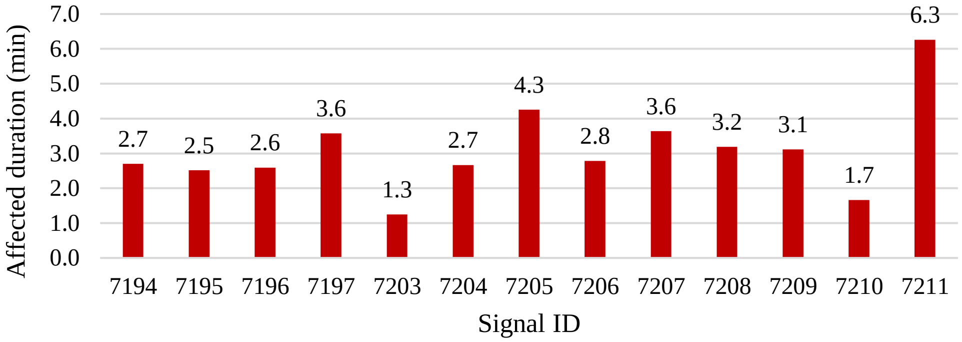

Figure D.1 Affected duration for 700 East Cottonwood by signal.

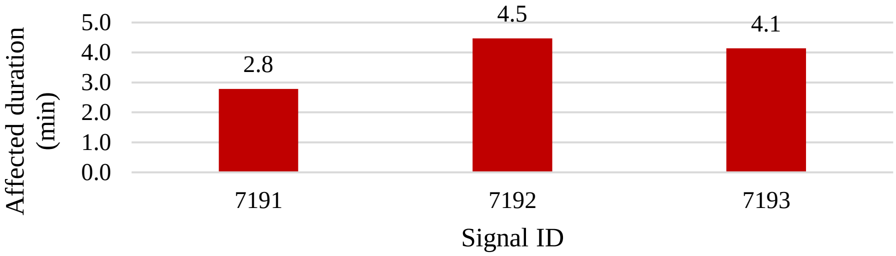

Figure D.2 Affected duration for 700 East Murray by signal.

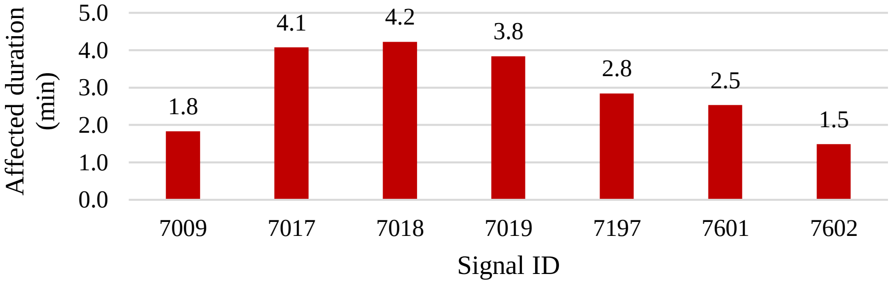

Figure D.3 Affected duration for East 9000 South by signal.

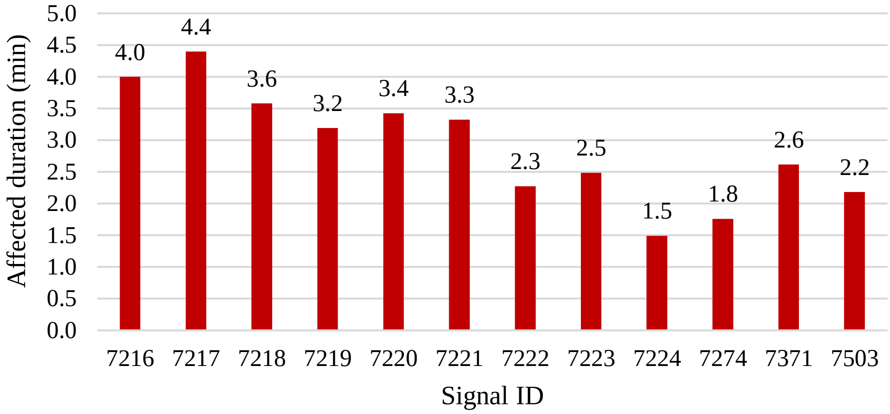

Figure D.4 Affected duration for Foothill by signal.

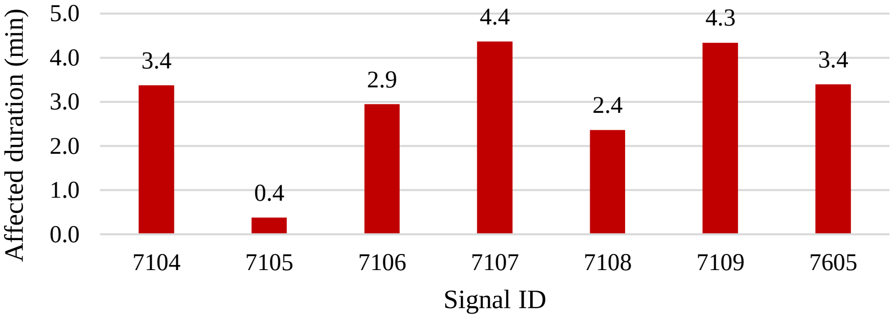

Figure D.5 Affected duration for Redwood Murray by signal.

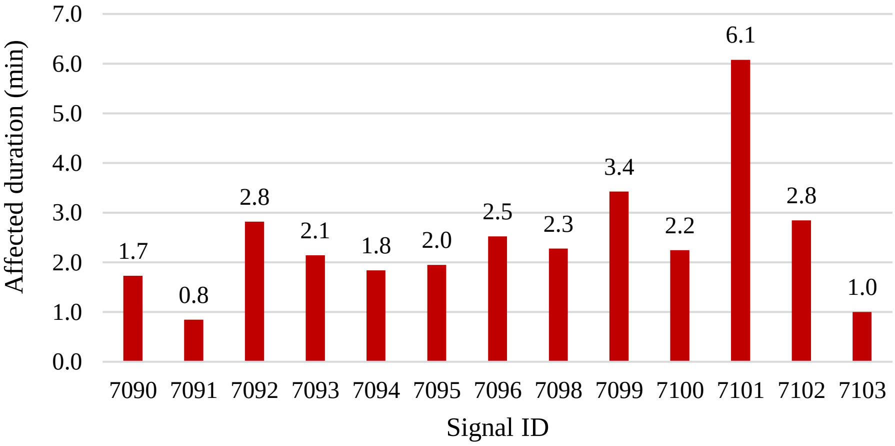

Figure D.6 Affected duration for Redwood SLC by signal.

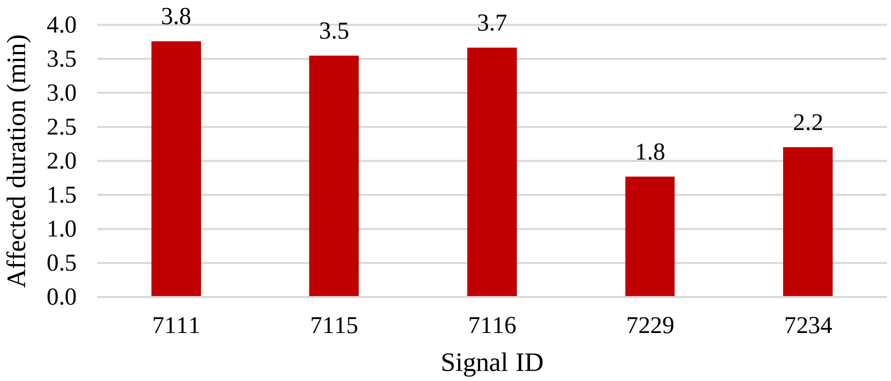

Figure D.7 Affected duration for Redwood West Jordan by signal.

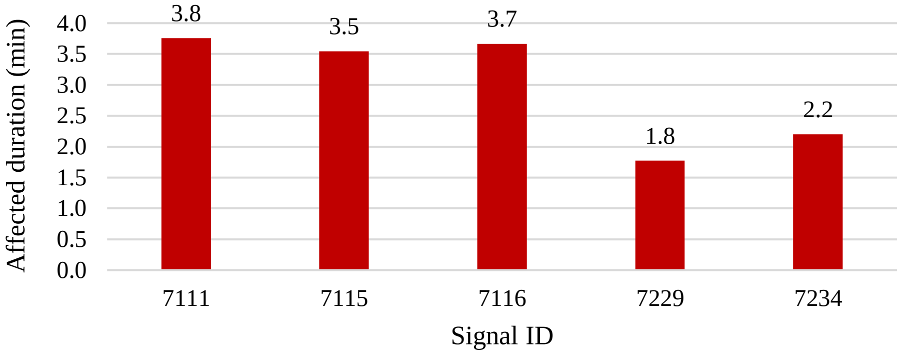

Figure D.8 Affected duration for West 9000 South by signal.

APPENDIX E. Speed Limits on Equipped and Not-Equipped Routes

This appendix shows the differences in speed limits on both equipped and not-equipped routes. Due to the length of the selected routes, the speed limit changes throughout each route. These zones of specific speed limits were used to gather travel speed data from the ClearGuide database. Travel speed data were analyzed by percentage of speed limit. How speed limits change on equipped routes is shown in Table E.1, where the changes for not-equipped routes are shown in Table E.2.

Table E.1 Speed Limits for Equipped Routes

Route	Shed	Speed Limit (mph)	Zones
East 9000 South from 700 East to Wasatch Boulevard	Cottonwood	40	
Redwood Road from 12600 South to 5400 South	West Jordan	45	*12600 South to Bennion Blvd*
		40	*Bennion Blvd to 5400 South*
Redwood Road from 5400 South to 3500 South	Murray	40	
Redwood Road from 3500 South to 400 South	Salt Lake	40	*3500 South to 1900 South*
		45	*1900 South to California Ave*
		40	*California Ave to 800 South*
		45	*800 South to 400 South*
700 East from 9000 South to 4500 South	Cottonwood	40	*9000 South to Fort Union Blvd*
		45	*Fort Union Blvd to 4500 S*
700 East from 4500 South to 3300 South	Murray	45	
Foothill Drive from I-80 to 1300 East	Parleys Canyon	45	*From I-80 to Before Thunderbird Dr.*
		40	
West 9000 South from 4000 West to Redwood Road	West Jordan	40	

Table E.2 Speed Limits for Not-Equipped Routes

Route	Comparable Route	Shed	Speed Limit (mph)	Zones
Van Winkle from 900 East to I-215	700 East	Cottonwood	50	900 E to 6100 S
			40	6100 S to I-215
Wasatch Boulevard from I-215 to Little Cottonwood Road	East 9000 South Foothill Drive	Cottonwood	50	
4500 South from I-15 to I-215	West 9000 South	Murray	40	I-215 to Redwood Rd
			50	Redwood Rd to Mackinac Dr
			40	Mackinac Dr to I-15
State Street from 400 South to Ford Avenue	Redwood Road	Salt Lake East	30	400 S to 900 S
			35	900 S to 3300 S
			40	3300 S to Ford Ave
State Street from Ford Avenue to 9000 South		Murray	40	

APPENDIX F. Safety Data for Equipped and Not-Equipped Routes

This appendix shows the information gathered from crash data. It includes the number of crashes for each analyzed snow season, the average number of crashes per day with snow, and the associated winter crash rate that was found. This was done for equipped routes, segments, and not-equipped routes. Any cell in the table that is bolded represents that the route or segment had a below-average crash rate compared to the four-year average that was calculated.

Table F.1 Crash Data for Equipped Routes

Route	**Crashes**				**Crashes per Day with Snow**			
	2016-2017	*2017-2018*	*2018-2019*	*2019-2020*	*2016-2017*	*2017-2018*	*2018-2019*	*2019-2020*
Redwood	117	89	132	132	3.90	3.71	3.77	2.81
700 East	32	26	50	33	1.07	1.08	1.43	0.70
Foothill	9	5	13	7	0.30	0.21	0.37	0.15
W 9000 S	16	9	16	24	0.53	0.38	0.46	0.51
E 9000 S	17	6	24	11	0.57	0.25	0.69	0.23

Table F.2 Crash Data for Equipped Segments

Segment	**Crashes**				**Crashes per Snow Day**			
	2016-2017	*2017-2018*	*2018-2019*	*2019-2020*	*2016-2017*	*2017-2018*	*2018-2019*	*2019-2020*
Redwood SLC	28	25	29	35	0.93	1.04	0.83	0.74
Redwood Murray	32	22	35	37	1.07	0.92	1.00	0.79
Redwood West Jordan	57	42	68	60	1.90	1.75	1.94	1.28
700 E Murray	9	7	12	6	0.30	0.29	0.34	0.13
700 E Cottonwood	23	19	38	27	0.77	0.79	1.09	0.57
Foothill Parleys	9	5	13	7	0.30	0.21	0.37	0.15
W 9000 S	16	9	16	24	0.53	0.38	0.46	0.51
E 9000 S	17	6	24	11	0.57	0.25	0.69	0.23

Table F.3 Crash Data for Not-Equipped Routes

Route	**Crashes**				**Crashes per Snow Day**			
	2016-2017	*2017-2018*	*2018-2019*	*2019-2020*	*2016-2017*	*2017-2018*	*2018-2019*	*2019-2020*
State	55	42	36	57	1.83	1.75	1.03	1.21
Van Winkle	4	3	4	2	0.13	0.13	0.11	0.04
Wasatch	8	5	10	5	0.27	0.21	0.29	0.11
4500 South	36	19	13	17	1.20	0.79	0.37	0.36

Table F.4 Crash Severity for Equipped Route

Crash Severity	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**	**Average**
No injury/PDO	136	96	171	133	134
Possible injury	33	23	40	54	38
Suspected Minor Injury	16	14	21	16	17
Suspected Serious Injury	5	2	2	4	3
Fatal	1	0	1	0	1

Table F.5 Crash Severity for Not-Equipped Route

Crash Severity	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**	**Average**
No injury/PDO	80	60	47	59	62
Possible injury	12	9	9	15	11
Suspected Minor Injury	11	0	5	6	6
Suspected Serious Injury	0	0	2	1	1
Fatal	0	0	0	0	0

Table F.6 Changes in Roadway Crash Rates by Equipped Routes

Route	**Roadway Crash Rate**							
	2016-2017	*Change*	*2017-2018*	*Change*	*2018-2019*	*Change*	*2019-2020*	*Average*
Redwood	7.59	-1.82	**5.77**	0.10	**5.87**	-1.50	**4.37**	5.90
700 E	**4.25**	0.07	4.31	1.37	5.69	-2.89	**2.80**	4.26
Foothill	2.01	-0.61	**1.40**	1.09	2.49	-1.49	**1.00**	1.72
W 9000 S	6.99	-2.08	**4.92**	1.08	**6.00**	0.70	6.70	6.15
E 9000 S	4.86	-2.72	**2.14**	3.74	5.88	-3.87	**2.01**	3.72

Table F.7 Changes in Roadway Crash Rates by Equipped Segments

Segment	**Roadway Crash Rate**							
	2016-2017	*Change*	*2017-2018*	*Change*	*2018-2019*	*Change*	*2019-2020*	*Average*
Redwood SLC	5.81	0.67	6.48	-1.33	**5.16**	-0.52	**4.64**	5.52
Redwood Murray	12.40	-1.74	**10.66**	0.97	11.63	-2.47	**9.15**	10.96
Redwood West Jordan	5.18	-0.41	4.77	0.53	5.30	-1.82	**3.48**	4.68
700 E Murray	4.57	-0.13	4.44	0.78	5.22	-3.28	**1.95**	4.05
700 E Cottonwood	**4.11**	0.13	**4.24**	1.58	5.82	-2.74	**3.08**	4.31
Foothill Parleys	2.01	-0.61	**1.40**	1.09	2.49	-1.49	**1.00**	1.72
W 9000 S	6.99	-2.08	**4.92**	1.08	**6.00**	0.70	6.70	6.15
E 9000 S	4.86	-2.72	**2.14**	3.74	5.88	-3.87	**2.01**	3.72

Table F.8 Changes in Roadway Crash Rates by Not-Equipped Routes

Route	**Roadway Crash Rate**							
	2016-2017	*Change*	*2017-2018*	*Change*	*2018-2019*	*Change*	*2019-2020*	*Average*
State	9.61	-0.44	9.17	-3.78	**5.39**	0.97	**6.36**	7.63
Van Winkle	1.65	-0.10	1.55	-0.13	1.42	-0.89	**0.53**	1.29
Wasatch	2.71	-0.59	**2.12**	0.79	2.91	-1.82	**1.08**	2.20
4500 S	10.70	-3.64	7.06	-3.75	**3.31**	-0.09	**3.23**	6.08